

EVALUATING TECHNOLOGIES AND METHODS TO LOWER NITROGEN OXIDE EMISSIONS FROM HEAVY-DUTY VEHICLES

Final Report

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Prepared for:

California Air Resources Board

Prepared by:

**Christopher A. Sharp, Staff Engineer
Cynthia C. Webb, Staff Engineer
Gary D. Neely, Sr. Research Engineer
Ian Smith, Research Engineer**

**Southwest Research Institute
P. O. Drawer 28510
San Antonio, Texas 78228-0510**

**6220 Culebra Road
San Antonio, Texas 78238-5166**

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Prepared by:

Christopher A. Sharp, Staff Engineer
Catalyst and Aftertreatment R&D
Diesel Engine & Emissions R&D Dept.

Approved by:

Charles E. Roberts, Jr., Director
Diesel Engine & Emissions R&D Dept.

ENGINE, EMISSIONS, AND VEHICLE RESEARCH DIVISION

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TABLE OF CONTENT

	Page
LIST OF FIGURES	III
LIST OF TABLES	XVII
NOMENCLATURE.....	XXII
EXECUTIVE SUMMARY	XXV
<i>Program Overview.....</i>	<i>xxv</i>
<i>Program Cycles</i>	<i>xxvii</i>
1.0 INTRODUCTION.....	1
2.0 CNG ENGINE PROGRAM.....	4
2.1 TASK 1: ENGINE, TEST CYCLES AND AFTERTREATMENT TECHNOLOGIES.....	4
2.1.1 <i>Test Cycles Selection.....</i>	<i>4</i>
2.1.2 <i>Test Engine.....</i>	<i>10</i>
2.1.3 <i>Initial Aftertreatment Technology Selection</i>	<i>12</i>
2.1.4 <i>Aftertreatment Aging Approach.....</i>	<i>15</i>
2.2 TASK 2: ENGINE BASELINE AND ULTRA-LOW NO_x CALIBRATION.....	18
2.2.1 <i>Baseline FTP, RMC, WHTC, and CARB Idle Results</i>	<i>19</i>
2.2.2 <i>Baseline Vocational Test Cycle Results.....</i>	<i>30</i>
2.2.3 <i>Engine Upgrades to Improve AFR Control</i>	<i>37</i>
2.2.4 <i>Steady State Engine Calibrations</i>	<i>38</i>
2.2.5 <i>Transient Engine Calibration</i>	<i>39</i>
2.3 TASK 4: CATALYST DOWN-SELECTION AND FINAL DEMONSTRATION RESULTS	42
2.3.1 <i>Catalyst Down-Selection.....</i>	<i>42</i>
2.3.2 <i>Final Engine Calibration.....</i>	<i>50</i>
3.0 DIESEL PROGRAM.....	78
3.1 TASK 1: TEST ENGINE AND AFTERTREATMENT TECHNOLOGIES.....	78
3.1.1 <i>Test Cycles Selection.....</i>	<i>78</i>
3.1.2 <i>40 CFR 1065 Compliance and Preconditioning Procedures</i>	<i>80</i>
3.1.3 <i>Test Engine.....</i>	<i>81</i>
3.1.4 <i>Proposed Aftertreatment Technologies.....</i>	<i>85</i>
3.2 TASK 2: ENGINE BASELINE AND ULTRA-LOW NO_x CALIBRATION.....	94
3.2.1 <i>Overview</i>	<i>94</i>
3.2.2 <i>Baseline FTP, RMC, WHTC, and CARB Idle Results</i>	<i>95</i>
3.2.3 <i>Baseline Vocational Test Cycle Results.....</i>	<i>105</i>

3.2.4	<i>Cold-Start Engine Calibration.....</i>	107
3.3	TASK 3: AFTERTREATMENT TECHNOLOGY SCREENING	123
3.3.1	<i>Aftertreatment Systems and Options Screened</i>	126
3.3.2	<i>Transient Reactor Bench.....</i>	135
3.3.3	<i>Aftertreatment Integration Controller</i>	139
3.3.4	<i>Traditional Technology Configurations</i>	139
3.3.5	<i>Advanced Technology Configurations.....</i>	146
3.3.6	<i>Enhanced Configurations</i>	154
3.3.7	<i>Impact of SCRF Regeneration on Fuel Consumption and GHG Emissions.....</i>	166
3.3.8	<i>Technology Ranking.....</i>	168
3.4	TASK 4: FINAL SYSTEM INTEGRATION AND ULTRA-LOW NO_x DEMONSTRATION	184
3.4.1	<i>Aftertreatment Aging Approach.....</i>	184
3.4.2	<i>Engine Integration and Testing of Final Candidate Aftertreatment Systems</i>	188
3.4.3	<i>Final Controls Implementation and Calibration for Final Candidate System Configuration 5.....</i>	229
3.4.4	<i>Final Aging</i>	235
3.4.5	<i>Final Demonstration Testing – FTP, RMC, and CARB Idle</i>	245
3.4.6	<i>Vocational Cycle Demonstration Testing</i>	284
4.0	SUMMARY AND CONCLUDING REMARKS	295
4.1	<i>CNG Engine – Cummins ISX12-G.....</i>	295
4.2	<i>Diesel Engine – Volvo MD13TC.....</i>	301
5.0	REFERENCES.....	312
		No. of Pages
APPENDIX A	Second-by-Second Vocational Cycle Schedules	32

LIST OF FIGURES

	Page
Figure 1. Schematic of Final Low NO _x CNG Engine Aftertreatment System.....	xxx
Figure 2. Temperature Histogram of the SBC Cycle for Final Aging of the CNG Engine Catalysts	xxx
Figure 3. Comparison of Cold Start FTP NO _x – Low NO _x Engine Versus Baseline	xxxii
Figure 4. Comparison of Cold-Start FTP NO _x – Low NO _x Engine Versus Baseline.....	xxxii
Figure 5. Comparison of Cold-Start Exhaust Temperatures – MD13TC Engine Versus Non-Turbo Compound Engine (MD13 VGT).....	xxxvi
Figure 6. Engine-Out Temperature Comparison – Modified Calibration Versus Baseline....	xxxvii
Figure 7. Engine-Out no _x Comparison - Modified Calibration Versus Baseline	xxxvii
Figure 8. SwRI HOT-GAS TRANSIENT REACTOR (HGTR).....	xxxviii
Figure 9. Composite ultra-Low NO _x Potential of Various Technology Configurations.....	xl
Figure 10. cComposite NO _x Potential and GHG Impact of Various Technology Options.....	xli
Figure 11. Diesel Engine Final Ultra-Low no _x Configuration.....	xliv
Figure 12. Diesel Engine Final Aging Cycle (4-Hour Duration per Cycle)	xlv
Figure 13. Aftertreatment Components Following Canning Failure During Final Aging	xlvi
Figure 14. Cold-Start Exhaust Temperature Comparison for WHTC vs. FTP – cng Program Engine.....	5
Figure 15. Normalized NYBC(x4) Cycle	7
Figure 16. Normalized Cruise-Creep (x10)	8
Figure 17. Normalized OCTA Bus Cycle.....	8
Figure 18. Schematic of Team A Catalyst Configuration.....	13
Figure 19. Schematic of Team B Catalyst Configurations	14
Figure 20. Schematic of Team C Catalyst Configuration.....	14
Figure 21. Standard Bench Cycle (SBC)	16
Figure 22. Catalyst Bed Temperature for ISX-12G and Doosan Engines	17

Figure 23. SBC Lambda, Catalyst Temperature, and Secondary Air Injection Over Time	18
Figure 24. Catalyst Bed Temperature for Cold and Hot-Start FTP Cycle.....	22
Figure 25. Cold and Hot-Start FTP NO _x Dilute Mass Rate.....	22
Figure 26. RMC-SET Catalyst Bed Temperature.....	23
Figure 27. RMC-SET NO _x Dilute Mass Rate.....	24
Figure 28. RMC-SET Raw Tailpipe Ammonia	24
Figure 29. NO _x Emissions for the US Heavy-Duty FTP and RMC-SET for the Cummins-Westport ISX12-G.....	25
Figure 30. Methane Emissions over the FTP and RMC-SET Compared to 2014/2017 GHG Standard Levels	25
Figure 31. Carbon Dioxide Emissions over the FTP and RMC-SET Compared to 2014/2017 GHG Standard Levels	26
Figure 32. Catalyst Bed Temperature over Cold and Hot Start WHTC	28
Figure 33. Dilute NO _x Mass Rate Emissions over Cold and Hot Start WHTC.....	29
Figure 34. Tailpipe Ammonia Emissions over Cold and Hot Start WHTC	29
Figure 35. CARB Idle NO _x Dilute Mass Rate and Catalyst Bed Temperature for Cummins-Westport ISX12-G.....	30
Figure 36. Emissions Summary for Vocational Cycles Plotted with US 2010 Heavy-Duty Emissions Standard	32
Figure 37. Catalyst Bed Temperature during NYBC Vocational Cycle.....	33
Figure 38. Dilute NO _x Mass Rate Emissions during NYBC Vocational Cycle	33
Figure 39. Catalyst Bed Temperature during Cruise-Creep Vocational Cycle	34
Figure 40. Dilute NO _x Mass Rate Emissions during Cruise-Creep Vocational Cycle	34
Figure 41. Tailpipe Ammonia Emissions during Cruise-Creep Vocational Cycle.....	35
Figure 42. Catalyst Bed Temperature during OCTA Bus Cycle	36
Figure 43. Dilute NO _x Mass Rate Emissions During OCTA Bus Cycle	36
Figure 44. Tailpipe Ammonia Emissions During OCTA Bus Cycle.....	37

Figure 45. Air-Fuel-EGR Mixer Resulting in Improved Mixture Homogeneity.....	38
Figure 46. Boost Recirculation Flow Circuit.....	38
Figure 47. Intake Manifold Filling Used With Speed-Density Calculation	40
Figure 48. Transport Delay Time for Engine Air-Fuel-EGR Mixture during the FTP	41
Figure 49. US FTP engine speed and load - boxed areas indicate no closed loop fueling.	42
Figure 50. Team A Catalyst Configuration.....	43
Figure 51. Team A Catalyst Bed Temperature for Cold and Hot FTP	44
Figure 52. Team A NO _x emissions for Cold and Hot FTP	44
Figure 53. Team B Catalyst Configurations (Option 1 and 2).....	45
Figure 54. Team B, Option 1, Catalyst Bed Temperature for Cold and Hot FTP	46
Figure 55. Team B, Option 1, NO _x emissions for Cold and Hot FTP	46
Figure 56. Team B, Option 2, Catalyst Bed Temperature for Cold and Hot FTP	47
Figure 57. Team B NO _x emissions for Cold and Hot FTP	47
Figure 58. Team C Catalyst Configuration.....	48
Figure 59. Team C Catalyst Bed Temperature for Cold and Hot FTP	48
Figure 60. Team C NO _x emissions for Cold and Hot FTP	49
Figure 61. SwRI Catalyst Configuration	49
Figure 62. Cold-start FTP long time constant VE correction.	50
Figure 63. Hot-start FTP long time constant VE correction.	51
Figure 64. Cold-start WHTC long time constant VE correction.	51
Figure 65. Typical Catalyst Bed Temperature for Cold and Hot-Start FTP Cycle.....	54
Figure 66: Dilute NO _x Mass Rate versus Underfloor Catalyst Bed Temperature during Cold-Start FTP	54
Figure 67. Typical Demonstration Cold and Hot-Start FTP NO _x Dilute Mass Rate.....	55
Figure 68. Typical Demonstration Cold and Hot-Start FTP Ammonia Concentration	56
Figure 69. Demonstration Cold and Hot-Start FTP CO and Methane Dilute Mass Rate	56

Figure 70: Test-to-Test NO _x Emission Variation over Five Days of FTP Testing	57
Figure 71. RMC-SET Catalyst Bed Temperature.....	58
Figure 72. Typical Demonstration RMC-SET NO _x Dilute Mass Rate	58
Figure 73. Typical Demonstration RMC-SET Raw Tailpipe Ammonia	59
Figure 74. Typical Demonstration Cold and Hot-Start RMC-SET CO and Methane Dilute Mass	59
Figure 75. Final Demonstration Methane Emissions over the FTP and RMC-SET Compared to 2014/2017 GHG Standard Levels	60
Figure 76. Final Demonstration Carbon Dioxide Emissions over the FTP and RMC-SET Compared to 2014/2017 GHG Standard Levels.....	61
Figure 77. WHTC NO _x and Methane Dilute Mass Rate Emissions with Engine Operating in Closed Loop Throughout Entire Map.	62
Figure 78. Demonstration Catalyst Bed Temperature Over Cold and Hot Start WHTC	63
Figure 79. Demonstration Dilute NO _x Mass Rate Emissions over Cold and Hot Start WHTC ...	64
Figure 80. Demonstration Tailpipe Ammonia Concentration over Cold and Hot Start WHTC ..	65
Figure 81. Demonstration Cold and Hot-Start WHTC CO and Methane Dilute Mass	65
Figure 82. Demonstration CARB Idle NO _x Dilute Mass Rate and Catalyst Bed Temperature for Cummins-Westport ISX12-G.....	66
Figure 83. CARB Idle Tailpipe Ammonia Concentration for Baseline and Demonstration Cummins-Westport ISX12-G.....	67
Figure 84. Demonstration Catalyst Bed Temperature During NYBC Vocational Cycle and Extended Idle.....	68
Figure 85. Demonstration Dilute NO _x Mass Rate Emissions During NYBC Vocational Cycle..	69
Figure 86. Demonstration Tailpipe Ammonia Concentration During NYBC Vocational Cycle.	69
Figure 87. Demonstration Dilute CO and Methane Mass Rate Emissions During NYBC Vocational Cycle	70
Figure 88. Demonstration Catalyst Bed Temperature During “Creep” Mode of Cruise-Creep Vocational Cycle	71
Figure 89. Demonstration Dilute NO _x Mass Rate Emissions During “Creep” Mode of Cruise- Creep Vocational Cycle.....	72

Figure 90. Demonstration Tailpipe Ammonia Emissions During “Creep” Mode of Cruise-Creep Vocational Cycle	72
Figure 91. Demonstration Dilute CO and Methane Mass Rate During “Creep” Mode of Cruise-Creep Vocational Cycle.....	73
Figure 92. Demonstration Catalyst Bed Temperature During OCTA Bus Cycle.....	74
Figure 93. Demonstration Dilute NO _x Mass Rate Emissions During OCTA Bus Cycle	74
Figure 94. Demonstration Tailpipe Ammonia Emissions During OCTA Bus Cycle.....	75
Figure 95. Demonstration Dilute CO and Methane Mass Rate During OCTA Bus Cycle	75
Figure 96. Final Demonstration Emissions Summary for Vocational Cycles Plotted with US 2010 HDE Emissions Standard	77
Figure 97. Cold-Start Exhaust Temperature Comparison for WHTC vs. FTP - Program Engine	79
Figure 98. Cold-Start FTP Exhaust Temperature Comparison for Volvo Engines	83
Figure 99. 2014 Volvo MD13TC Engine	84
Figure 100. Schematic of Two System Categories.....	86
Figure 101. Schematic of Full-Flow Heated Dosing Concept.....	90
Figure 102. Electrically Heated Catalyst	92
Figure 103. Schematic of Side-Flow Mini-Burner	93
Figure 104. Full Load Performance of Volvo MD13TC	95
Figure 105. Regulatory Cycle Tailpipe NO _x Data from Diesel Baseline.....	97
Figure 106. GHG Results from Diesel Baseline	97
Figure 107. Exhaust Temperatures for Diesel Baseline Cold-start FTP.....	98
Figure 108. Tailpipe NO _x for Diesel Baseline Cold-start FTP	99
Figure 109. Cumulative Tailpipe BS NO _x and Conversion Efficiency for Diesel Baseline Cold-start FTP	99
Figure 110. Exhaust Temperatures for Diesel Baseline Hot-start FTP	100
Figure 111. Tailpipe NO _x for Diesel Baseline Hot-start FTP	101
Figure 112. Cumulative Tailpipe BSNO _x and Conversion Efficiency for Diesel Baseline Hot-	

start FTP	101
Figure 113. Exhaust Temperatures for Diesel Baseline RMC-SET	102
Figure 114. Tailpipe NO _x for Diesel Baseline RMC-SET	103
Figure 115. continuous no _x and temperature data for baseline carB idle test.....	104
Figure 116. NYBC x 4 Cycle Exhaust Temperatures and NO _x for Diesel Baseline.....	105
Figure 117. Cruise+Creep x 10 Cycle Exhaust Temperatures and NO _x for Diesel Baseline	106
Figure 118. OCTA Bus Cycle Exhaust Temperatures and NO _x for Diesel Baseline.....	107
Figure 119. Baseline Cold-start FTP Results with Engine Calibration Focus Area Highlighted	109
Figure 120. Engine Speed and Load Points from Baseline FTP along with Selected Steady-state Test Points for Calibration Studies.....	110
Figure 121. Injection Patterns used during Calibration Investigations: a) Single Post, b) Double Post	111
Figure 122. Temperature, Exhaust Flow and Energy Results at Idle	112
Figure 123. Engine-out NO _x , EGR Rate and Fuel Flow Rate Results at Idle.....	113
Figure 124. Steady-state Calibration Tuning Results Obtained at Test Point 2 (1000 RPM, 500 Nm).....	114
Figure 125. Steady-state Calibration Tuning Results Obtained at Test Point 7 (1800 RPM, 500 Nm).....	115
Figure 126. Target FTP Engine Speed Profiles for Base and Elevated Idle Tests	117
Figure 127. Cold-start FTP Results: Engine Speed and Exhaust Temperature Comparison	118
Figure 128. Cold-start FTP Results: Instantaneous and Cumulative Engine-out NO _x Comparison	119
Figure 129. Example of EGR Valve Command Discrepancy during Rapid Pedal Increase (From Run 80)	120
Figure 130. EGR Valve Command and NO _x Comparison between Cold Cals 1 and 2.....	121
Figure 131. Torque Response Comparison between Cold Cals 1 and 2.....	121
Figure 132. Hot-Start to Cold-Start Tailpipe NO _x Mass Emission Trade-Off to Achieve Various Targeted Composite Emissions Levels	124

Figure 133. Baseline Cold-Start FTP Tailpipe NO _x Emissions Compared to an Ultra-Low NO _x Example.....	125
Figure 134. Baseline Hot-Start FTP Tailpipe NO _x Emissions Compared to an ULN Example	125
Figure 135. Overview of Operating Modes that Result in Low Temperature Operation and Some Technologies that can be Utilized to Increase Exhaust Energy	126
Figure 136. Stock DEF Injector and Dosing Layout in Exhaust	128
Figure 137. DEF Dosing Approaches Considered.....	128
Figure 138. Supplemental Heat Addition Options Considered	131
Figure 139. Advanced Technology Configuration with Options.....	133
Figure 140. Traditional Technology Configurations with Options	134
Figure 141. Example Layout of Aftertreatment for Screening Exercise	135
Figure 142. Schematic of Transient Reactor Bench	136
Figure 143. Comparison of Baseline Exhaust Gas Conditions Between the Engine and the HGTR	137
Figure 144. Baseline Tailpipe NO _x Emissions from the Stock ATS; Top Shows the Cold-Start Cycle, Bottom Shows the Hot-Start Cycle.....	138
Figure 145. Schematic of Integration Controller Function.....	139
Figure 146. Tailpipe NO _x Emission Comparison between the Baseline Engine Calibration and Cold Cal 1 for the Stock Emissions System.....	140
Figure 147. Measured Instantaneous and Accumulated DEF during the Baseline and Cold Cal 1 Cold-Start FTP Cycles.....	141
Figure 148. SCR Catalyst Inlet Temperature for the ULN Cold Cal 1 Calibration on Production ATS Compared to Same Configuration with Addition of a MB during Catalyst Warm Up Period.....	142
Figure 149. Measured DEF Dosing for Baseline Engine Calibration on Production ATS Compared to Cold Cal 1 Calibration with Addition of a Mini burner during Cold-Start	142
Figure 150. Composite NO _x Potential of Production ATS with Modified Engine Calibration and Supplemental Heat Addition	143
Figure 151. Comparison of Instantaneous and Accumulated Tailpipe NO _x Emissions for Production ATS Tests	144

Figure 152. Configuration of Traditional Technology Systems Tested	144
Figure 153. Improved Traditional Technology Systems with Modifiers	145
Figure 154. Composite Tailpipe NO _x Potential for Improved Traditional Technology System with Modifiers	146
Figure 155. DOC Based Advanced Technology Configurations Tested.....	147
Figure 156. Measured SCRF Inlet Gas Temperature and Accumulated Tailpipe NO _x Mass Emissions over the Cold-FTP for the DOC Based Advanced Technology System	148
Figure 157. Tailpipe Composite NO _x Potential for the DOC Based Advanced Technology Configurations Tested	149
Figure 158. PNA Based Advanced Technology Configurations Tested	150
Figure 159. Comparison of PNA-BASED Advanced Technology System Utilizing DEF Injection only and Utilizing Heated Dosing	151
Figure 160. Exhaust Gas Temperature Inlet to the SCRF for Standard DEF Approach and for Heated Dosing and Gaseous NH ₃ injection.....	152
Figure 161. Continuous and Accumulated Tailpipe NO _x over a Cold-FTP for the PNA Based Advanced Technology System.....	153
Figure 162. Tailpipe NO _x Potential for the PNA Based Advanced Technology Systems.....	154
Figure 163. Summary of Early Screening Results for Potential Composite Tailpipe NO _x on TC- Engine.....	155
Figure 164. Tested First SCR Catalyst Positions.....	156
Figure 165. Measured Exhaust Gas Temperature into First SCR Catalyst and Theoretical Energy (no heat loss) Required to Reach 200 °C during First 400 Seconds after Cold-Start	157
Figure 166. First SCR Catalyst Inlet Temperature Comparing LO SCR to SCRF Configuration	158
Figure 167. Low Temperature NO _x Conversion efficiency of LO SCR under Standard SCR Reaction for Idle and Moderate Flow and N ₂ O at Idle Conditions.....	159
Figure 168. TP NO _x and N ₂ O for PNA Based Advanced Technology Configuration with and without LO SCR.....	160
Figure 169. Traditional and Advanced Technology Configurations Compared during MB Positioning Comparison	161

Figure 170. Fuel and Air Delivered to MB during Three Separate Cold-Start FTP Tests, Utilizing the Same MB Calibration	161
Figure 171. Measured Exhaust Gas Temperature Upstream of the First SCR Catalyst for Both Traditional and Advanced Technology Configurations	162
Figure 172. SCRF Catalyst Inlet NO _x and Injected Fuel Energy and Thermal Energy for Advanced Technology Configurations.....	163
Figure 173. Tailpipe NO _x and N ₂ O Accumulated Mass Emissions for Alternate MB location	164
Figure 174. First SCR Catalyst Inlet Temperature during cold ftp for Various advanced technology Configurations	165
Figure 175. Tailpipe NO _x Emissions during Cold FTP for PNA-based Advanced Technology System with Various Thermal Manage Strategies	165
Figure 176. Soot Regeneration Results for DPF versus SCRF Configurations.....	167
Figure 177. Aftertreatment Technologies and Engine Control Approaches and Their Cumulative Composite NO _x Potential on Test Engine.....	169
Figure 178. Summary of Composite ultra Low NO _x Potential of Various Technology Configurations	170
Figure 179. Technology Configurations Considered and Ranked under Screening Task.....	171
Figure 180. Composite NO _x Potential and Fuel Economy Penalty of Various Traditional and Advanced Technology Combinations	175
Figure 181. Potential Additional cold-start Fuel consumption and CompositeFuel Economy Penalty of Various Traditional and Advanced Technology Combinations.....	176
Figure 182. Modular Packaging of SCR System Catalysts for Screening.....	189
Figure 183. Final Multi-Bed SCR System Package.....	190
Figure 184. SCR Catalyst Inlet Showing NH ₃ Sensor Probe (and Production Temperature Sensor).....	191
Figure 185. Mixer Installed Upstream of Electrically Heated Catalyst.....	192
Figure 186. Mixer Installation After Mini-Burner with Shorter Distance to SCRF Inlet.....	193
Figure 187. Schematic of Model-Based Dosing Controller.....	194
Figure 188. Aftertreatment System Diagram with Sensors	194
Figure 189. Schematic of SCR Catlyst Model with Multiple Cells.....	196

Figure 190. Schematic of Ammonia Coverage Control.....	197
Figure 191. Schematic of Sensor Feedback Correction Approach	197
Figure 192. Average Ammonia Coverage and Temperature Over Hot-Start Transient FTP	198
Figure 193. Coverage Profile of the SCRF Catalyst Over Hot-Start Transient FTP Cycle.....	199
Figure 194. DEF Dosing Rate Over Hot-Start Transient FTP Compared to Stoichiometric Demand (Based on ANR 1 and System Inlet NO _x), Average Cycle.....	200
Figure 195. DEF Dosing Rate Over Hot-Start Transient FTP Compared to Stoichiometric Demand, Following High Temperature Event	201
Figure 196. FINAL Candidate Configuration 1 – PNA+HD1+SCRF+SCR+ASC.....	201
Figure 197. Modified NO _x Calibrations Early in Engine Optimization – configuration 1	202
Figure 198. Early Cold Cycle Oxygen and CO Levels with Modified engine Calibration – configuration 1	203
Figure 199. Hot-Start FTP Cycle Temperatures Upstream of DEF Dosing Point and the SCRF Inlet – configuration 1 without thermal management	204
Figure 200. Hot-Start FTP NO _x for configuration 1 without Thermal Management in Early Cycle	205
Figure 201. Comparison of Hot-Start FTP Tailpipe NO _x with and without EHC for Configuration 1.....	205
Figure 202. Cumulative Cold-Start NO _x Mass Emissions at Various Points in the System for final candidate Configuration 1	206
Figure 203. Cold-Start NO _x and Temperature at Various Points in final candidate System Configuration 1, HD1-1.8kW.....	207
Figure 204. Cold-Start NO _x and Temperature at Various Points in final candidate System Configuration 1 with Upgraded Heater, HD1-6kW	208
Figure 205. Cumulative Cold-Start NO _x Mass Emissions at Various Points in System for final candidate Configuration 1 with 6kW EHC	210
Figure 206. Final Candidate System Configuration 2 – Light-Off SCR+PNA+ SCRF+SCR+ASC with Partial Flow Heated Dosing (HD2).....	211
Figure 207. Final Candidate System configuration 2 Used for Concept evaluation on Engine of LoSCR Approach	212
Figure 208. Cold-Start NO _x and Temperatures Before and After LoSCR, First 300 Seconds,	

Configuration 2.....	213
Figure 209. LOSCR Performance Over the Full Cold-Start FTP Cycle (NH ₃ Off at 565 Seconds), Configuration 2.....	214
Figure 210. SCRF Outlet Temperature – LoSCR (configuration 2) versus Configuration 1 with 6kW EHC	214
Figure 211. Cold-Start FTP NO _x and Temperatures for Configuration 2, 0-450 Seconds	215
Figure 212. Accumulated Cold-Start FTP NO _x Mass for Configuration 2 (Lo-SCR) at Various Points in the System	216
Figure 213. Final Candidate System Configuration 3 – PNA+HD1+SCR+SCRF+SCR+ASC. 217	
Figure 214. Final Candidate System Configuration 4 (not Examined on Engine) – EHC+DOC+SCRF+SCR+ASC	218
Figure 215. Final Candidate System Configuration 5 (Final Approach) – PNA+MB+SCRF+SCR+ASC.....	219
Figure 216. Mini-Burner Installation, Downstream of PNA	220
Figure 217. Mini-Burner Connections (Fuel, Air, Spark)	221
Figure 218. SCRF Inlet Temperature Comparison – Mini-Burner versus 6kW EHC.....	221
Figure 219. Cold-Start FTP NO _x and Temperatures for Configuration 5 (Mini-Burner) – 0-450 Seconds.....	222
Figure 220. Cold-Start FTP Cumulative NO _x Mass at Various Points – Configuration 5 with Development Aged Parts.....	223
Figure 221. Hot-Start FTP NO _x and Temperature for Configuration 5 – Preliminary Results with Development Aged Parts.....	224
Figure 222. Hot-Start FTP Cumulative NO _x at Various Locations – Configuration 5 Preliminary Data with Development Aged Parts	225
Figure 223. Cold-Start N ₂ O Emissions for Configuration 5, development aged parts.....	227
Figure 224. Hot-Start N ₂ O Emissions for Configuration 5 development aged parts.....	227
Figure 225. Cumulative Cold-Start NO _x and Analysis of Cold Cal 2 Option without PNA.....	228
Figure 226. Cold-Start WHTC NO _x and Temperature – Development Aged Parts and Final Controller, 0-450 Seconds	231
Figure 227. Comparison of Early Cold-Start Cycle Behavior Across PNA – WHTC versus FTP	

.....	232
Figure 228. Temperature and NO _x Over Hot WHTC with Development Aged Parts – final configuration	233
Figure 229. Engine-Out and Tailpipe NO _x Mass Over Hot WHTC with Development Aged Parts – final configuration	233
Figure 230. Cumulative Hot WHTC NO _x Mass with Development Aged Parts – final configuration	234
Figure 231. Initial Cycle for Final Aging (2.5 Hour Duration)	236
Figure 232. Final Durability Cycle Used for Final Aging (4-Hour Duration).....	239
Figure 233. PNA Immediately Following Canning Failure.....	240
Figure 234. SCRF Inlet Following PNA Canning Failure.....	241
Figure 235. Borescope Inspection of SCRF Following Canning Failure	242
Figure 236. CT-Scan Analysis of SCRF Following PNA Canning Failure	242
Figure 237. SCRF Weight and Measured Oil Consumption Over the Course of Final Aging...	244
Figure 238. Cold-Start PNA Behavior for Preliminary Results on Development Aged Parts ...	256
Figure 239. Cold-Start PNA Behavior for Final Controller Results on Development Aged Parts	256
Figure 240. Cold-Start PNA Behavior for Final Aged Parts	257
Figure 241. Comparison of PNA-Stored NO _x for all Three Cases in Early Cold-Start FTP	257
Figure 242. Hot-Start FTP NO _x and Temperature – Development Aged Parts.....	259
Figure 243. Hot-Start FTP NO _x and Temperature – Final Aged Parts	259
Figure 244. Comparison of Hot-Start FTP SCRF-Outlet NO _x – Development Aged versus Final Aged Parts	260
Figure 245. Comparison of Hot-Start FTP Tailpipe NO _x – Development Aged versus Final Aged Parts	260
Figure 246. RMC-Set NO _x , NH ₃ , and Temperature – Development Aged Parts	262
Figure 247. RMC-Set NO _x , NH ₃ , and Temperature – Final Aged Parts	262
Figure 248. RMC-Set NO _x , NH ₃ , and Temperature – Final Aged Parts, Increased Storage Targets	

.....	263
Figure 249. RMC-Set SCRF-Out N ₂ O – Final Aged Parts versus Development Aged Parts	263
Figure 250. Cumulative Tailpipe NO _x Comparison – Final Aged Versus Development Aged .	275
Figure 251. Cold-Start whtc pna Behavior – Development Aged Parts	275
Figure 252. Cold-Start whtc pna Behavior– Final Aged Parts	276
Figure 253. Comparison of Cold-Start whtc pna storage – Final Aged Parts Versus Development Parts	276
Figure 254. Comparison of WHTC Cold-Start scrf-out NO _x Mass Rates – Final Aged Parts Versus Development Parts	277
Figure 255. Comparison of WHTC Cold-Start Tailpipe NO _x Mass Rates – Final Aged Parts Versus Development Parts	277
Figure 256. Hot-Start whtc NO _x and Temperature for Development Aged Parts	279
Figure 257. Hot-Start whtc NO _x and Temperature for Final Aged Parts.....	279
Figure 258. Comparison of scrf-out no _x Mass – Final Aged Parts Versus Development Parts .	280
Figure 259. Comparison of Tailpipe no _x Mass – Final Aged Parts Versus Development Parts..	280
Figure 260. Temperature and NO _x Mass for Baseline Carb Idle Test	282
Figure 261. Temperature and NO _x Mass for Final Aged Carb Idle Test (with Burner Re-Light Enabled).....	282
Figure 262. Temperature and NO _x Mass for Final Aged Carb Idle Test (with Burner Re-Light Disabled)	283
Figure 263. Baseline NO _x and Temperature Data for NYBC Vocational Cycle.....	286
Figure 264. Final Aged NO _x and Temperature data for NYBC Vocational Cycle, with Re-Light	286
Figure 265. Final Aged NO _x and Temperature Data for NYBC Vocational Cycle, without Re-Light	287
Figure 266. Baseline NO _x and Temperature Data for the Cruise-Creep Vocational Cycle.....	290
Figure 267. Final Aged NO _x and Temperature Data for the Cruise-Creep Vocational Cycle, with Re-Light.....	290
Figure 268. Final Aged NO _x and Temperature Data for the Cruise-Creep Vocational Cycle,	

without Re-Light	291
Figure 269. Baseline NO _x and Temperature Data for the OCTA Bus Vocational Cycle	293
Figure 270. Final Aged NO _x and Temperature Data for the OCTA Bus Vocational Cycle	294
Figure 271. SCHEMATIC OF FINAL LOW NO _x CNG ENGINE AFTERTREATMENT SYSTEM	296
Figure 272. Composite ultra-Low NO _x Potential of Various Technology Configurations	302

LIST OF TABLES

	Page
Table 1. Program Vocational Cycles	xxviii
Table 2. CNG Engine NO _x Emissions Comparison – Low NO _x Engine Versus Baseline, g/hp-hr	xxxi
Table 3. CNG Engine Comparison of Other Emissions – Low NO _x Engine Versus Baseline	xxxi
Table 4. CNG Engine Vocational Cycle Emissions – Low NO _x Engine Versus Baseline	xxxiii
Table 5. Final Technology Rankings Based on Screening Results	xliii
Table 6. Diesel Engine NO _x EMISSIONS COMPARISON –LOW NO _x ENGINE VERSUS BASELINE, g/hp-hr	xlvi
Table 7. Diesel Engine NO _x Aftertreatment Performance – Low NO _x Engine Versus Baseline	xlviii
Table 8. Diesel Engine Comparison of GHG EMISSIONS – Low NO _x Engine Versus Baseline .	1
Table 9. Diesel Engine Vocational Cycle Emissions – Low NO _x Engine Versus Baseline	lii
Table 10. Baseline NO _x Engine Emissions and Conversion Efficiencies OVER THE FTP.....	1
Table 11. Example of Cycle Specific NO _x Emissions in an Ultra-low NO _x Application	2
Table 12. Initial Development Targets	4
Table 13. Summary of Vocational Cycles Chosen for ARB Low NO _x Demonstration	6
Table 14. Pre-Conditioning Procedures for the Vocational Cycles	9
Table 15: Performance specifications of Doosan GL11K and Cummins ISX12-G	11
Table 16. Cummins-Westport ISX12-G Engine Specifications	18
Table 17. CARB Certification Natural Gas Blend Specifications	19
Table 18. Baseline Composite FTP Tailpipe Emissions for Cummins-Westport ISX12-G.....	21
Table 19. Baseline RMC-SET Tailpipe Emissions for Cummins-Westport ISX12-G.....	23
Table 20. WHTC Tailpipe Emissions.....	26
Table 21. WHTC Engine-Out Emissions.....	28
Table 22. Catalyst Conversion Efficiency over WHTC	28

Table 23. Tailpipe Emissions for NYBC, Cruise-Creep, and OCTA Vocational Cycles	31
Table 24. Engine-Out Emissions for NYBC, Cruise-Creep, and OCTA Vocational Cycles	31
Table 25. Catalyst Conversion Efficiency for NYBC, Cruise-Creep, and OCTA Vocational Cycles	31
Table 26. Tailpipe Emissions for Cold and Hot FTP with Catalyst Configuration from Team A	43
Table 27. Tailpipe Emissions for Cold and Hot FTP with Catalyst Configuration from Team B, Option 1 (close-coupled and underfloor catalyst)	45
Table 28. Tailpipe Emissions for Cold and Hot FTP with Catalyst Configuration from Team B, Option 2 (single underfloor catalyst).....	47
Table 29. Tailpipe Emissions for Cold and Hot FTP with Catalyst Configuration from Team C	48
Table 30. Tailpipe Emissions for Cold and Hot FTP with Catalyst Configuration from SwRI...	49
Table 31. CARB Certification Natural Gas Blend Specifications	52
Table 32. Cold and Hot Ranges for Raw and Dilute Emissions Benches	52
Table 33. Final Demonstration Composite FTP Tailpipe Emissions for Cummins-Westport ISX12-G	53
Table 34: Final Demonstration RMC-SET Tailpipe Emissions for Cummins-Westport ISX12-G	57
Table 35. Raw and Dilute GHG Emissions for the Final Demonstration FTP and RMC-SET compared to the 2014/2017 GHG Standards.....	60
Table 36. WHTC Emissions with Full Closed Loop Fueling Map.....	62
Table 37. Demonstration WHTC Tailpipe Emissions	63
Table 38. Demonstration Tailpipe Emissions for NYBC	68
Table 39. Demonstration Tailpipe Emissions for Cruise-Creep	70
Table 40. FINAL Demonstration Tailpipe Emissions for OCTA.....	73
Table 41. FINAL Demonstration Emissions Summary for Vocational Cycles.....	77
Table 42. Initial Development Targets FOR diesel AGED AFTERTREATMENT SYSTEM ...	78
Table 43. 2014 Volvo MD13TC Engine Specifications.....	95
Table 44: Baseline Composite FTP Tailpipe Emissions for Volvo MD13TC	96

Table 45: Baseline Composite RMC-SET Tailpipe Emissions for Volvo MD13TC.....	96
Table 46: Baseline Composite WHTC Tailpipe Emissions for Volvo MD13TC	103
Table 47. baseline carb idle test results for volvo md13tc.....	104
Table 48. Target Speed and Load Settings for Selected Steady-state Test Points.....	110
Table 49. Summary of Steady-state Calibration Tuning at Test Points 1-8	116
Table 50. Cold-start FTP Emissions Summary for Engine Calibration Task.....	119
Table 51. Cold-start FTP Emissions Summary for Engine Calibration Task with Cold Cal 2 Results Added.....	122
Table 52. Baseline NO _x Engine Emissions and Conversion Efficiencies.....	123
Table 53. Typical Catalyst Volumes.....	134
Table 54. Filter Inlet PM Emissions (downstream of system DOC)	168
Table 55. Predicted Regeneration Frequency for Baseline DPF and SCRF Configurations.....	168
Table 56. Technology Ranking Table - FTP Composite NO _x Potential	173
Table 57. Fuel Economy Impact of Various Calibrations, Heat Addition Options and Technologies that Impact Passive Regeneration	174
Table 58. Technology Ranking Table - Fuel Economy Impact.....	177
Table 59. Technology Ranking Table - Durability Rating	179
Table 60. Technology Ranking Table - Complexity Rating.....	180
Table 61. Technology Ranking Table - Additional Cost Rating	181
Table 62. Final Technology Ranking Table	183
Table 63. DAAAC Aging Calculations	185
Table 64. final candidate Configuration 1 - FTP Cycle NO _x , G/HP-HR (development aged)...	206
Table 65. final candidate Configuration 1 - FTP Cycle NO _x , G/HP-HR Higher Capacity EHC Heater (6kW).....	209
Table 66. Summary NO _x Emissions for Configuration 2 with Lo-SCR	216
Table 67. Summary of NO _x Emissions for Configuration 5 with Mini-Burner and PNA	225

Table 68. Preliminary Summary of CO ₂ Impact of Configuration 5 – with Development Aged Parts	226
Table 69. Comparison of Tailpipe NO _x Levels for Preliminary and Final Controls Using development Aged Parts – final configuration.....	230
Table 70. WHTC NO _x Levels for the Final Controller with Development Aged Parts	231
Table 71. Comparison of Hot-Start Conversion Behavior for WHTC and FTP Cycles.....	234
Table 72. Results of SCRF Regeneration Experiments	235
Table 73. Final Aging Chronology and Significant Events	237
Table 74. Summary of Individual Dilute and Raw Tailpipe Test Results for Final Aged Parts – FTP and RMC-Set Cycles	250
Table 75. Summary of Individual Engine-Out Emission Levels for Final Aged Parts – FTP and RMC-Set Cycles.....	251
Table 76. Overall Summary of Regulated Tailpipe Emissions for Both Raw and Dilute measurements – ftp and rmc-set cycles.....	252
Table 77. NO _x Emissions Summary for FTP and RMC Cycles, Based on Dilute Tailpipe Measurements – final configuration, final aged parts	253
Table 78. Comparison of Tailpipe and Dilute NO _x Measurements Based on Overall Averages from Five Replicates	253
Table 79. Comparison of NO _x from Final Aged Parts to Earlier Data Sets	254
Table 80. Impact of Low NO _x Configuration on CO ₂ Emissions Based on Final Aged Data....	265
Table 81. Tailpipe N ₂ O Data for FTP and RMC-Set Cycles	266
Table 82. Summary of Calculations to Determine UAF for the Final Low NO _x System.....	267
Table 83. Summary of Individual Dilute and Raw Tailpipe Test Results for Final Aged Parts – WHTC Cycles	270
Table 84. Summary of Individual RAW ENGINE-OUT Test Results for Final Aged Parts – WHTC Cycles	271
Table 85. Overall Summary of Regulated Tailpipe Emissions for Both Raw and Dilute – WHTC Cycles	272
Table 86. NO _x Emissions Summary for whtc cycles	273
Table 87. Comparison of Tailpipe and Dilute whtc Measurements Based on Overall Averages	

from three Replicates.....	273
Table 88. Comparison of Final Aged whtc Results to Earlier Data.....	273
Table 89. Comparison of co2 Emissions on whtc Cycle – Final Low no _x Configuration Versus Engine Baseline.....	278
Table 90. Summary of Carb Extended Idle Test Results – Final Aged versus Baseline.....	281
Table 91. Summary of NYBC Vocational Cycle Results.....	285
Table 92. Summary of Cruise-Creep Vocational Cycle Results.....	288
Table 93. Summary of Octa Bus Vocational Cycle Results	293
Table 94. CNG Engine NO _x Emissions Comparison – Low NO _x Engine (Final Aged Parts) Versus Baseline, g/hp-hr	296
Table 95. CNG Engine Comparison of GHG and NH3 Emissions – Low NO _x Engine (Final Aged Parts) Versus Baseline	296
Table 96. CNG Engine Vocational Cycle Emissions – Low NO _x Engine (Final Aged Parts) Versus Baseline	299
Table 97. Diesel Engine NO _x Emissions Comparison –Low NO _x Engine Versus Baseline, g/hp-hr.....	303
Table 98. Diesel Engine NO _x Aftertreatment Performance – Low NO _x Engine Versus Baseline	303
Table 99. Diesel Engine Comparison of GHG EMISSIONS – Low NO _x Engine Versus Baseline	307
Table 100. Diesel Engine Vocational Cycle Emissions – Low NO _x Engine (final Aged Parts) Versus Baseline	308

NOMENCLATURE

- ACC: Accumulated
- ACES: Advanced Collaborative Emissions Study
- ACM: Aftertreatment Control Module
- AFR Air-Fuel Ratio
- AHI: Auxiliary Hydrocarbon Injector
- ANR: Ammonia NO_x Ration
- ASC: Ammonia Slip Catalyst
- ATS: Aftertreatment System
- BO: Burner Out - used on HGTR Simulation - Equivalent to "Engine-Out"
- BSFC Brake-specific Fuel Consumption
- BSPM: Brake-specific Particulate Matter
- CAD: Crank Angel Degrees
- CARB: California Air Resources Board
- CC1-EI: Cold-Calibration I - Elevated Idle
- CC1-SI: Cold-Calibration I - Standard Idle
- CC2-EI: Cold-Calibration 2 - Elevated Idle
- CFR: Code of Federal Regulation
- CFV: Continuous Flow Valve
- CMD: Command
- CNG: Compressed Natural Gas
- CO₂: Carbon Dioxide
- CoV: Coefficient of variability
- Cu-Z Copper-Zeolite
- CVS: Continuous Volume Sampling
- DAAAC: SwRI Diesel Aftertreatment Accelerate Aging Consortium
- DEF: Diesel Exhaust Fluid – 32.5% urea, 67.5% water
- DOC: Diesel Oxidation Catalyst
- DPF: Diesel Particulate Filter
- ECU: Engine Control Unit
- EGR: Exhaust Gas Recirculation
- EH: Electric Heater
- EHC: Electrically Heated Catalyst
- EHC: Electrically Heated Catalyst
- EI: Elevated Idle
- EMA: Engine Manufacturers Association
- EMTC: Emission Measurement and Testing Committee

- EO: Exhaust Out
- EPA: Environmental Protection Agency
- FBC: Fuel Borne Catalyst
- FOCAS: Fuel/Oil Catalyst Aging System
- FTIR: Fourier Transform Infrared Spectroscopy
- FTP: Federal Test Procedure
- G/HP-HR: Grams per brake-horsepower-hour
- GHG: Green House Gas
- HC: Hydrocarbon
- HD1: Heated design option 1 - full-flow, 2kW
- HD2: Heated design option 2 - partial-flow, 1kW
- HDE: Heavy Duty Engine
- HGTR: Hot Gas Transient Reactor
- INST: Instantaneous
- IT: Intake Throttling
- KLSA: Knock-limited Spark Advance
- LOSCR: Light-Off SCR
- MB: Mini-Burner, Diesel Fueled; 10kW
- MECA: Manufacturers of Emission Controls Association
- MECA: Manufacturers of Emissions Controls Association
- N₂O: Nitrous Oxide
- NAAQS: National Ambient Air Quality Standards
- NH₃: Gaseous Ammonia Injection
- NMHC: Non-methane Hydrocarbon
- NO: Nitric Oxide
- NO₂: Nitrogen Dioxide
- NPRM: Notice of Proposed Rulemaking
- NYBC: New York Bus Cycle
- OCTA: Orange County Transit Authority
- OEM: Original Equipment Manufacturer
- PM: Particle Matter
- PNA: Passive NO_x Adsorber
- RFP: Request for Proposal
- RMC-SET: Ramped Modal Cycle Supplemental Emissions Test
- RT: Real Time
- SBC: Standard Bench Cycle
- SCR: Selective Catalytic Reduction
- SCR: Selective Catalytic Reduction

- SCRF: SCR on Filter
- SCRF: Selective Catalytic Reduction on Filter
- SFI: Supplemental Fuel Injection (in-exhaust dosing)
- SI: Standard Idle
- SMD: Sauter Mean Diameter
- SwRI: Southwest Research Institute
- TC Out T: Turbo-compounder Outlet Temperature
- TC: Turbo-compounder
- TDC: Top Dead Center
- THC: Total Hydrocarbon
- TM: Thermal Mass
- TP Tailpipe
- TWC: Three Way Catalyst
- UEGO: Unheated Exhaust Gas Oxygen Sensor
- ULN: Ultra-low NO_x
- UWS: Urea Water Solution, also called DEF
- VE: Volumetric Efficiency
- VVA: Variable Valve Actuation
- WHTC: World Harmonized Heavy-Duty Transient Cycle

EXECUTIVE SUMMARY

The 2010 emission standards for heavy-duty engines have established a limit for oxides of nitrogen (NO_x) emissions of 0.20 g/hp-hr, a 90% reduction from the previous emission standards. However, it is projected that even when the entire on-road fleet of heavy-duty vehicles operating in California is compliant with the 2010 emission standards, the upcoming National Ambient Air Quality Standards (NAAQS) requirements for ambient particulate matter (PM) and ozone will not be achieved in California without further significant reductions in NO_x emissions from the heavy-duty vehicle fleet [1][2]. The 2010 emission standards provided little incentive for manufacturers to pursue NO_x emission reductions beyond 0.20 g/hp-hr at the outset of this work. In 2013, California Air Resources Board (CARB) promulgated optional lower NO_x standards (at 0.02, 0.05, and 0.1 g/hp-hr levels), and provided some incentive funding in an effort to encourage development towards lower NO_x levels. In September, 2015 CARB published technology assessments for both heavy-duty diesel and natural gas fueled engines, in an effort to evaluate the state of technology available to lower NO_x emissions further [3][4].

However, although the literature reflects the potential for further significant NO_x reductions, there is limited information available regarding the feasibility of achieving very low NO_x emission levels below 0.20 g/hp-hr. To address this lack of information, CARB funded a research program to explore and investigate the feasibility of significantly reducing NO_x emissions below today's standard in Class 8 capable heavy-duty engines (HDE).

Program Overview

This project studied two different engine platforms; a compressed natural gas (CNG)-based engine system and a diesel-based engine system. The exhaust gas chemistries of these two systems are quite different (CNG is a near stoichiometric chemistry, whereas diesel exhaust is a lean environment). The catalyst technologies utilized to achieve the heavy-duty 2010 NO_x emissions standard on these two systems are also different and relatively new to the heavy-duty market. As the technologies mature, there will be opportunities to reduce the NO_x levels below the current 2010 standard levels.

This study involved identifying advanced, production feasible emission control solutions for both of these platforms, screening and developing modified engine and emissions system control strategies on aged combinations of advanced aftertreatment systems, then selecting, refining, and demonstrating ultra-low NO_x (ULN) emission levels with the selected systems.

The goal was to demonstrate NO_x emission levels significantly lower than the current heavy-duty standard of 0.20 g/hp-hr. The project target for tailpipe NO_x emission was 0.02 g/hp-hr, which represented a 90% reduction from 2010 emission levels. An additional goal of the project was that the demonstration be conducted with technologies feasible for production systems, as well as being consistent with a path toward meeting current and future heavy-duty greenhouse gas (GHG) and fuel economy standards. Essentially, the program needed to balance NO_x reduction efficiency with fuel consumption changes to achieve maximum NO_x reduction

for the minimum increase in fuel consumption. Given the program goals, there were two primary areas of focus for the development effort:

- Developing substantial improvements in cold-start emission control and aftertreatment system warm-up as compared to current production systems.
- Achieving very high rates of NO_x reduction, in excess of 99%, across the aftertreatment system during warmed up operation.

Under Task 1 of this program, several test cycles representing various types of vocational engine operation were developed based on cycle information supplied by CARB. Two heavy-duty engine platforms were obtained for this study:

- CNG: A 2012 Cummins ISX 12-G engine certified to 2010 emissions standards (supplied by SwRI).
- Diesel: A 2014 Volvo MD13TC engine certified to Euro VI standards, but capable of meeting 2010 emissions standards as well (supplied by Volvo).

Task 1 also involved identification of advanced aftertreatment solutions that could be leveraged to meet ULN levels for both of these two platforms. The aftertreatment systems selected for the CNG application were similar in function to three-way catalyst (TWC) used in stoichiometric gasoline applications. For the diesel application, the selected systems were combinations of selective catalytic reduction (SCR) and diesel particulate filter (DPF) technologies with some planned means for accelerating catalyst warm-up and providing thermal management. The Manufacturers of Emission Controls Association (MECA) provided and conditioned all the emission control aftertreatment systems used in this study and supported aging of these systems for final demonstration testing.

Under Task 2 of the program, baseline engine emissions for both platforms were measured, with the stock emission systems and controls, over the targeted test cycles (selected under Task 1), and updated engine calibrations were developed in order to enable the integrated systems to reach program targets. During baseline testing, continuous modal emissions, temperature, exhaust flow, and integrated emissions were measured. The engine emissions were characterized using modal raw and dilute gas analyzers, Fourier Transform Infrared Spectroscopy (FTIR), and integrated bag and particulate filter samples. This work was conducted in a 40 CFR 1065 compliant test cell. The engines were then relocated to development cells, wherein modified engine control strategies to lower NO_x emissions were developed.

Under Task 3 of the project, candidate aftertreatment systems underwent initial screening and early control development. Because stoichiometric TWC technology is fairly mature due to experience gained from years of application on light-duty, there were not a large variety of technologies offered for the stoichiometric CNG system. As a result, the off-engine screening phase of the program was bypassed on the CNG system, and the work proceeded directly to the engine integration under Task 4.

For the diesel system, it was anticipated that there would be many advanced technology options offered and that accelerating the light-off of the catalysts in this system would be more difficult and require increased development. Therefore, Task 3 involved an extensive screening and calibration development effort for the diesel platform. To maximize the number of options that were examined, Southwest Research Institute (SwRI) leveraged the capability of the burner-based FOCAS[®] Hot Gas Transient Reactor (HGTR[®]) system to screen aftertreatment options. This off-engine screening allowed for higher efficiency in screening and selection of candidate systems for final optimization. Task 2 (engine management strategy development) and Task 3, (aftertreatment component screening), were conducted simultaneously to develop stable, feasible strategies that simultaneously achieved high NO_x reductions while attempting to minimize any negative impact on GHG emissions and fuel consumption.

Through this parallel screening and calibration development process, many different aftertreatment systems and combinations of systems were tested and tuned. Task 3 concluded with a review of the performance and penalties and feasibility of all the components and combinations of components assembled into complete systems. Based on the results, candidate technology systems were identified and ranked, with the highest ranked systems progressing to on-engine integration and final demonstration in Task 4.

In Task 4, the engines were relocated to a 40 CFR 1065 compliant transient test cell. Candidate systems identified in Task 3 were integrated on the engine, along with engine NO_x management strategies developed under Task 2. The calibrations and controls were tuned to reduce NO_x emission levels to meet the program target over the Federal Test Procedure (FTP) test cycle, RMC-SET, and WHTC cycles. Emissions were also examined over the other test cycles identified in Task 1. For each platform, a set of aftertreatment components was aged over a Final Aging protocol that was designed to simulate full-useful life (FUL) to the degree possible within the scope of the program. Final Aging efforts were supported by additional funds from MECA.

At the conclusion of the program, final demonstration tests were conducted under Task 4 on both engine platforms using the Final Aged parts. Replicate tests were conducted on all cycles of interest in order to characterize the performance of the emission control system on both engines.

Program developments and results are summarized for each of the two engine platforms separately below.

Program Cycles

As noted above, the primary test cycles for this program were the current regulatory cycles. These include the U.S. Heavy-Duty FTP transient, the steady-state RMC-SET cycle, and the CARB extended idle test. In addition the European Worldwide Harmonized Test Cycle (WHTC) was also included as a primary cycle for the program.

The program target was that these primary cycles would be used for both demonstration of emissions, with a development target of 0.02 g/hp-hr, and for the assessment of the GHG

impact of the technology solution used to meet that target. The CARB idle test is not regulated in terms of brake-specific emissions, therefore no specific target was given for that cycle. The program target was to examine how much reduction was available over that cycle, and what the GHG impact of such reductions would be.

Beyond these regulatory targets, however, it is also important to examine real-world emission control performance, especially in the case of low load vocational and urban cycle applications. In order to examine this question, several Vocational cycles were developed in order to examine the performance of both the Baseline engines and the final Low NO_x engine systems under these kinds of operation. It should be noted that emissions controls and calibrations were not specifically developed to deal with these Vocational cycles. Rather, the systems were developed to meet targets in the regulatory cycles, and then those systems would be run on the Vocational cycles to examine potential performance differences. The results could then be used to inform future development and regulatory efforts, aimed at closing any observed performance gaps between the current regulatory cycles and this kind of low load field operation. A brief description of the three Vocational cycles and the kinds of operation they are intended to target is given in Table 1 below. Detailed cycle profiles are given in the later in the body of this report.

TABLE 1. PROGRAM VOCATIONAL CYCLES

Cycle	Description	ARB Intent
Idle + NYBC x 4	30min idle + 41 min urban operation	• Highly transient • Low speed with severe demand spikes • Sustained Low temperature with high transient
Cruise+Creep x 10	50mph cruise for 20 min followed by 42 min of “creep” operation	• Sustained light load • Ability of system to maintain heat • Thermal management behavior • Cold-start versus extended low load
OCTA Bus	Based on OCTA cycle data ~ 32 min	• Realistic vocational cycle for California • Transit bus data • Less aggressive transients than FTP

CNG Engine – Cummins ISX12-G



The development of the CNG engine platform to meet ultra-low NO_x (ULN) levels was generally more straightforward than the diesel platform. Although a considerable amount of development effort was still required, the fact that the engine was a stoichiometric spark ignition (SI) unit allowed the use of the more mature TWC technology that is capable of very high NO_x reduction, as long as the engine's air-fuel ratio (AFR) can be appropriately controlled.

The primary development efforts on the CNG engine involved:

- Selection of a three-way catalyst system from the options provided by MECA
- Implementation of advanced AFR controls in the ISX 12G engine
- Calibration of the AFR controls to achieve maximum performance
- Development of a cold-start warm-up strategy to get the TWC system to light off temperature as quickly as possible

The baseline engine was essentially a throttle body injected spark ignition (SI) engine. There was some discussion of moving to port-fuel injection (PFI) in the early phases of the program. However, it ultimately proved unnecessary to take this step, and sufficient control was achieved with an advanced form of throttle body injection. However, advanced injection hardware and controls were not available from the engine original equipment manufacturer (OEM) during the program. Therefore an advanced third-party system produced by EControls was installed on the engine. This system used a model-based control approach and employed proprietary injection and mixing hardware. The ISX 12-G engine employed a high-pressure loop EGR system, which allowed for control of engine-out NO_x levels. It was essential to ensure very good mixing between air-fuel-and EGR, and this was done via the proprietary mixing hardware that was part of the EControls system.

The final catalyst system chosen was a combination of a close-coupled three way catalyst (ccTWC) and a conventional under-floor TWC (ufTWC), which is similar to configurations used on Tier 2 gasoline light-duty passenger vehicles. A schematic of the system is show in Figure 1 below.

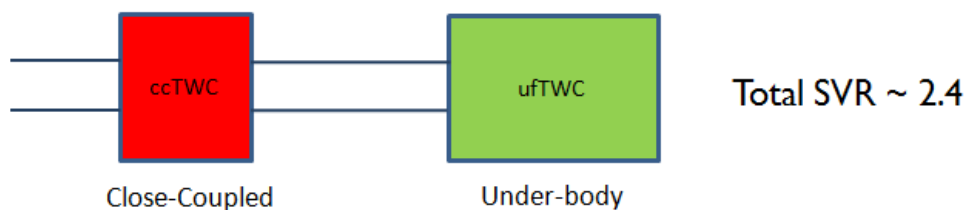


FIGURE 1. SCHEMATIC OF FINAL LOW NO_x CNG ENGINE AFTERTREATMENT SYSTEM

The final aftertreatment system was aged using methods based on the EPA Standard Bench Cycle (SBC) methodology, which is the accepted approach for aging of TWC systems to reach full useful life. The aging calculations were based on 435,000 miles of operation of the OCTA bus vocational cycle, which was representative of the urban transit bus application that would be typical for this engine. Figure 2 below shows the temperature histogram of the cycle, which was run for 137 hours using a CNG-fired burner-based aging rig.

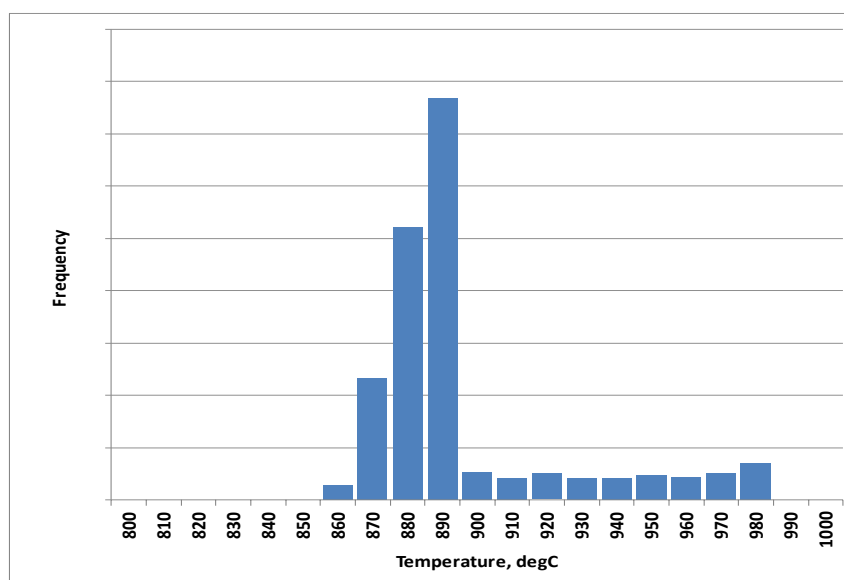


FIGURE 2. TEMPERATURE HISTOGRAM OF THE SBC CYCLE FOR FINAL AGING OF THE CNG ENGINE CATALYSTS

Table 2 and Table 3 below summarize the final tailpipe test results on the CNG Low NO_x demonstration engine using the Final Aged parts. The results are shown in comparison to results for the Baseline engine before modifications. In general the results show roughly an order of magnitude reduction in tailpipe NO_x emissions for the Low NO_x engine, as compared to the Baseline. For all regulatory test cycles, tailpipe NO_x emissions were below the 0.02 g/hp-hr target. In addition, the Low NO_x engine generally showed significantly lower NH₃ and methane emissions, as compared to the Baseline engine. This was generally the result of improved air-fuel ratio control with the Low NO_x engine.

The CO₂ emissions impact of varied by cycle, but in general there was an increase of about 1% on duty cycles which featured a cold-start, due to the impact of the rapid cold-start

warm-up strategy. However, this was generally offset by lower methane emissions in terms of overall GHG impact. It should be noted that NH₃ did exceed the program target of 10 ppm cycle average. However, this was due to a shortcoming of the AFR controller, which did not include an oxygen storage model for the catalysts at the time of development. However, such controls technology is in production on Tier 2 gasoline engines, and could be added to a heavy-duty CNG engine given sufficient development time and resources. The resulting improved AFR control would likely result in lower NH₃ emissions.

TABLE 2. CNG ENGINE NO_x EMISSIONS COMPARISON – LOW NO_x ENGINE VERSUS BASELINE, G/HP-HR

Engine	FTP			RMC-SET	WHTC		
	Cold	Hot	Composite		Cold	Hot	Composite
Baseline	0.247	0.093	0.115	0.012	0.310	0.308	0.308
Low NO_x Engine	0.065	0.001	0.010	0.001	0.043	0.006	0.011
% Reduction	74%	99%	91%	92%	86%	98%	96%

TABLE 3. CNG ENGINE COMPARISON OF OTHER EMISSIONS – LOW NO_x ENGINE VERSUS BASELINE

Engine	Pollutant	FTP	RMC-SET	WHTC
Baseline	CH ₄ , g/hp-hr	0.96	1.20	1.54
	NH ₃ , avg ppm	76	162	100
	CO ₂ , g/hp-hr	542	454	510
Low NO _x Engine	CH ₄ , g/hp-hr	0.15	0.93	0.10
	NH ₃ , avg ppm	52	37	44
	CO ₂ , g/hp-hr	547	445	513
% Change from Baseline	CH ₄	-84%	-23%	-94%
	NH ₃	-32%	-77%	-56%
	CO ₂	0.9%	-2.0%	0.6%

An example of the improved transient cycle NO_x performance is given below in Figure 3 for the cold-start FTP, and in Figure 4 for the hot-start FTP. For the cold-start, it can be seen that the initial NO_x peak is somewhat smaller, but also that full NO_x control is achieved within about 60 seconds on the Low NO_x CNG engine, whereas the baseline saw significant breakthrough events up to 300-400 seconds into the cycle. This improvement is due to the combination of faster catalyst light-off and improved air-fuel ratio control, which helps to reduce breakthrough later in the cycle. For the hot-start the improvement can be seen in the removal of smaller NO_x breakthrough events throughout the cycle, which is due to the improvement in air-fuel ratio control.

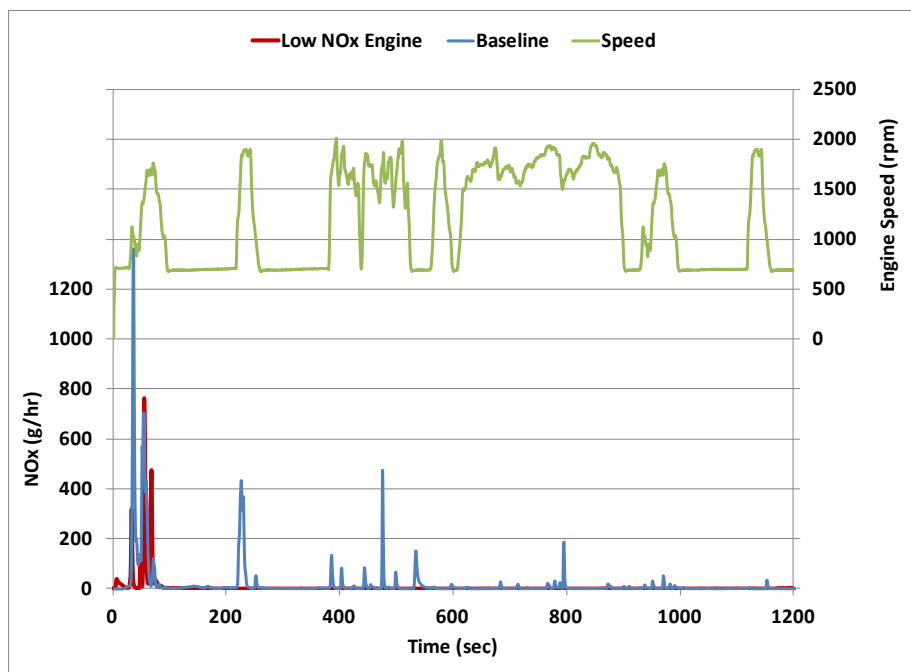


FIGURE 3. COMPARISON OF COLD START FTP NO_x – LOW NO_x ENGINE VERSUS BASELINE

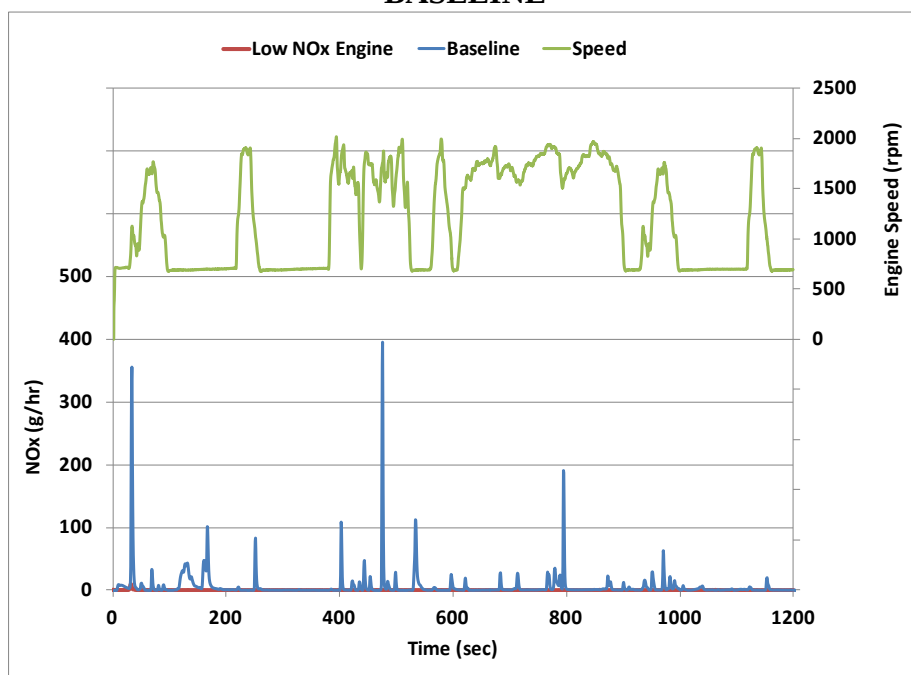


FIGURE 4. COMPARISON OF HOT-START FTP NO_x – LOW NO_x ENGINE VERSUS BASELINE

Another important aspect of the CNG engine results can be observed in the Vocational cycle test results, which are given below in Table 4. The Low NO_x CNG engine is able to achieve sustained very low NO_x levels, essentially near zero NO_x, on all of the different vocational cycles, as well as generally lower methane and NH₃ levels compared to the baseline.

This result implied that the CNG engine will be able to provide sustained low NO_x levels even during lower load field duty cycles. In addition, while the highly transient nature of some of these cycles proved problematic for the controls on the Baseline engine, the improved air-fuel ratio control on the Low NO_x engine was more robust to this kind of operation. That said, there is still room for improvement as evidenced by the NH₃ emission levels observed on some of these cycles. It should be noted that the same improvements discussed earlier, such as the inclusion of a robust oxygen storage model, would benefit these cycles as well.

TABLE 4. CNG ENGINE VOCATIONAL CYCLE EMISSIONS – LOW NO_x ENGINE VERSUS BASELINE

Cycle	Baseline			Low NO _x Engine		
	NO _x , g/hp-hr	NH ₃ , ppm	CH ₄ , g/hp-hr	NO _x , g/hp-hr	NH ₃ , ppm	CH ₄ , g/hp-hr
NYBC	0.91	12	1.9	0.002	25	0.5
Cruise Creep	0.07	124	1.6	0.002	85	1.0
OCTA	0.11	92	1.1	0.0003	47	0.04

Overall, the results indicate the feasibility of reaching NO_x levels below 0.02 g/hp-hr on a CNG engine over the vocational cycles. While the catalysts are somewhat larger than those used on current 2010 CNG engines, this can be improved over time. The required improvements in air-fuel ratio control are achievable using available control technologies, and controls can be further improved via the incorporation of more control approaches already in use for light-duty gasoline engines. In addition, further improvements in performance are likely available via the adoption of port fuel injection approaches, although this did not prove necessary to reach 0.02 g/hp-hr on ISX 12-G engine. Based on the data shown above and what is available in the public domain, it appears that some form of limit on NH₃ emissions may be important in ensuring robust air-fuel ratio controls.

It should be noted that the advent of heavy-duty OBD requirements for CNG engines in the 2018 timeframe will introduce additional work effort on the introduction of a low NO_x CNG engine. However, the oxygen-storage based approaches used for TWC catalyst monitoring on smaller gasoline catalysts should be applicable, although they will need to be calibrated and tested. Misfire monitoring should also be noted as a challenge on engines of this size that will be installed in a variety of different larger applications.

CNG Engine Recommendations and Next Steps

The CNG engine demonstration effort was generally successful in showing the feasibility of meeting a 0.02 g/hp-hr level with a stoichiometric CNG engine. The demonstration was accomplished with technologies available in the marketplace, and with systems feasible for production. Given that there is a production CNG engine now available that is certified to a level of 0.02 g/hp-hr under the CARB Voluntary Low NO_x standard, it is unlikely that further development efforts are needed regarding demonstration.

It is understood that there are some similarities between the current program engine and the now certified Cummins 9L CNG engine. Both engines are stoichiometric CNG engines

equipped with EGR, and both engine approaches did not require the use of port fuel injection. The engine for this program was a larger engine at a 12L displacement, with a relatively low power rating. The catalyst strategy was different, in that the program 12L engine utilized a close-coupled light-off catalyst in addition to an under-floor main catalyst, whereas the 9L engine utilizes a single catalyst bed. The information from both engines indicates that there are multiple ways to approach ULN NO_x levels with a CNG engine, with regard to aftertreatment architecture and controls. Manufacturers will determine which options are most efficient for each given engine.

The results of the program, as well as information available about the certified 9L engine, do imply some areas that should be monitored in the event of a widespread deployment of CNG engines to meet a 0.02 g/hp-hr level, even under the voluntary program.

- Tailpipe NH₃ emissions – Tailpipe ammonia levels, while lower than the baseline engine, were still quite high in certain situations. This was the case for both regulatory cycles and some of the vocational cycles. It is understood that this is the case for production offerings as well at the moment. This can generally be mitigated by improved air-fuel ratio controls, but the question remains whether such controls will be deployed in the absence of a regulatory driver. Given that NH₃ is itself an irritant, and can also be a precursor for secondary PM formation, it may be important to ensure that tailpipe NH₃ remains well controlled in the event of a large-scale adoption of CNG engines.
- Methane emissions – While CH₄ emissions were generally lower on the Low NO_x engine than for the Baseline, methane was still above the 0.1 g/hp-hr cap for Phase 1 and Phase 2 GHG standards, in some cases by a significant amount, including on some Vocational cycles. While the total GHG emissions were below the 2017 Phase 1 targets, the methane emissions nevertheless offset some of the GHG benefit of the CNG fuel. Given that the increased methane can also be mitigated at least in part by improved AFR controls, it may be important to ensure that such controls are deployed in the event of a large-scale adoption of CNG engines.
- It is apparent from the results that even a small loss of air-fuel ratio control can result in large increases in NO_x and other emissions (such as ammonia and methane). Given the importance of air-fuel ratio control in maintaining low NO_x levels, it will be important to that this control is maintained over time. It is understood that HD-OBD requirements will apply to CNG engines starting in 2018, and robust AFR monitoring will be important to insuring that the low NO_x potential of stoichiometric CNG engines is realized in the field. The level of effort associated with such robust OBD monitoring should not be underestimated, and this may be an area where future development or demonstration could be warranted. It is assumed that the same methodology associated with light-duty gasoline will be applicable, but it may be important to validate this assumption.

Diesel Engine – 2014 Volvo MD13TC



The diesel engine platform presented a much greater challenge to achieving ultra-low NO_x emissions levels. As with all diesel engines, the combination of lean exhaust and lower exhaust temperatures makes NO_x control particularly difficult. The 2014 Volvo MD13TC engine was chosen for this program based on discussions with the OEM partner for this program. Initially it had been planned to use a 2011 Volvo MD13 engine. However, it was pointed out that this engine would not be representative of engines in the post-2017 timeframe. The MD13 engine had significantly lower engine-out NO_x levels than were already available on engines, even in 2013. In addition, only a limited number of hardware levers were available on the MD13 engine for recalibration. Furthermore, the OEM indicated that the MD13TC engine was representative of the direction that they intended to pursue for meeting upcoming Phase 2 GHG targets, which were still under discussion at that time. Because a US version of this engine did not exist at the start of the program, a Euro VI version of the engine was supplied. Baseline testing indicated that this engine was able to meet the 2010 US emission limits. In addition, the engine-out NO_x level of the baseline engine was on the order of 3 g/hp-hr, which was representative of engines on the U.S. market in the 2013-2016 timeframe.

The drawback to this choice of engine was that it employed high temperature waste heat recover (WHR) in the form of a mechanical turbocompound system. This technology did enable the engine to be capable of reaching the 2017 Phase 1 GHG targets for Class 8 engines. However, it also meant that engine-out exhaust temperatures on the MD13TC engine were significantly lower than what was anticipated for the original engine choice, as shown below in Figure 5. It was understood that this would pose a significant challenge to the program, but it was felt that this was still a better choice than to proceed with the 2011 MD13 engine, which would have been open to significant criticism of being unrepresentative. Initially, it was anticipated that the temperature issue could be mitigated in part using a bypass or similar approach that would allow the diversion of exhaust around the turbocompound during cold-start operation. Following the start of development, however, it became apparent that such an approach was not feasible within the scope and budget limits of the program.

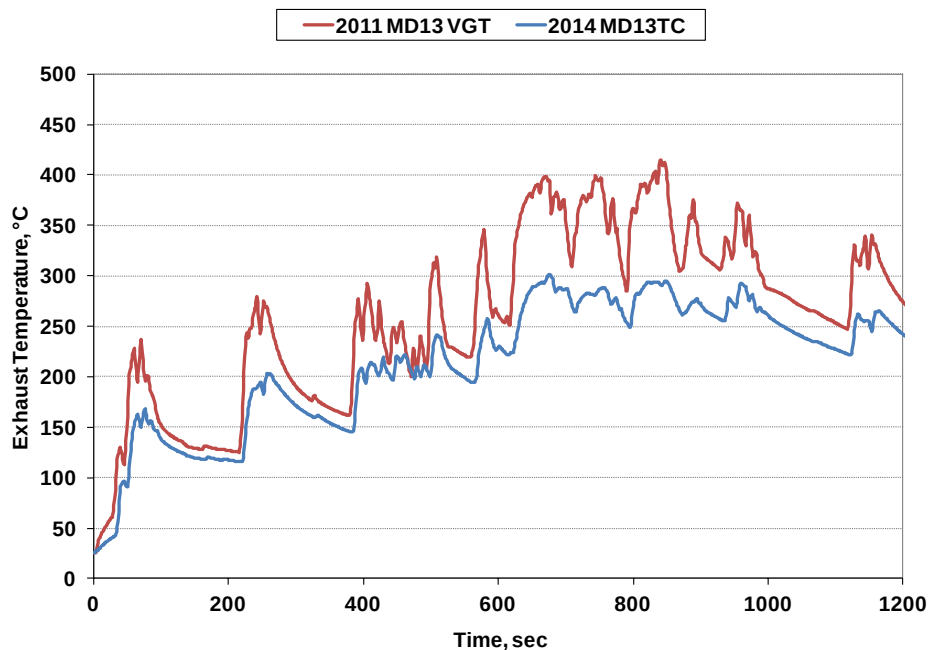


FIGURE 5. COMPARISON OF COLD-START EXHAUST TEMPERATURES – MD13TC ENGINE VERSUS NON-TURBO COMPOUND ENGINE (MD13 VGT)

As a result of the engine architecture, this particular diesel engine was an even more significant challenge in terms of achieving ultra-low NO_x levels. Viewed from the current vantage point, at the end of the program, it is apparent that this engine probably represents more of a corner case with regard to potential approaches to meeting GHG Phase 2 targets. As such, the resulting technology approach to achieving ultra-low NO_x levels should likely be viewed as closer to a “worst-case” example of what is required to reach 0.02 g/hp-hr, rather than a typical application. Nevertheless, an example of this type of engine is currently in production in the U.S., and therefore this case remains a useful one in illustrating the challenge that can be presented by adopting different approaches to meeting engine system efficiency targets.

Diesel Engine Calibration Changes

It was understood that the primary aftertreatment de-NO_x technology that would be used for this program would be ammonia selective catalytic reduction (SCR). Given the challenge presented by the low exhaust temperature, it was recognized that the engine calibration would need to be significantly modified in order to achieve two goals during cold-start operation:

- Increased exhaust temperatures to promote more rapid catalyst light-off
- Reduced engine-out NO_x levels prior to catalyst light-off

A modified engine calibration was developed which employed a number of different engine technologies including:

- Increased use of cooled EGR
- Intake throttling
- Multiple injections via the common rail fuel injection system available on the engine
- Elevated idle speed during cold-start warm-up

The net effect of the modified calibrations on engine-out temperature and NO_x is illustrated in Figure 6 and Figure 7, respectively.

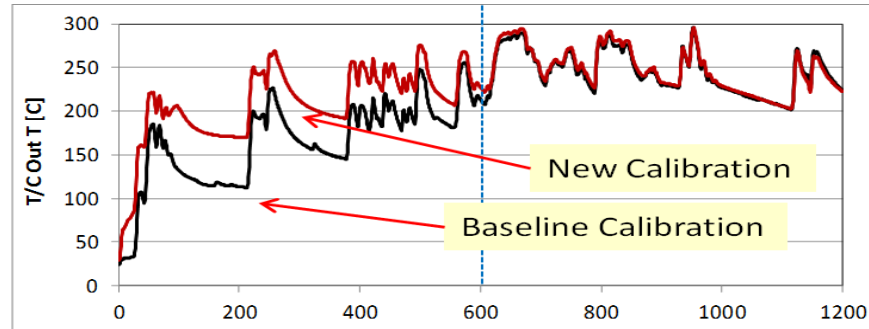


FIGURE 6. ENGINE-OUT TEMPERATURE COMPARISON – MODIFIED CALIBRATION VERSUS BASELINE

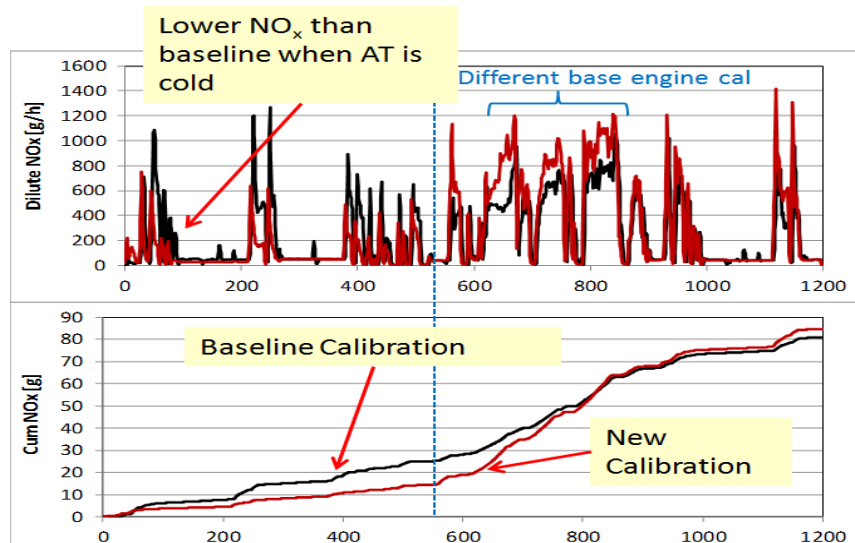


FIGURE 7. ENGINE-OUT NO_x COMPARISON - MODIFIED CALIBRATION VERSUS BASELINE

As shown in the figures, the strategy approach that was taken was to modify engine behavior when the aftertreatment was not yet warm, and then to release the calibration back to the baseline high efficiency mode once the aftertreatment was sufficiently warm to achieve very high efficiency NO_x reduction. The dashed blue vertical line indicates that point in this example where the engine calibration reverted from the cold-start mode to the high-efficiency mode. The figures show that the modified calibration achieves both increased temperature and reduce NO_x emissions during the early cold-start. This approach is not without cost, however, and the

modifications resulted in a composite increase of 0.4% in CO₂ emissions over the FTP cycle (2.5% on the cold-start itself). After catalyst light-off is achieved, it is possible to actually increase NO_x emissions somewhat in an effort to offset some of the increase. Nevertheless, a net increase in CO₂ and fuel consumption was observed as indicated.

Diesel Engine Aftertreatment Screening and Development

With this modified engine calibration as a starting point, an extensive technology screening effort was conducted to identify promising candidate aftertreatment technologies, and to determine the GHG impact of those technologies. This effort was conducted in parallel with continuing on-engine work by utilizing the novel approach of simulating the transient engine exhaust with SwRI's HGTR system. The HGTR is depicted in Figure 8, along with an example of the fidelity of the NO_x simulation it was able to produce on the cold-start FTP, as compared to the engine. The use of this approach allowed for the rapid screening of many technologies in a shorter period of time.

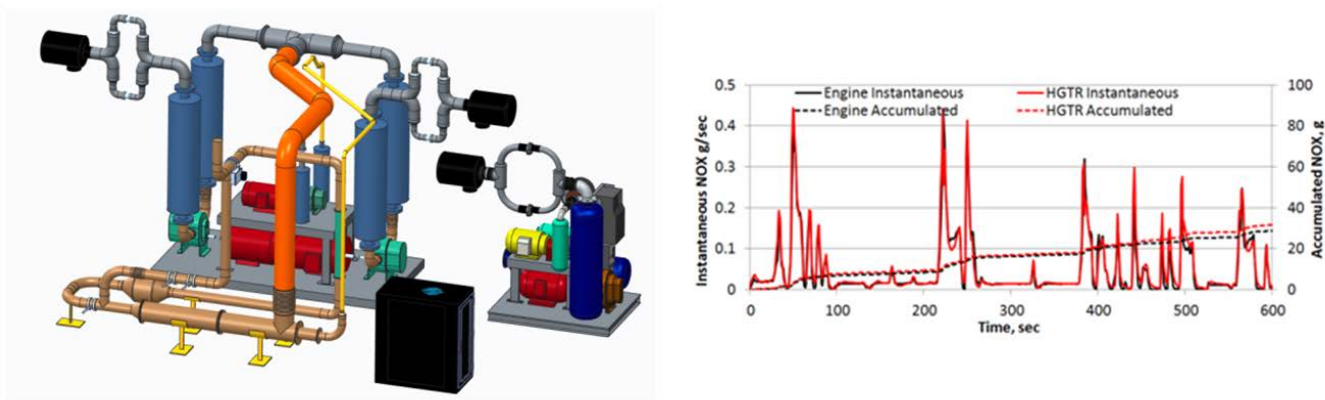


FIGURE 8. SWRI HOT-GAS TRANSIENT REACTOR (HGTR)

A wide variety of technology approaches were evaluated for this program. It should be noted that all of the catalysts evaluated in the screening process were hydrothermally aged to approximate full useful life based on the baseline engine characteristics. These parts are termed Development Aged parts, and these were produced by aging catalysts for 100 hours at temperatures ranging from 625°C to 650°C, depending on the component. It should be noted that a more rigorous Final aging process was only run on the final technologies down-selected for demonstration. Technology approaches evaluated for this program for the diesel engine are summarized in the listing below:

Low Thermal Loss/Mass Components

- Air gap exhaust manifolds
- Air gap transfer pipes
- Catalyst packaging
- Catalyst positioning
- Thin wall substrates

Advanced Technology Components

- SCR on Filter (SCRF)
- Passive NO_x Adsorber (PNA)
- Light-Off SCR (LO SCR)
- Advanced technology washcoats

Traditional Technology Components

- Diesel Oxidation Catalyst (DOC)
- Diesel Particulate Filter (DPF)
- Selective Catalytic Reduction(SCR)
- Ammonia Slip Catalyst (ASC)

Dosing Options

- Compact mixer/doser
- Full flow heated dosing
- Partial flow heated dosing
- Gaseous NH₃ injection

Supplemental Energy Options

- Electrically Heated Catalyst (EHC) (2-6 kW)
- Diesel fueled mini-burner (5-20 kW)
- EHC assisted catalytic oxidation

The various technologies evaluated were grouped into two broad categories in terms of strategy. The first group was labeled as Traditional approaches, which involved the continued use of a DPF upstream of the SCR. This approach was complicated by the large thermal inertia of the DPF itself, which made it more difficult to heat the downstream SCR components. The second group was labeled as Advanced approaches, and these involved the use of SCR-on-Filter (SCRF) as a core technology. The SCRF approach is a way to mitigate the problem of the thermal inertia of the DPF, by bringing some SCR onto the filter itself. It should be noted that the Passive NO_x Adsorber catalysts evaluated in this program are different from more traditional NO_x adsorber catalysts in that they release NO_x thermally at lower temperatures, and they do not require a deliberate rich regeneration event to remove stored NO_x.

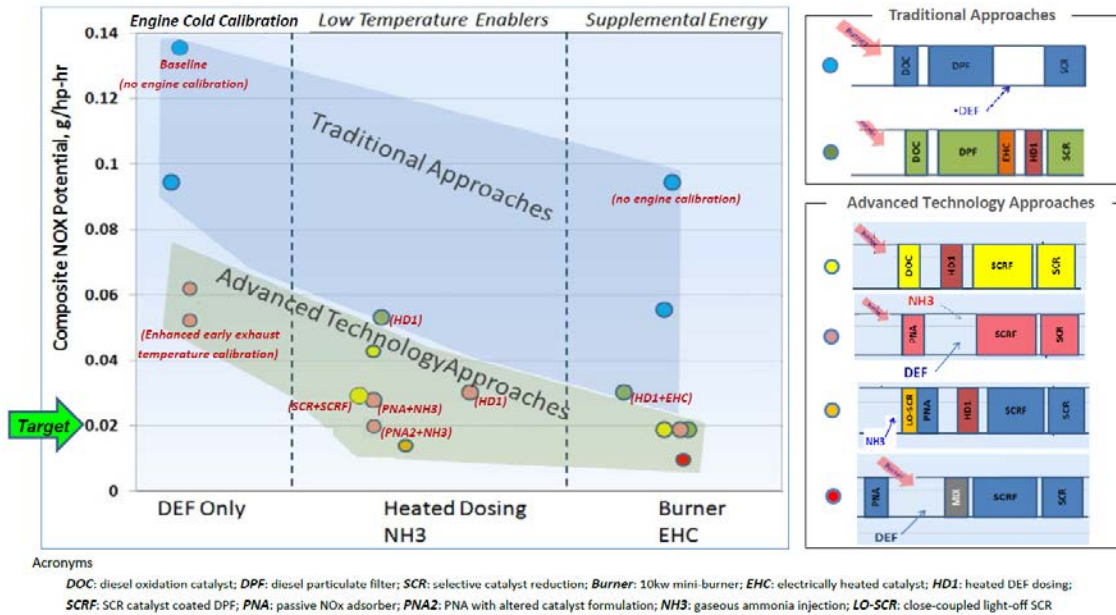


FIGURE 9. COMPOSITE ULTRA-LOW NO_x POTENTIAL OF VARIOUS TECHNOLOGY CONFIGURATIONS

The final result of the screening process is depicted in Figure 9. The data in the figure are based on the HGTR screening results for the various technology options. The Traditional approaches were able to approach NO_x levels of roughly 0.05 g/hp-hr. Lower levels (near 0.03 g/hp-hr) were achievable with the Traditional approach, but only through the application of significant amounts of supplemental heat addition, using either electrical heat or a mini-burner. The Advanced approaches were able to reach levels on the order of 0.03 g/hp-hr by leveraging the capability of the SCRf in combination with smaller technology changes such as heated dosing systems. The use of a PNA enabled several configurations to get reliably below the target level of 0.02 g/hp-hr, at varying margins depending on the amount of supplemental heat that was used.

Overall, the screening effort indicated that there were multiple potential technology pathways to reach 0.02 g/hp-hr on the MD13TC engine. However, it should be pointed out that more of these technology options would likely be viable given a more favorable exhaust temperature environment without the turbocompound architecture. A limited set of screening tests were conducted to simulate such an environment, and these indicated a reduced need for supplemental heat, possibly permitting a simpler system configuration. However, given that such a change was not possible for the MD13TC engine, this possibility was not pursued further.

Figure 10 below shows a summary of both NO_x potential and fuel consumption impact of various technology options. In general, the Advanced technology options with SCRf were able to reach a lower composite NO_x level for a given fuel consumption increase.

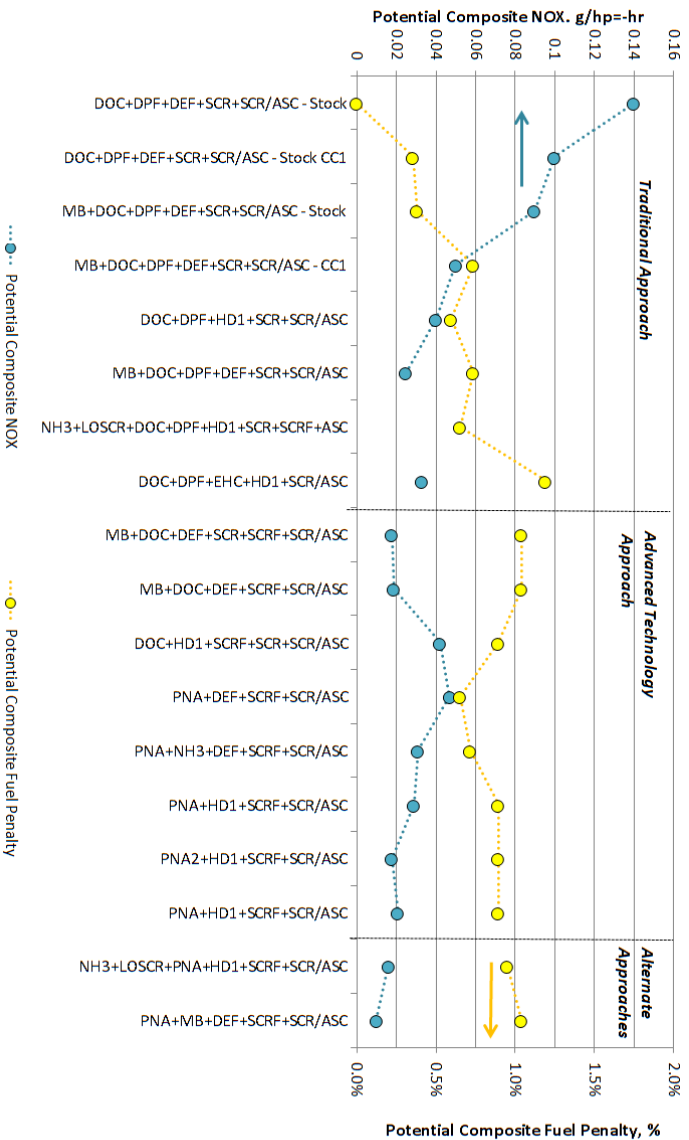


FIGURE 10. CCMPOSITE NO_x POTENTIAL AND GHG IMPACT OF VARIOUS TECHNOLOGY OPTIONS

The technology configurations that showed NO_x potential at or below 0.02 g/hp-hr appeared to cause an increase of roughly 1% in composite FTP fuel consumption. It should be noted that these projections from screening are based primarily on weighted cold-start fuel consumption impact, and they assume a negligible penalty under hot-start conditions.

To reach ULN composite emissions levels below 0.02 g/hp-hr, significant cold-start FTP emission reductions (on the order of current technology hot-start emissions) must be achieved as well as very high conversion efficiencies for the entire hot-start cycle. A key part of obtaining the necessary cold-start emission reductions was reducing the time to achieve SCR light-off. Increased exhaust energy was needed to obtained rapid SCR light-off and was provided by engine measures and direct in-exhaust heat addition in the form of electric heaters or burners. Each approach had a fuel consumption increase versus energy increase trade-off.

To reduce the fuel penalty realized by in-exhaust thermal management, many aspects were considered. The elements that affected total energy addition and potential fuel from an exhaust thermal management strategy included: catalyst positioning, positioning of supplemental heat, leveraging of low temperature dosing enablers, and devices designed to reduce SCR inlet NO_x mass during catalyst warm-up period

The screening exercise identified many characteristics that were common to the configurations that were able to achieve low NO_x performance. These characteristics, and some of the technologies that enabled these performance features included:

- Ability to begin dosing within 60-150 seconds

- Lower temperature dosing ability
 - Heated dosing or gaseous NH₃ injection
 - Light-off SCR
- Reduced time to dosing by addition of high levels of supplemental heat
 - Mini-burner or catalytic fuel combustion
- Low temperature NO_x suppression until the first SCR catalyst reached light-off temperature
 - Passive NO_x adsorber (PNA) technology
 - Engine calibration

Based on the screening results, several promising approaches were identified and ranked in terms of NO_x reduction potential, GHG impact, complexity, robustness, and cost. The final rankings, which are based in part on stakeholder feedback, are shown in Table 5. The options shaded in green were considered to have the potential to meet 0.02 g/hp-hr on the MD13TC engine. The options shaded in yellow were not considered viable to reach 0.02 g/hp-hr on this engine, but could potentially be usable on a non-turbocompound engine.

TABLE 5. FINAL TECHNOLOGY RANKINGS BASED ON SCREENING RESULTS

System	Composite NO _x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + HD1 + SCRf + SCR/ASC	0.02	0.9	8/13.3	5/10	4/9.8
NH3 + LO SCR + PNA + HD1 + SCRf + SCR/ASC (HD1)	0.016	0.95	12/20.7	11/20.7	11/12.5
EHC/DOC + DEF + SCRf + SCR + SCR/ASC - (underevaluation)	///	1.05	7/9.4	7/9	4/6.2
PNA + MB + DEF + SCRf + SCR/ASC	0.01	1.04	13/16.2	10/13.1	9/12.5
MB + DOC + DEF + SCR + SCRf + SCR/ASC	0.019	1.04	9/10.7	8/10	8/7.7
MB + DOC + DEF + SCRf + SCR + SCR/ASC	0.018	1.04	9/10.7	8/10	8/7.7
DOC + MB + SCRf + SCR + SCR/ASC - (notevaluated)	//////////	1.04	9/10.7	8/10	7/7.7
MB + DOC + DPF + SCR + SCR/ASC	0.025	0.62	6/6.4	6/7	7/6.3
EHC/DOC + DPF + HD1+ SCR + SCR/ASC - (notevaluated)	//////////	0.98	5/8.6	6/9	5/8.4
PNA + HD1 + SCRf + SCR/ASC	0.029	0.9	8/13.3	5/13	4/9.8
PNA + NH3 + DEF + SCRf + SCR/ASC	0.031	0.72	8/13.4	8/13	7/12.3
NH3 + LO SCR + DOC + DPF + HD1 + SCR+SCRf + SCR/ASC (notevaluated)	//////////	0.65	4/15.2	9/16	10/12.4
DOC + DPF + EHC + HD1 + SCR + SCR/ASC	0.033	1.2	2/7.2	2/7	6/7.7
Base engine, stock calibration: 4852 g					
Base engine, CC1: 4973 g					

These approaches were integrated onto the engine, and were evaluated in combination with further modifications to the engine calibration and thermal strategy. Evaluations were conducted in the ranked order, which generally indicated the desirability of the system from the standpoint of complexity and cost. Given the low temperature exhaust environment of the MD13TC engine, even after modification, most of these approaches involved the use of both SCRf and an upstream PNA. Nevertheless, it was felt that a wider variety of options would be available with a more favorable engine architecture.

It was hoped that through further engine calibration, the amount the supplemental heat input to the system could be reduced, while still reaching a level below 0.02 g/hp-hr. However, it was found that the combination of the MD13TC engine architecture, the use of the PNA, and the requirement to maintain good torque response, limited the flexibility available to reduce engine-out NO_x further during early cold-start. As a result, although a number of technology options produced emission levels on the order of 0.025 g/hp-hr, significant supplemental heat input was still required to reach levels below 0.02 g/hp-hr on this engine. Therefore, the mini-burner was adopted as the most efficient means of generating the levels of heat required.

The final diesel ULN aftertreatment system configuration for the MD13TC engine is shown below in Figure 11:

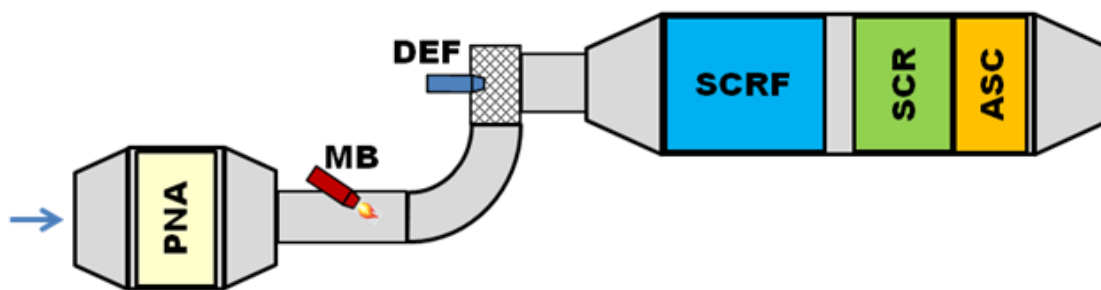


FIGURE 11. DIESEL ENGINE FINAL ULTRA-LOW NO_x CONFIGURATION

The key components of this system are:

- A passive NO_x Adsorber (PNA) for low temperature NO_x storage. The PNA also serves the functions of a traditional DOC in this system, including generation of the exotherm needed for regeneration of the filter (via supplemental fuel injection using in the exhaust).
- Supplemental Heat for additional thermal management in the form of a Mini-burner (MB). It should be noted that the mini-burner is not sized for regeneration of the filter, and is intended only for thermal management events such as cold start and low temperature operation.
- A multi-bed SCR system consisting of an SCR-on-Filter (SCRF) followed by a flow-thru SCR catalyst
- A dual-layer Ammonia Slip Catalyst (ASC)

This aftertreatment system was controlled using an advanced, model-based DEF dosing controller, and a state-based thermal management controller that was flexible enough to achieve robust control on a wide variety of duty cycles. Production NO_x and temperature sensors were used for the controls. The dosing controller also incorporated a production ammonia sensor at the outlet of the SCRF to provide a real-time feedback signal for the system. The controls were calibrated in terms of SCR catalyst ammonia storage targets, temperature triggers, and thermal management heat rates. It should be noted that the controls were not custom calibrated to every individual duty cycle, but rather a single controls calibration was developed for FTP and RMC cycles, and that calibration was used for all other cycles. The exception to this was the WHTC which did feature a small adjustment to storage and thermal targets.

Much of the initial development and controls calibration on the system was conducted using the same Development Aged parts that were used for screening. This was necessary because the development was conducted in parallel with the Final Aging. Using the Development Aged parts, this system was able to reliably demonstrate emission levels below 0.02 g/hp-hr.

Diesel Engine Aftertreatment Final Aging

The Final Aging protocol for the diesel engine parts was developed based on methodology that was developed by SwRI as part of the Diesel Aftertreatment Accelerated Aging Consortium (DAAAC) program [5], which was an industry consortium run at SwRI that

was aimed at development of diesel aftertreatment aging protocols. This is similar in principal to the SBC approach, and it provides means to accelerate both hydrothermal and chemical aging (to a lesser degree) in a representative fashion. The Final Aging was conducted on a mule engine which was a 2009 Cummins ISX engine that had been modified to increase oil consumption in accordance with the DAAAC methodology.

Using the DAAAC protocol and field cycle data from the OEM, an approach was developed to approximate full useful life aging of the aftertreatment to 435,000 miles. The final methodology was based on the fact that the vast majority of hydrothermal aging exposure in the diesel catalysts happens during active regeneration of the filter, in this case the SCRF. Therefore the Final Aging approach involved performing a full lifetime of actual active regenerations. It should be noted that the SCR function on the SCRF does result in increased need for active regeneration as compared to a DPF. In this case the full useful life amount of regeneration was 194 hours with the SCRF, as compared to 113 hours with the baseline DPF. Both of these values would be over a full useful life of 435,000 miles (roughly 11,000 hours). These regenerations were conducted at an SCRF inlet temperature of 600°C. In between regenerations, the aftertreatment system was exposed to temperatures equivalent to FTP and RMC average values, and at higher speed to promote more oil consumption. A small amount of higher temperature operation accurate to the field data was later added to manage an issue of coke and soot buildup on the PNA inlet. The active regenerations were performed using in-exhaust diesel fuel injection in front of the PNA to generate heat, as would be done in the real application. The Final Aging cycle is shown in Figure 12.

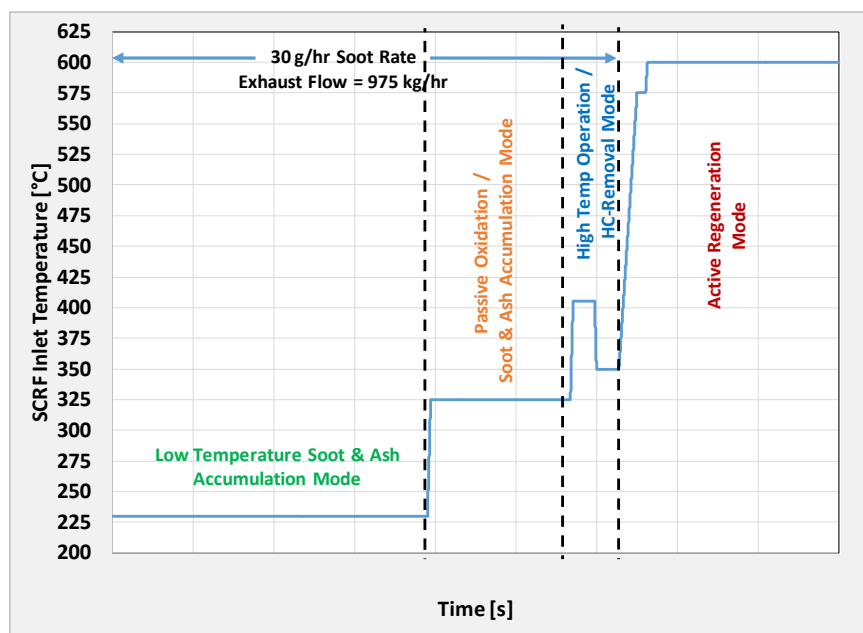


FIGURE 12. DIESEL ENGINE FINAL AGING CYCLE (4-HOUR DURATION PER CYCLE)

The Final Aging protocol resulted in the exposure of the diesel aftertreatment system to the equivalent of 100% full useful life in terms of hydrothermal aging, and roughly 23% full useful life in terms of chemical poisoning and ash accumulation, over the course of 850 hours of

operation. Larger chemical exposure could have been problematic due to the need for ash cleaning of the SCRF, which is not yet a well developed process. This accelerated process was as close to true full useful life aging as was practical within the time and scope limits of the program.

It should be noted that there was an unusual incident which happened during the final aging which may have resulted in some abnormally large degradation of the catalysts. At the 710 hour mark, a canning failure occurred with the PNA as shown in the pictures below in Figure 13.

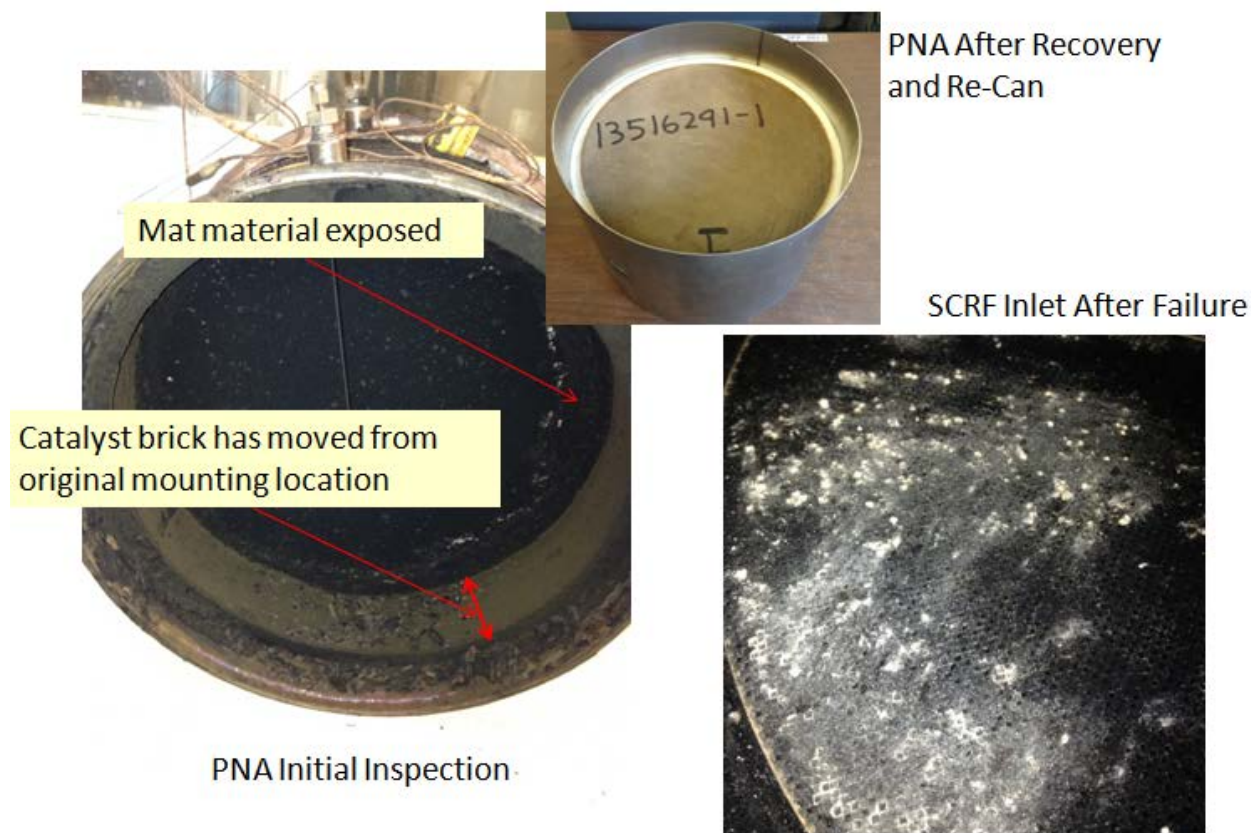


FIGURE 13. AFTERTREATMENT COMPONENTS FOLLOWING CANNING FAILURE DURING FINAL AGING

As a result of this failure there was abnormally large buildup of soot and hydrocarbon on the PNA, which may have caused additional degradation beyond normal. In addition, some of the matting was ingested by the SCRF downstream, which likely caused flow distribution issues and localized soot buildup and high exotherms (temperature exposure). New parts were not available at the time, therefore a restart of Final Aging would have delayed the program by at least 6 months, as well as requiring additional funding. As a result, the parts were recovered in a manner that did not further disturb aging, and Final Aging was completed. However, this incident needs to be noted because it may have had an influence on the Final Aged demonstration results, as discussed below.

Diesel Engine Emission Results and Discussion

Following the completion of Final Aging, the parts were installed on the engine and demonstration tests were run. It should be noted that the dosing controller used in this program did not incorporate a long-term adaptive algorithm (as is typical for many production SCR controllers), because the calibration of such an algorithm was beyond the scope and budget of the program. Therefore, a small global adjustment was made in the storage targets in order to manually simulate the action of such an algorithm.

The final results for the diesel Low NO_x engine are summarized in Table 6 and Table 7 below, along with the Baseline engine results for comparison. Results are given for the final demonstration parts in both the Fresh and Final Aged states. Results for the Development Aged parts are also shown for comparison. The results are presented in Table 6 as tailpipe values, and then in Table 7 in terms of aftertreatment NO_x conversion performance as a percentage of engine-out emissions.

TABLE 6. DIESEL ENGINE NO_x EMISSIONS COMPARISON – LOW NO_x ENGINE VERSUS BASELINE, G/HP-HR

Engine		FTP			RMC-SET	WHTC		
		Cold	Hot	Composite		Cold	Hot	Composite
Baseline		0.710	0.047	0.140	0.084	0.492	0.049	0.115
Low NO _x Engine	Devel Aged	0.062 ¹	0.008	0.016¹	0.015	0.089 ¹	0.008	0.019
	Final Parts Fresh	0.027	0.005	0.008	0.010	n/a	n/a	n/a
	Final Parts Aged	0.114	0.021	0.034	0.038	0.149	0.018	0.036
% Reduction from Baseline	Devel Aged	91%	83%	89%	82%	82%	84%	83%
	Final Aged	84%	55%	76%	55%	70%	63%	69%
¹ Note: Development PNA was slightly compromised by raw fuel exposure due to a cold-start engine malfunction that occurred during development.								

It should be noted that the numbers given in Table 6 do not include the upward adjustment factor (UAF) for infrequent regeneration. This value is unknown for the Baseline engine. Based on the conversion capability of the catalysts at regeneration temperatures, and the final regeneration frequency that is estimated for the Low NO_x configuration, a UAF of 0.004 g/hp-hr is estimated for both the FTP and the RMC-SET cycle. This factor would be added to both FTP and RMC-SET results for any of the Low NO_x configuration values. Therefore, the adjusted tailpipe NO_x for the Final Aged parts would be 0.038 g/hp-hr for the FTP, and 0.042 g/hp-hr for the RMC-SET. Sufficient data was not available to properly estimate the UAF for the WHTC, but it would likely be similar to the FTP value. It should be noted that this value can likely be reduced via reformulation of the SCRF, or possibly through the use of multipoint DEF

dosing that would allow reduced DEF dosing before the SCRF on a periodic basis in order to promote passive regeneration.

TABLE 7. DIESEL ENGINE NO_x AFTERTREATMENT PERFORMANCE – LOW NO_x ENGINE VERSUS BASELINE

Engine		FTP			RMC-SET	WHTC		
		Cold	Hot	Composite		Cold	Hot	Composite
Baseline	Engine-Out, g/hp-hr	2.8	3.0	3.0	2.6	3.1	3.5	3.4
	% Conversion	75%	98.4%	95.2%	96.7%	84%	98.6%	96.7%
Low NO _x Engine	Engine-Out, g/hp-hr	2.8	3.0	3.0	2.0	3.0	3.4	3.4
	Devel Aged, % Conversion	97.7%	99.7%	99.5%	99.3%	97.5%	99.8	99.4%
	Final Parts Fresh, % Conversion	99.0%	99.8%	99.7%	99.5%	n/a	n/a	n/a
	Final Parts Aged, % Conversion	95.8%	99.3%	98.8%	98.2%	95.1%	99.5%	98.8%
% Conversion calculated as [Engine-Out – Tailpipe] / Engine-Out, based on TP results from table above								

As can be seen in the tables, the Development Aged parts were able to demonstrate emission levels below the 0.02 g/hp-hr target. Although the Final parts demonstrated levels at half the target when Fresh, the Final Aged parts were not below the target, and generally demonstrated a tailpipe level on the order of 0.034 to 0.038 g/hp-hr, depending on the cycle. This represented a loss of roughly 0.9% conversion over the FTP cycle in NO_x conversion. The change observed on the WHTC was very similar, while the RMC-SET showed a 1.3% loss of conversion. Nevertheless, the Final Aged system still produced a tailpipe NO_x reduction of 70 to 75% from the Baseline on transient cycles, and 55% on the RMC, despite the difficulties encountered in the final aging process.

About half of the change in the composite FTP can be attributed to a 3% loss of cold-start FTP conversion efficiency, which was due primarily to a loss of storage capacity on the PNA. It is not known how much of this change was the result of normal aging, and how much could be the result of the large soot and HC exposure that occurred during the canning failure. The results for the Development parts in comparison to the Fresh results indicate that it is possible to lose some storage capacity on the PNA and still produce results under 0.02 g/hp-hr, if hot-start performance remains stable.

The other half of the change can be attributed to at 0.5% loss of hot-start FTP conversion performance, primarily due a combination of degradation on the SCRF, and a small increase in the tendency of the system to oxidize ammonia into NO. It is not clear how much of this degradation was the result of normal aging, and how much could have resulted from high soot loadings and localized exotherm due to the matting material from the canning failure. The change in hot performance could also be related to migration of precious metal from the PNA to

the SCRF, however this cannot be verified without a destructive post-mortem analysis of the parts. The RMC-SET results indicate similar mechanisms of degradation to the hot-start FTP, but to a slightly larger degree due to the higher cycle temperatures.

Overall, the Low NO_x Engine was able to achieve substantial reductions in tailpipe NO_x levels, on the order of 60 to 75%, from the Baseline engine, generally demonstrating a level of 0.035 g/hp-hr with Final Aged parts. This level was demonstrated on a test article with unusually low exhaust temperatures (due to the mechanical turbocompound system), and with parts that may have been compromised in part by an unusual canning failure during the aging process. The results with the Development Aged parts indicate that more performance is potentially available if the robustness of some of the aftertreatment components can be improved somewhat.

It should be further noted that the robustness of these aftertreatment components remains an area for further development. The improvement of the PNA formulation to make the technology more robust during exposure to rich conditions is an active development area. Furthermore, the incorporation of a small precious metal layer upstream of the PNA could be an effective countermeasure to prevent degradation due to localized exposure to higher molecular weight hydrocarbons, which occurred during the early aging process due to coke and soot buildup. In a similar fashion, the durability of SCRF is another very active current area of development, given the interest in that technology for a number of applications beyond the Low NO_x application explored in this program. Therefore it is reasonable to assume that these systems can be made more durable in the future. Whether such developments will be sufficient to ensure durable performance at tailpipe levels below 0.02 g/hp-hr is a valid question, but the performance of the Final Aged parts even in the face of an abnormal failure is a source of some encouragement.

Given the results shown for the Final Aged parts, it is clear that the development of a robust system for this low temperature engine platform at a tailpipe NO_x level below 0.02 g/hp-hr is a significant challenge. The margin for loss of performance due to degradation on this engine is small, only about 0.3% composite conversion. Even with more flexibility on a different engine platform that margin is unlikely to be greater than 0.5%. However, due to the unusual failure that occurred during the Final Aging process, it is not clear exactly what the level of conversion performance loss would have been if Final Aging had run without incident. Discussions with the catalyst supplier have indicated that the change in hot-start and RMC-SET performance appeared unusual based on the aging conditions that were seen outside of the failure itself. If time and budget were available for a repeat of the Final Aging experiment and demonstration tests, it would be possible to resolve some of the questions related to the final performance level.

The final aftertreatment configuration was highly influenced by the low engine-out exhaust temperatures due to the presence of the mechanical turbocompound WHR system on the MD13TC engine. With regard to the key system components described earlier, it is likely that the SCRF would remain a key component for reaching ULN levels, even on a different engine platform. However, it is likely that the requirement for both low temperature NO_x storage (in the form of a PNA) and a large amount of supplemental heat addition (in the form of the mini-

burner) would not be as great on a different engine platform. A higher engine-out exhaust temperature, or greater flexibility to increase exhaust temperature could reduce the need for supplemental heat addition, and thus allow the use of a less complicated heat system than the mini-burner. Alternatively, more flexibility on the engine platform in terms of both temperature and NO_x could permit the removal of the PNA, or at least could allow for reduced reliance on the NO_x storage function. Lessons learned, and information gained from this program could be leveraged to allow the examination of ULN solutions for other engine platforms, if time and funding are available to do so. The results of the extensive screening effort conducted on this program indicate a number of potential directions for future development of ULN technologies.

Diesel Engine GHG Results and Discussion

A comparison of GHG emissions between the Low NO_x engine and the Baseline engine are also given in Table 8 below. These results summarize CO₂ and N₂O emissions over various cycles. In the case of CO₂ emissions the reported values are those measured during the actual demonstration testing. It should be noted that due to both a location change and the time between baseline and final demonstration testing (more than two years), it was necessary to correct these values for small measurement discrepancies in order to provide a valid comparison between the Baseline and Low NO_x engine values.

The N₂O emissions show an increased tendency towards N₂O generation with the final Low NO_x configuration, and the Final Aged parts indicated N₂O levels just at the 0.1 g/hp-hr cap standard specified for GHG Phases 1 and 2. However, this increase for the Final Aged parts may be due in part to precious metal migration, and it is not clear how much of that may have resulted from the canning failure incident during Final Aging. It is clear, however, that the Low NO_x Engine would have been well over the 0.05 g/hp-hr limit that was originally proposed for the GHG Phase 2 program, even without this possible noise factor.

TABLE 8. DIESEL ENGINE COMPARISON OF GHG EMISSIONS – LOW NO_x ENGINE VERSUS BASELINE

Engine		Pollutant	FTP			RMC-SET	WHTC Composite
			Cold	Hot	Composite		
Baseline		CO ₂ , g/hp-hr	574	543	547	458	485
		N ₂ O, g/hp-hr	0.024	0.047	0.044	0.05	0.06
Low NO _x Engine	Devel Aged	CO ₂ , g/hp-hr	600	547	555	462	491
		N ₂ O, g/hp-hr	0.075	0.087	0.085	0.033	0.085
	Final Aged	CO ₂ , g/hp-hr	604	549	558	464	494
		N ₂ O, g/hp-hr	0.101	0.108	0.107	0.055	0.086

For the FTP cycle, which is used to assess Vocational applications, the Final Aged values indicate an increase of in GHG emissions over the baseline of 5.3% on the cold-start FTP and 1.1% on the hot-start FTP, resulting in a composite increase of 2%. The cold-start increase is due to a combination of 2.5% from engine calibration changes and 2 to 2.5 % from fuel consumption by the mini-burner. A small amount is also likely due to increase backpressure. The hot-start increase is due to a combination of about 0.5% to 0.7% fuel consumed by the mini-

burner for thermal management, with the remainder attributed to increased backpressure. However, these values should be adjusted upwards by a further 0.6% to account for the impact of increased SCRF regeneration and the fuel consumption required to drive the air for the mini-burner. Therefore the final composite FTP impact on GHG is on the order of a 2.5% increase on the FTP. The WHTC is very similar at 2.4%.

The RMC-SET, which is the cycle relevant for Tractor application, showed an increase of 1.3% for the Final Aged parts, likely due primarily to the increased backpressure of the final system. This should again be adjusted to account for increased SCRF regeneration, which would result in a final GHG impact of 1.6% on the RMC-SET cycle. It should be noted that the mini-burner did not activate on the RMC-SET due to the elevated temperature of that cycle.

These values represent a substantial increase in GHG emissions and fuel consumption compared to the baseline engine, especially in light of the upcoming Phase 2 GHG limits. It is likely that a portion of this could be mitigated by improved thermal packaging of the aftertreatment system to reduce the need for supplemental heat, and from an improved mixing design that helps to lower overall system backpressure.

However, it should be noted that a significant portion of the GHG increase observed was due to the need to add substantial amounts of heat to the exhaust in order to counteract the loss of exhaust heat due to the presence of the mechanical turbocompound system on the MD13TC engine. Given that the system could not be bypassed or modified, the presence of the turbocompound likely increased the GHG impact of the final Low NO_x approach for this engine. In the case of the FTP cycle, the need for supplemental heat addition essentially eliminated the likely benefit of the turbocompound system. For the RMC-SET there is still likely a net gain from the turbocompound, but its presence still results in a more complicated aftertreatment system. Given that this engine architecture does not appear to represent the mainstream of approaches to meeting upcoming GHG limits, it is likely that the GHG impact observed on this engine is at the high end of the spectrum as compared to other engines.

Nevertheless, it does appear that some level of impact in GHG emissions should be anticipated as a consequence of adopting a Low NO_x standard on the order of 0.02 g/hp-hr. This would result in the likely need to expend more effort to meet GHG Phase 2 standards than would otherwise be the case. However, the magnitude of this impact is also likely to be smaller than what was observed during this program, on this particular engine.

Further development efforts to apply ULN technologies to other platforms would be beneficial in determining the impact of a given Low NO_x standard on the overall industry effort required to meet Phase 2 GHG targets. Such information will be important in determining where an eventual regulatory standard should be set.

Diesel Engine Vocational Cycle Results

The results for the three Vocational cycles are shown in Table 9 below. Different behaviors were observed for each of the three cycles, as can be seen from the results in the table, but certain consistent trends were still apparent in all three cycles. First, the Low NO_x engine

had consistently lower tailpipe emissions than the Baseline engine for all three cycles, though the amount of reduction varied. Second, on two of the three cycles, the NYBC and the Cruise Creep, while performance on the Low NO_x engine was better, aftertreatment conversion was still not as high as the levels observed on the FTP and RMC cycles. NO_x conversion for the Low NO_x engine on these two cycles was 90% and 82% respectively. While better than the baseline, this is not nearly as good as the 98 to 99% conversion observed on the regulatory cycles, indicating room for further improvement. It should be noted that the performance of both engines on these cycles could likely be improved with further calibration effort, although it appears that the Low NO_x engine likely has more flexibility to reach lower levels. Interestingly, on these cycles, little impact on fuel consumption and CO₂ was observed when comparing the Low NO_x engine to the Baseline.

TABLE 9. DIESEL ENGINE VOCATIONAL CYCLE EMISSIONS – LOW NO_x ENGINE VERSUS BASELINE

Cycle	Baseline				Low NO _x Engine				% TP NO _x Reduction
	EO NO _x , g/hp-hr	TP NO _x , g/hp-hr	Fuel Rate, kg/hr	CO ₂ , g/hp-hr	EO NO _x , g/hp-hr	TP NO _x , g/hp-hr	Fuel Rate, kg/hr	CO ₂ , g/hp-hr	
NYBC	6.1	2.3	5.3		3.9	0.4	5.3		83%
OCTA	3.8	0.023		529	2.7	0.006		534	74%
		NO _x , g/hr	Fuel Rate, kg/hr			NO _x , g/hr	Fuel Rate, kg/hr		
Cruise Creep - 10 cycles	72	13.3	2.8		41	7.5	2.8		44%
Cruise Creep - last 3 cycles	71	27			40	11.3			58%

On the NYBC cycle, the Low NO_x engine performed very well, and demonstrated an 83% reduction in tailpipe emission from the Baseline, relatively similar to what was observed for the reduction observed on the regulatory cycles, albeit starting from a much higher baseline emission rate. It appeared that the updated engine calibration was slightly more efficient under these operating conditions, which likely offset the relatively minor use of the thermal management system on the NYBC cycle. In the case of both engines, the fact that average engine power is only 5% of maximum on this cycle makes the brake-specific NO_x values seem quite large.

The Cruise Creep cycle was less favorable for the Low NO_x engine with its current calibration, and the engine was much more reliant on the thermal management system calibration to maintain improved NO_x performance. Still, the Low NO_x engine was able to achieve roughly a 50% reduction in tailpipe NO_x, without a measureable penalty on fuel consumption. It should be noted that the Cruise Creep NO_x is reported as mass rate because the work is so low that the brake-specific NO_x becomes arbitrarily large.

The OCTA bus cycle, while being highly transient in nature had a significantly higher load factor than the other two vocational cycles. Both the Baseline and Low NO_x engines were well within their operating range for these cycles, and both had tailpipe emissions well below the levels observed on the Regulatory cycles. Nevertheless, the Low NO_x engine still demonstrated a 74% reduction in NO_x as compared to the Baseline. The Low NO_x engine was well below 0.02 g/hp-hr, but there was a 1% increase in CO₂ emissions on this cycle, likely the result of a combination of engine calibration and backpressure. Thermal management was not active on this cycle, as temperatures were well above the range where it was needed.

Overall these results indicate that there is much that can be done to reduce the emission performance gap between regulatory cycle operation and low load field cycle operation. The Stage 2 program effort will examine the effect of further optimization of the Low NO_x engine for low load cycles. However, these results do provide some very encouraging indications with respect to the potential for further emission reductions on low load cycles.

Diesel Engine Recommendations and Next Steps

Overall, the diesel program results indicate that there is technology available to achieve ULN NO_x levels substantially lower than current tailpipe NO_x levels, with a 0.035 g/hp-hr demonstrated using aged parts, despite a challenging low temperature platform and unusual failure during aging. The results indicate that there is available technology to reach levels at or near 0.02 g/hp-hr, but there are some significant challenges with respect to system robustness and complexity. The Final Aged system was not below the target level of 0.02 g/hp-hr, however it did still demonstrate significant NO_x reduction from the Baseline, especially over some of the low temperature Vocational cycles.

More effort could also be directed at reducing the GHG impact observed in the program, which was on the order of 1.5% to 2.5% depending on the regulatory cycle, although it should be noted that the Vocational cycles indicated either no impact on GHG or a much smaller impact than the regulatory cycles. Several important questions are left open at the conclusion of the program, and these suggest direction for further efforts.

- Final Aging issues and the NO_x potential of the final configuration for the MD13TC engine – as detailed earlier, the abnormal issues that were encountered during Final Aging, and especially the canning failure, leave some question as to whether at least some of the observed degradation in the aftertreatment system was not representative. In order to answer these questions, if time and budget were available it would be desirable to repeat the Final Aging and testing experiment on another set of parts. This would answer questions regarding abnormal versus normal degradation and provide a more definitive answer regarding the robustness of the system.
- Performance potential of ULN technology – The low temperature presented by the MD13TC platform, and the limited options for addressing that on engine, likely resulted in a more complicated aftertreatment system technology package being needed to reach ULN levels. As discussed earlier, this package is likely to represent more of a worst case

of the level of effort required to reach ULN levels. In order to make a more broadly applicable assessment, it would be useful to look at a second engine platform that is more representative of the broader industry approach to GHG Phase 2 targets. Such an effort could leverage the information and lessons learned from the current program in order to generate another valuable data point for determining the technical feasibility for ULN levels.

- GHG Impact of ULN technology – the MD13TC platform represents a particular challenging case due to the use of the turbocompound technology. This drove the development of a system with a significant GHG impact due to the need for large amounts of supplemental heat addition. While this is useful for looking at a worst case example, it would be preferable to look at another more representative platform in order to make a more broadly applicable determination of the impact of a given Low NO_x standard on the overall industry effort required to meet Phase 2 GHG targets. The knowledge gained and lessons learned from the current effort could be leveraged to apply ULN technology on a more flexible and representative engine platform.
- Low load and vocational field cycles – The current program was focused primarily on regulatory cycles, given that these are the primary current targets for any emissions development. The Vocational cycle tests give some insight into the potential for low load cycle emission controls, and there are some promising initial signs, but much more work can be done in this area. A significant amount of information is needed with regard to the potential for low load cycle emissions controls, and the associated GHG impact of those controls. The Stage 2 effort which is just getting under way will provide some of this information, but more effort in this area is recommended. Any other efforts on a different engine platform should incorporate low load cycle NO_x control as a target, rather as a relatively small demonstration test. A robust regulatory scheme to insure the real world NO_x reductions are achieved even on low-load duty cycles will hopefully be an important feature of any upcoming NO_x regulation.
- Measurement and testing variation – The current program has produced a test article that can generate emissions at ULN levels, with hot-start emissions in the area of 0.01 g/hp-hr in some cases. The program provided an initial data set regarding the repeatability the test and measurement process at these levels, but this remains a limited data set that leaves several questions open with regard to the test process. These include questions regarding the influence of different preconditioning approaches, test cell environment, and other factors. In addition, other portions of the regulatory process, such as in-use measurement and PEMS, will need to be examined at these much lower levels. A robust effort to examine these issues would be recommended, and this is an area where a cooperative program could prove valuable. The current test article could be used to examine such issues, and the data set from the current program could be analyzed in detail to look at measurement related questions. It should be noted that these issues apply not only to NO_x measurement, but also to the accurate determination of small changes in CO₂ that are critical for assessing the GHG impact, wherein even changes less than 0.5% are considered very important.

While this program has provided much valuable information regarding the potential for ultra-low NO_x levels, additional investigation in the recommended areas would be valuable to help fully inform future low NO_x regulatory efforts.

1.0 INTRODUCTION

The 2010 emission standards for heavy-duty engines established a limit for oxides of nitrogen (NO_x) emissions of 0.20 grams per brake-horsepower-hour (g/hp-hr). However, it is projected that even when the entire on-road fleet of heavy-duty vehicles operating in California is compliant with the 2010 emission standards, the upcoming National Ambient Air Quality Standards (NAAQS) requirements for ambient particulate matter (PM) and ozone will not be achieved in California without further significant reductions in NO_x emissions from the heavy-duty vehicle fleet [1][2].

The California Air Resources Board (CARB) contracted Southwest Research Institute (SwRI) to demonstrate the feasibility of achieving NO_x emissions lower than the current engine standard. This was researched by evaluating enhanced aftertreatment technology choices, aftertreatment configurations, catalyst optimizations, urea dosing strategies, engine tuning, and engine management practices for two heavy-duty engines: one natural gas engine with three-way catalyst (TWC), and one diesel engine with selective catalytic reduction (SCR). The target NO_x ultra-low NO_x (ULN) emission rate for this project was 0.02 g/hp-hr, which is a 90 percent reduction from the current standard.

ULN is defined as a composite of the HD engine Federal Test Procedure (FTP) NO_x mass emission of less than 0.02 g/hp-hr. This is a 90% reduction from the current 2010 heavy-duty composite NO_x emission standard of 0.20 g/hp-hr. The composite emission is a weighted sum comprised of 1/7 from the cold-start FTP and 6/7 from the hot-start FTP. Under the current emission regulations, it is possible to achieve the composite emission target of 0.20 g/hp-hr by primarily focusing on controlling emissions during high space velocity events and improved catalytic conversion efficiency of NO_x from the beginning of the hot start portion of the test cycle. Over time since 2010, diesel engine-out NO_x levels have been increasing slowly as aftertreatment performance has improved, and this has enabled engine manufacturers to recalibrate engines to improve fuel economy. Some low-temperature thermal management has been utilized as part of this change, but more potential remains to lower tailpipe NO_x levels, especially during cold-start and low-load operating cycles.

As an example, the baseline diesel engine uses a typical post-2010 aftertreatment emissions control configuration, consisting of a diesel oxidation catalyst-diesel particulate filter-selective catalyst reduction (DOC-DPF-SCR). The baseline diesel engine NO_x emissions and catalyst conversion efficiencies over the FTP cycle are provided in Table 10.

TABLE 10. BASELINE NO_x DIESEL ENGINE EMISSIONS AND CONVERSION EFFICIENCIES OVER THE FTP

Test	BSNO _x [g/hp-hr]		NO _x Conversion Efficiencies [%]
	Engine-out	Tailpipe	
Cold	2.82	0.715	74.7
Hot	2.98	0.047	98.4
Composite	2.96	0.140	95.2

Under a ULN emissions control strategy, one must aggressively reduce the cold-start emissions, as well as provide superior hot start and high space velocity NO_x control.

To achieve composite emissions levels below 0.02 g/hp-hr, the cold-start FTP emissions must be very low; on the order of current technology hot-start emissions, and the hot-start emissions must be near zero for the entire cycle. Both cycles will require some degree of thermal management to heat the catalyst system to levels required to obtain high conversion efficiency quickly. The elements of a ULN application included:

1. Reduce time to light-off
2. Modified catalyst configurations
3. Supplemental heat and/or distributed heat
4. Engine calibration for increased exhaust temperature
5. Reduce SCR system inlet NO_x until light-off achieved
6. More aggressive engine out NO_x reduction at low coolant temperature
7. Low temperature NO_x storage catalysts
8. Consideration to Phase II GHG approaches

An example of the cycle specific emissions that could meet a ULN level is shown in Table 11. This example shows the development targets that were used for this program. It was understood

TABLE 11. EXAMPLE OF CYCLE SPECIFIC NO_x EMISSIONS IN AN ULTRA-LOW NO_x APPLICATION

Test	BSNO _x [g/hp-hr]		NO _x Conversion Efficiencies [%]
	Engine-out	Tailpipe	
Program Targets			
FTP Composite	n/a	0.02	n/a
Example ULN Emissions Requirements (Diesel)			
Cold	2.82	0.06	97.9
Hot	2.98	0.01	99.7
Composite	2.96	0.017	99.4

This program was conducted by SwRI under the direction of CARB staff, but there were several other program partners whose input was also vital to the conduct of the program. Program partners included Volvo who supplied the diesel engine and engineering support to the program. The Manufacturers of Emission Controls Association (MECA) was also a key program partner in several ways. Various MECA member companies supplied aftertreatment technology in-kind to the program (on an anonymous basis), and MECA also provided funding to support several key tasks including Final Aging, a portion of Technology Screening, and supplemental efforts to assess filter regeneration for various configurations. The initial CNG engine was supplied by Doosan, although ultimately that engine could not be utilized, and the program had

to shift to a Cummins engine that was available at SwRI. Gas engine controls and control hardware were provided by EControls.

The program was also guided in part by input from an advisory group consisting of various other key stakeholders. This group was designated as the Program Advisory Group (PAG), and it consisting of stakeholders from various groups including the U.S. EPA, the U.S. DOE, the South Coast Air Quality Management District (SCAQMD), the California Energy Commission (CEC), the Truck and Engine Manufacturer's Association (EMA), MECA, and various individual heavy-duty engine manufacturer's. Program progress was presented to this group at several meetings early in the program and at the conclusion of key program tasks. This group provided important feedback and input on program direction and conduct.

The remainder of the report describes in detail conduct of the demonstration program, as well as providing technical details of the technologies examined and the results of the program. Section 2 details the CNG engine program, while Section 3 presents the details of the Diesel engine program. Section 4 of the report provides a final discussion and concluding results for both engines.

2.0 CNG ENGINE PROGRAM

2.1 TASK 1: Engine, Test Cycles and Aftertreatment Technologies

2.1.1 Test Cycles Selection

2.1.1.1 Primary Cycles

The primary cycles for this program were cycles that were established as certification procedures, and these primary cycles were used for calibration development and for demonstration of the final system in comparison to the 0.02 g/hp-hr target.

In accordance with the program proposal and with established emission certification procedures, the primary cycle of focus for this effort was the heavy-duty transient Federal Test Procedure (FTP). This cycle served as the primary development screening tool, and was also the primary metric for determining the emission level achieved by the final emission system configuration. For this cycle, the development target was to reach a level below 0.02 g/hp-hr on the composite emission value. It was anticipated that achieving the required emission levels on the cold-start portion of the cycle would be representative of the primary technical challenge during this program. Table 12 summarizes projected cold-start and hot-start emission levels that were required to demonstrate the desired composite level. The target emission value was below 0.02 g/hp-hr, so as to provide some margin for measurement. The intent was to meet this target with an aged aftertreatment system, therefore, the development targets for a fresh system were somewhat lower, to provide an aging margin.

TABLE 12. INITIAL DEVELOPMENT TARGETS

	Initial Target, g/hp-hr
Cold-FTP (1/7 th of composite)	0.06
Hot-FTP (6/7 th of composite)	0.009
Composite FTP	0.016

In addition, the cycles requested by CARB in the initial Request for Proposal (RFP), SwRI also determined that it would be necessary to demonstrate emission levels less than 0.02 g/hp-hr on the steady-state Ramped Modal Cycle Supplemental Emissions Test (RMC-SET) cycle. This was because the RMC-SET cycle is the primary cycle that was used to demonstrate compliance with GHG emission regulations for Tractor engines. Given that this application was a key target for the heavy-duty engines evaluated in this program, an assessment of GHG emissions over the RMC-SET was critical for determining the impact of the final system. The assessment would not be meaningful if the system did not also meet the 0.02 g/hp-hr level on the cycle, and therefore this cycle was added as a target to the program.

A secondary target cycle for this program was the World Harmonized Heavy-Duty Transient Cycle (WHTC), which is one of the primary tools used for emission certification in Europe. This cycle was requested by CARB as well, and it was chosen to represent a cycle in which the exhaust temperature remained at a lower average level than the FTP for a longer

period. The desire was to demonstrate an emission level below 0.02 g/hp-hr for the WHTC as well. The WHTC includes a cold-start and hot-start phase, similar to the FTP, and the same cold-hot weight factors are specified. Figure 14 provides a comparison of cold-start exhaust temperatures for both cycles. As can be seen in the chart, FTP exhaust temperatures are similar to those of the WHTC during the first 400 seconds, but are significantly hotter from 600 seconds onward. However, it should be noted that the WHTC duration is 1800 seconds, as compared to 1200 seconds for the FTP, and similar temperatures are achieved by the end of the cycle, prior to the ensuing hot-start cycle. In addition, the WHTC used only a 10-minute engine-off soak, as opposed to the 20-minute engine-off soak used for the FTP.

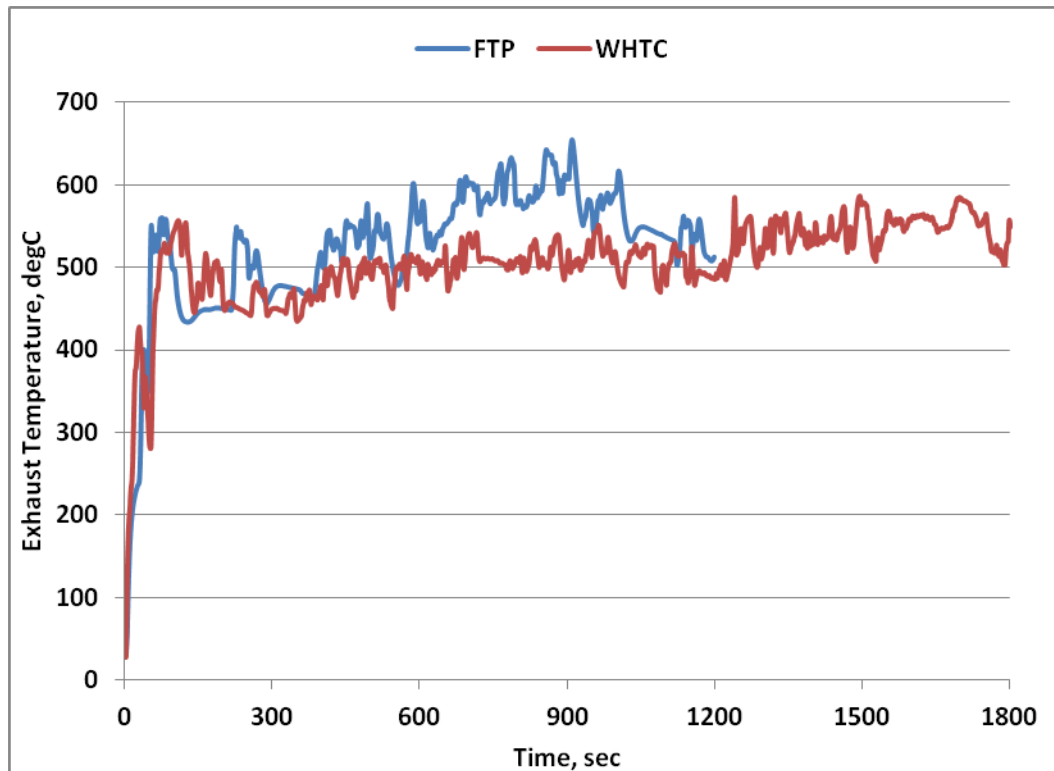


FIGURE 14. COLD-START EXHAUST TEMPERATURE COMPARISON FOR WHTC VS. FTP – CNG PROGRAM ENGINE

Another secondary target cycle for this program was the CARB Idle Test. This is a California-specific test designed to ensure a level of NO_x control during a sustained idle period. It consists of an FTP cycle warm-up, followed by two 30-minute idle periods. The first idle period was at the designated low idle speed (i.e., “curb idle”), while the second 30-minute period was at an elevated idle (no-load) speed of 1100 rpm. The current limit for this cycle is 30 g/hr average NO_x rate, integrated separately of each of the two 30-minute idle periods. While this was a cycle of interest, no specific limit was proposed as a target for the program. Therefore, the intent under the program was to examine the performance of the final system, which was calibrated for the FTP and WHTC cycles on this CARB idle cycle. It was anticipated that significantly lower levels (relative to the baseline application) would be observed.

2.1.1.2 Additional Cycles

In addition to the primary cycles described above, several additional cycles were desired for use on a demonstration-only basis. These cycles were selected to be more representative of different kinds of in-field operation, with a particular focus on vocational applications that would be characterized by lower temperatures and/or more transient operation than the primary (certification) cycles that were the primary program targets. The intent behind these cycles was to examine how well the reduction of emissions to 0.02 g/hp-hr on the certification cycles might translate to operation on other, potentially more challenging duty cycles from the field.

These “Vocational” cycles were developed as part of the program, based on input from CARB. Much of the initial down-selection and cycle screening was performed by CARB staff. They selected from among a wide variety of available vehicle duty cycles to target particular types of operation that might be challenging to the aftertreatment and control systems. Table 13 provides a brief description of the final cycles that were chosen, and the intent behind the selection each cycle.

TABLE 13. SUMMARY OF VOCATIONAL CYCLES CHOSEN FOR ARB LOW NO_x DEMONSTRATION

Cycle	Description	ARB Intent
Idle + NYBC x 4	30min idle + 41 min urban operation	• Highly transient • Low speed with severe demand spikes • Sustained Low temperature with high transient
Cruise+Creep x 10	50mph cruise for 20 min followed by 42 min of “creep” operation	• Sustained light load • Ability of system to maintain heat • Thermal management behavior • Cold-start versus extended low load
OCTA Bus	Based on OCTA cycle data ~ 32 min	• Realistic vocational cycle for California • Transit bus data • Less aggressive transients than FTP

In the case of the New York Bus Cycle (NYBC) and Orange County Transit Authority (OCTA) bus cycles, the profiles were available only on a vehicle speed basis. Therefore, it was necessary to transform these cycles to an equivalent engine-based profile, so that they could be executed on an engine dynamometer for demonstration purposes. CARB provided the data for these translations by executing the cycles on a chassis dynamometer and monitoring the engine speed and load via ECU broadcast channels.

After some initial processing and averaging, CARB provided the cycle information to SwRI at 10 Hz schedules of speed and torque, along with engine torque curve data. SwRI then translated these data into a set of normalized 1 Hz schedules that were available in a format identical to the one used for certification cycles, like the FTP. This allowed the schedules to be executed on any engine and in any engine test cell, following the same cycle de-normalization procedures that are normally applied for the FTP in 40 CFR Part 1065. In the case of the Cruise-Creep cycle, the cycle was already available as a normalized 1 Hz schedule, so very little effort was required to finalize the profile once it was decided.

The finalized cycle profiles are depicted in Figure 15, Figure 16 and Figure 17, for the NYBC, Cruise-Creep, and OCTA bus cycles, respectively. The actual profiles are available from CARB in a second-by-second format for anyone who wishes to run these cycles for themselves. Note that the NYBC cycle is actual four successive repeats of the NYBC cycle profile, but they vary slightly due to variations in the actual driving when the cycle data were developed.

The Cruise-Creep cycle, shown in Figure 16, is a combination of two different CARB cycle profiles. The first portion, which is the “Cruise” is based on vehicle data from a 45 mph average speed trip to a work location. This portion is essentially a conditioning phase. The second portion of the cycle consists of 10 repeats of the CARB Creep Cycle. This short cycle was intended to represent a light load, transient application that might be characterized by a truck working in a freight yard, or something similar.

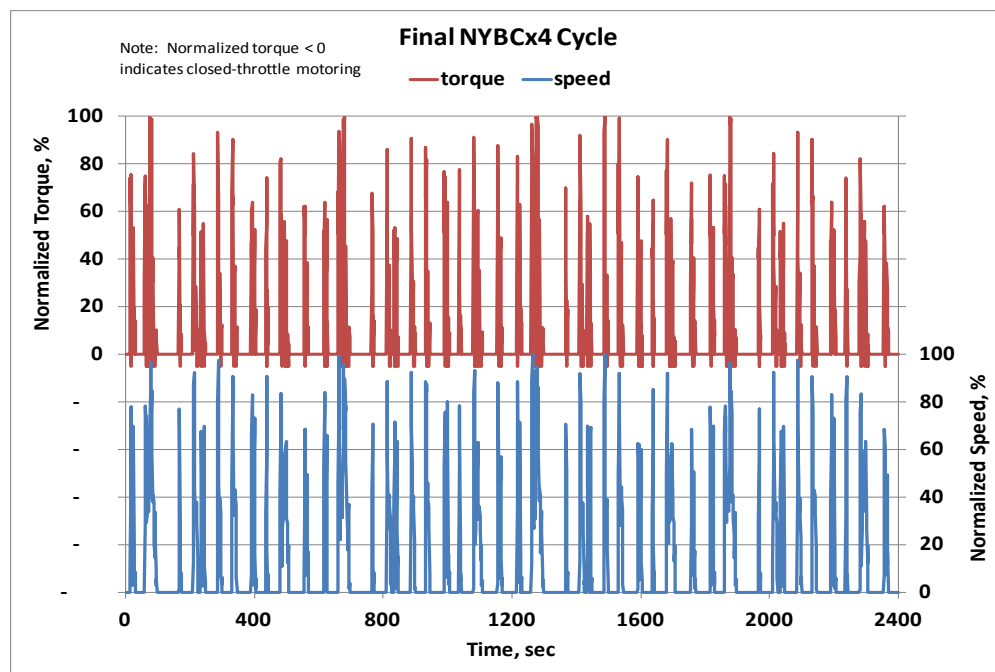


FIGURE 15. NORMALIZED NYBC(X4) CYCLE

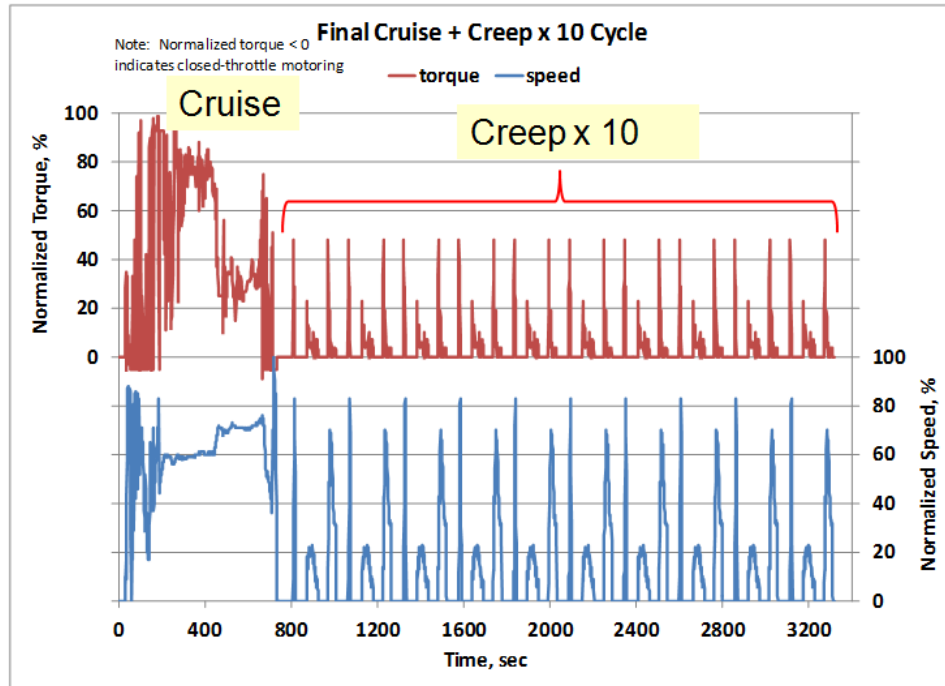


FIGURE 16. NORMALIZED CRUISE-CREEP (X10)

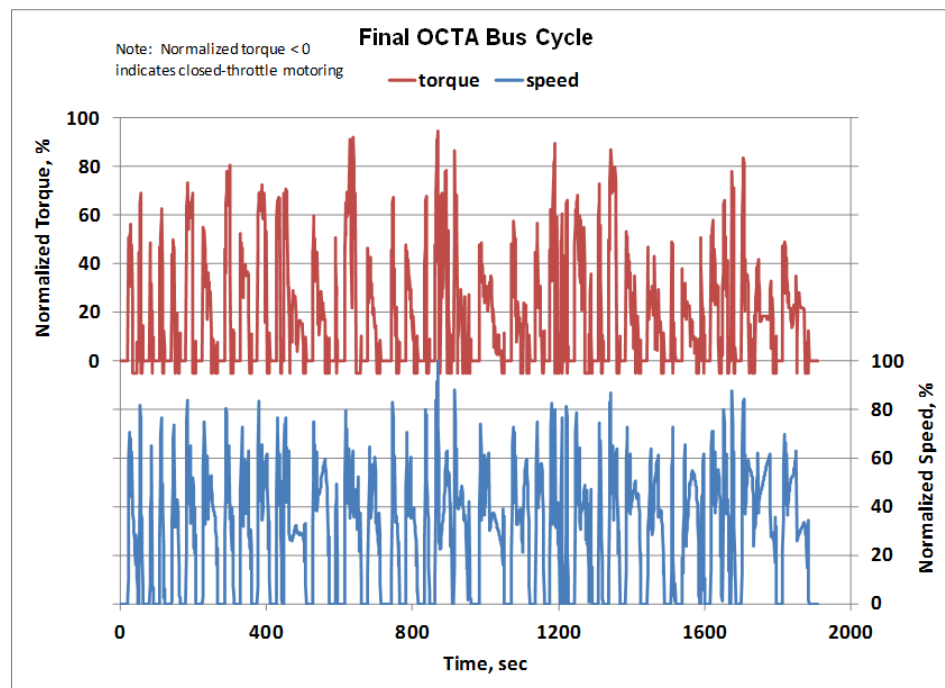


FIGURE 17. NORMALIZED OCTA BUS CYCLE

The OCTA bus cycle was developed based on transit bus data collected on a bus in Orange County, and therefore is considered representative of urban field operation on California.

Each of the final cycles was executed using the diesel engine in the test cell to ensure the final cycles were useable. An important part of the development of the cycles involved the choice of pre-conditioning procedure for each cycle. It is well understood that previous operation can have a significant effect on the performance of an SCR-based aftertreatment system over any given cycle. Therefore, appropriate pre-conditioning procedures were necessary to generate consistent and meaningful results.

The general approach to pre-conditioning was similar to the approach and intent outlined in the procedures in 40 CFR Part 1065. The desire was for the emission system to achieve equilibrium with the cycle being tested, on the assumption that the test cycle would theoretically represent a small window or “snapshot” of normal operation on that same duty cycle. In some cases, such as the NYBC or Cruise-Creep, the cycle incorporates some kind of conditioning step, but operation even prior to that test is still influential. Therefore, the general approach was to execute the test cycle portion prior to the start of operation for record. In the case of the NYBC cycle, there was intent to target low temperature operation, and therefore a 30-minute idle was incorporated prior to the beginning of the cycle-for-record. In the case of the OCTA Bus cycle, there was zero dwell between the end of the preconditioning cycle and the start of the test for record.

The one exception to this was the Cruise-Creep cycle, because the high temperature cruise portion was already intended as the pre-scribed preconditioning. In that case, the preconditioning consisted only of a warm-up as described in 40 CFR Part 1065, which was completed by a test at NTE Speed C and 75 percent load. The final pre-conditioning approach for each cycle is described in Table 14.

TABLE 14. PRE-CONDITIONING PROCEDURES FOR THE VOCATIONAL CYCLES

Cycle No.	Cycle Name	Pre conditioning	Start Notes
1	NYBCx4	1. Warm-up 2. Run prep NYBCx4 cycle 3. Idle for 30-min 4. Run test for record	Start at idle Hot running start at end of 30-min idle segment
2	Cruise + Creep x 10	1. Warm-up (C75 10 min) 2. Run test for record	Start at idle < 1 min after coming down from warm-up
3	OCTA Bus	1. Warm-up 2. Run prep OCTA Bus cycle 3. Run test for record	Start at idle immediately following end of prep cycle (< 1 min dwell at idle allowed)

As noted earlier, these vocational cycles were intended for demonstration purposes only. There was no effort made to calibrate the performance of the emission system to improve performance on these cycles. Rather, the systems were taken as calibrated for the primary cycles, and the vocational cycles were executed to demonstrate performance. This allowed comparison of the performance on these duty cycles with performance on the certification cycles.

The vocational cycles were also executed as part of the baseline data generation for each engine, which allowed for an initial comparison on current technology engines between certification cycles and these different field duty cycles.

A second-by-second schedule for each cycle is included in this report in Appendix A, in a normalized format. These cycles were meant to be de-normalized following the same process used for the FTP transient cycle, as described in 40 CFR Part 1065.

2.1.2 Test Engine

The initial plan within the proposal was to utilize a Doosan GL11K natural gas engine that SwRI had used in a previous program and was still on-site. The engine was converted from lean burn to stoichiometric and a low-pressure-loop, cooled exhaust gas recirculation (EGR) system was added. The fueling system consisted of six injectors fueling into a mixer upstream of the throttle. The engine was controlled using a Woodward controller that allowed full authority over the engine (air-fuel ratio, spark timing, etc.). The engine had achieved the gaseous emission targets (namely NO_x emissions less than 0.02 g/hp-hr composite over the FTP). However, the engine failed the PM emissions limit. The PM emissions were not measured under initial transient testing because PM is generally not a problem with CNG engines; however, a hot FTP showed roughly 0.05 g/hp-hr of particulate emissions (well above the 0.01 g/hp-hr limit).

Soot forms when locally rich combustion is combined with high reaction temperature – either poor fuel-air mixing or abnormally high oil consumption can result in locally rich combustion. When the PM problem with the Doosan engine was observed, different fuel-air mixers were tested to aid in both the temporal and spatial mixing but no discernible effect on PM emissions was noted. The cylinder head was altered to incorporate tumble plates and increase turbulence and mixing in-cylinder but no reduction in PM was observed. Next high swirl heads and new fuel injectors were installed but again no reduction in PM was measured.

The engine was ultimately characterized by high crankcase pressure which can result in increased oil consumption. The blowby filter was replaced and the PM emissions dropped to 0.02 g/hp-hr. The engine was then calibrated to operate as a lean burn engine (as it was designed) and the PM was reduced to 0.003 g/hp-hr. Operating this engine at stoichiometric conditions and with EGR, can exacerbate the problem with PM emissions due to a lack of oxygen compared to lean combustion. However, it was necessary for the test engine to operate at stoichiometric conditions with EGR to meet the stringent gaseous emissions targets.

The Doosan engine used dry liners for the cylinders. Dry liners have a metal-to-metal interface between the coolant and the liner. This interface can have poor thermal conductivity and thus create hot spots on the liner, distorting the cylinder bore and increasing oil consumption. Two Cummins-Westport engines and one Mack engine that operate at stoichiometric conditions with natural gas and have low PM emissions have wet liners. The wet liner has direct contact with the coolant reducing bore distortion and oil consumption. Another possible problem with the Doosan engine is the ring pack of the piston – it is lacking a second ring for oil control. A second ring is necessary for oil control due to the low manifold air pressures associated with throttling.

Because the Doosan engine did not meet the PM emissions limit, and the high oil consumption could deteriorate the catalyst at an increased rate, it was decided to continue efforts on achieving the gaseous emissions targets in addition to the PM targets with a different engine. SwRI had access to a Cummins ISX12-G engine that was used for a previous project and decided to use this as the replacement. The Cummins ISX12-G engine shares similar performance to the Doosan engine. Table 15 shows the performance specifications of each engine.

TABLE 15: PERFORMANCE SPECIFICATIONS OF DOOSAN GL11K AND CUMMINS ISX12-G

	Doosan GL11K	Cummins ISX12-G
Displacement (L)	11	11.9
Type	4 stroke, turbocharged & intercooled, inline 6, stoichiometric ¹	4 stroke, turbocharged & intercooled, inline 6, stoichiometric
Power (hp)	285 at 2200 RPM	320 at 1800 RPM
Torque (lb-ft)	904 at 1260 RPM	1150 at 1200 RPM

The Cummins ISX12-G engine was evaluated before modifications were made to achieve the ULN program emissions targets. An aftermarket, prototype Engine Control Unit (ECU) from EControls was installed on the engine to allow full authority over engine operation and provide more precise control of the air-fuel ratio. A more in-depth discussion on the engine calibration can be found in Section 2.2 TASK 2: Engine Baseline and Ultra-Low NO_x Calibration and Section 2.3 TASK 4: Catalyst Down-Selection and Final Demonstration Results. The following items were added to the engine to improve air-fuel ratio control and transient operation:

- High energy ignition system
- Improved air-fuel-EGR mixer
- Boost recirculation valve
- Electronic wastegate controller
- EGR measurement system with feedback
- Pressure differential sensor in addition to UEGO sensor
- Closed crankcase ventilation system

The high-energy ignition system was necessary for the high levels of EGR being used and to ensure stable combustion throughout the operating map of the engine. The closed crankcase ventilation system was added to reduce any oil consumption due to blowby. The remainders of the parts added were to aid in air-fuel ratio control during transient operation.

¹ Converted to stoichiometric

2.1.3 Initial Aftertreatment Technology Selection

As part of the initial proposal process for this program, SwRI secured involvement of the Manufacturers of Emission Controls Association as a partner in this program. As part of this commitment, MECA members agreed to supply advanced aftertreatment technologies for this program as an in-kind contribution. In addition, MECA as a whole agreed to participate by providing additional funding for technology screening, as well as for catalyst aging to be conducted later in the program.

For the majority of the aftertreatment system components, MECA members organized into technology teams, each of which was led by one of the major catalyst suppliers. Each team was responsible for specifying a range of technologies that would be supplied to the program. The catalyst supplier would also coordinate the substrate supply, canning, and development aging. SwRI initially supplied data for the Doosan GL11K engine to MECA members to aid in the design of the systems. Each supplier put together an initial system design and strategy, including several suggested modifications to the system to try different technology approaches. It should be noted that while these teams were to be initially evaluated separately from each other, the final system configuration could incorporate elements from multiple teams, at the discretion of SwRI and ARB.

Throughout the program, the identity of the individual system suppliers was kept confidential, and the groups were referred to only by a generic team letter designation that was assigned by SwRI as hardware arrived. SwRI was aware of the identity of the suppliers, and worked closely with all of the suppliers to aid in the design process. It was planned that this working relationship would continue throughout the program, with SwRI sharing data from technology screening with each supplier for their system hardware.

In addition to the primary teams, other individual MECA members provided aftertreatment technology in the form of system modifiers, energy input devices, sensors, and other technologies. SwRI coordinated with all of these suppliers to obtain a large pool of potential aftertreatment technologies.

The intent of this effort was to start with a large pool of possible approaches to reaching the 0.02 g/hp-hr target. This would allow the rapid screening of multiple approaches, with the goal of identifying not only a path to reaching 0.02 g/hp-hr, but also of selecting an approach that was the most advantageous in terms of impact on GHG emissions. In addition, considerations of system complexity, robustness, and packaging were all to be taken into account in the down-selection of the final configuration at the end of the technology-screening phase of the program.

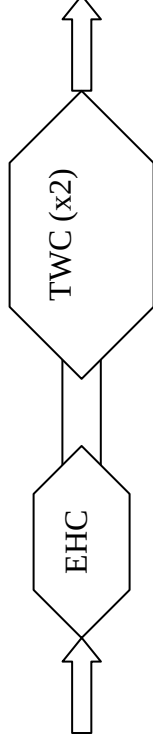
For the catalyst systems, suppliers were asked to provide four sets of samples. Two sets were provided to support the screening effort, one set degreened and the other aged. Details of the aging process are discussed in Section 2.1.4 Aftertreatment Aging Approach. A third set of parts was held in reserve for final aging in the event that those catalysts were down-selected for the final configuration. A fourth set of parts was available as a spare.

Following is a brief description of the technologies chosen to participate in the screening, as well as some of the considerations related to those technologies.

2.1.3.1 General description of systems

The aftertreatment systems supplied by the MECA members were all three-way catalysts; however, there were several system configurations. These various configurations can be seen in Figure 18 through Figure 20.

Team A's configuration is composed of one electrically heated close-coupled catalyst primarily responsible for methane oxidation. The two three-way catalysts further downstream are equal in size; the upstream catalyst is responsible for hydrocarbon oxidation and the last catalyst brick is responsible for NO_x reduction. To account for the GHG impact of the EHC, the power consumption must be measured during testing. This power consumption was then adjusted by an alternator efficiency representative of a production application, in order to predict the engine power requirement (and fuel consumption).

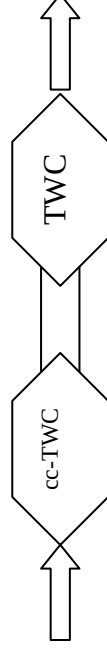


Close-coupled electrically heated catalyst (3.2 liters) with two under-floor three-way catalysts (11.1 liters each)

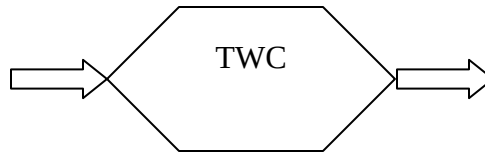
FIGURE 18. SCHEMATIC OF TEAM A CATALYST CONFIGURATION

For the purposes of this program, a practical limit of 5 kW was considered for the size of any electrical heating systems. Considering a device below that limit was practical to incorporate into a heavy-duty vehicle without major electrical system re-design, given that it would likely only operate for limited periods of time during cold-start. Above that limit, it was felt that considerable modification and cost would be required to support a larger power draw.

Team B submitted two options for this program. The first option consists of a close-coupled three-way catalyst responsible for fast light off and NO_x reduction. The under-floor catalyst was equal in size to the close-coupled catalyst and responsible primarily for methane and hydrocarbon oxidation. The second option submitted consisted of a single under-floor three-way catalyst.



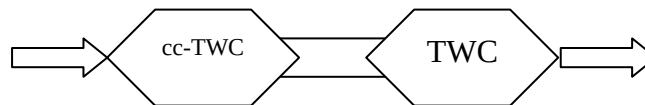
Option 1: Close-coupled catalyst (9 liters) with under-floor three-way catalyst (9 liters)



Option 2: Larger under-floor three-way catalyst (20 liters)

FIGURE 19. SCHEMATIC OF TEAM B CATALYST CONFIGURATIONS

Team C’s configuration consisted of the smallest volume catalysts. The close-coupled catalyst was formulated for fast light off and responsible for CO oxidation and NOx reduction. The under-floor catalyst was designed for NOx slip at high space velocities.



Close-coupled catalyst (5.7 liters) with under-floor catalyst (8.5 liters)

FIGURE 20. SCHEMATIC OF TEAM C CATALYST CONFIGURATION

Some practical considerations were also considered in the initial system designs, such as packaging. While it might be advantageous to close couple the entire aftertreatment system to the engine with minimal distance, the requisite aftertreatment size for the heavy-duty application meant that such an approach would not be practical from a packaging standpoint. Therefore, any close-coupled components, if used, would have to be relatively compact. This can be seen by the size of the each close-coupled catalyst compared to larger “under-floor” catalysts. Additionally, all of the under-floor catalysts were located a minimum of 6 feet downstream of the turbocharger to be realistic of packaging constraints.

A formal screening task was not performed for the natural gas engine side of this program. Instead, each catalyst configuration was tested on-engine with a preliminary engine calibration and the final system was down-selected. Additional engine calibration continued to lower the tailpipe emissions even further.

A key point for all of the technologies offered is that they are all taken from either production or production intent hardware. In some cases, systems may have been developed to the point of commercialization and field trials, but may not have yet entered actual production due to changes in market demand. Therefore, all of the technologies considered in this program are at least feasible for production.

2.1.3.2 Passive Heat Retention

These technologies generally comprised various modifications to the exhaust system, both on and off the engine, designed to help retain heat in the exhaust and prevent loss to the ambient environment. Several different technologies were proposed by MECA members for inclusion in the program, including:

- Air gap insulated, fabricated exhaust manifolds

- An air gap insulated transfer pipe from the engine to the aftertreatment
- Air gap insulated inlet and outlet cones incorporated into the catalyst canning

In addition, SwRI also planned to utilize insulation and system configuration in an effort to minimize heat loss in the final system configuration. Although each of these measures has a small individual contribution to the overall system performance, they could in combination result in increased system efficiency. One key design point is that the benefits of any insulating concept have to be balanced against the potential increase in thermal mass of a given part, which could actually serve to slow down catalyst light off.

2.1.4 Aftertreatment Aging Approach

A key part of the demonstration target is that the system must demonstrate emissions using aged components. The aging is intended to be representative of full useful life, which is 435,000 miles for a heavy heavy-duty on highway application (generally about 11,000 hours of operation). However, the program does not contain sufficient scope, time, or funding to actually age parts on engine all the way to full useful life. Therefore, an alternative approach must be used to develop parts, which are as representative as possible within the scope constraints of the program. As a result, part of the initial technology selection involved coming up with an appropriate methodology for catalyst aging to reach this target.

Early in the process development, it was realized that there were actually two different aging targets for different phases of the program. Therefore, the process was split into two phases. The first phase, which was designated “Development Aging”, was intended to produce parts relatively quickly in order to support the Technology Screening effort under Task 3. The second phase, which was designated “Final Aging”, was intended to produce the final demonstration parts which would be utilized for the emissions demonstration at the end of Task 4. These two different phases had different goals, and would be supported by different funding mechanisms. The base program did not have any dedicated budget allocated to aging. A basic methodology was used as the starting point for both Development and Final aging protocols, and then was modified as needed to reach the targets for two protocols.

2.1.4.1 Basic Approach

A similar methodology to the Environmental Protection Agency’s (EPA) Standard Bench Cycle (SBC) protocol was used to age the catalysts for the CNG program. The SBC protocol involves running stoichiometric exhaust chemistry over the catalysts for 40 seconds then operating rich for 10 seconds, then five seconds afterwards introducing 3% excess air via a secondary injection for 10-second duration, and then returning to stoichiometric. The SBC can be seen in Figure 21, below.

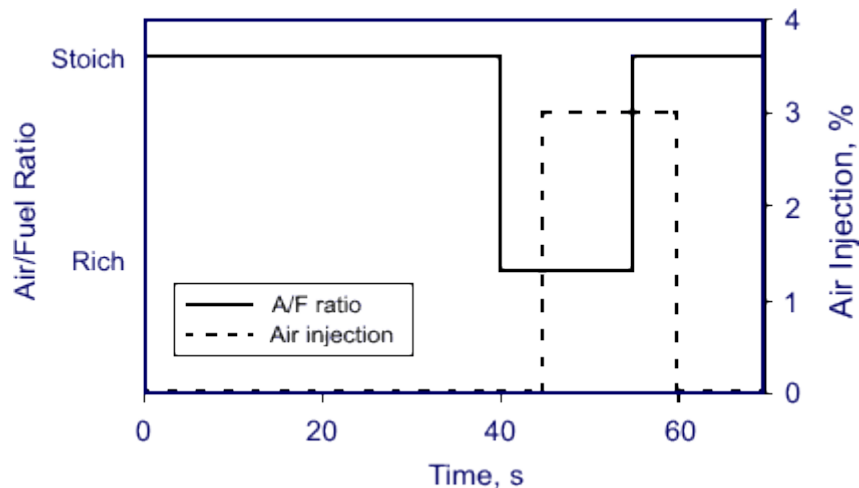


FIGURE 21. STANDARD BENCH CYCLE (SBC)

2.1.4.2 Development Aging

The target for development aging was to produce parts that were somewhat representative of full useful life aging, but that were all aged in a consistent manner in order to allow a proper comparison between different technologies. At the same time, development aging was to be provided by all of the individual suppliers for their hardware. This meant that a large number of parts needed to be produced, many of which would not be selected for the final demonstration. As a result it was necessary to limit the level of effort, while at the same time produce parts to enable a valid comparison.

As a result of these objectives, the basic approach to aging was adjusted in several ways. First, it was determined that chemical aging would not be part of the development aging. Each technology might react differently to chemical poisoning requiring different approaches, which would take significant time to determine and implement. In addition, the positioning of components in the system also has a significant effect on exposure to lube oil components, and the final configuration would not be known at the start of screening. Some specific effects, such as sulfur sensitivity could also be examined during the screening process. Finally, representative chemical aging is generally very time consuming and expensive, and might not be of significant aid to the down-selection process. Therefore, chemical poisoning could be excluded from the Development aging.

In addition, it was determined that a consistent process would be used for all parts, and that this process would be based on the thermal aging characteristics already calculated for the base approach. Therefore, the base approach would be used, with some modifications depending on the parts being aged. Temperatures were also increased somewhat in order to shorten times and account for other possible issues. For development aging, it was decided to allow oven aging to prepare the aged screening parts. In the case of oven aging, it was determined that the aging would be done in air containing roughly 10% steam to provide sufficient water content.

2.1.4.3 Final Aging

For the final aging, the primary target was to be as representative as feasible of full useful life for the final system configuration. SwRI obtained engine data and catalyst temperatures from running the OCTA bus cycle on the Cummins ISX12-G. The OCTA bus cycle data represents 13 miles of driving over 3,800 seconds and is representative of the typical operation for the Cummins ISX12-G engine applied to transit buses in California. Figure 22 below shows the histogram of the catalyst temperature for the ISX-12G and the Doosan GL11K. It can be seen that the ISX-12G operates at a significantly lower temperature over the OCTA bus cycle than the Doosan engine (roughly 100°C lower).

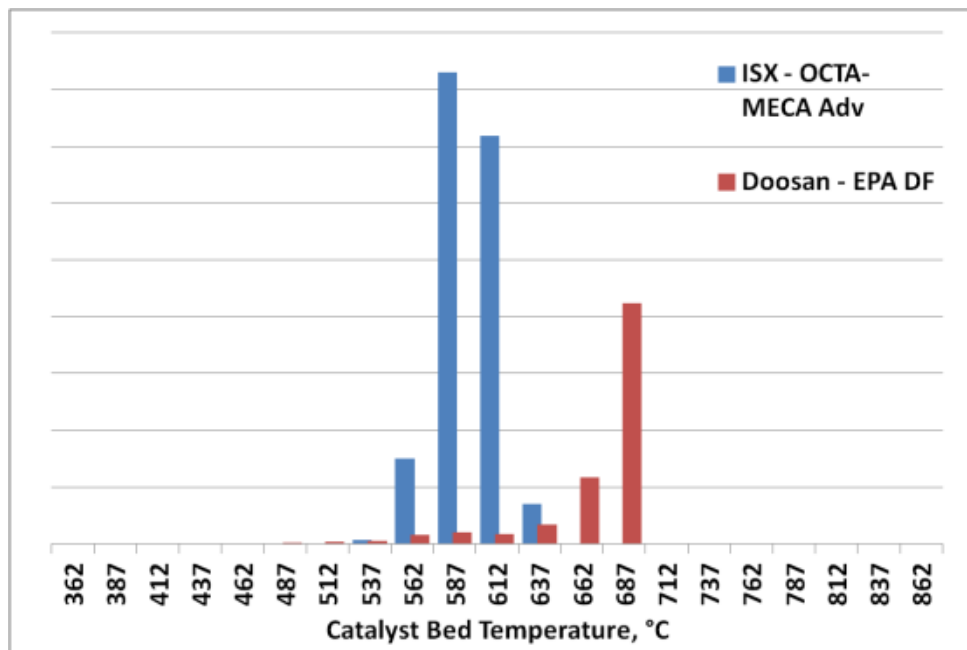


FIGURE 22. CATALYST BED TEMPERATURE FOR ISX-12G AND DOOSAN ENGINES

Given the catalyst temperature histogram, a low control temperature and reference temperature can be defined to give a suitable number of hours of aging following the SBC, shown in Figure 23.

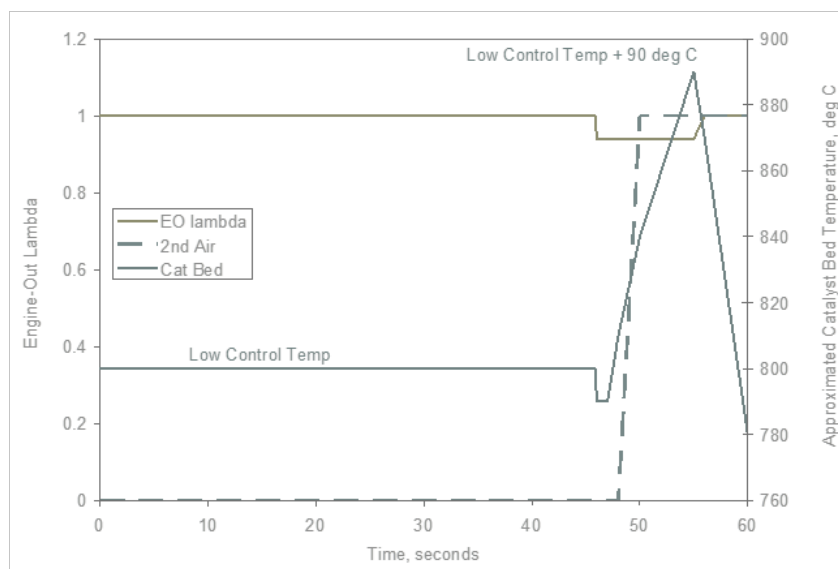


FIGURE 23. SBC LAMBDA, CATALYST TEMPERATURE, AND SECONDARY AIR INJECTION OVER TIME

Given the engine data, it was determined that a low control temperature of 875 °C and exothermal peak temperature of 965 °C will result in a reference temperature of 900 °C with an exhaust flow rate of 190 kg/hr. This allows the catalysts to be aged for 137 hours to be equivalent to 435,000 miles on the OCTA bus cycle with an in-use correction factor of 1.1 applied.

2.2 TASK 2: Engine Baseline and Ultra-Low NO_x Calibration

The engine was certified to meet US 2010 emission standards under both the 298 and 238 kW power ratings; however, the lower power rating was used to better match the flow rates and temperatures of the Doosan GL11K engine that was previously used for the program (see Section 2.1.2 Test Engine). The engine specifications are listed in Table 16.

TABLE 16. CUMMINS-WESTPORT ISX12-G ENGINE SPECIFICATIONS

Parameter	Units	Value
Displacement (L)	L	11.9
Bore x Stroke (mm)	mm	130 x 150
Rated Power	kW	238
Rated Speed	RPM	1800
Peak Torque	Nm	1559
Peak Torque Speed	RPM	1200
Fuel System	-	Compressed Natural Gas
Turbocharger	-	Fixed Geometry
EGR System	-	Cooled, high pressure
Emission Certification	-	US 2010
Application	-	Regional-haul, truck/tractor, vocational, and refuse

The engine was baseline tested using the stock ECU and ignition control module (ICM) as well as all stock hardware. Further testing of the engine to meet the emissions targets was done with an aftermarket prototype ECU provided by EControls. The ECU interface enabled access to various calibration tables (such as air-fuel ratio, boost pressure, and EGR rates), numerous transient fueling models, as well as, manual control actuators if desired. The engine was instrumented with cylinder pressure transducers for each cylinder to allow optimization of burn durations for increased engine efficiency. Kistler 6045A pressure sensors were installed and crank-angle-based cylinder pressure was used during this task to monitor combustion quality during both steady-state and transient engine testing. An enhanced air-fuel-EGR mixer, high-energy ignition system, boost recirculation valve, electronic wastegate controller, and various EGR measurement/feedback devices were installed. The additional items allowed the engine to obtain improved air-fuel ratio control during transient operation, as well as allowed an increase in EGR rates to lower engine-out NO_x emissions.

2.2.1 Baseline FTP, RMC, WHTC, and CARB Idle Results

Baseline testing for the US heavy-duty FTP was composed of three sets of cold-start and hot-start FTPs. Each cold-start FTP was followed by three (3) hot-start FTPs with the proper twenty minute soak time in between. The testing was performed in accordance with 40 CFR Part 1065 procedure and in a 1065 certified engine test cell. Testing was done using California Air Resource Board certification blend natural gas; the specifications for that fuel blend can be seen in Table 17, below.

TABLE 17. CARB CERTIFICATION NATURAL GAS BLEND SPECIFICATIONS

Gas Species	Concentration (vol. %)
Methane (CH ₄)	90.0 ± 1.0
Ethane (C ₂ H ₆)	4.0 ± 0.5
C ₃ and Higher	2.0 ± 0.3
C ₆ and Higher	0.2 max
Oxygen (O ₂)	0.5 max
Inert Components (CO ₂ and N ₂)	3.5 ± 0.5
Hydrogen (H ₂)	0.1 max
Carbon Monoxide (CO)	0.1 max
Sulfur (S)	16 ppm max

The average composite FTP tailpipe emissions for the Cummins-Westport ISX12-G engine rated at 238 kW can be seen in

Table 18, below. The average is taken over the three separate composite FTP results and a standard deviation (SD) and coefficient of variation (CoV) is reported. The engine meets the US 2010 standards for heavy-duty on-road engines.

TABLE 18. BASELINE COMPOSITE FTP TAILPIPE EMISSIONS FOR CUMMINS-WESTPORT ISX12-G

	Composite FTP Tailpipe, g/hp-hr						Composite FTP Tailpipe, ppm	
	NO _x	PM	NMHC	CO	CO ₂	CH ₄	NH ₃	N ₂ O
Average	0.115	0.002	0.124	2.956	541.8	0.956	75.8	0.629
SD	0.00305	0.00008	0.00234	0.43951	2.948	0.029	4.2	0.082
CoV	2.7%	3.3%	1.9%	14.9%	0.5%	3.0%	5.6%	13.0%
US 2010 Standard	0.20	0.01	0.14	15.5				
SD % Standard	1.5%	0.8%	1.7%	2.8%	n/a	n/a	n/a	n/a

Three-way catalysts can simultaneously reduce NO_x and oxidize CO and hydrocarbon emissions if the air-fuel ratio is stoichiometric. If the mixture is too lean, the catalysts lose NO_x reduction and if too rich, the catalysts lose CO and hydrocarbon oxidation. This conversion efficiency is greatest when the exhaust mixture is perfectly stoichiometric (however, in practice the exhaust mixture is constantly switching between rich and lean to store and deplete oxygen in ceria within the catalyst). This conversion efficiency is also highly temperature dependent – a typical three-way catalyst will see near 100% conversion efficiency if the temperature is above 400 °C. Additionally, a typical three-way catalyst lights-off (reaches 50% conversion efficiency) at around 220 to 270 °C. Because of this temperature dependence, it is important to note the catalyst temperature over various engine drive cycles.

Figure 24 shows the catalyst bed temperature (located 25.4 mm down from the front face of the catalyst, in the center) during a typical cold and hot start FTP. For the cold-start FTP cycle the catalyst reaches light-off at roughly 130 seconds (or slightly after the first speed “hill”) and sustains temperatures above 400 °C at roughly 260 seconds (or slightly after the second speed “hill”).

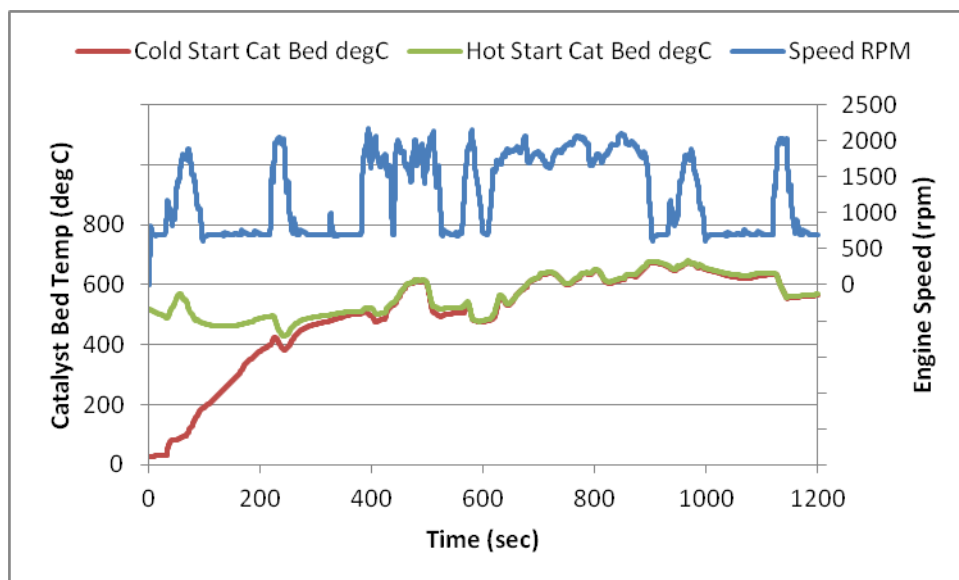


FIGURE 24. CATALYST BED TEMPERATURE FOR COLD AND HOT-START FTP CYCLE

The effects of a cold catalyst can be seen in Figure 25 during the first 130 seconds where the NO_x emissions are roughly four times higher for the cold start FTP than for the hot start FTP. The spikes in NO_x emissions seen at 400 to 800 seconds are not due to catalyst temperature, but rather, poor air-fuel ratio control and a loss of NO_x reduction and oxygen storage.

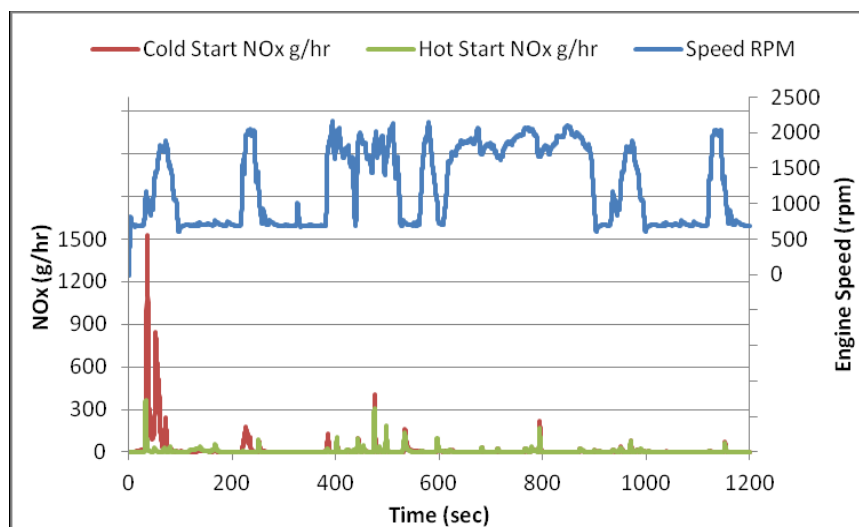


FIGURE 25. COLD AND HOT-START FTP NO_x DILUTE MASS RATE

In addition to emissions measurements taken over the engine drive cycles, engine equivalence ratio was also measured and analyzed for areas of improvement.

The average results for the steady state RMC-SET engine drive cycle can be seen in Table 19. The 2010 emissions standards for the RMC-SET are the same as those for the US heavy-duty FTP. Catalyst temperature, shown in Figure 26 stays above 600 °C throughout the test cycle and NO_x emissions are quite low. The spikes in NO_x emissions, shown in Figure 27, occur when the engine is either changing speed or load indicating areas where the air-fuel ratio control can be improved.

TABLE 19. BASELINE RMC-SET TAILPIPE EMISSIONS FOR CUMMINS-WESTPORT ISX12-G

	RMC-SET Tailpipe, g/hp-hr						RMC-SET Tailpipe, ppm	
	NO _x	PM	NMHC	CO	CO ₂	CH ₄	NH ₃	N ₂ O
Average	0.012	0.0006	0.090	1.563	453.8	1.198	161.6	0.0
SD	0.00262	0.00005	0.00163	0.27939	1.014	0.012	12.4	0.0
CoV	21.3%	7.4%	1.8%	17.9%	0.2%	1.0%	7.7%	n/a
US 2010 Standard	0.20	0.01	0.14	15.5				
SD % Standard	1.5%	0.8%	1.7%	2.8%	n/a	n/a	n/a	n/a

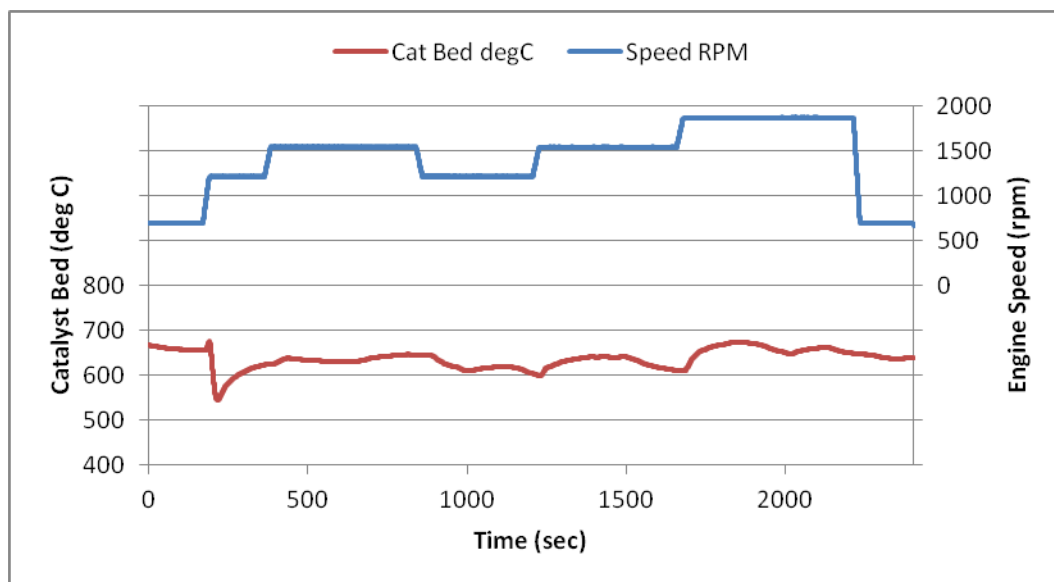


FIGURE 26. RMC-SET CATALYST BED TEMPERATURE

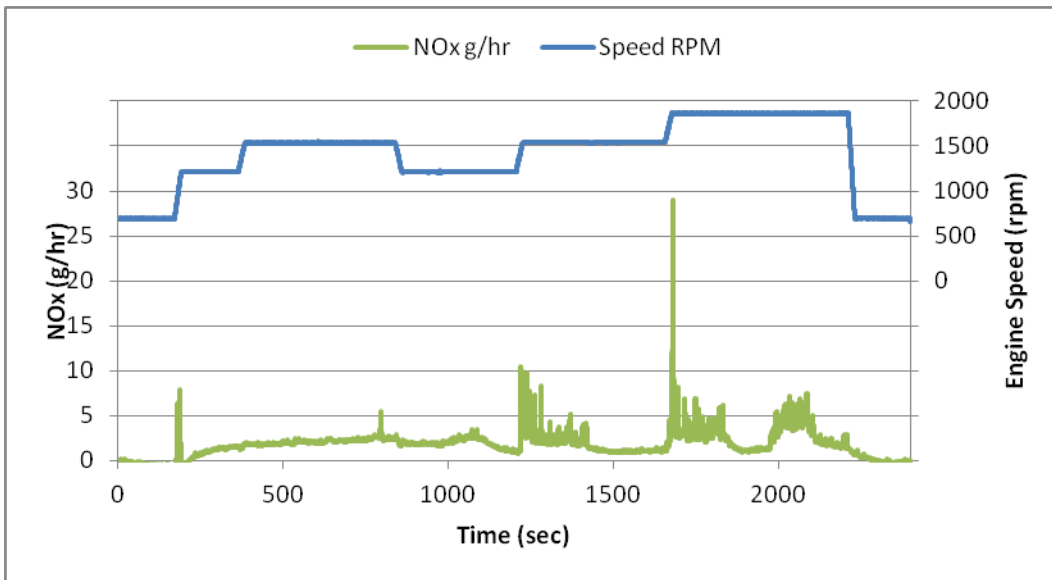


FIGURE 27. RMC-SET NO_x DILUTE MASS RATE

Although there is no formal standard limiting ammonia emissions, it is still of particular interest for this program to keep ammonia as low as possible. The relatively large ammonia emissions seen during the RMC-SET in Figure 28 are indicative of an overall rich engine operation.

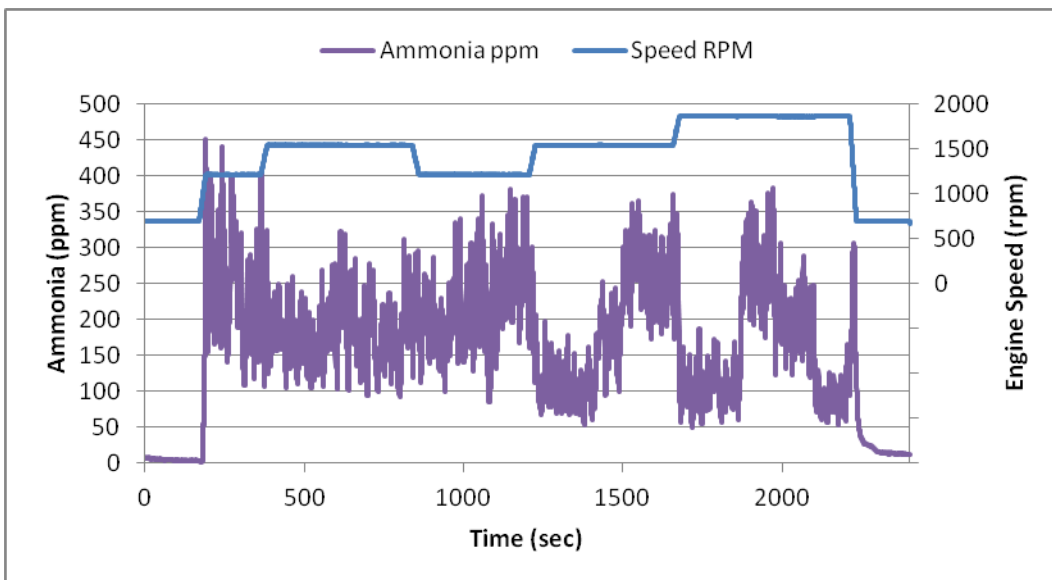


FIGURE 28. RMC-SET RAW TAILPIPE AMMONIA

A summary of the FTP and RMC-SET emissions on a daily basis is shown in Figure 29. For the demonstration of this program, five consecutive composite repeats are required. This figure shows that the engine is operating in a reliable manner.

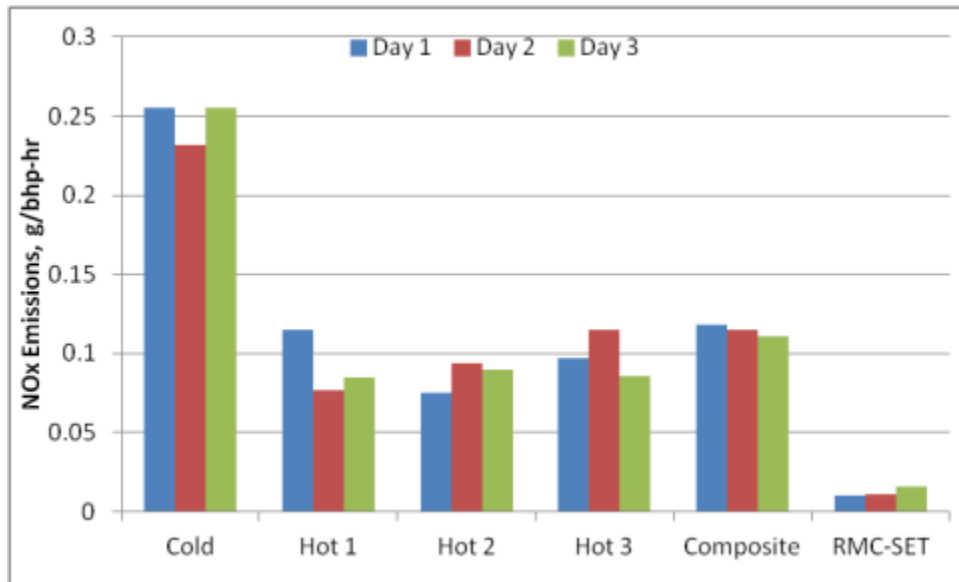


FIGURE 29. NO_x EMISSIONS FOR THE US HEAVY-DUTY FTP AND RMC-SET FOR THE CUMMINS-WESTPORT ISX12-G.

Greenhouse Gas (GHG) emissions – methane and carbon dioxide – were of interest to this baseline evaluation. The EPA’s 2014 and 2017 GHG standard for HDE and vehicles sets a limit on the amount of methane and carbon dioxide that can be emitted over the FTP and RMC-SET. Figure 30 shows the methane emissions for the baseline engine over the FTP and RMC-SET. In both test cycles the methane emissions are well over the standard. However, Figure 31 shows the carbon dioxide standard, in which, the baseline engine is well below even the 2017 standard.

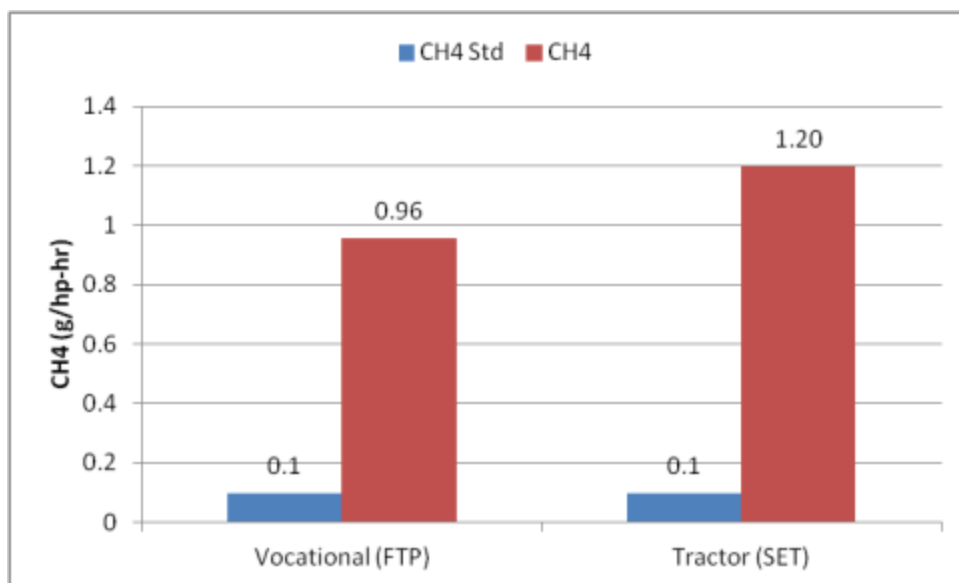


FIGURE 30. METHANE EMISSIONS OVER THE FTP AND RMC-SET COMPARED TO 2014/2017 GHG STANDARD LEVELS

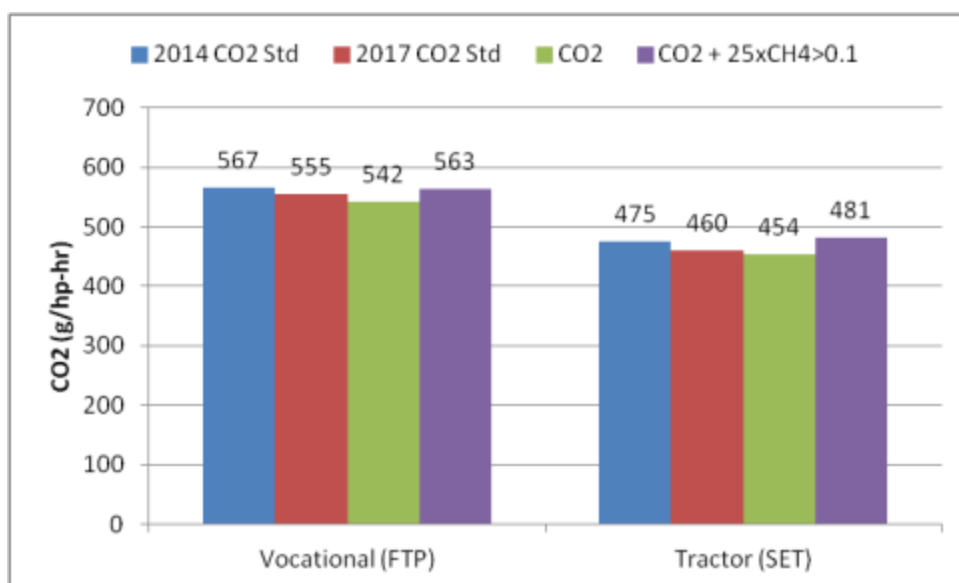


FIGURE 31. CARBON DIOXIDE EMISSIONS OVER THE FTP AND RMC-SET COMPARED TO 2014/2017 GHG STANDARD LEVELS

The World Harmonized Transient Cycle (WHTC) is a transient engine test cycle adopted for EURO VI emissions regulations. The baseline engine was tested over the WHTC to examine its emissions performance. Similar to the US heavy-duty FTP, the test cycle is defined as having a cold start cycle and hot start cycle. However, unlike the FTP, NO_x emissions are relatively unchanged from the cold start to the hot start WHTC as shown in Table 20. This shows that the baseline engine calibration was focused on FTP and RMC-SET test cycle performance rather than the WHTC.

TABLE 20. WHTC TAILPIPE EMISSIONS

	WHTC Tailpipe (g/hp-hr)						ppm	
	NO _x	PM	NMHC	CO	CO ₂	CH ₄	NH ₃	N ₂ O
WHTC Cold	0.310	0.002	0.160	3.376	510.0	1.537	99.7	5.415
WHTC Hot	0.308	0.001	0.113	1.343	504.3	0.994	86.3	0.000
Composite	0.308	0.001	0.119	1.628	505.1	1.070	88.1	0.758

Table 21 shows the engine out emissions over the WHTC and Table 22 shows the catalyst conversion efficiency over the WHTC. Although catalyst conversion efficiency is near 95% over both the cold and hot-start cycles, that is still not enough to meet even a 0.2 g/hp-hr NO_x emission target. This shows a need to reduce engine out emissions as well as increase catalyst conversion efficiency.

TABLE 21. WHTC ENGINE-OUT EMISSIONS

	WHTC Engine Out (g/hp-hr)				
	NO _x	NMHC	CO	CO ₂	CH ₄
WHTC Cold	6.102	0.122	29.510	457.7	4.543
WHTC Hot	6.559	0.156	28.513	445.3	4.474
Composite	6.495	0.151	28.653	447.0	4.483

TABLE 22. CATALYST CONVERSION EFFICIENCY OVER WHTC

	Catalyst Conversion Efficiency		
	NO _x	CO	CH ₄
WHTC Cold	94.9%	88.6%	66.2%
WHTC Hot	95.3%	95.3%	77.8%
Composite	95.3%	94.3%	76.2%

Figure 32 shows the catalyst bed temperature for both the cold and hot start WHTC. The catalyst does not reach temperatures in excess of 400 °C until roughly 300 seconds, similar to the FTP. However, tailpipe NO_x and ammonia emissions remain relatively high even after the catalyst has reached temperature (Figure 33 and Figure 34). The large spikes in NO_x indicate that the baseline engine air-fuel ratio controller is inadequate for stringent emissions control.

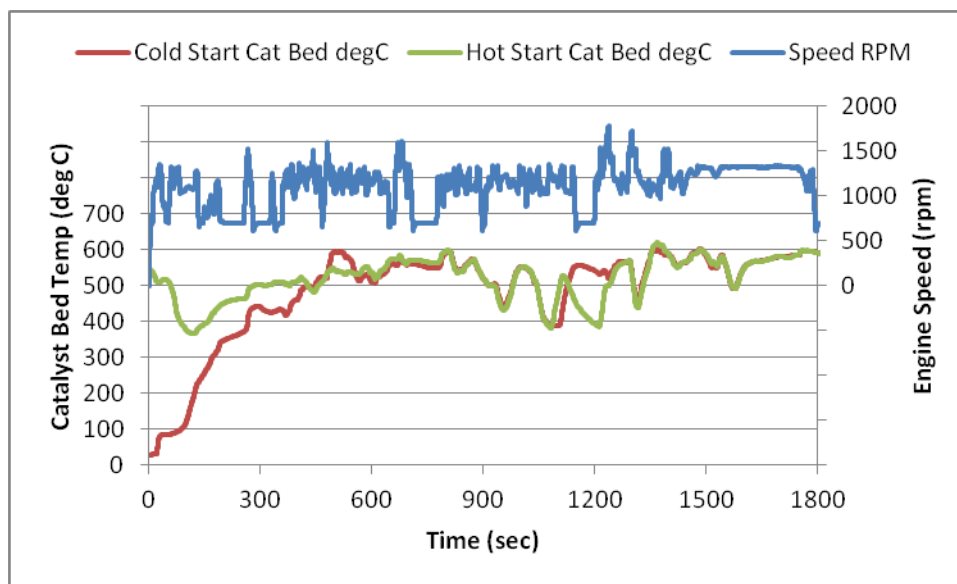
**FIGURE 32. CATALYST BED TEMPERATURE OVER COLD AND HOT START WHTC**

Figure 33 shows NO_x emission spikes larger during the first set of accelerations (0 to 100 seconds) for the hot start than for the cold start. This is unlike the FTP, where the cold start emissions are much higher.

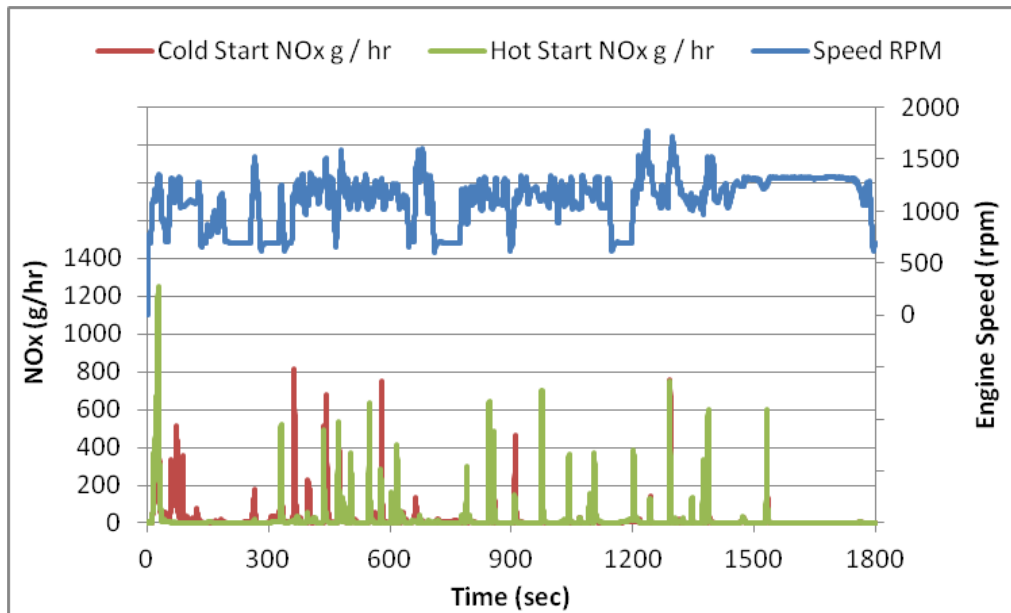


FIGURE 33. DILUTE NO_x MASS RATE EMISSIONS OVER COLD AND HOT START WHTC

Ammonia levels, shown in Figure 34, over the cold and hot-start WHTC are very high compared to the FTP and RMC cycles. With both large levels of NO_x and NH₃, it is clear that the engine's air-fuel ratio control is poor during the opening 200 seconds of the WHTC and further improvements can be made.

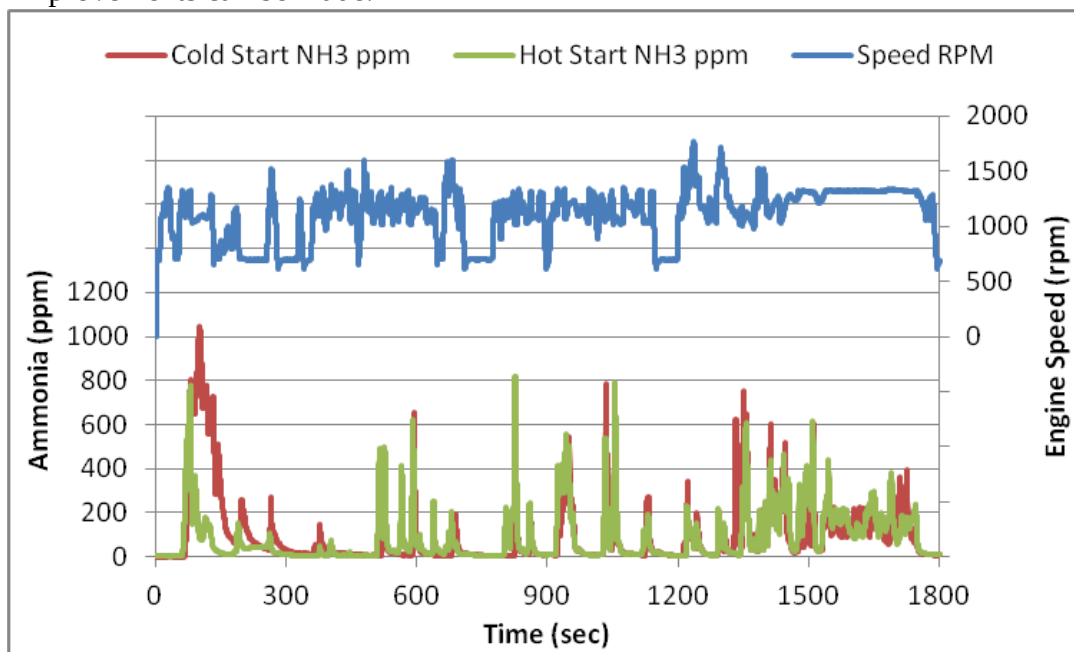


FIGURE 34. TAILPIPE AMMONIA EMISSIONS OVER COLD AND HOT START WHTC

An additional cycle that was tested during baseline was the CARB idle test. This is a California-specific test designed to ensure a level of NO_x control during a sustained idle period. It consists of an FTP cycle warm-up, followed by two 30-minute idle periods. The first idle period is at designated low idle speed (i.e., “curb” idle), while the second 30-minute period is at an elevated idle (no-load) speed of 1100 rpm. The current limit for this cycle is 30 g/hr average NO_x rate, integrated separately of each of the two 30-minute idle periods. Figure 35 shows the results of the CARB Idle test on the Cummins-Westport ISX12-G. Towards the end of the first 30-minute idle the catalyst temperature begins to drop below 400 °C. NO_x emissions begin increasing rapidly as the temperature drops towards 360 °C. This indicates that this catalyst must maintain temperatures above 360 °C in order to achieve near 100% conversion efficiency. Once the elevated idle begins, the exhaust temperature increases and NO_x emissions drop.

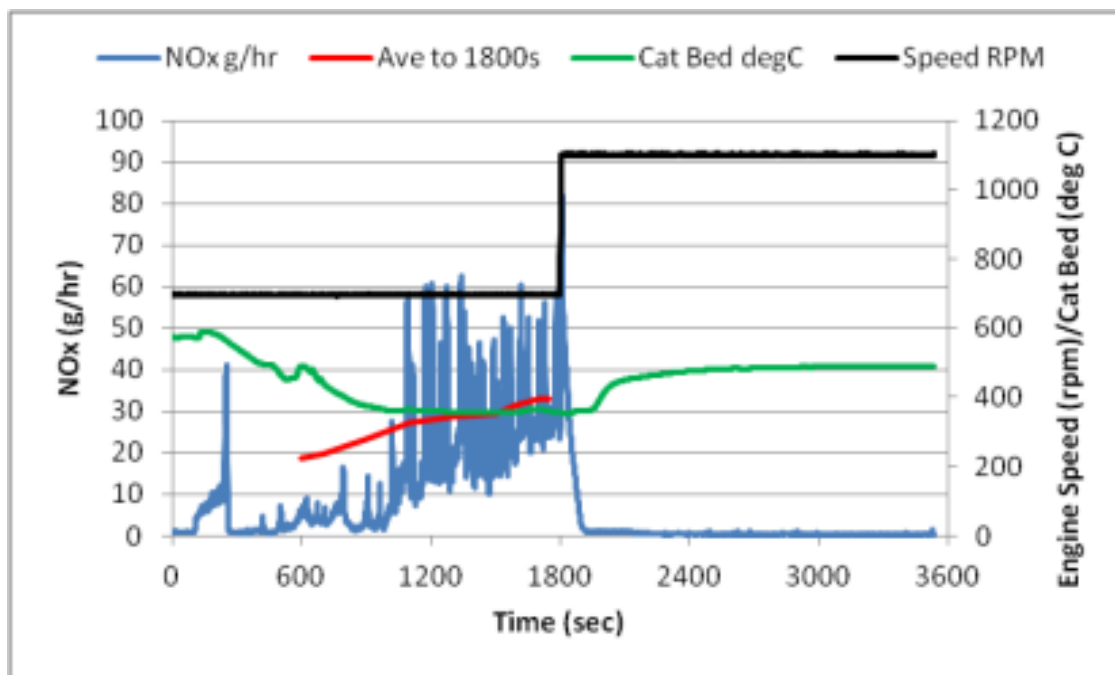


FIGURE 35. CARB IDLE NO_x DILUTE MASS RATE AND CATALYST BED TEMPERATURE FOR CUMMINS-WESTPORT ISX12-G

2.2.2 Baseline Vocational Test Cycle Results

In addition to the primary cycles described above, several additional cycles were desired for use on a demonstration-only basis. These cycles were selected to be more representative of various types of in-field operation, with a particular focus on vocational applications that would be characterized by lower temperatures and/or more transient operation than the primary (certification) cycles that are the program targets. The intent behind these cycles is to examine how well the reduction of emissions to 0.02 g/hp-hr on the certification cycles might translate to operation on other, potentially more challenging duty cycles from the field. The vocational cycles examined during baseline testing included the New York City Bus Cycle (NYBC), the

Orange County Transit Authority Bus Cycle (OCTA) and the Cruise-Creep cycle. Further detail on these cycles can be found in Section 2.1.1.2 Additional Cycles.

Each vocational cycle was performed once in a 40 CFR Part 1065 compliant test cell and with standard line natural gas. Tailpipe emissions were measured using a continuous volume sampling (CVS) dilution tunnel, raw engine-out emissions were measured using a Horiba MEXA-7100DEGR analyzer, and tailpipe ammonia was monitored using a Fourier Transform Infrared spectrometer. This data is shown in Table 23, Table 24, Table 25, and Figure 36.

TABLE 23. TAILPIPE EMISSIONS FOR NYBC, CRUISE-CREEP, AND OCTA VOCATIONAL CYCLES

	Tailpipe, g/hp-hr						ppm
	NO _x	PM	NMHC	CO	CO ₂	CH ₄	NH ₃
NYBCx4	0.907	0.0009	0.190	1.580	672.4	1.893	11.7
Cruise-Creepx10	0.07	0.0038	0.157	2.774	612.3	1.596	124.4
OCTA	0.112	0.0024	0.107	2.350	552.8	1.078	91.9

TABLE 24. ENGINE-OUT EMISSIONS FOR NYBC, CRUISE-CREEP, AND OCTA VOCATIONAL CYCLES

	Engine Out, g/hp-hr				
	NO _x	NMHC	CO	CO ₂	CH ₄
NYBCx4	7.827	0.037	43.269	596.4	7.626
Cruise-Creepx10	7.162	0.428	27.23	568.2	6.1
OCTA	6.338	0.183	36.991	489.0	4.945

TABLE 25. CATALYST CONVERSION EFFICIENCY FOR NYBC, CRUISE-CREEP, AND OCTA VOCATIONAL CYCLES

	Catalyst Conversion Efficiency	
	NO _x	CO
NYBCx4	88.4%	96.3%
Cruise-Creepx10	99.0%	89.8%
OCTA	98.2%	93.6%

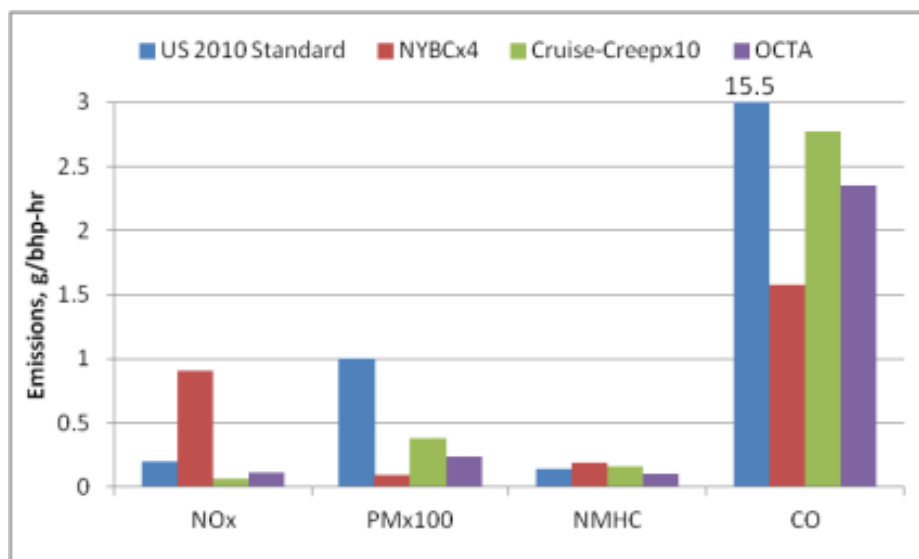


FIGURE 36. EMISSIONS SUMMARY FOR VOCATIONAL CYCLES PLOTTED WITH US 2010 HEAVY-DUTY EMISSIONS STANDARD

The catalyst conversion efficiency for NO_x over the NYBC was shown to be the lowest of the three vocational cycles tested. To examine this low conversion efficiency, catalyst temperature and NO_x emissions were plotted over the cycle. Figure 37 shows the catalyst bed temperature drops towards 360 °C during the extended idle portion of the cycle. This low temperature is below the NO_x light-off temperature and thus there is little to no NO_x abatement towards the end of the idle period. This is most evident from -1200 seconds² to 0 seconds plotted on Figure 38. After the first number of accelerations, the catalyst temperature reaches 550 – 600 °C; however, there are large NO_x breakthrough events. In this case, the large breakthroughs are due to very aggressive transient behavior that is outside the capability of the baseline engine air-fuel ratio controller. As is to be somewhat expected, the tailpipe ammonia emissions for the engine are the lowest of the three vocational cycles – evident of overall lean air-fuel ratio at operating points due to aggressive transient operation.

²Figure 37 and Figure 38 reference a time less than 0. This is because there is an extended idle period of 30 minutes prior to the start of the NYBC cycle. Time 0 corresponds to the beginning of the cycle.

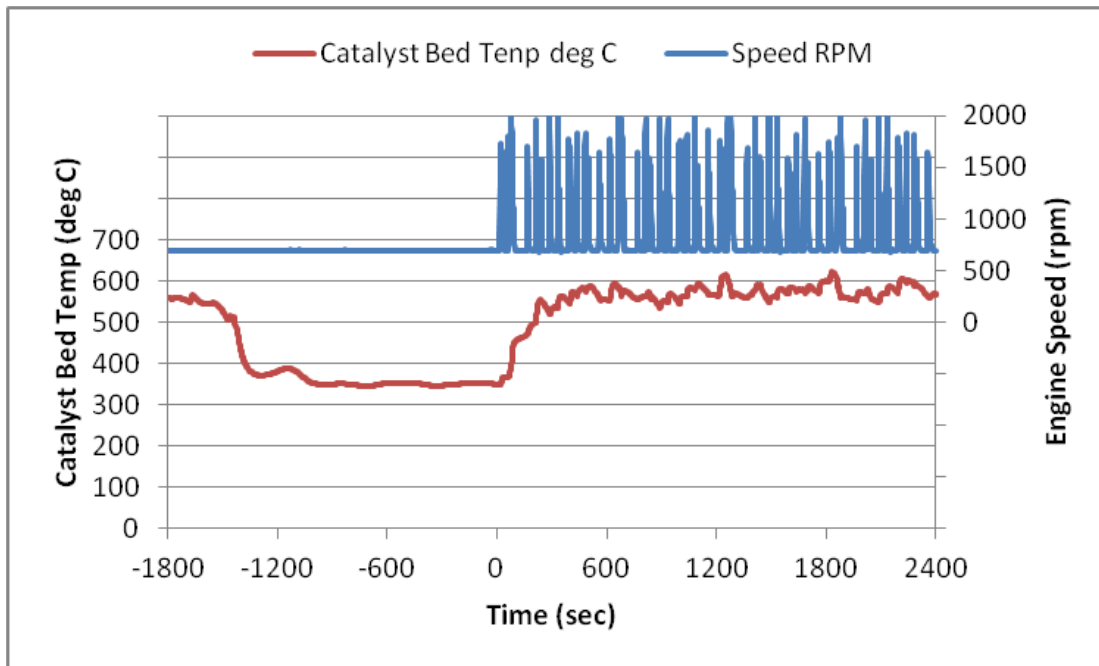


FIGURE 37. CATALYST BED TEMPERATURE DURING NYBC VOCATIONAL CYCLE

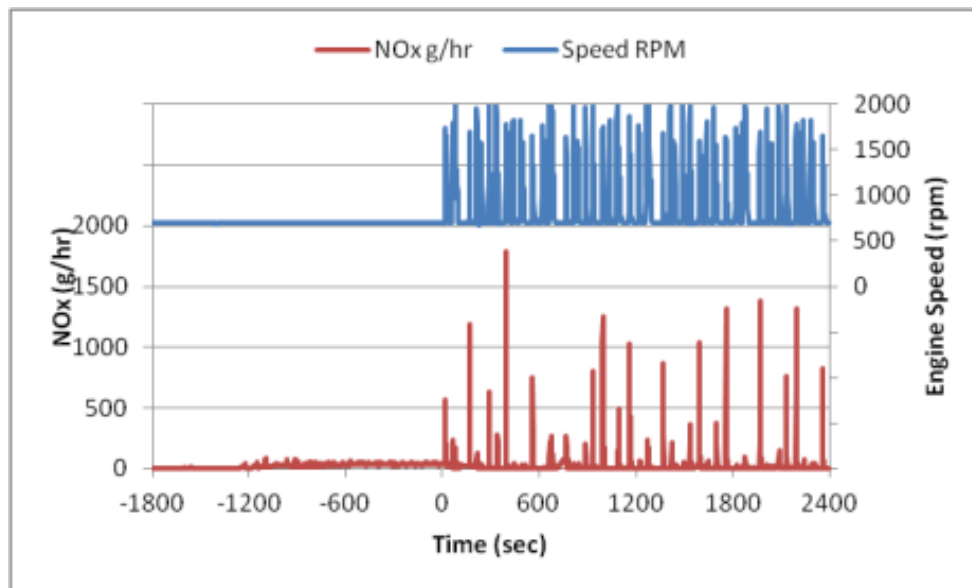


FIGURE 38. DILUTE NO_x MASS RATE EMISSIONS DURING NYBC VOCATIONAL CYCLE

The catalyst conversion efficiency for NO_x over the Cruise-Creep cycle was shown to be the highest of the three vocational cycles tested. Figure 39 shows that Catalyst bed temperature over the “cruise” portion of the cycle (0-750 seconds) was above 600 °C; and during “creep” operation catalyst temperature was steadily around 450 °C. This temperature is above the NO_x

light-off temperature so it is expected that with proper air-fuel ratio control NO_x emissions should be low.

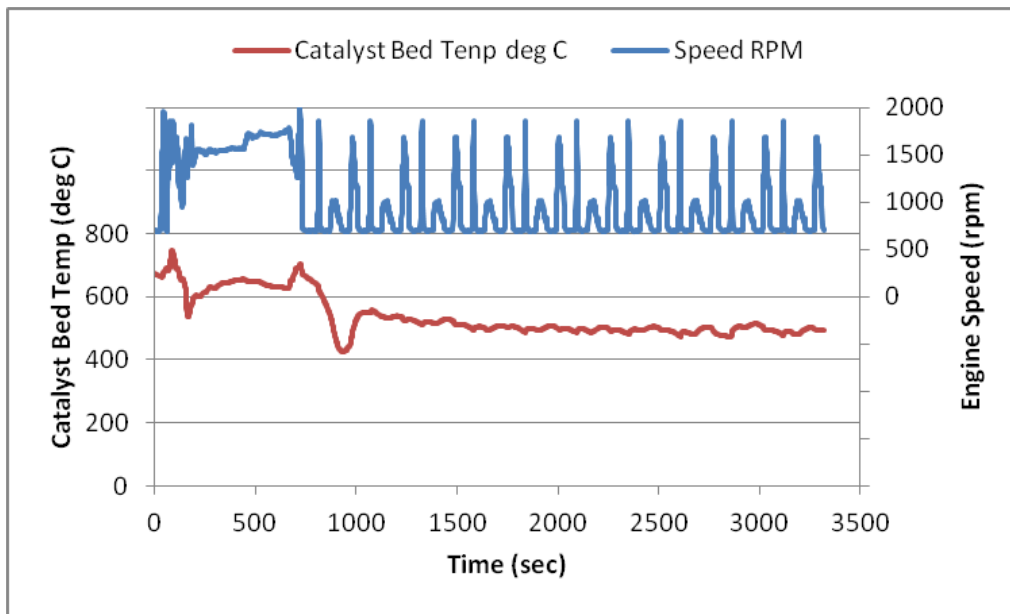


FIGURE 39. CATALYST BED TEMPERATURE DURING CRUISE-CREEP VOCATIONAL CYCLE

Figure 40 shows the NO_x emissions over the vocational cycle. NO_x emissions were highest during aggressive transient operation at the beginning and end of the “cruise” portion of the cycle. Transient behavior over the “creep” modes is not as extreme as the NYBC and is within the capability of the baseline engine air-fuel ratio controller. NO_x emissions are near zero for all “creep” operation.

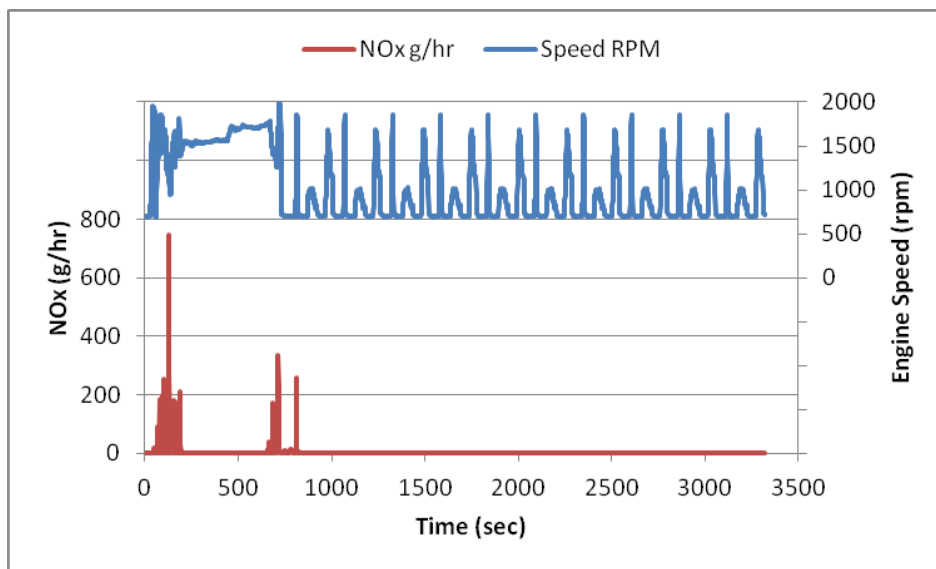


FIGURE 40. DILUTE NO_x MASS RATE EMISSIONS DURING CRUISE-CREEP VOCATIONAL CYCLE

Figure 41, shows the tailpipe ammonia emissions over the vocational cycle. Ammonia emissions over the Cruise-Creep were the highest of the three vocational cycles tested.

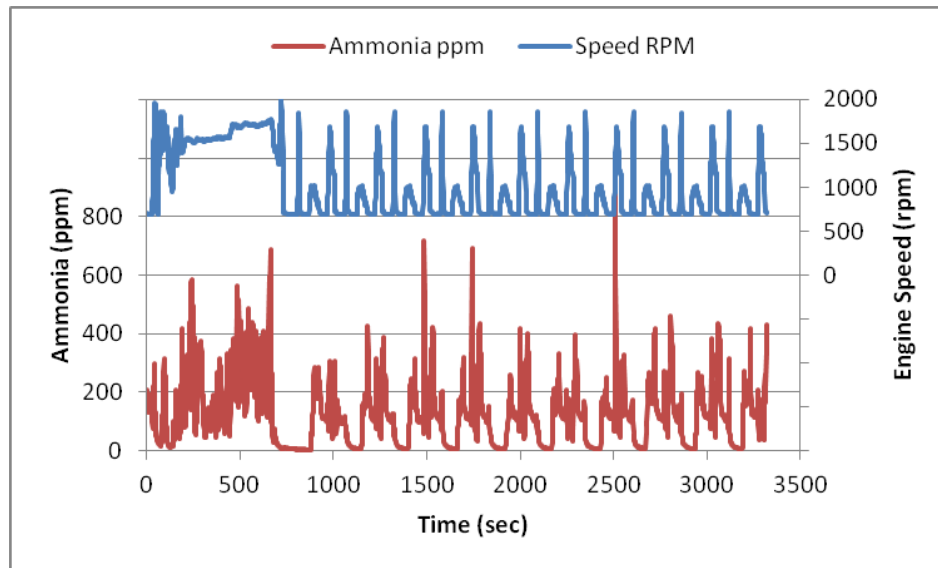


FIGURE 41. TAILPIPE AMMONIA EMISSIONS DURING CRUISE-CREEP VOCATIONAL CYCLE

Large ammonia emissions over the “cruise” portion of the cycle indicate that the equivalence ratio is biased slightly rich. This rich bias is also evident over the “creep” portion of test cycle, where each transient is followed by a spike in ammonia.

The last vocational cycle examined was the OCTA bus cycle. The OCTA bus cycle features transient behavior that is more aggressive than that of the Cruise-Creep vocational cycle, but not as extreme as the NYBC. Figure 42 shows high catalyst bed temperatures throughout the test cycle.

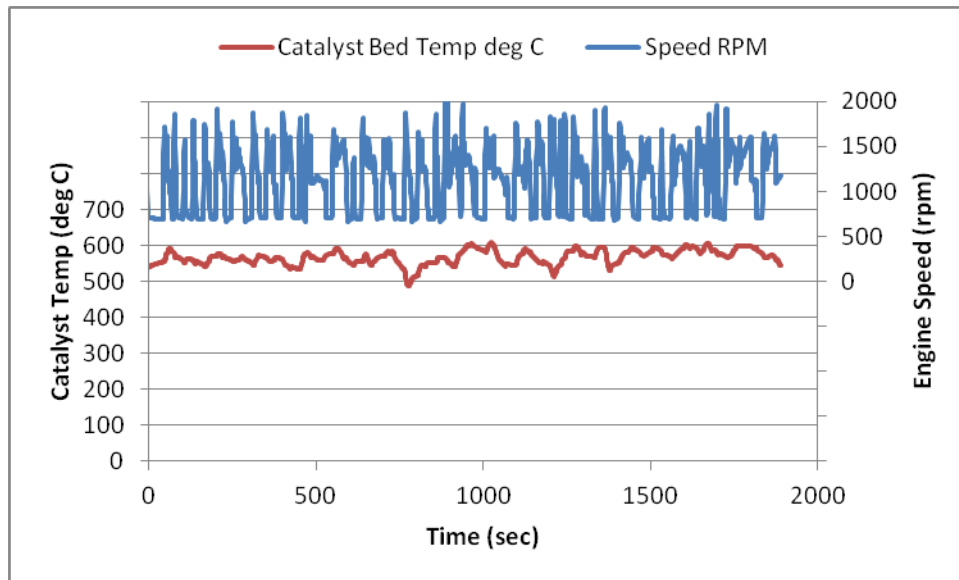


FIGURE 42. CATALYST BED TEMPERATURE DURING OCTA BUS CYCLE

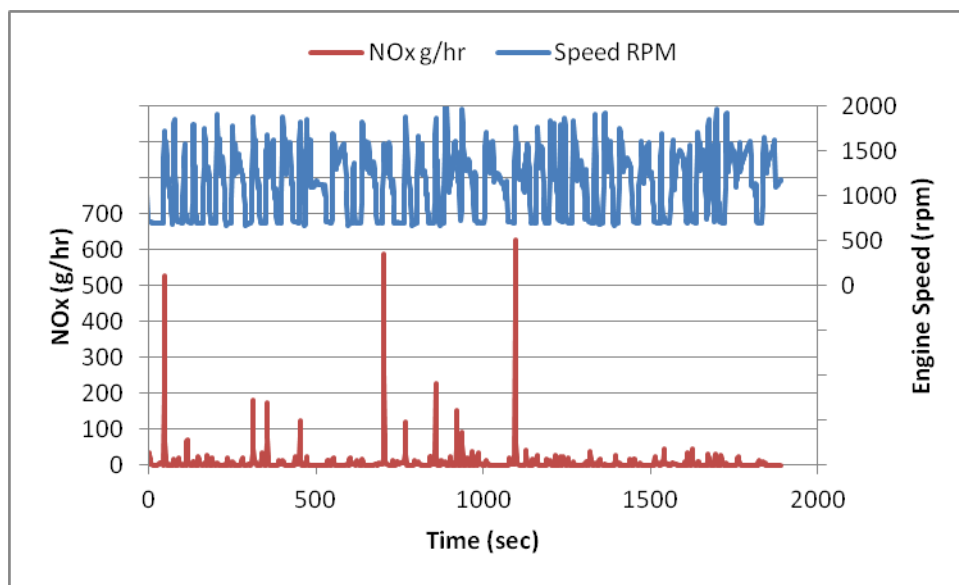


FIGURE 43. DILUTE NO_x MASS RATE EMISSIONS DURING OCTA BUS CYCLE

Figure 43, above, shows NO_x emissions over the OCTA bus cycle. The largest NO_x breakthroughs occur on aggressive transients that are outside of the capability of the baseline engine air-fuel controller. Figure 44, below, shows the tailpipe ammonia emissions over the OCTA bus cycle. Each spike in ammonia follows a transient operation indicating that the air-fuel ratio controller is biasing the mixture slightly rich and overloading the catalyst.

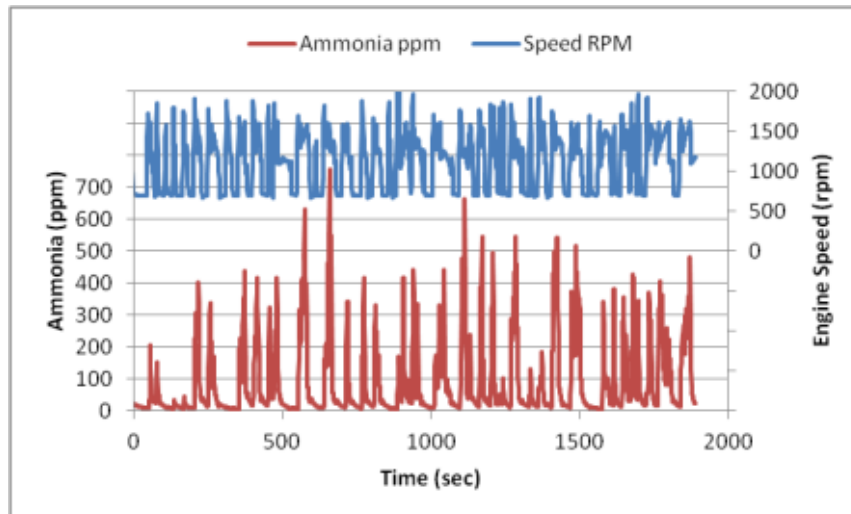


FIGURE 44. TAILPIPE AMMONIA EMISSIONS DURING OCTA BUS CYCLE

2.2.3 Engine Upgrades to Improve AFR Control

There were a number of upgrades to the engine that were made in an effort to improve air-fuel ratio control. Primarily, an aftermarket, prototype ECU from EControls was used for controlling the engine. This ECU provided full authority over all of the engine actuators (boost pressure, air-fuel ratio, ignition timing, wastegate duty cycle etc.). This ECU also provided a more robust means of transient fueling utilizing advanced throttle model fueling corrections as well as feedback on fueling.

In order to have precise air-fuel ratio control during transient operation the EGR gas mass flow rate must be well known. For this reason, a differential pressure (Delta-P) sensor and venturi orifice plate, coupled with temperature and pressure measurement allow for precise measurement of EGR gas flow. Additionally, a UEGO sensor was fitted on the air-fuel-EGR mixer to accurately measure oxygen concentration (and thus EGR rate). Additional control algorithms used these measurements for feedback control of the EGR rate.

An upgraded air-fuel-EGR mixer was added downstream of the throttle to ensure proper mixture homogeneity, shown in Figure 45. During aggressive tip-out (throttle-out) transient operation excess air can make its way into the combustion chamber leading to an overall lean mixture. To combat this problem, a boost recirculation valve was added after the compressor outlet and intercooler but before the throttle. The excess air was then rerouted back to the compressor inlet. A schematic of the flow for the boost recirculation valve is shown in Figure 46. An electronically controlled wastegate was added to precisely control boost pressure being delivered to the engine both at steady state and during transient operation.

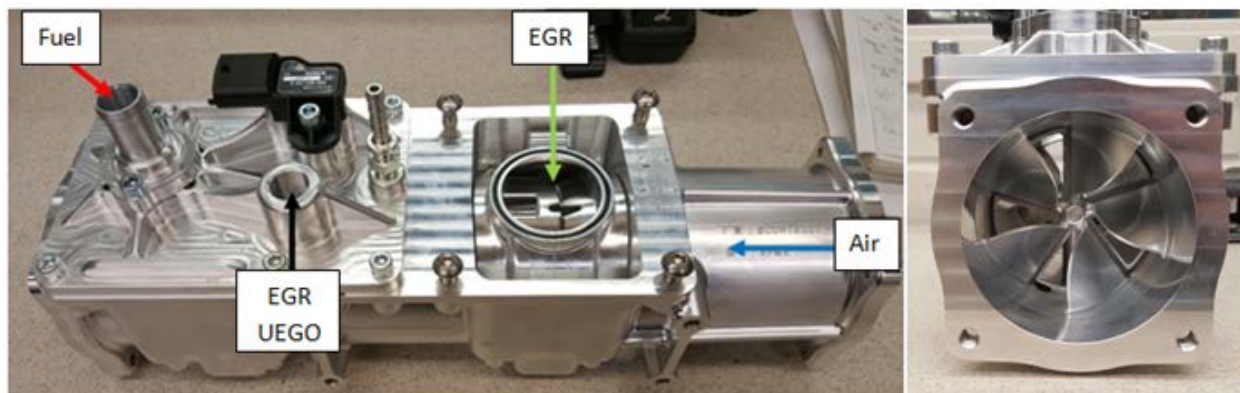


FIGURE 45. AIR-FUEL-EGR MIXER RESULTING IN IMPROVED MIXTURE HOMOGENEITY

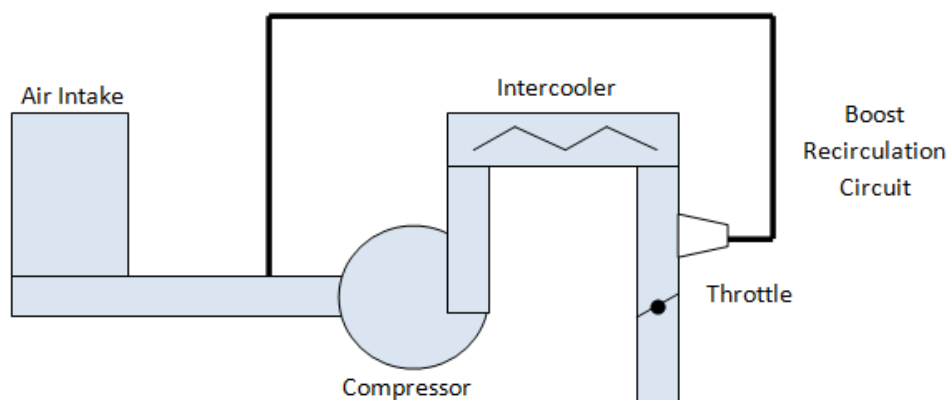


FIGURE 46. BOOST RECIRCULATION FLOW CIRCUIT

A continuous flow valve (CFV) was used for fuel delivery to the engine. The CFV allows for consistent flow rates and fuel metering, regardless of pressure variations, and improves fuel-metering accuracy. The stock engine's ignition system uses alternating current; however, that ignition control module, was not able to interface with the prototype ECU. For this reason, a typical, high energy, direct current ignition coil system was used. The higher energy ignition system was needed for the high levels of EGR being used to lower in-cylinder temperatures (and NO_x emissions) as well as ensure stable combustion throughout the operating map of the engine. The closed crankcase ventilation (CCV) system was added to reduce any oil consumption due to blow-by. This reduced the amount of particulate and hydrocarbon emissions of the engine

2.2.4 Steady State Engine Calibrations

Engine calibration started with population of volumetric efficiency, ignition timing, air-fuel ratio, EGR percentage, and throttle inlet pressure tables to match the baseline performance of the Cummins-Westport ISX12-G engine.

The volumetric efficiency table was populated from data gathered from previous benchmarking and baseline testing of the engine using the stock ECU with a 320 horsepower

calibration. The ECU incorporates a number of volumetric efficiency corrections based on coolant temperature, intake air temperature, whether the engine is opening/closing the throttle, and cylinder wall temperature. However, all of the corrections are short acting (small time constant) and a longer acting (large time constant) volumetric efficiency correction based on past engine load history was generated – details of this correction can be found in Section 2.2.5 Engine Transient Calibration.

Ignition timing was determined utilizing the in-cylinder pressure transducers and optimizing burn durations for all six cylinders. Ignition timing was set to produce a location of mass-fraction-burn of 50% (CA50) of 8-12 crank angle degrees (CAD) at top dead center (TDC) or set to knock-limited spark advance (KLSA) for the majority of the engine operating map. However, ignition timing was retarded at idle operation for the engine in order to keep the catalysts at temperature. Two ignition timing maps were produced – one for the minimum allowable EGR (zero for all but high speed and load), and one for nominal EGR. Ignition timing was interpolated between these two tables and extrapolated beyond so that ignition timing was always optimized for the EGR rate, speed, and load.

Air-fuel ratio, ϕ , was calibrated at steady state utilizing a UEGO located upstream of the catalysts. This UEGO sensor was used by the ECU for air-fuel ratio measurement for feedback. There were two ways the proper equivalence ratio for different speeds and loads was determined. The first was using a Horiba Mexa 7200D dilute gas emissions bench sampling post-catalyst; equivalence ratio was adjusted until both CO and NO_x emissions were near zero. The second way was utilizing a HEGO sensor located post-catalyst; the equivalence ratio was adjusted until the voltage read by the HEGO was ~0.700 V. The equivalence ratio at idle conditions was biased slightly rich to aid transient emissions and keep NO_x low during extended idle conditions.

In order to drive the higher EGR rates that were used, the wastegate was shut while the throttle was not fully open. This allowed a larger pressure differential between the EGR loop and the intake air stream driving higher EGR rates. A CO₂ cart was used to verify EGR rates and calibrate the differential pressure sensor and orifice plate. No EGR was used at idle in order to keep the catalysts at temperature during longer idle periods. EGR was scheduled based on engine coolant temperature, where no EGR was used with a coolant temperature less than 43 °C and the nominal EGR rate was used when the coolant temperature was above 71 °C with a linear interpolation between.

2.2.5 Transient Engine Calibration

Transient emissions are much harder to calibrate for than steady state operation. There was a need to match the fuel flow to the airflow accurately. In order to match the fuel flow there must be an accurate calculation for the airflow at the fueling point. A Speed-Density calculation takes the engine speed, manifold pressure, manifold temperature, and volumetric efficiency at this point in order to calculate a fuel flow rate. However, there are a number of transient phenomena that affect this calculation:

1. The volumetric efficiency changes during transient operation (changes in cylinder wall temperature have an effect and is discussed further)
2. The filling and emptying of the manifold volume between the fueling point and the intake valve of the engine

When the throttle was opened, the mass flow at the fuel valve includes flow into the engine, as well as flow that fill the manifold, shown in Figure 47. If the flow to fill the manifold is not accounted for then the fueling is too low and a lean mixture results. The opposite holds true for when the throttle is closed.

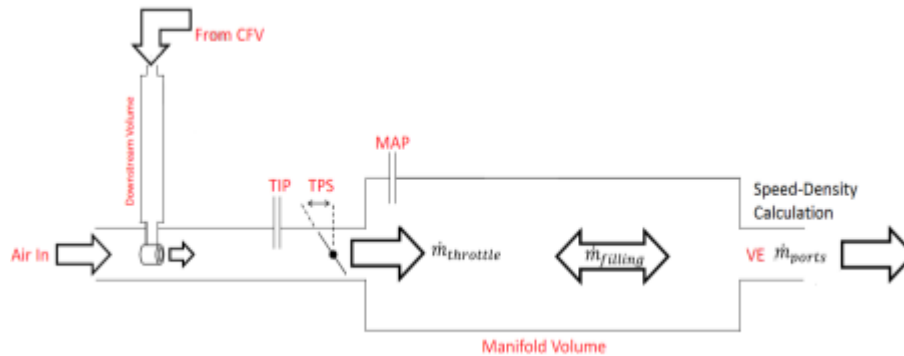


FIGURE 47. INTAKE MANIFOLD FILLING USED WITH SPEED-DENSITY CALCULATION

As can be seen, these calculations rely on knowledge of the total volume between the fueling point (CFV in this case) and the intake valves. For calibration purposes, the intake manifold volume, air-fuel-EGR mixer, fuel hose, intake port volume, and any additional volumes were physically measured and entered into the ECU software. The volume between the CFV and the fueling point of the air-fuel-EGR mixer was a critical variable in the calculations used for transient fueling and as such small errors can produce large errors in transient fueling. Iterations were made on this volume until tip-in & tip-out fueling at various conditions was acceptable.

Discussed earlier in this section was the effect of cylinder wall temperature on. As the cylinder walls cool, a more dense volume of air was drawn into the cylinder. However, stoichiometry was not based on volume of fuel to volume of air; because the air was denser, the mass of air was higher than it needs to be leading to an overall lean mixture. The EControls ECU offers three different cylinder wall temperature corrections, all of which are fast acting (short time constant) corrections, a single point correction that gets applied to all operating conditions, a 1-D table based on tip-in/tip-out and engine speed, and a 2-D table based on engine manifold air pressure (MAP) and engine speed. Due to time constraints and scope for the project, the 1-D table was chosen. The engine was run at various speeds and underwent numerous step changes in load in order to determine the best fueling corrections. As to be expected, the amount of fueling that was needed for a tip-in off of idle was larger than that needed for a tip-in off of higher speed (due to less flow rate in the engine allowing the cylinder walls to cool). However, this correction did not take into account the load history of the engine, which had a major effect on the cylinder wall temperature. An additional volumetric efficiency correction was developed and applied to the ECU in order to improve overall air-fuel ratio control and is discussed in Task 4.

The ECU utilizes feedback control on the fueling for the engine during steady state and some transient operation. As long as the transient operation was longer than the transport delay time of the engine feedback, fueling was applied. To give an idea of this transport delay, the typical delay during idle was 500 ms, and the typical delay during “cruise” operation typical of the 600 to 900 second mark of the FTP was 150 to 300ms. An example of transport delay for this engine is shown in Figure 48.

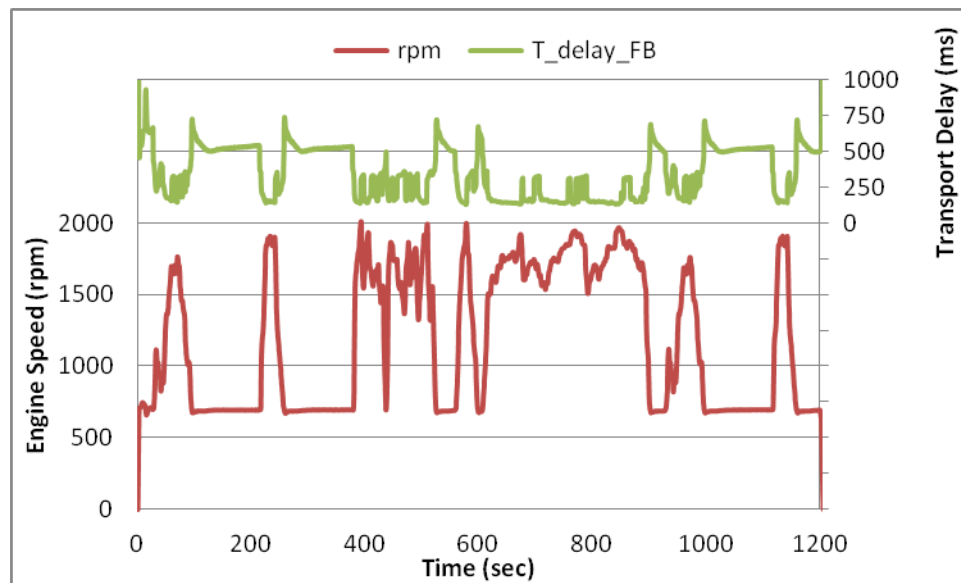


FIGURE 48. TRANSPORT DELAY TIME FOR ENGINE AIR-FUEL-EGR MIXTURE DURING THE FTP

Areas of the US Heavy Duty FTP where the engine was not in closed loop fueling can be seen in Figure 49, below, the blue box indicates an area where the UEGO sensor was not active during cold start operation. The area where the engine was not in closed loop fueling was smaller for when the engine was started already warm, as the UEGO sensor does not need as long to heat up – typically the engine will become closed loop during the middle of the first acceleration. The green box indicates an area where the transient operation of the engine was faster than the transport delay of the engine and closed loop feedback on fueling was not possible.

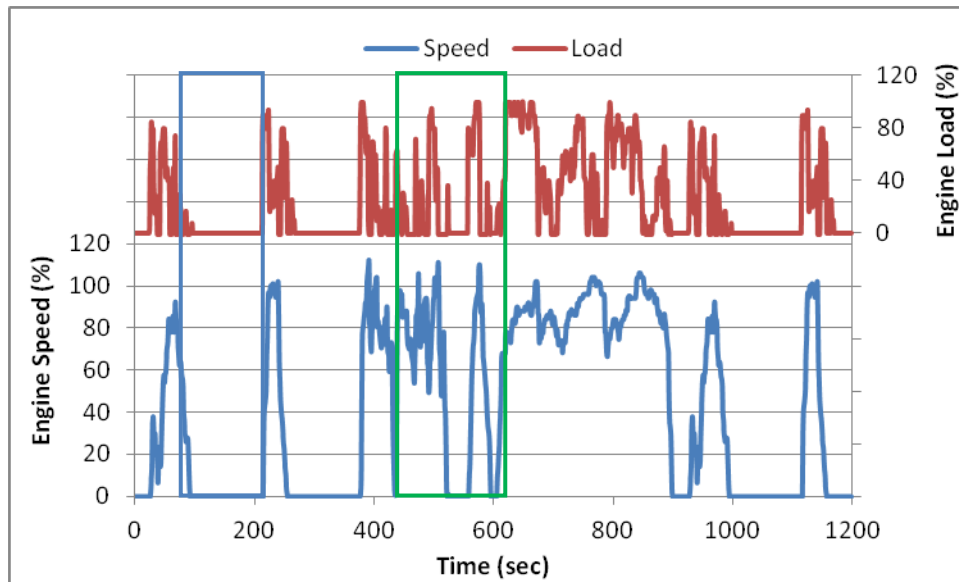


FIGURE 49. US FTP ENGINE SPEED AND LOAD - BOXED AREAS INDICATE NO CLOSED LOOP FUELING.

Transport delay was based off the volume of air-fuel-EGR mixture in the intake path from the fueling point and the volume of exhaust up to the UEGO sensor. In order to minimize this transport delay and increase the amount of transient operation that allows closed loop feedback on fueling the UEGO sensor was placed as close as possible to the turbine outlet of the turbocharger. The placement of the UEGO sensor also allows for it to be turned on earlier during cold start operation. Because the UEGO sensor must be warm before sampling, the closer the sensor can be to the turbocharger outlet the faster it will warm up and the faster the engine can enter closed loop fueling.

An additional fueling correction that was used by the ECU was a coarse grid adaptive table that uses the feedback from the UEGO sensor to populate a fueling correction based on engine speed and load. This adaptive table can be very helpful for most engine operation; however, the adaptive table was only updated when the engine was in closed loop (which was not the area a correction was needed). Over cycles like the FTP and WHTC the adaptive table gets updated during the last half of the cycle when the engine was in closed loop and hot. When the engine started up for the next cycle, this adaptive correction was wrong, and takes a significant amount of time to update before becoming correct. This problem was addressed with the additional volumetric efficiency correction developed and discussed further in the following Section 2.3, Task 4.

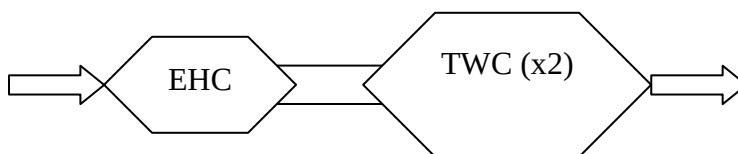
2.3 TASK 4: Catalyst Down-Selection and Final Demonstration Results

2.3.1 Catalyst Down-Selection

Once an engine calibration was developed that produced emissions results near the target levels, all of the catalyst configurations submitted by the MECA members were tested in order to determine which aftertreatment system would provide the easiest path forward to meeting the

emissions targets. The following section will detail the emissions performance of each degreened catalyst configuration tested with a preliminary engine calibration.

Team A's catalyst configuration can be seen in Figure 50. The configuration was composed of one electrically heated close-coupled catalyst primarily responsible for methane oxidation. The two three-way catalysts further downstream are equal in size; the upstream catalyst was responsible for hydrocarbon oxidation and the last catalyst brick was responsible for NO_x reduction. To properly account for the GHG impact of the EHC, the power consumption was measured during testing. This power consumption was adjusted by a practical alternator efficiency in order to predict the engine power requirement (and fuel consumption).



Close-coupled electrically heated catalyst (3.2 liters) with two under-floor three-way catalysts (11.1 liters each)

FIGURE 50. TEAM A CATALYST CONFIGURATION

TABLE 26. TAILPIPE EMISSIONS FOR COLD AND HOT FTP WITH CATALYST CONFIGURATION FROM TEAM A

	Tailpipe, g/hp-hr				
	NO _x	NMHC	CO	CO ₂	CH ₄
FTP Cold	0.109	0.109	3.040	614.2	0.762
FTP Hot	0.038	0.000	2.894	563.8	0.773
FTP Composite	0.048	0.016	2.915	571.0	0.771

In order to improve the resolution for the Hot FTP emissions measurement, lower concentration gas ranges were used (e.g. 25 ppm NO_x range). Overall, Team A emissions did not meet the target of 0.02 g/hp-hr NO_x emissions (see Table 26). The catalysts exhibited a severe NO_x breakthrough event at ~600 seconds on both the Cold and Hot FTP. The Hot FTP NO_x emissions were typically 3 to 4 g/hr throughout the cycle, which indicates that the overall volume for the system was a bit too small. In order to meet the emissions targets for the Hot FTP (0.009 g/hp-hr), NO_x emissions must average less than 0.5 g/hr over the cycle.

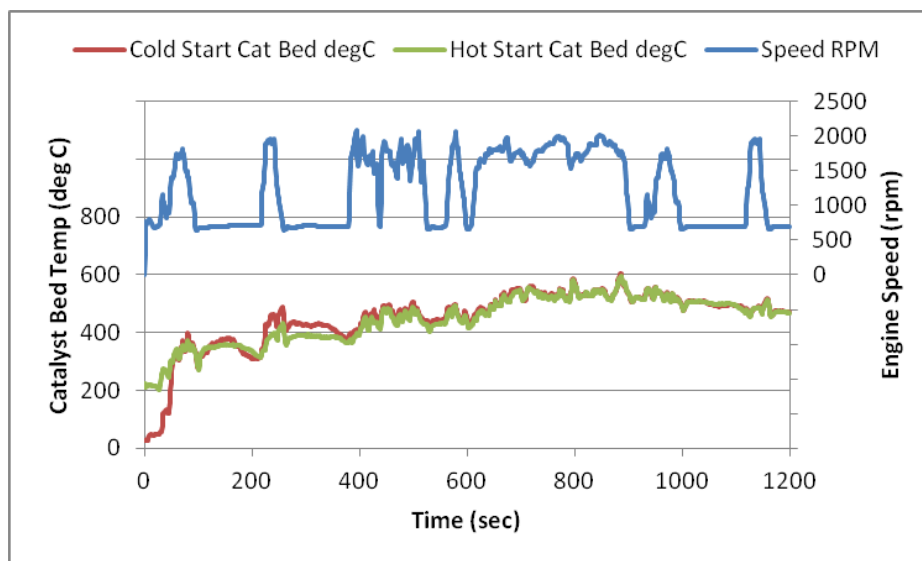


FIGURE 51. TEAM A CATALYST BED TEMPERATURE FOR COLD AND HOT FTP

Emissions during the first acceleration of the Cold Start FTP were high due to the catalyst bed temperature, shown in Figure 51, being below the light off temperature and the engine running overall lean due to cool cylinder walls. Cooler cylinder wall temperature leads to more mass of air per volume and results in the engine running overall lean. This problem was addressed in further calibration efforts described in Task 4. Emissions during the beginning of the Hot Start FTP are not nearly as high due to less of a problem with cool cylinder wall temperature. Both Cold and Hot Start FTP's do not allow the catalyst to reach light off temperature of 400 °C until right after the second acceleration. This was a problem, as the main NO_x conversion capacity was in the last brick of the aftertreatment system. Figure 52 shows the real time NO_x emissions over the cold and hot-start FTP using Team A's catalyst configuration.

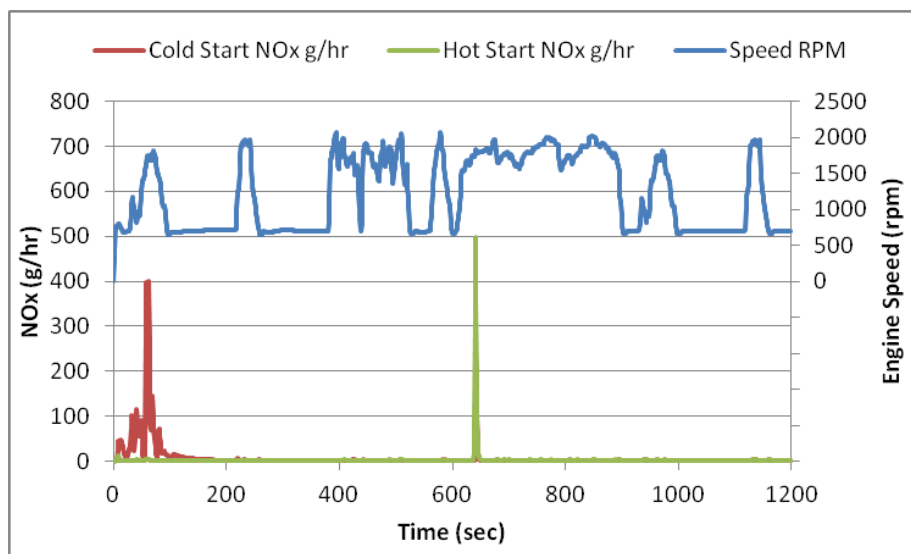
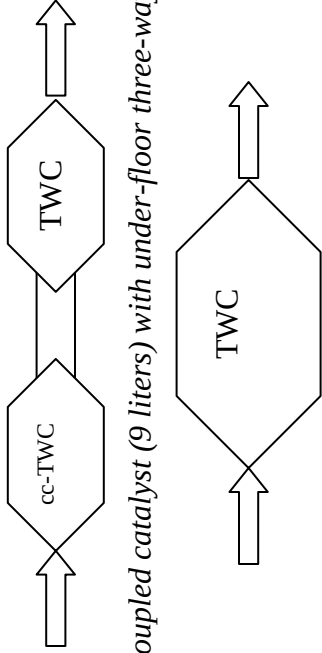


FIGURE 52. TEAM A NO_x EMISSIONS FOR COLD AND HOT FTP

Team B submitted two options for this program, illustrated in Figure 53. The first option consists of a close-coupled three-way catalyst responsible for fast light off and NO_x reduction. The under floor catalyst was equal in size to the close-coupled catalyst and responsible primarily for methane and hydrocarbon oxidation. The second option submitted consisted of a single under floor three-way catalyst.



Option 1: Close-coupled catalyst (9 liters) with under-floor three-way catalyst (9 liters)

Option 2: Larger under-floor three-way catalyst (20 liters)

FIGURE 53. TEAM B CATALYST CONFIGURATIONS (OPTION 1 AND 2)

TABLE 27. TAILPIPE EMISSIONS FOR COLD AND HOT FTP WITH CATALYST CONFIGURATION FROM TEAM B, OPTION 1 (CLOSE-COUPLED AND UNDER-FLOOR CATALYST)

	Tailpipe, g/hp-hr				
	NO _x	NMHC	CO	CO ₂	CH ₄
FTP Cold	0.082	0.001	4.741	613.3	0.212
FTP Hot	0.024	0.000	2.94	551.3	0.226
FTP Composite	0.032	0.000	3.197	560.2	0.224

Team B, catalyst configuration option 1, was the catalyst configuration closest to meeting the emissions targets with degreened catalysts (see Table 27). Good cold start emissions can be attributed to the close-coupled three-way-catalyst’s formulation for rapid light off and NO_x reduction. Team B did not exhibit the severe NO_x breakthrough at 600 seconds like Team A. However, examining Figure 55, the Hot Start FTP NO_x emissions are still too large to meet the emissions targets. The small spikes in NO_x emissions are a result of too small a catalyst volume and not enough oxygen storage.

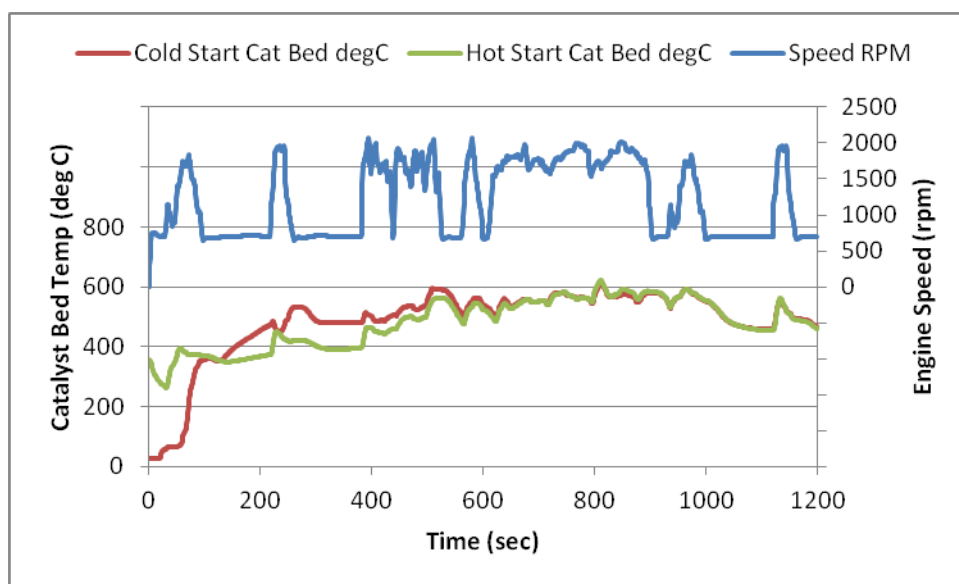


FIGURE 54. TEAM B, OPTION 1, CATALYST BED TEMPERATURE FOR COLD AND HOT FTP

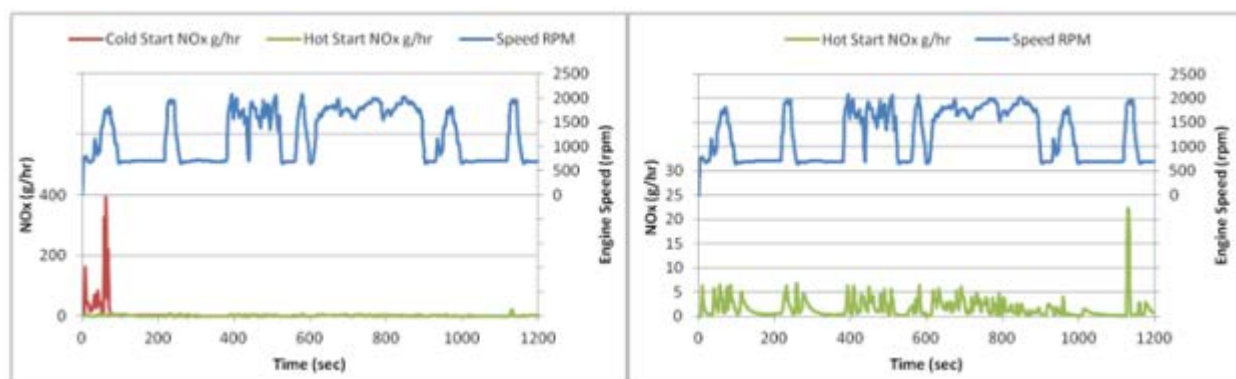


FIGURE 55. TEAM B, OPTION 1, NO_x EMISSIONS FOR COLD AND HOT FTP

The results for Team B, catalyst configuration option 2, are shown below in Table 28. Catalyst bed temperatures for Team B, option 2, are seen in Figure 56. It was clear that the catalyst supplied for this configuration was inadequate for both the cold start and the hot start FTP. However, the testing performed with this catalyst was done before the cold start operation was optimized, as can be seen by the large NO_x emissions during the first 200 seconds of the FTP in Figure 57. Additional examination of the exhaust flow showed that the physical layout of the catalyst was not ideal and was leading to a smaller effective area.

TABLE 28. TAILPIPE EMISSIONS FOR COLD AND HOT FTP WITH CATALYST CONFIGURATION FROM TEAM B, OPTION 2 (SINGLE UNDER-FLOOR CATALYST)

	Tailpipe, g/hp-hr				
	NO _x	NMHC	CO	CO ₂	CH ₄
FTP Cold	0.594	0.003	1.972	613.0	0.620
FTP Hot	0.042	0.000	2.308	547.8	0.378
FTP Composite	0.121	0.000	2.260	557.1	0.413

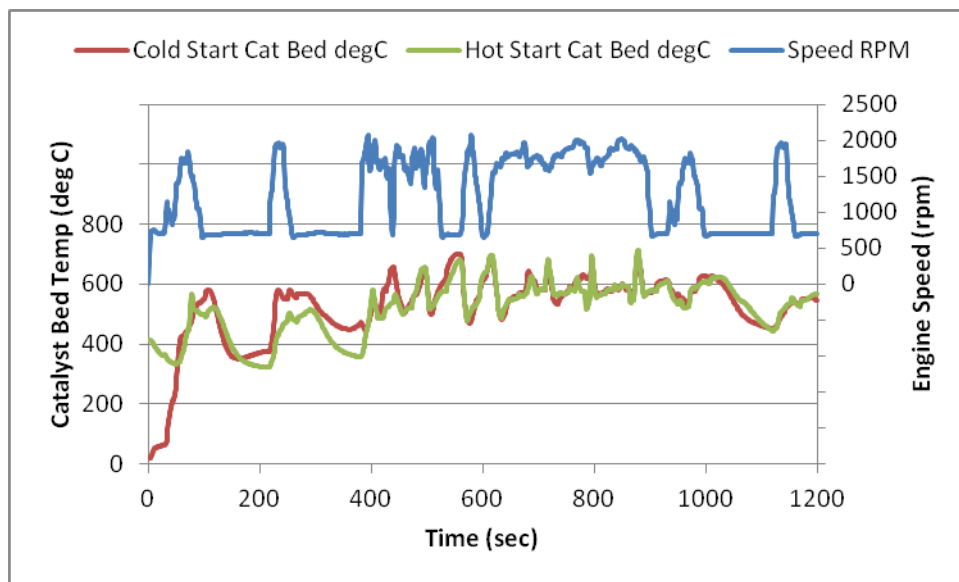


FIGURE 56. TEAM B, OPTION 2, CATALYST BED TEMPERATURE FOR COLD AND HOT FTP

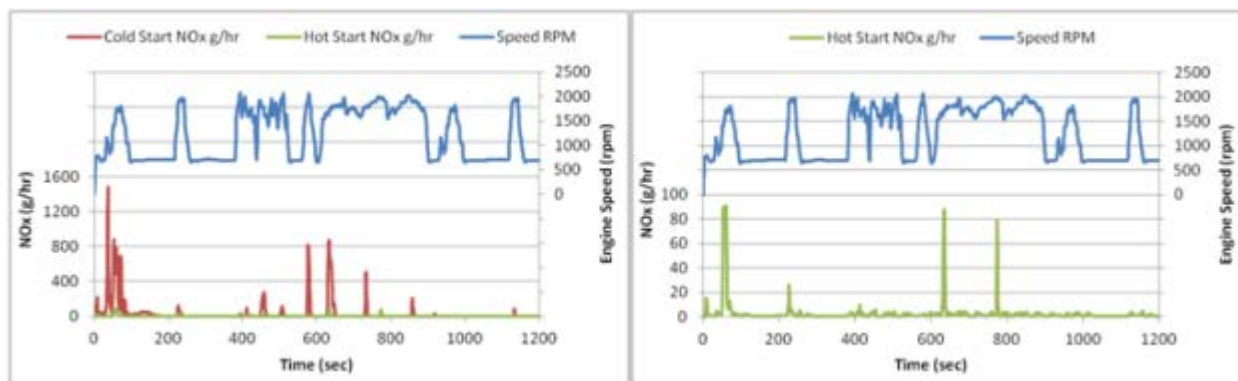
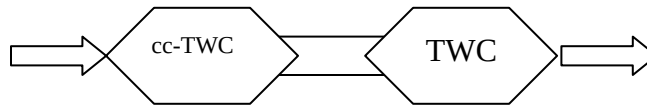


FIGURE 57. TEAM B NO_x EMISSIONS FOR COLD AND HOT FTP

Team C's configuration, illustrated in Figure 58, consisted of the smallest volume catalysts. The close-coupled catalyst was formulated for fast light off and responsible for CO oxidation and NO_x reduction. The under-floor catalyst was designed for NO_x slip at high space velocities.



Close-coupled catalyst (5.7 liters) with under-floor catalyst (8.5 liters)

FIGURE 58. TEAM C CATALYST CONFIGURATION

The emissions results for Team C can be seen in Table 29. The fact that both NO_x and CO are high was an indication that the catalysts provided did not have enough oxygen storage for transient operation. The catalyst configuration does exhibit excellent NO_x emissions during the first 200 seconds due to the lower thermal mass for the close-coupled three-way-catalyst; however, the smaller overall catalyst volume does lead to problems with both high NO_x and CO emissions.

TABLE 29. TAILPIPE EMISSIONS FOR COLD AND HOT FTP WITH CATALYST CONFIGURATION FROM TEAM C

	Tailpipe, g/hp-hr				
	NO _x	NMHC	CO	CO ₂	CH ₄
FTP Cold	0.813	0.000	6.224	609.1	0.531
FTP Hot	0.763	0.000	6.322	552.3	0.787
FTP Composite	0.770	0.000	6.308	560.4	0.750

Catalyst bed temperature over the cold and hot-start FTP can be seen in Figure 59. Notice the rapid heating of the catalyst during cold-start due to the lower thermal mass. Real time NO_x emissions can be seen in Figure 60.

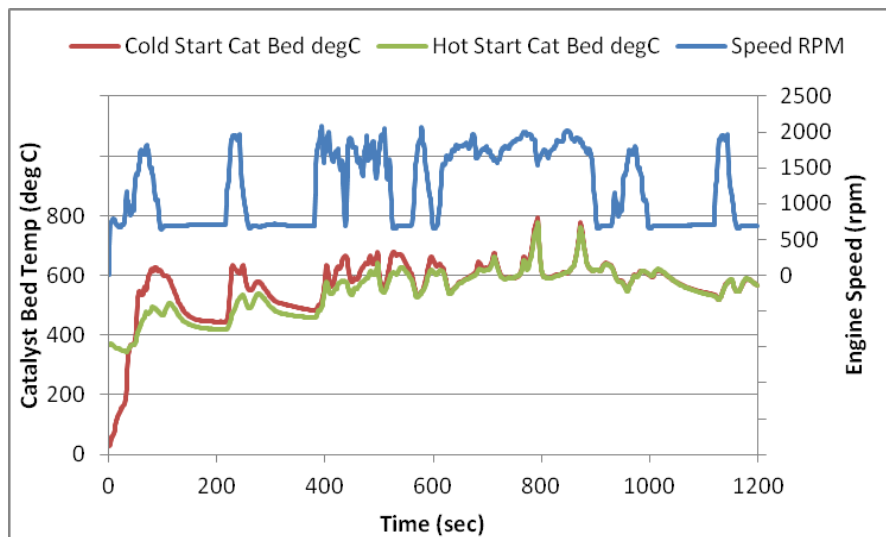


FIGURE 59. TEAM C CATALYST BED TEMPERATURE FOR COLD AND HOT FTP

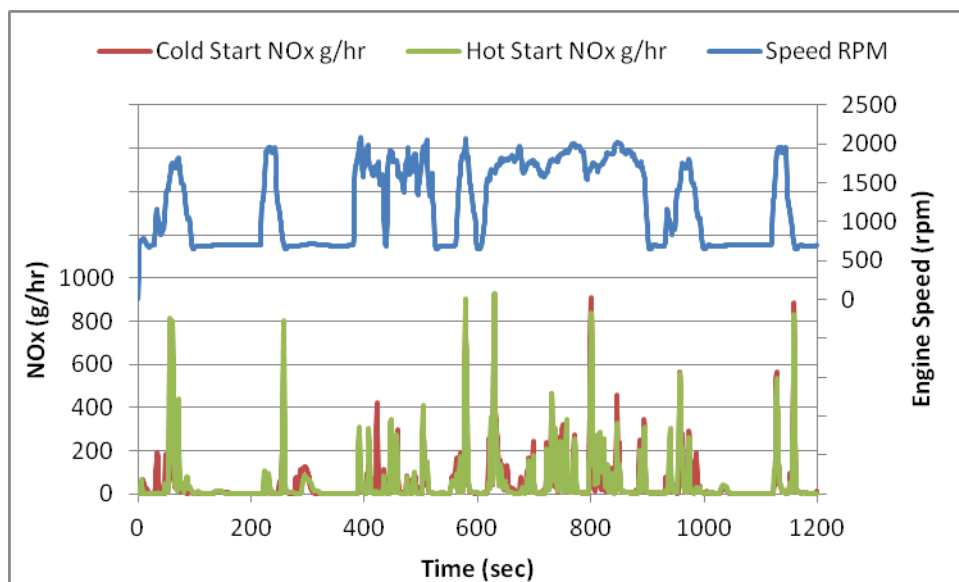
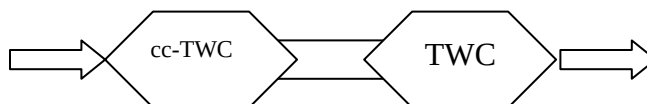


FIGURE 60. TEAM C NO_x EMISSIONS FOR COLD AND HOT FTP

Southwest Research Institute took the information gathered from screening these four catalyst configurations and went forward with a custom catalyst configuration that can be seen in Figure 61, below. This catalyst configuration utilizes a close-coupled catalyst from Team B, option 1, and the under-floor catalyst from Team B, option 2. These catalysts were tested using the same engine calibration as Teams A through C and the results can be seen in Table 30.



Close-coupled catalyst (9 liters) with under-floor catalyst (20 liters)

FIGURE 61. SWRI CATALYST CONFIGURATION

TABLE 30. TAILPIPE EMISSIONS FOR COLD AND HOT FTP WITH CATALYST CONFIGURATION FROM SWRI

	Tailpipe, g/hp-hr				
	NO _x	NMHC	CO	CO ₂	CH ₄
FTP Cold	0.082	0.001	2.734	591.4	0.273
FTP Hot	0.005	0.000	2.054	543.5	0.120
FTP Composite	0.016	0.000	2.149	550.2	0.141

Even though these emissions were meeting the composite over the FTP, further calibration effort continued to improve the robustness of the air-fuel ratio control and more discussion can be found in Task 4.

2.3.2 Final Engine Calibration

The volumetric efficiency (VE) correction depends on three main properties for the engine, past engine speed, load, and coolant temperature. In lieu of adding a VE correction based on whether the engine was in open loop fueling during start-up, a simple enrichment during open loop start-up was used.

All of the variables used by this VE correction are recorded by the ECU software and can be used to provide a long acting VE correction. Much like the typical transient fueling tables in the ECU software, this VE correction relies on engine tests to populate a table of VE corrections based on engine coolant temperature. The VE correction also relies on a VE correction based on maximum engine power and increasing/decreasing time constants for corrections on both tip-in and tip-out. Figure 62 and Figure 63 show examples of the long acting VE correction used for the US heavy-duty FTP for cold-start and hot-start, respectively.

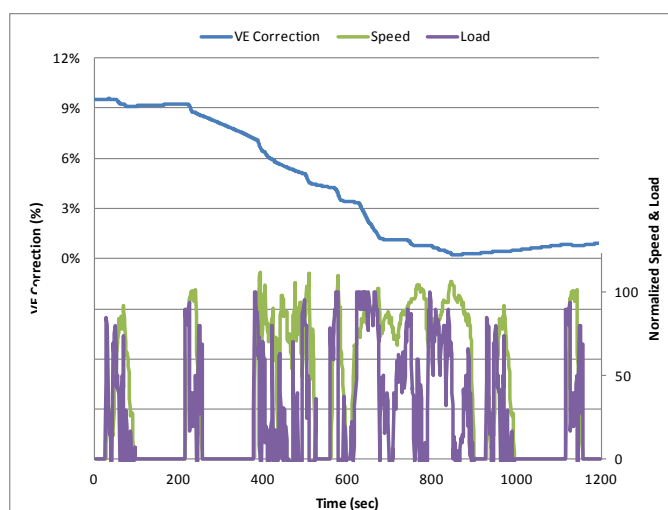


FIGURE 62. COLD-START FTP LONG TIME CONSTANT VE CORRECTION.

The VE correction during the cold-start FTP was greater than that during the hot-start FTP because the dominant factor influencing the correction was heat transfer. The VE correction tends towards zero during the “high-speed” portion of the FTP (600 – 1000 seconds) and begins to increase again towards the end of the cycle due to the extended idle portions of the cycle that cool the cylinder walls. Similarly, the VE correction during the beginning of the hot-start FTP was higher than the latter half of the cycle, owing to cooler cylinder walls.



FIGURE 63. HOT-START FTP LONG TIME CONSTANT VE CORRECTION.

Figure 64 shows that this correction can be made for more than just the US heavy-duty FTP; the WHTC VE correction shares a similar start-up VE correction to the cold-start FTP. The highly transient nature of the cycle from 600 seconds to 1200 seconds shows the need for an almost constant VE correction; with the cylinder walls not warming until the very end of the test cycle (requiring 0% VE correction).

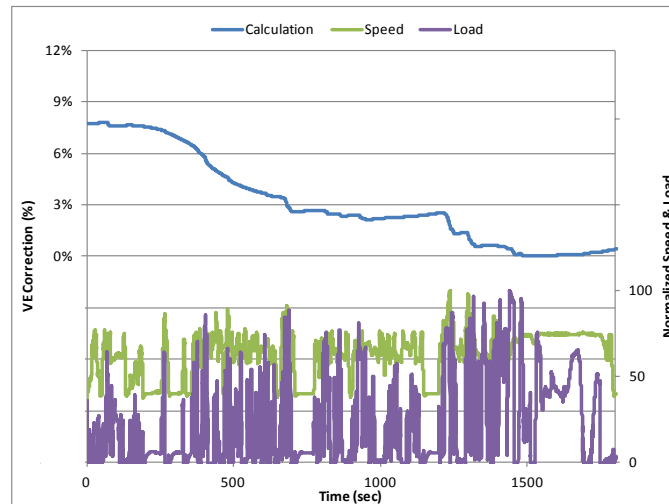


FIGURE 64. COLD-START WHTC LONG TIME CONSTANT VE CORRECTION.

2.3.2.1 Demonstration Results

The following cycles were tested for demonstration: US heavy-duty FTP, RMC, WHTC, CARB Idle, NYBC, OCTA, and the Cruise-Creep cycle. Details of these cycles can be found in Section 2.1 TASK 1: Engine, Test Cycles and Aftertreatment Technologies of this report. For demonstration purposes, five repeats of one cold FTP and three hot FTPs was needed, as well as, five repeats of RMC cycles. WHTC testing required three repeats of one cold WHTC and three hot WHTCs. The CARB Idle, NYBC, OCTA, and Cruise-Creep cycles required three tests.

Emissions targets had to have been met for both the US heavy-duty FTP as well as the RMC – all other cycles were for reference only. Testing for all cycles, including the WHTC and vocational cycles was performed with CARB certification blend natural gas. The specifications for that fuel blend, and average measured concentration from the fuel used for the demonstration can be seen in Table 31 below.

TABLE 31. CARB CERTIFICATION NATURAL GAS BLEND SPECIFICATIONS

Gas Species	Concentration Specification (vol. %)	Average Measured Concentration (vol. %)
Methane (CH ₄)	90.0 ± 1.0	90.4
Ethane (C ₂ H ₆)	4.0 ± 0.5	4.1
C ₃ and Higher	2.0 ± 0.3	2.1
C ₆ and Higher	0.2 max	0.0
Oxygen (O ₂)	0.5 max	0.0
Inert Components (CO ₂ and N ₂)	3.5 ± 0.5	3.4
Hydrogen (H ₂)	0.1 max	0.0
Carbon Monoxide (CO)	0.1 max	0.0
Sulfur (S)	16 ppm max	0.0

One should note that the baseline testing for the WHTC and the vocational cycles was performed using line natural gas and not the CARB certification blend. Due to the low concentrations of pollutants that were to be measured, it was of interest to compare raw emissions measurement, post catalyst, to that of the dilution tunnel for each test cycle. Raw emissions were measured via a Horiba MEXA-7100DEGR emissions bench and dilute emissions were measured via a Horiba MEXA-7200D emissions bench. While it was of interest to compare the raw and dilute emissions, the WHTC's ten-minute soak time limited emissions measurement to just dilute emissions using the cold-start set of ranges. The cold/hot ranges for the dilute and raw emissions bench can be seen in Table 32. Due to the enrichment and spark retard (catalyst heating) during the opening two minutes of the FTP the CO, THC, and CH₄ ranges need to be quite large. However, after the catalysts were sufficiently heated and the engine was operating in closed loop fueling, the CO and CH₄ emissions drop significantly, as evident in Figure 69.

TABLE 32. COLD AND HOT RANGES FOR RAW AND DILUTE EMISSIONS BENCHES

Gas Species	Dilute Bench Cold / Hot		Raw Bench Cold / Hot	
CO ₂ [%]	6	6	16	16
CO(L) [ppm]	5000	5000	5000	5000
CO(H) [ppm]	--	--	60000	5000
THC [ppm]	5000	1000	25000	25000
CH ₄ [ppm]	2500	1000	25000	25000
NO _x [ppm]	300	25	3000	300
NO [ppm]	300	25	--	--
O ₂ [%]	--	--	23	23

The average cold, hot, and composite FTP tailpipe emissions for the final demonstration can be seen in Table 33, below. The composite result for each day of testing was calculated using the average of the three hot start emissions. Each composite was then used to calculate an average, standard deviation, and coefficient of variation. Raw and Dilute emissions for NO_x, CO, CH₄, CO₂ and BSFC results are shown for comparison.

TABLE 33. FINAL DEMONSTRATION COMPOSITE FTP TAILPIPE EMISSIONS FOR CUMMINS-WESTPORT ISX12-G

		NO _x	CO	CH ₄	CO ₂	BSFC	PM	NH ₃ Avg.	N ₂ O Avg.
		g/hp-hr				lb/bhp-hr	g/hp-hr	ppm	ppm
Cold Avg.	Raw	0.065	3.549	0.216	590.1	0.500	0.0016	40.3	0.69
	Dilute	0.068	3.359	0.212	595.3	0.504			
Hot 1 Avg.	Raw	0.000	1.592	0.151	539.1	0.455	0.0013	60.4	0.05
	Dilute	0.001	1.608	0.151	543.9	0.459			
Hot 2 Avg.	Raw	0.000	1.495	0.148	537.2	0.453	0.0012	52.5	0.03
	Dilute	0.001	1.507	0.148	541.5	0.457			
Hot 3 Avg.	Raw	0.000	1.470	0.133	537.3	0.453	0.0012	49.8	0.01
	Dilute	0.001	1.489	0.135	541.3	0.457			
Composite Avg.	Raw	0.009	1.803	0.154	545.2	0.460	0.0012	52.3	0.12
	Dilute	0.010	1.790	0.154	549.7	0.464			
Composite Std. Dev	Raw	0.003	0.083	0.035	4.178	0.004	0.0002	5.9	0.03
	Dilute	0.004	0.092	0.036	4.120	0.003			
Composite CoV	Raw	36.9%	4.6%	22.7%	0.8%	0.8%	20.0%	11.3%	22.0%
	Dilute	36.3%	5.1%	23.2%	0.7%	0.8%			

The emissions target of 0.02 g/hp-hr NO_x was met while passing the CO standard (15.5 g/hp-hr), PM standard (0.01 g/hp-hr), and the 2014 CO₂ standard (567 g/hp-hr). Composite emissions results differed less than 1% between the raw and dilute emissions benches. Catalyst bed temperature was measured one inch below the front face, in the centers, of the close-coupled and under-floor catalysts. Figure 65 shows the typical catalyst bed temperatures over the FTP. In order to achieve fast light-off of the close-coupled catalyst the engine operates 5% rich in open loop (roughly the 50 seconds of the FTP for the cold-start and 35 seconds for the hot-start) with a significant ignition retard (25 CAD) offset from the base ignition timing table. This results in ignition timing near TDC or a TDC for the majority of the first acceleration. Close-couple catalyst temperature rises above 400 °C within the first 50 seconds of the cold-start FTP. Under-

floor catalyst temperature rises above 400 °C after the first acceleration (roughly 120 seconds into the cycle). In order to keep the catalysts from cooling too much during the idle portions of the FTP, retarded ignition timing was used. The retarded ignition timing means that the exhaust gas exiting the cylinder was hotter and thus more heat was transferred to the exhaust. However, because the ignition timing was retarded off the maximum efficiency timing, there was a BSFC penalty.

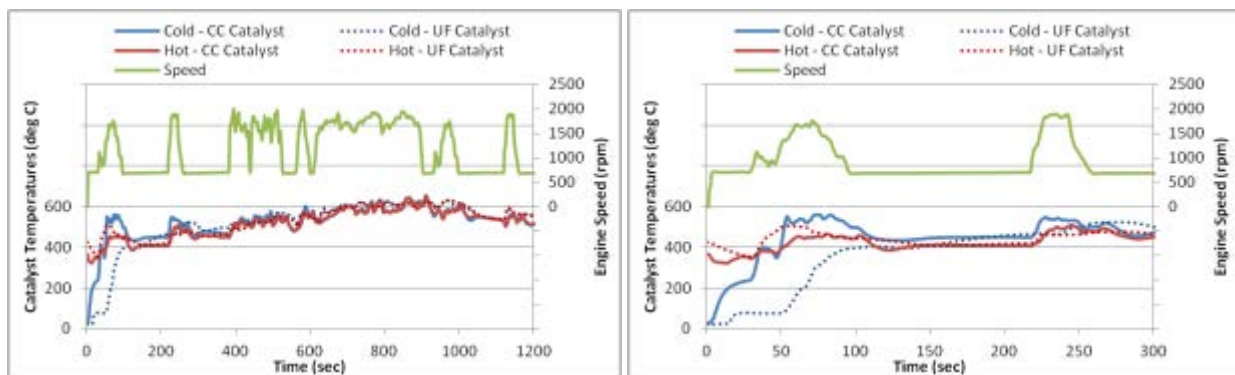


FIGURE 65. TYPICAL CATALYST BED TEMPERATURE FOR COLD AND HOT-START FTP CYCLE

Once both catalysts have reached 400 °C, the NO_x conversion efficiency was near 100% and any NO_x breakthroughs that may occur are solely due to poor air-fuel ratio control. Figure 66 shows that NO_x emissions drop toward zero once the under-floor catalyst temperature reaches 400 °C while operating stoichiometrically.

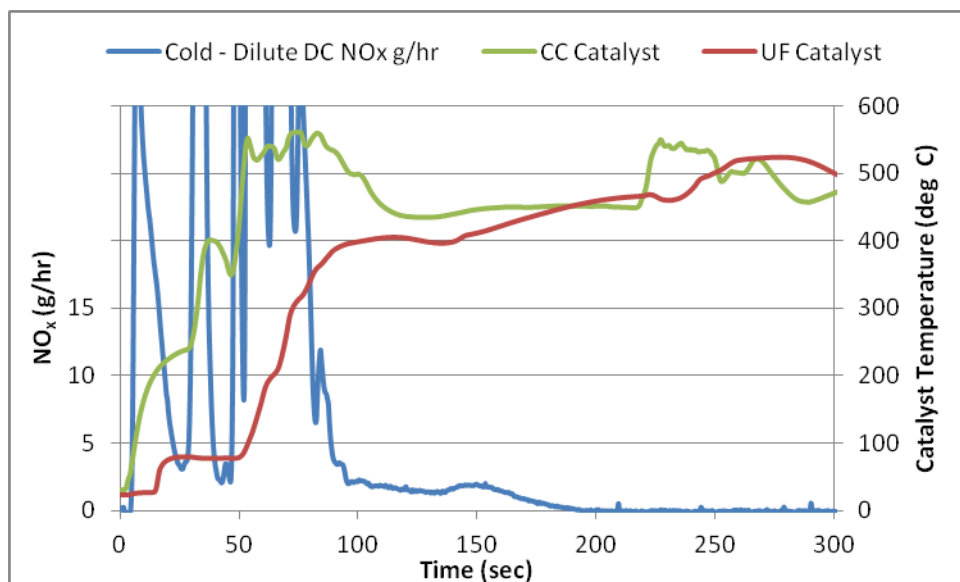


FIGURE 66: DILUTE NO_x MASS RATE VERSUS UNDER-FLOOR CATALYST BED TEMPERATURE DURING COLD-START FTP

Figure 67 shows typical real-time dilute drift corrected NO_x emissions over the cold-start and hot-start FTP cycle. The brake specific NO_x emissions over the cold-start and hot-start shown below were 0.086 g/hp-hr and 0.000 g/hp-hr respectively. It was clear to see that once the catalysts were brought to a temperature above 400 °C and once the engine was in closed-loop fueling, NO_x emissions were near zero. The only NO_x emissions during the hot-start result from the beginning of the first acceleration when the engine was still in open loop fueling.

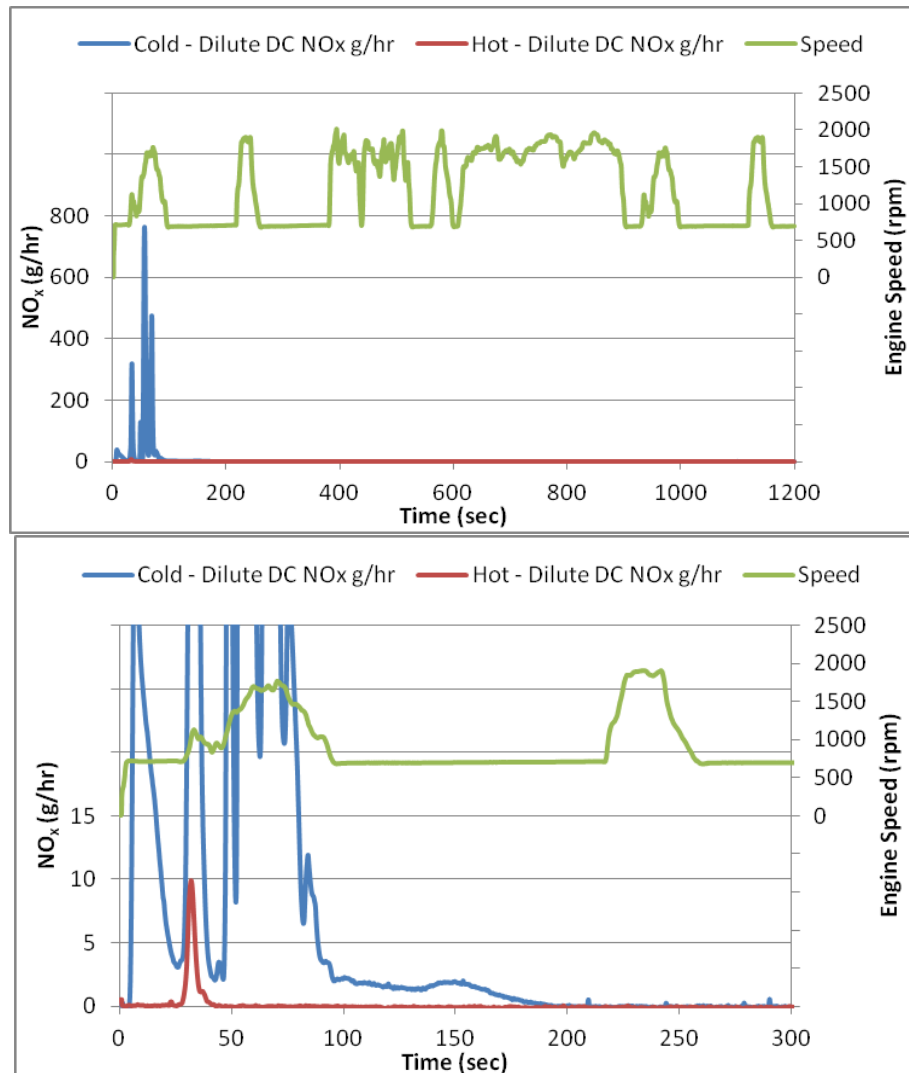


FIGURE 67. TYPICAL DEMONSTRATION COLD AND HOT-START FTP NO_x DILUTE MASS RATE

Because the engine was operating stoichiometrically over a three-way catalyst, there was the opportunity for ammonia, NH₃, to be produced. Ammonia is typically produced when an overall rich exhaust gas mixture passes over a three-way catalyst. Ammonia is not regulated, but a goal of this project was to keep the ammonia as low as possible and be lower than the base engine calibration/hardware. Figure 68 shows the typical ammonia concentration for a cold-and hot start FTP. The cold-start cycle average ammonia concentration was 48 ppm while the hot-start cycle average ammonia concentration was 49 ppm. Nitrous oxide, N₂O, was also of interest.

Like ammonia, N_2O forms when rich exhaust gas passes over a three-way catalyst. N_2O was not plotted below, but for the same runs shown in Figure 68, the cycle average N_2O was 0.784 and 0.018 ppm for the cold and hot-start FTPs respectively.

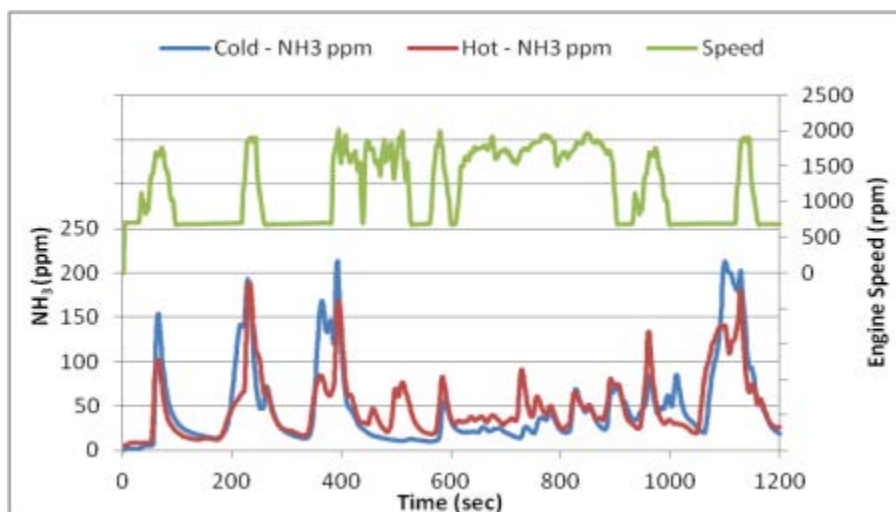


FIGURE 68. TYPICAL DEMONSTRATION COLD AND HOT-START FTP AMMONIA CONCENTRATION

For completeness, CO and CH_4 emissions are plotted, shown in Figure 69. Products of the enrichment and aggressive ignition retard offset during catalyst heating are shown in the very large CO and CH_4 emissions during the first acceleration. However, once the engine was in closed loop fueling and the ignition timing returns to its base timing the CO emissions can be seen to be quite low. Methane emissions are also quite low during the majority of the cycle with the exception of the first few tip-ins. Upon further examination of the O_2 sensor data along with the fact that there was not a spike in CO during the CH_4 spikes at 200 and 400 seconds the engine was not operating overly rich. High speed cylinder pressure measurement indicates that one cylinder of the engine suffered a misfire during the hard accelerations and thus unburned fuel made its way through the engine and did not oxidize at the catalysts due to lack of sufficient oxygen as well as the space velocity associated with these accelerations.

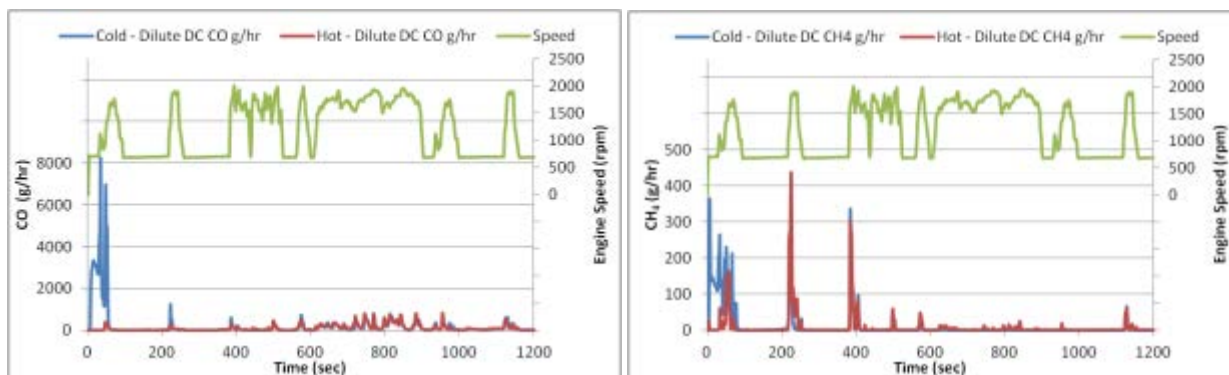


FIGURE 69. DEMONSTRATION COLD AND HOT-START FTP CO AND METHANE DILUTE MASS RATE

The day-to-day repeatability of the engine's emissions was examined in Figure 70. Average cold-start NO_x emissions were 0.068 g/hp-hr with a standard deviation of 0.025 g/hp-hr and a CoV of 37%. Average hot-start NO_x emissions were 0.001 g/hp-hr with a standard deviation of 0.0005 g/hp-hr and a CoV of 84.5%. However, due to the very small concentrations in NO_x that were measured over the hot-start FTP cycles the CoV measurement was likely not very accurate. Just like light-duty vehicles, the majority of the exhaust emissions formed during the first portions of the cold-start. The results are average composite emissions of 0.010 g/hp-hr with a standard deviation of 0.004 g/hp-hr.

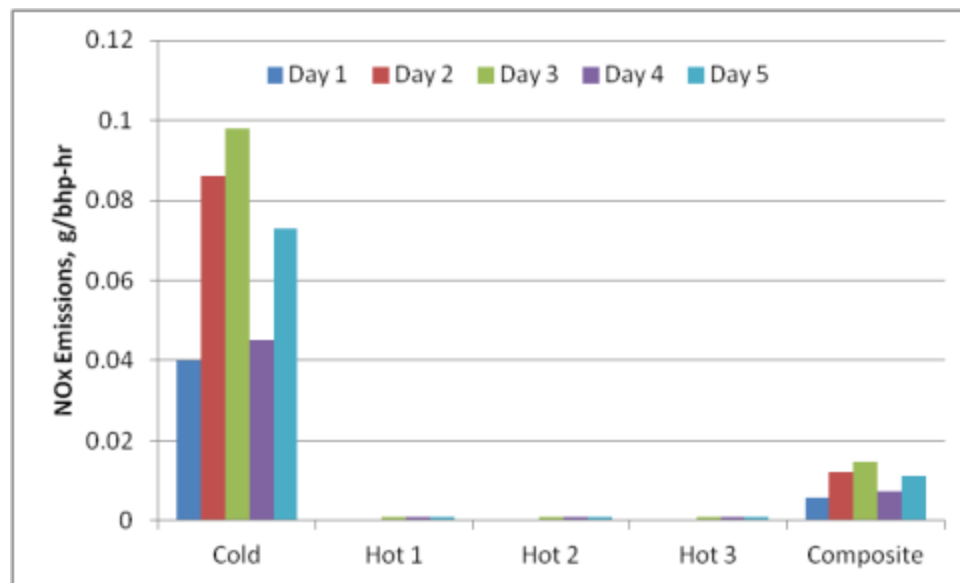


FIGURE 70: TEST-TO-TEST NO_x EMISSION VARIATION OVER FIVE DAYS OF FTP TESTING

The average results for the five demonstration steady state RMC-SET engine drive cycles can be seen in Table 34. As to be expected from the results of the FTP, the engine calibration/hardware changes allowed the engine to meet the 0.02 g/hp-hr NO_x emission target.

TABLE 34: FINAL DEMONSTRATION RMC-SET TAILPIPE EMISSIONS FOR CUMMINS-WESTPORT ISX12-G

		NO _x	CO	CH ₄	CO ₂	BSFC	PM	NH ₃ Avg.	N ₂ O Avg.
		g/hp-hr				lb/bhp-hr	g/hp-hr	ppm	
Average	Raw	0.0006	0.905	0.934	448.7	0.380	0.0003	36.8	0.09
	Dilute	0.0008	0.907	0.923	441.2	0.374			
Std. Dev.	Raw	0.0005	0.184	0.116	4.204	0.004	0.0001	12.6	0.05
	Dilute	0.0004	0.185	0.110	3.645	0.0034			
CoV	Raw	91.3%	20.3%	12.4%	0.9%	1.0%	21.1%	34.2%	51.3%
	Dilute	55.9%	20.4%	12.0%	0.8%	0.9%			

The test cycle was run as two RMC's back-to-back with the first RMC being the pre-conditioning run and the second RMC being the cycle that emissions and particulates are

officially sampled with. The opening and closing idle are zero torque idles which causes the catalyst temperature to drop. Throughout the majority of the test cycle, the close-couple catalyst was above 550 °C and the under-floor catalyst was above 600 °C. With the catalyst temperature being above 400 °C for the entirety of the test cycle, the conversion efficiency should be near 100% and thus any NO_x breakthroughs that occur are due to the engine not maintaining stoichiometry.

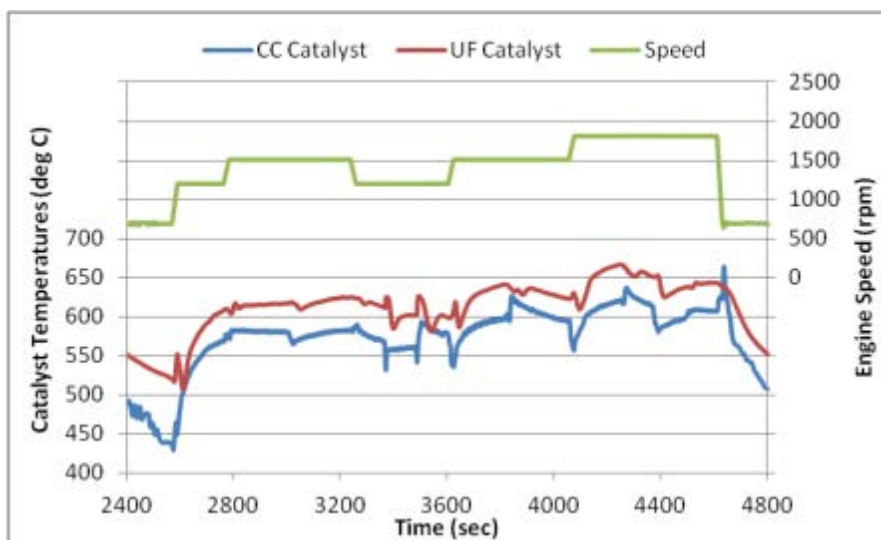


FIGURE 71. RMC-SET CATALYST BED TEMPERATURE

Figure 72 shows the typical NO_x dilute mass rate emission during the RMC-SET cycle. While there are two instances where the NO_x emissions are non-zero, the emission mass rate was less than 30 g/hr, which was over 25 times less than the largest NO_x spike during the first minute of the cold-start FTP. These NO_x spikes occur when the engine was changing speed and load and indicate that the equivalence ratio became slightly lean.

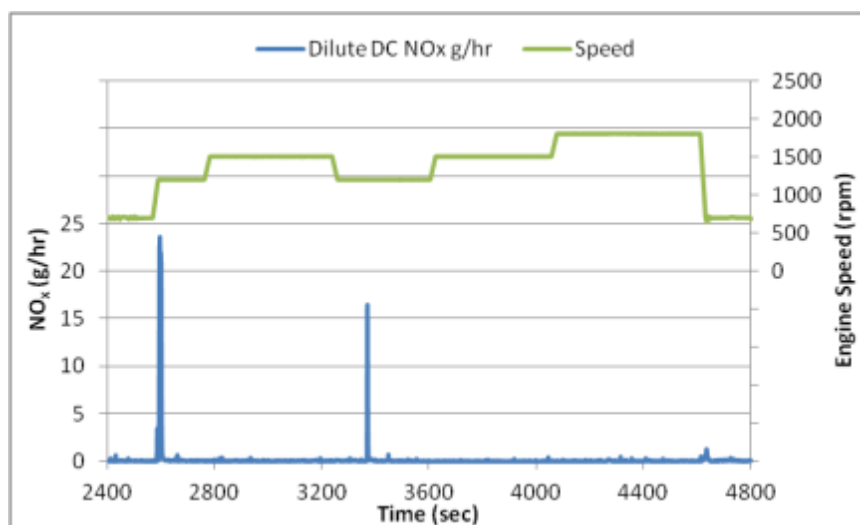


FIGURE 72. TYPICAL DEMONSTRATION RMC-SET NO_x DILUTE MASS RATE

Ammonia emissions over the RMC-SET are four times lower than the baseline engine hardware and calibration. The largest spike in ammonia, shown in Figure 73, comes when the engine was moving from high speed / high load to a zero torque idle. During this transition, the engine's equivalence ratio goes slightly rich, but due to the high space velocity, the catalysts release a large amount of ammonia.

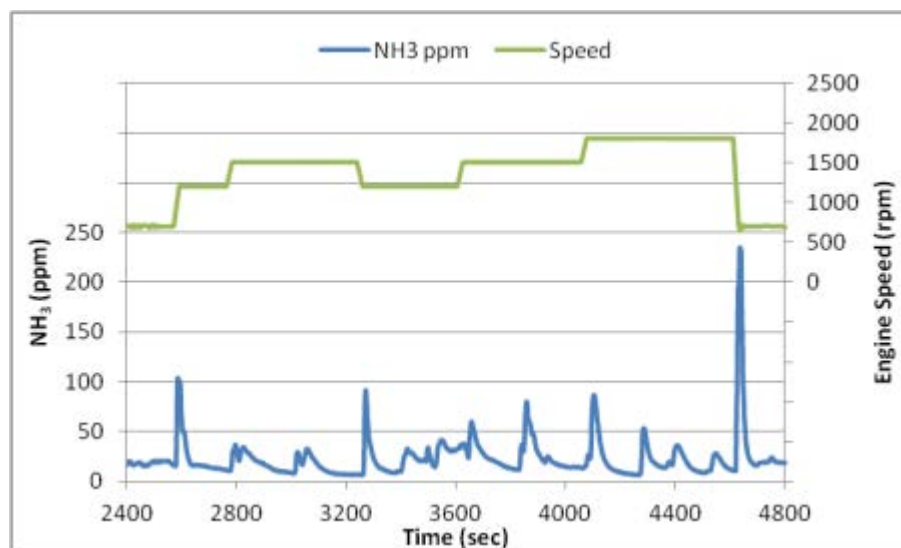


FIGURE 73. TYPICAL DEMONSTRATION RMC-SET RAW TAILPIPE AMMONIA

Typical CO and methane emissions over the RMC-SET are shown in Figure 74.

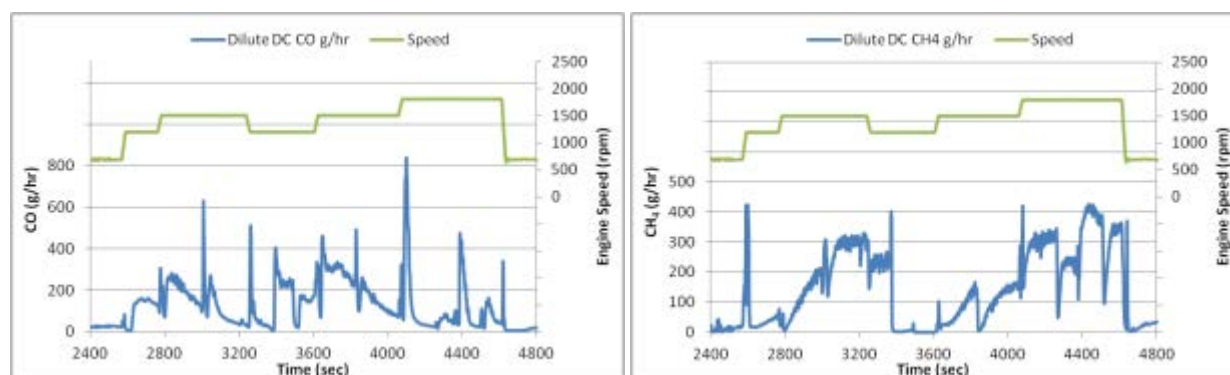


FIGURE 74. TYPICAL DEMONSTRATION COLD AND HOT-START RMC-SET CO AND METHANE DILUTE MASS

Greenhouse Gas (GHG) emissions – methane and carbon dioxide – were of interest to this demonstration evaluation. The EPA's 2014 and 2017 GHG standard for heavy-duty engines and vehicles sets a limit on the amount of methane and carbon dioxide that can be emitted over the FTP and RMC-SET. Figure 75 shows the methane emissions for the demonstration engine over the FTP and RMC-SET. In both test cycles, the methane emissions are over the standard; however, the methane emissions for the FTP are much lower. Although the methane emissions are over the 0.1 g/hp-hr standard, the CO₂ emissions are below both the 2014 and 2017 CO₂ standards.

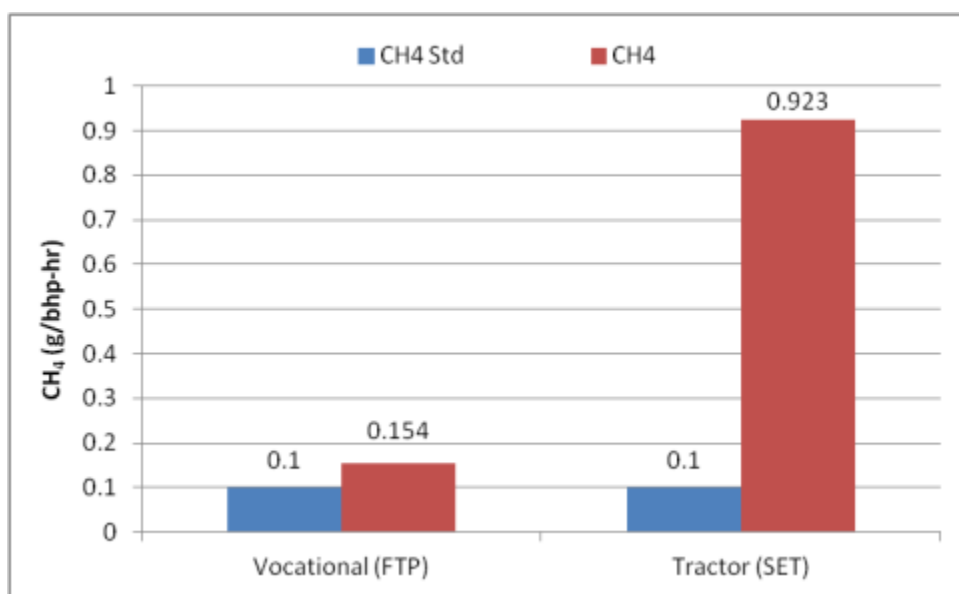


FIGURE 75. FINAL DEMONSTRATION METHANE EMISSIONS OVER THE FTP AND RMC-SET COMPARED TO 2014/2017 GHG STANDARD LEVELS

The total GHG emissions for the demonstration engine were calculated for both the FTP and RMC-SET using raw and dilute emissions measurement, shown in Table 35. The difference between the raw and dilute measurements was roughly 1%. The demonstration engine met the 2014 GHG standard on both the FTP and RMC measured dilute and raw. However, the demonstration engine fails the 2017 GHG standard over the RMC-SET measured both raw and dilute. However, it was very likely that with additional calibration and optimization to garner efficiency back the GHG emissions would fall below the 2017 standard. Figure 76 shows graphically the total GHG emissions (purple) for the demonstration engine over both the FTP and RMC-SET.

TABLE 35. RAW AND DILUTE GHG EMISSIONS FOR THE FINAL DEMONSTRATION FTP AND RMC-SET COMPARED TO THE 2014/2017 GHG STANDARDS.

	FTP (g/hp-hr)	RMC-SET (g/hp-hr)
2014 GHG Standard	567.0	475.0
2017 GHG Standard	555.0	460.0
GHG Measured – Raw	546.5	469.5
GHG Measured – Dilute	551.0	461.8

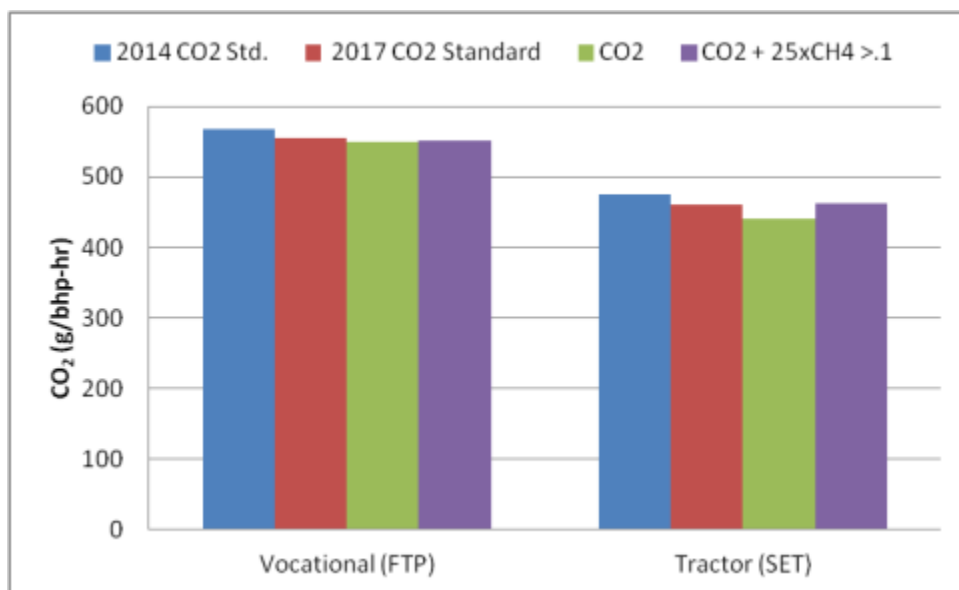


FIGURE 76. FINAL DEMONSTRATION CARBON DIOXIDE EMISSIONS OVER THE FTP AND RMC-SET COMPARED TO 2014/2017 GHG STANDARD LEVELS

The BSFC penalty associated with the demonstration method of achieving 0.02 g/hp-hr NO_x levels was roughly 4.5% over the FTP and less than 1% over the RMC-SET. It should be noted that while there was an efficiency (fuel economy) penalty associated with this engine calibration's cold-start catalyst light off strategy, further optimization was made to increase the NO_x emissions to a point closer to 0.02 g/hp-hr to garner some of the BSFC penalty back. Furthermore, an OEM optimized this by looking into a strategy that met the emissions targets, while not being a detriment to durability of the exhaust system. Additionally, if more time and budget was available, then further optimization in EGR dilution across the engine-operating map could be made to try to buy back some efficiency.

The World Harmonized Transient Cycle (WHTC) is a transient engine test cycle adopted for EURO VI emissions regulations. Similar to the US heavy-duty FTP, the test cycle is defined as having a cold-start cycle and hot-start cycle. Like the FTP, the cold-start emissions are an order of magnitude higher than the hot-start cycle. In order to meet the emission target of 0.02 g/hp-hr over the WHTC one simple calibration change was needed; allowing the engine to motor open loop at speeds between 1100 and 1500 rpm (3-5 psia manifold air pressure). Otherwise, the same strategy of enrichment in open loop and aggressive timing retard was used to heat the catalyst quickly to achieve fast NO_x light off. Likewise, the same transient engine calibration, and steady-state engine calibration tables were used (equivalence ratio set point, ignition timing, boost level, etc.).

As was stated above, the engine calibration was modified to allow the engine to motor in open loop fueling between 1100 and 1500 rpm. This was chosen because there are two spots of the WHTC cycle where the engine decreases load dramatically then was motored. When the engine tips-out heavily, there was a large spike in equivalence ratio and the closed loop was too slow to react to bringing it down while motoring (as the throttle must be closed – or nearly closed – to keep the engine from producing power). When the engine tips in from this increased

equivalence ratio the closed loop feedback pulls too much fuel and the overall exhaust mixture becomes lean. At this point the mixture was slightly lean of stoichiometric; however, the closed loop controller can only take small steps (50% of the error) to bring it back towards stoichiometry. While this slow acting closed loop correction was occurring the engine was under high speed and load causing significant NO_x breakthrough during both the cold and hot-start WHTC cycles. The slow acting closed loop control was evident in the left plot of Figure 77. Additionally the large spike in fuel from the tip-out and motoring coupled with aggressive tip-in causes a partial misfire resulting in increased methane emissions (and subsequently increased oxygen) flowing to the catalysts. This partial misfire exacerbates the NO_x breakthrough.

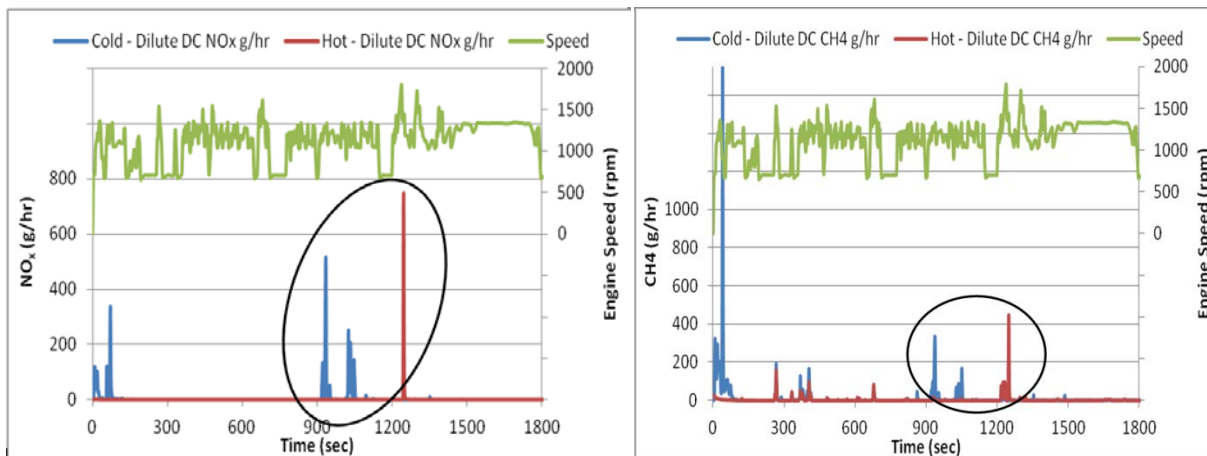


FIGURE 77. WHTC NO_x AND METHANE DILUTE MASS RATE EMISSIONS WITH ENGINE OPERATING IN CLOSED LOOP THROUGHOUT ENTIRE MAP.

With the engine in open loop fueling during these tip-outs/motoring events, the engine does not face a problem with the equivalence ratio spiking and not being able to drop to stoichiometry during motoring. At the point the engine tips in for the next acceleration, the equivalence ratio was near stoichiometry and thus no fuel was cut and the engine did not have a slow acting response to achieve stoichiometry. If the engine was operated without the modification to the calibration to allow for open loop, then the emissions do not meet the target of 0.02 g/hp-hr. Table 36 shows the composite WHTC emissions results with the engine operating with closed loop fueling control over the full operating map.

TABLE 36. WHTC EMISSIONS WITH FULL CLOSED LOOP FUELING MAP

	NO _x	CO	CH ₄	CO ₂	BSFC
Cold	0.077	1.287	0.152	539.7	0.455
Hot	0.023	0.971	0.045	505.0	0.425
<i>Composite</i>	0.031	1.015	0.060	509.9	0.429

Using the engine calibration that allows for the engine to operate in open loop fueling from 1100 to 1500 rpm while motoring (3-5 psia manifold air pressure) the demonstration engine meets the emissions target of 0.02 g/hp-hr. Table 37 shows the average emissions results for the

cold-start, each hot-start, and composite WHTC tests. Standard deviation and CoV was also reported for the composite tests.

TABLE 37. DEMONSTRATION WHTC TAILPIPE EMISSIONS

		NO _x	CO	CH ₄	CO ₂	BSFC	PM	NH ₃ Avg.	N ₂ O Avg.
		g/hp-hr				lb/bhp-hr	g/hp-hr	ppm	
Cold Avg.	Dilute	0.043	1.701	0.156	541.9	0.458	0.0008	39.7	0.255
Hot 1 Avg.	Dilute	0.002	1.181	0.099	509.0	0.429	0.0004	63.3	0.019
Hot 2 Avg.	Dilute	0.006	1.031	0.077	507.6	0.427	0.0003	43.3	0.040
Hot 3 Avg.	Dilute	0.010	0.939	0.092	507.0	0.427	0.0004	39.2	0.039
Composite	Dilute	0.011	1.141	0.098	512.6	0.432	0.0004	44.1	0.058
Composite Std. Dev.	Dilute	0.001	0.165	0.040	1.260	0.001	0.0001	8.249	0.022
Composite CoV	Dilute	5.1%	14.5%	40.8%	0.2%	0.2%	12.0%	18.7%	38.4%

Catalyst temperatures for the close-coupled and under-floor catalysts are similar to those of the FTP during cold-start and hot-start. The close-coupled catalyst reaches 400 °C around 50 seconds into the cold-start WHTC cycle. Because both the close-coupled and under-floor catalysts are at or above 400 °C for the majority of the WHTC any NO_x breakthroughs occur due to the air-fuel ratio going too lean and saturating the catalyst with oxygen.

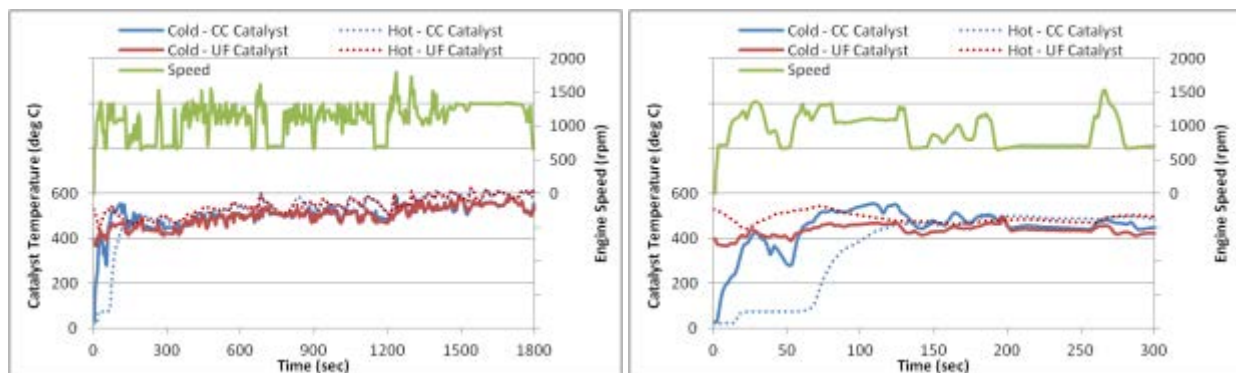


FIGURE 78. DEMONSTRATION CATALYST BED TEMPERATURE OVER COLD AND HOT START WHTC

Figure 79 shows the typical cold and hot-start NO mass rate emissions over the WHTC. Note that large NO_x emissions only occur during the opening 100 seconds of the WHTC. Once the catalyst was up to temperature and within closed-loop fueling, NO_x emissions are near zero.

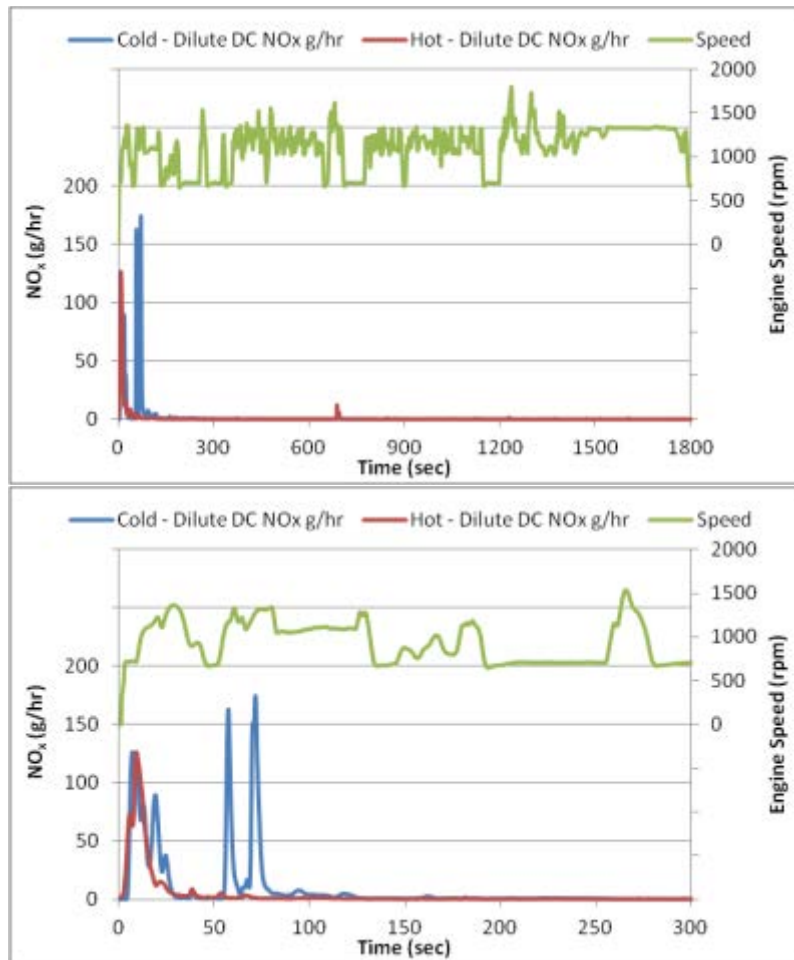


FIGURE 79. DEMONSTRATION DILUTE NO_x MASS RATE EMISSIONS OVER COLD AND HOT START WHTC

Ammonia concentration for the demonstration testing was roughly half that of the ammonia concentration for the baseline engine testing. The rather large spike in ammonia during the beginning of the cycle, shown in Figure 80, was due to the enrichment while the engine in open loop.

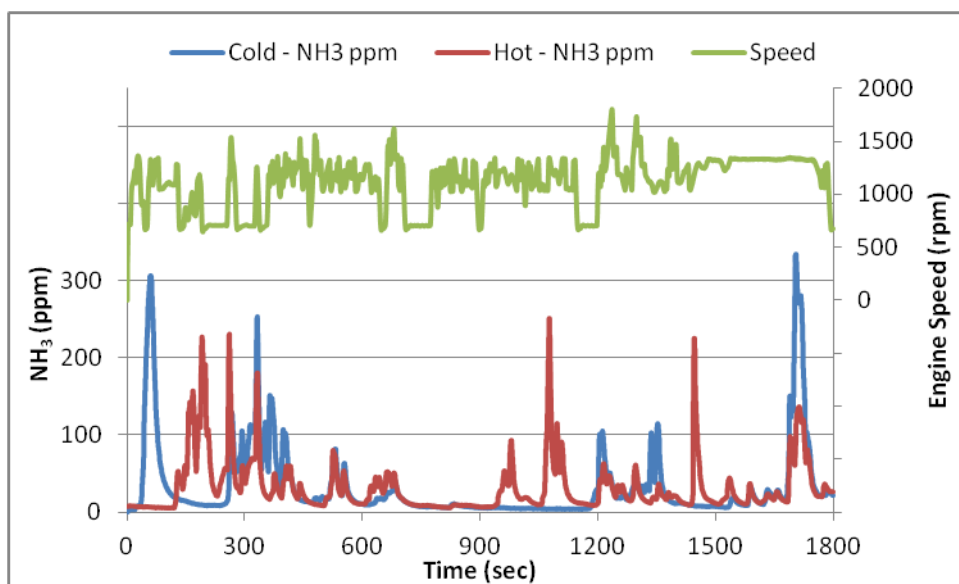


FIGURE 80. DEMONSTRATION TAILPIPE AMMONIA CONCENTRATION OVER COLD AND HOT START WHTC

Similar to the WHTC, the largest mass rate emissions of CO and CH₄ occur during first 100 seconds the cold-start cycle when the engine was undergoing catalyst heating (enriched in open loop with aggressive spark retard). Figure 81 shows that after the engine has gone into closed loop (and the enrichment was removed) CO and CH₄ emissions are relatively low. Unlike the FTP there do not appear to be any accelerations where the engine has misfired and caused a large spike in methane.

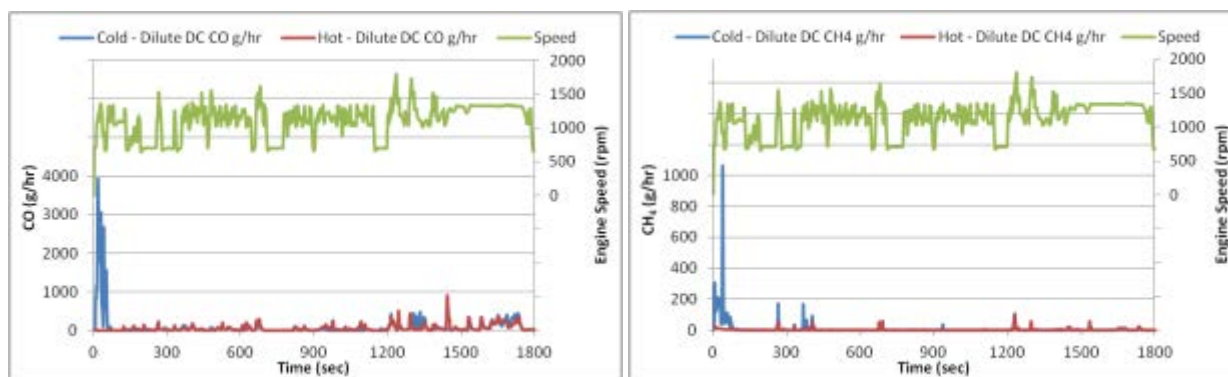


FIGURE 81. DEMONSTRATION COLD AND HOT-START WHTC CO AND METHANE DILUTE MASS

An additional cycle that was tested during demonstration was the CARB Idle test. This is a California-specific test designed to ensure a level of NO_x control during a sustained idle period. It consists of an FTP cycle warm-up, followed by two 30-minute idle periods. The first idle period was at designated low idle speed (i.e., “curb” idle), while the second 30-minute period was at an elevated idle (no-load) speed of 1100 rpm. The current limit for this cycle was 30 g/hr average NO_x rate, integrated separately of each of the two 30-minute idle periods.

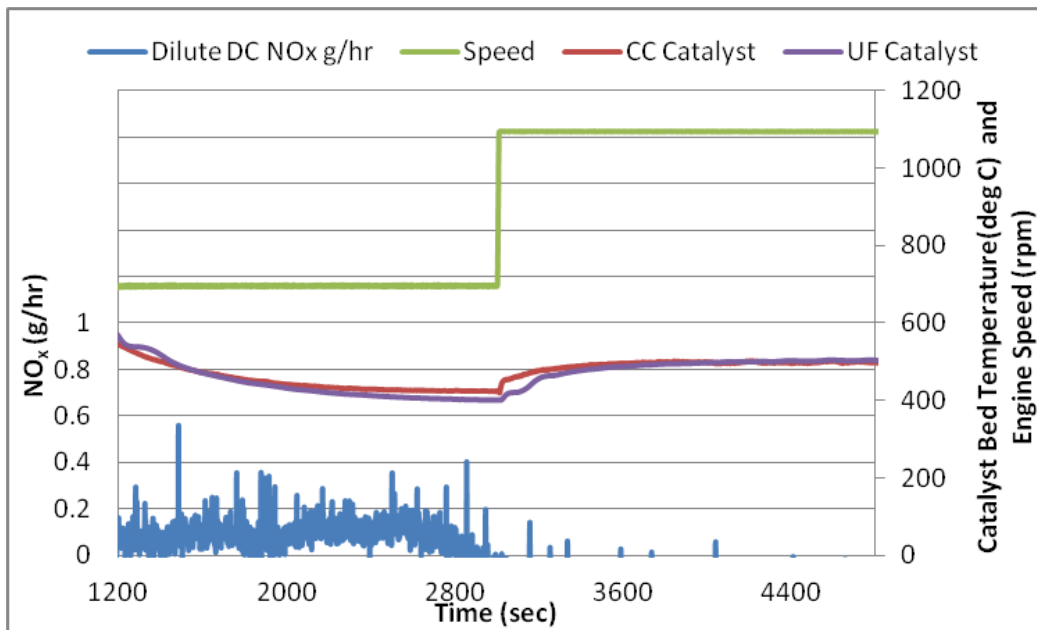


FIGURE 82. DEMONSTRATION CARB IDLE NO_x DILUTE MASS RATE AND CATALYST BED TEMPERATURE FOR CUMMINS-WESTPORT ISX12-G

Figure 82 shows that the NO_x mass rate emission for each 30-minute idle portion (curb and elevated) was essentially zero. It was interesting to note that the catalyst bed temperature begins to drop towards 400 °C at the end of the first 30-minute idle portion; however, there was still no significant NO_x breakthrough due to the slightly rich bias on the equivalence ratio at this speed and load. Of note was the fact that the catalyst temperature was not dropping quickly during this extended curb idle period. At idle, an ignition retard was used to keep the exhaust temperatures warm at the expense of efficiency.

Average tailpipe ammonia concentration over the first 30-minute curb idle was roughly 77 ppm for the demonstration engine and 10 ppm for the baseline engine, shown in Figure 83. While the ammonia concentration was high during the curb idle, average tailpipe ammonia concentration during the elevated idle was only 43 ppm for the demonstration engine compared to the 247 ppm for the baseline engine.

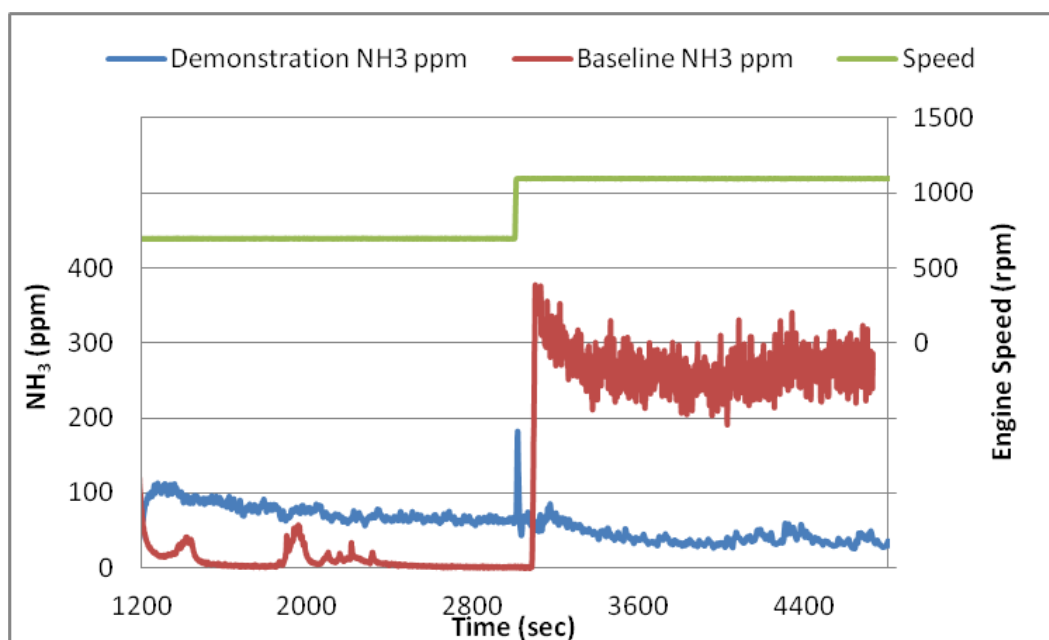


FIGURE 83. CARB IDLE TAILPIPE AMMONIA CONCENTRATION FOR BASELINE AND DEMONSTRATION CUMMINS-WESTPORT ISX12-G

2.3.2.2 Vocational Cycle Demonstration Results

In addition to the primary cycles described above, several additional cycles were desired for use on a demonstration-only basis. These cycles were selected to be more representative of various types of in-field operation, with a particular focus on vocational applications that would be characterized by lower temperatures and/or more transient operation than the primary (certification) cycles that are the program targets. The intent behind these cycles was to examine how well the reduction of emissions to 0.02 g/hp-hr on the certification cycles might translate to operation on other, potentially more challenging duty cycles from the field. The vocational cycles examined during baseline testing included the New York City Bus Cycle (NYBC), the Orange County Transit Authority Bus Cycle (OCTA) and the Cruise-Creep cycle. Further detail on these cycles can be found in Section 2.1.1.2 Additional Cycles.

Each vocational cycle was performed three times³ in a 40 CFR Part 1065 compliant test cell and with CARB Certification natural gas. Tailpipe emissions were measured using a CVS dilution tunnel as well as a Horiba MEXA-7100DEGR raw emissions bench, and tailpipe ammonia was monitored using a Fourier Transform Infrared spectrometer. The engine test cycle was composed of one full NYBC cycle followed by a 30 minute idle and then a second full NYBC cycle. The emissions presented Table 38, below, are for the second full NYBC.

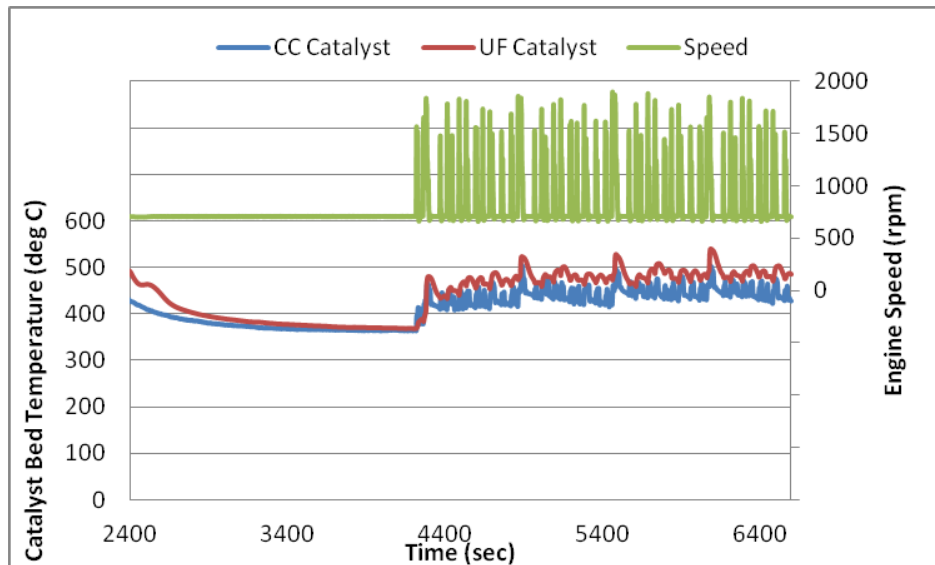
³ NYBC was performed four times.

TABLE 38. DEMONSTRATION TAILPIPE EMISSIONS FOR NYBC

		NO _x	CO	CH ₄	CO ₂	BSFC	PM	NH ₃ Avg.	N ₂ O Avg.
		g/hp-hr				lb/bhp-hr	g/hp-hr	ppm	
Average	Raw	0.001	0.782	0.479	655.6	0.552	0.0021	25.0	0.01
	Dilute	0.002	0.859	0.421	667.1	0.562			
Std. Dev.	Raw	0.002	0.133	0.072	12.967	0.011	0.0002	0.773	0.017
	Dilute	0.002	0.146	0.051	12.986	0.011			
CoV	Raw	200.0%	17.0%	15.1%	2.0%	2.0%	8.0%	3.1%	122.8%
	Dilute	85.7%	17.0%	12.2%	1.9%	1.9%			

The results presented above show that the calibration and hardware necessary for achieving the 0.02 g/hp-hr NO_x emissions on the certification cycles translates to near-zero NO_x emissions on the NYBC. While there was a great improvement in NO_x, CO, and methane emissions, average ammonia concentration was a little more than twice as high as the baseline engine. When comparing the demonstration results to the baseline results it should be noted that only one NYBC was performed for the baseline testing, and four NYBC cycles were performed for the demonstration. Likewise, the baseline engine was unable to pass the drive cycle statistics criteria and minimum/maximum work allowed for the NYBC, whereas, the demonstration engine was able to pass the work criteria.

Catalyst temperatures can be seen in Figure 84, with the 30-minute idle included. During this 30-minute idle the catalyst temperatures drop below 400 °C allowing a drop in NO_x conversion efficiency. However, once the cycle begins the catalyst temperature quickly rises above 400 °C and approaches 500 °C towards the end of the cycle.

**FIGURE 84. DEMONSTRATION CATALYST BED TEMPERATURE DURING NYBC VOCATIONAL CYCLE AND EXTENDED IDLE**

Due to the slight drop in NO_x conversion efficiency with the catalyst falling below 400 °C, there was a very small NO_x spike at the 4250-second mark during the second acceleration. However, the second small NO_x spike halfway through the cycle along with the drop in CO and NH₃ emissions was indicative of the engine's equivalence ratio dropping slightly lean. The engine's closed loop fueling control catches the lean excursion and NO_x emissions fall toward zero shortly afterwards.

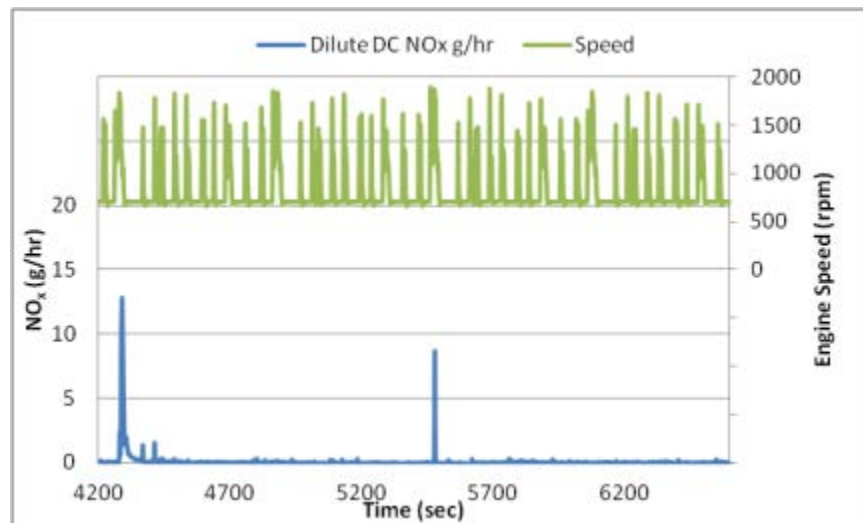


FIGURE 85. DEMONSTRATION DILUTE NO_x MASS RATE EMISSIONS DURING NYBC VOCATIONAL CYCLE

Typical tailpipe ammonia concentration is presented Figure 86 below. While there are large spikes in ammonia these spikes occur during the more aggressive accelerations of the drive cycle, and decrease during the lighter accelerations.

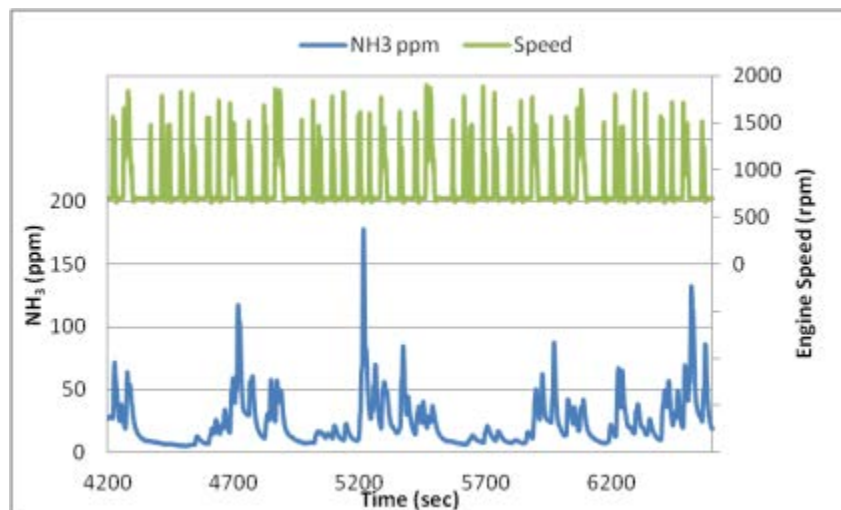


FIGURE 86. DEMONSTRATION TAILPIPE AMMONIA CONCENTRATION DURING NYBC VOCATIONAL CYCLE

CO and methane emissions are presented in Figure 87. While it appears as though CO emissions are high, they are roughly half of the baseline engine and methane emissions are roughly four times lower than the baseline engine calibration. The relatively large spike in methane during the beginning of the cycle was likely due to relatively cool catalyst temperatures and once the temperature rises above 400 °C the methane emissions drop substantially.

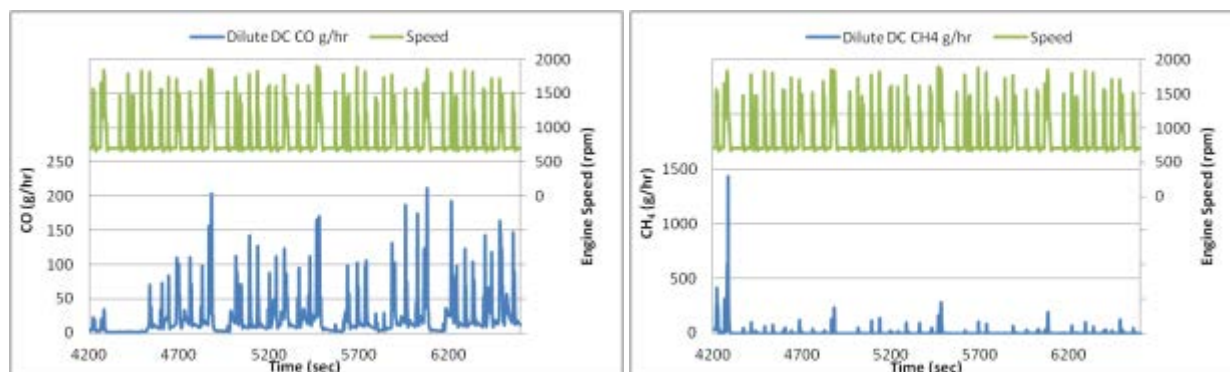


FIGURE 87. DEMONSTRATION DILUTE CO AND METHANE MASS RATE EMISSIONS DURING NYBC VOCATIONAL CYCLE

The second vocational cycle that was tested was the Cruise-Creep cycle. The first portion of the cycle (the “Cruise”) portion was based on vehicle data from a 45 mph average speed trip to a work location and was essentially the conditioning phase. The second portion of the cycle consists of ten repeats of the CARB Creep Cycle which was intended to represent a very light load, transient application (for example a truck working in a freight yard). Table 39 below shows the emissions over just the “Creep” portion of the test cycle. Because the baseline engine’s emissions were sampled and averaged over the full Cruise-Creep cycle the brake specific emissions needed to be adjusted to be averaged over just the “Creep” portion of the test cycle.

TABLE 39. DEMONSTRATION TAILPIPE EMISSIONS FOR CRUISE-CREEP⁴

		NO _x	CO	CH ₄	CO ₂	BSFC	PM	NH ₃ Avg.	N ₂ O Avg.
		g/hp-hr				lb/bhp-hr	g/hp-hr	ppm	
Average	Raw	0.000	2.387	1.000	896.7	0.758	0.0052	85.1	0.03
	Dilute	0.002	2.408	0.973	896.5	0.758			
Std. Dev.	Raw	0.000	1.140	0.170	27.056	0.024	0.0007	11.9	0.03
	Dilute	0.002	1.103	0.189	29.416	0.027			
CoV	Raw	NA	47.7%	17.0%	3.0%	3.2%	13.7%	14.0%	125.9%
	Dilute	89.2%	45.8%	19.5%	3.3%	3.6%			
Baseline Adjusted ⁵	Dilute	0.049	3.312	3.081	952.1	0.784	NA	110.7	0.00

⁴ Emissions averaged over the “creep” mode of the Cruise-Creep cycle.

⁵ Original baseline data averaged over the entire Cruise-Creep cycle. Adjusted baseline data averaged over the “creep” mode of the cycle. BSPM cannot be averaged over just the “creep” portion.

The results presented above show that the calibration and hardware necessary for achieving the 0.02 g/hp-hr NO_x emissions on the certification cycles translates to near-zero NO_x emissions on the Cruise-Creep. The results presented above also show that the new engine calibration and hardware improve air-fuel ratio control due to lower NO_x, CO, methane, and ammonia emissions. However, when comparing the demonstration results to the baseline results it should be noted that only one Cruise-Creep cycle was performed for the baseline testing whereas three sets of Cruise-Creep cycles were performed for the demonstration. Likewise, the baseline engine was unable to pass the drive-cycle statistics criteria and the minimum/maximum work allowed, whereas the demonstration engine was able to pass the work criteria.

Catalyst temperatures over the lightly loaded “Creep” portion of the Cruise-Creep are presented in Figure 88. Temperatures begin near 600 °C coming out of the “Cruise” portion of the cycle and eventually stabilize at 400 to 450 °C by the end of the test cycle. Because the catalyst temperatures are relatively high throughout the cycle, any NO_x breakthroughs that would occur would be due to improper air-fuel ratio control.

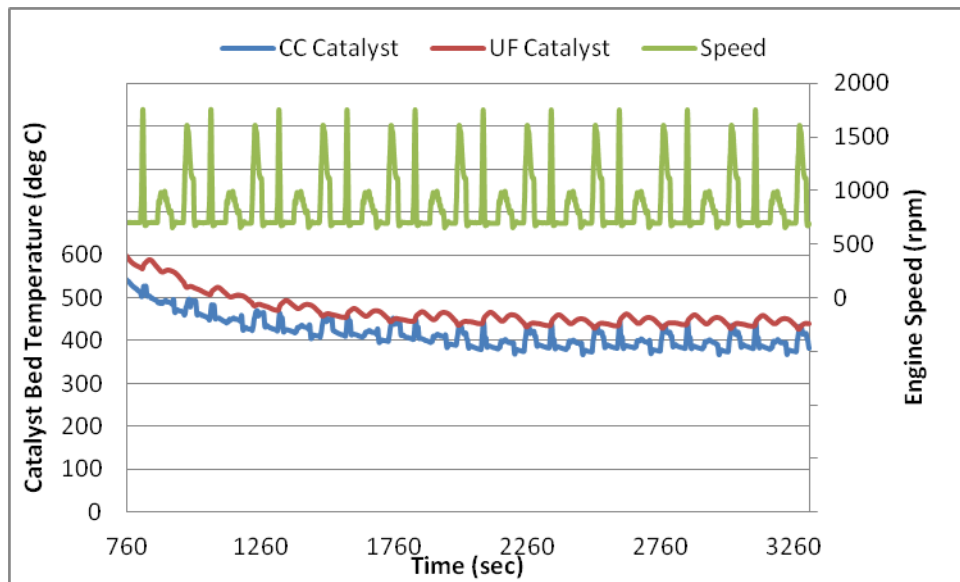


FIGURE 88. DEMONSTRATION CATALYST BED TEMPERATURE DURING “CREEP” MODE OF CRUISE-CREEP VOCATIONAL CYCLE

Typical NO_x mass rate emissions over the “creep” portion of the cycle can be seen in Figure 89.

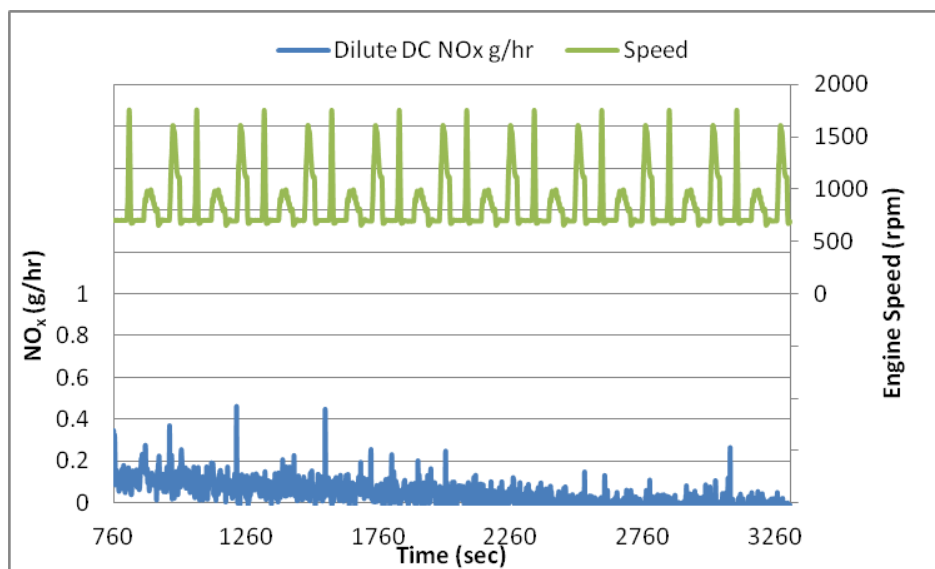


FIGURE 89. DEMONSTRATION DILUTE NO_x MASS RATE EMISSIONS DURING “CREEP” MODE OF CRUISE-CREEP VOCATIONAL CYCLE

Typical tailpipe ammonia concentration can be seen in Figure 90, and typical CO and methane emissions can be seen in Figure 91 below. It was interesting to note that as the creep cycle continues the ammonia and CO emissions begin dropping until they become stabilized towards the end of the cycle (roughly 2700 seconds). The near-zero NO_x emissions coupled with the non-zero CO and NH₃ emissions towards the end of the cycle indicate that the equivalence ratio set point was biased rich.

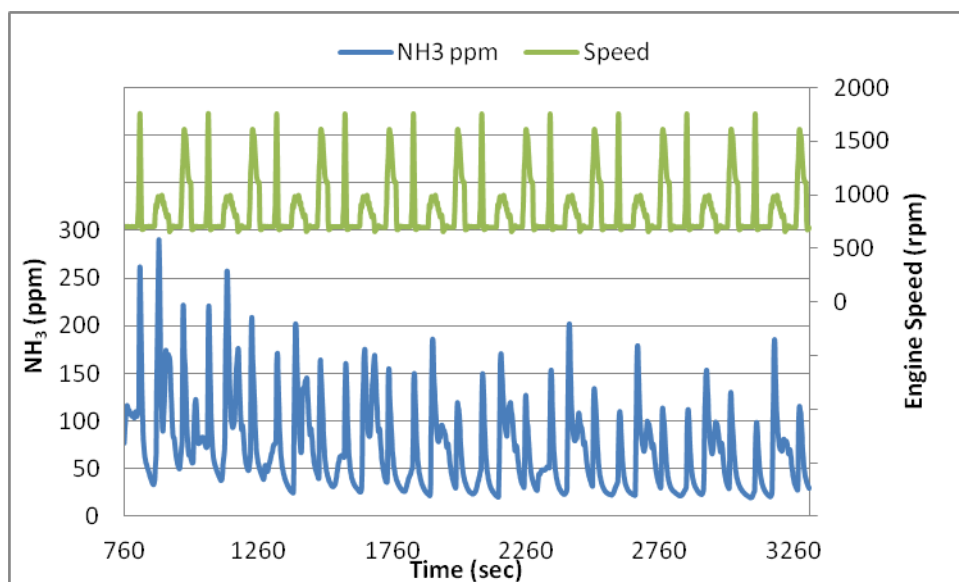


FIGURE 90. DEMONSTRATION TAILPIPE AMMONIA EMISSIONS DURING “CREEP” MODE OF CRUISE-CREEP VOCATIONAL CYCLE

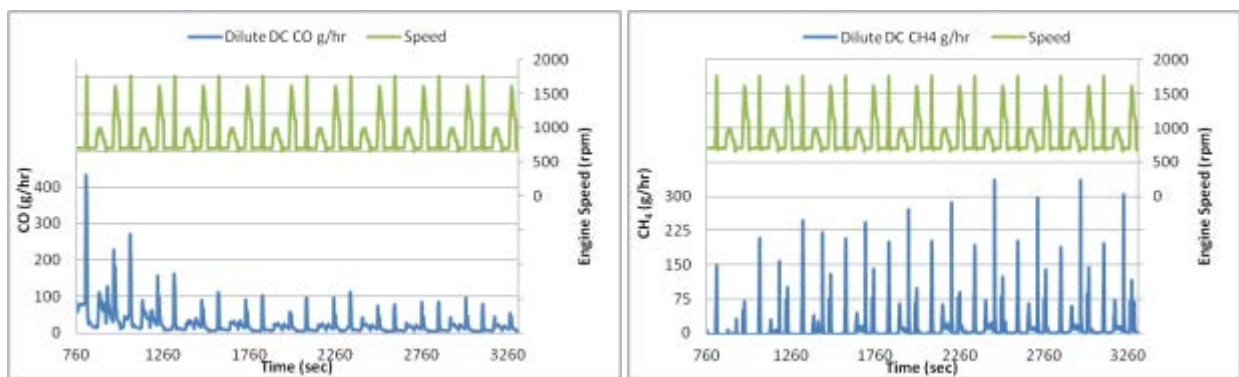


FIGURE 91. DEMONSTRATION DILUTE CO AND METHANE MASS RATE DURING “CREEP” MODE OF CRUISE-CREEP VOCATIONAL CYCLE

The last vocational cycle examined was the OCTA bus cycle. The OCTA bus cycle features transient behavior that was more aggressive than that of the Cruise-Creep vocational cycle, but not as extreme as the NYBC. The engine test cycle was composed of two full OCTA cycles run back-to-back with no idle portion between them with the first OCTA cycle being the pre-conditioning cycle. The emissions presented in Table 40 are for the second full OCTA cycle.

TABLE 40. FINAL DEMONSTRATION TAILPIPE EMISSIONS FOR OCTA

		NO _x	CO	CH ₄	CO ₂	BSFC	PM	NH ₃ Avg.	N ₂ O Avg.
		g/hp-hr				lb/bhp-hr	g/hp-hr	ppm	
Average	Raw	0.000	1.241	0.052	547.8	0.462	0.001	47.3	0.07
	Dilute	0.000	1.256	0.039	552.3	0.465			
Std. Dev.	Raw	0.000	0.008	0.006	1.501	0.001	0.000	1.864	0.038
	Dilute	0.001	0.008	0.005	0.755	0.001			
CoV	Raw	NA	0.7%	10.7%	0.3%	0.3%	39.2%	3.9%	50.7%
	Dilute	173.2%	0.6%	13.0%	0.1%	0.1%			

The results presented above show that the calibration and hardware necessary for achieving the 0.02 g/hp-hr NO_x emissions on the certification cycles translates to near-zero NO_x emissions on the OCTA bus cycle. The results presented above also show that the new engine calibration and hardware improve air-fuel ratio control due to lower NO_x, CO, methane, and ammonia emissions. However, when comparing the demonstration results to the baseline results it should be noted that only one OCTA bus cycle was performed for the baseline testing whereas three sets of Cruise-Creep cycles were performed for the demonstration. Likewise, the baseline engine was unable to pass the drive-cycle statistics criteria and the minimum/maximum work allowed, whereas the demonstration engine was able to pass both the statistics and work criteria.

Catalyst temperatures are shown in Figure 92. Because the second OCTA bus cycle starts immediately after the first OCTA bus cycle catalyst temperatures start high at 500 °C.

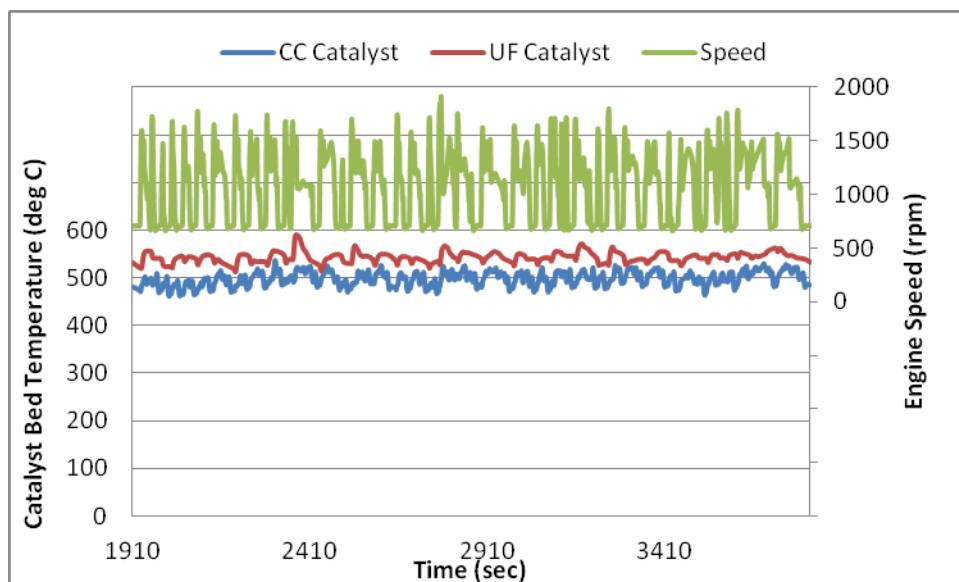


FIGURE 92. DEMONSTRATION CATALYST BED TEMPERATURE DURING OCTA BUS CYCLE

NO_x emissions are near-zero for the entirety of the drive cycle and can be seen in Figure 93. Typical tailpipe ammonia concentration along with CO and methane emissions can be seen in Figure 94 and Figure 95 respectively. The near-zero NO_x emissions along with the non-zero ammonia and CO emissions indicated that the engine's equivalence ratio was biased rich. Methane emissions were near-zero over the OCTA bus cycle due to the high catalyst temperature throughout the full cycle.

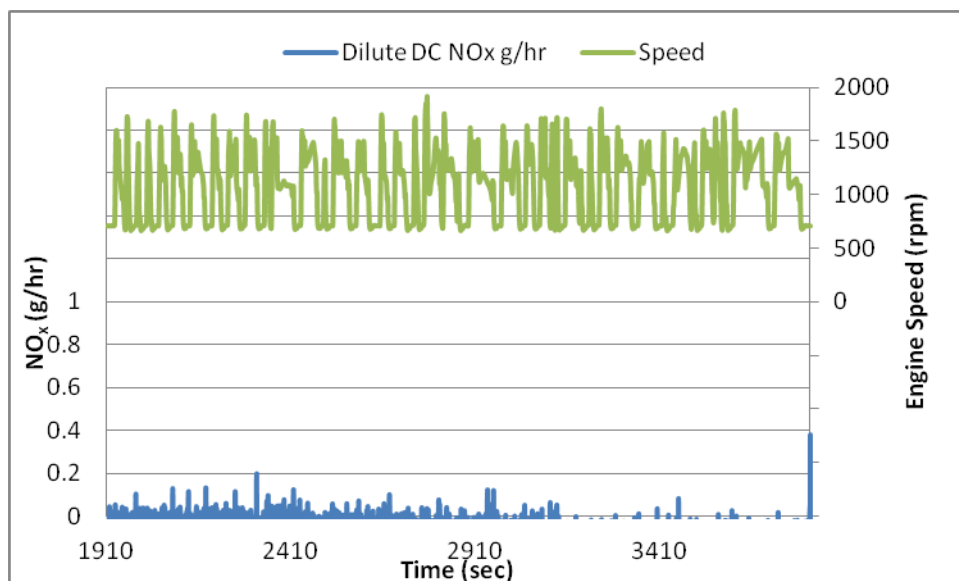


FIGURE 93. DEMONSTRATION DILUTE NO_x MASS RATE EMISSIONS DURING OCTA BUS CYCLE

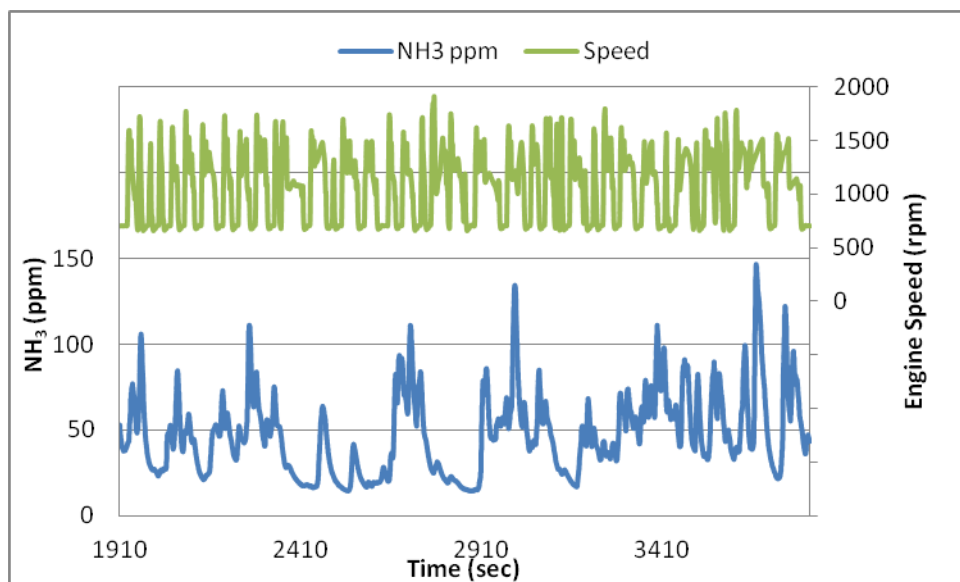


FIGURE 94. DEMONSTRATION TAILPIPE AMMONIA EMISSIONS DURING OCTA BUS CYCLE

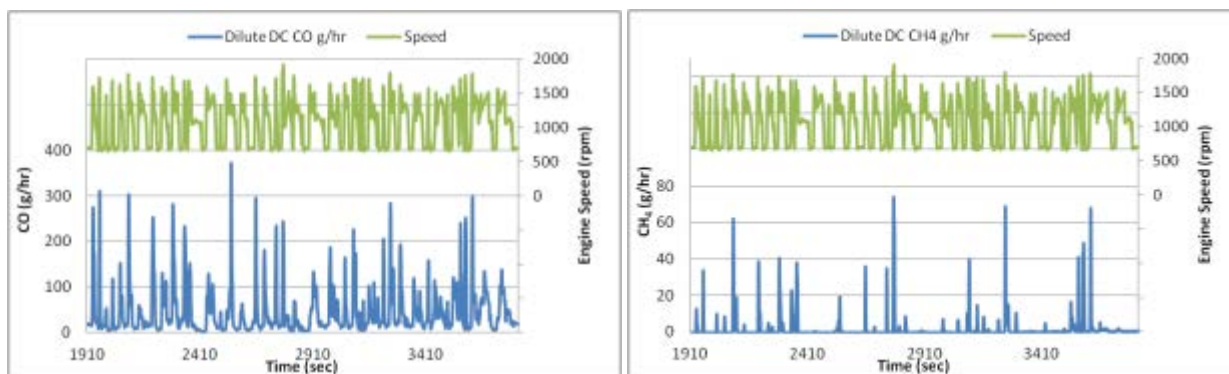


FIGURE 95. DEMONSTRATION DILUTE CO AND METHANE MASS RATE DURING OCTA BUS CYCLE

Table 41 and Figure 96 show an emission summary for the vocational cycles compared to the 2010 US Standards for NO_x, NMHC, CO and PM. The calibration and hardware upgrades that allow the Cummins-Westport ISX-12G engine to meet 0.02 g/hp-hr NO_x emissions over the FTP and RMC-SET allow for near-zero NO_x and zero NMHC emissions over the three vocational cycles.

TABLE 41. FINAL DEMONSTRATION EMISSIONS SUMMARY FOR VOCATIONAL CYCLES

	NO _x	PM _{x100}	NMHC	CO	NH ₃ Avg.
	g/hp-hr				ppm
US 2010 Standard	0.2	1.00	0.14	15.5	--
NYBC	0.002	0.2125	0.000	0.859	25.0
Cruise-Creep	0.002	0.5167	0.000	2.408	85.1
OCTA	0.000	0.0967	0.000	1.256	47.3

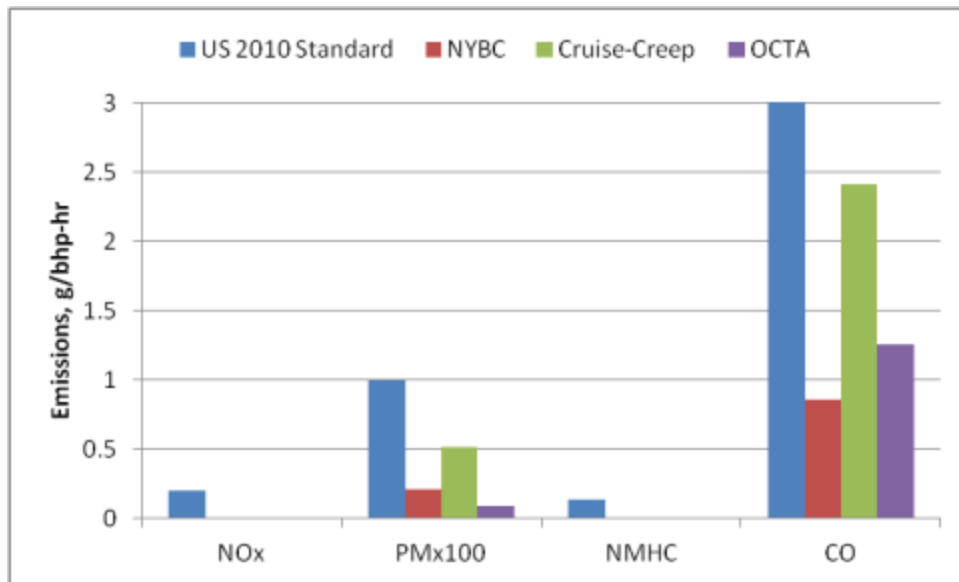


FIGURE 96. FINAL DEMONSTRATION EMISSIONS SUMMARY FOR VOCATIONAL CYCLES PLOTTED WITH US 2010 HDE EMISSIONS STANDARD

3.0 DIESEL PROGRAM

3.1 TASK 1: Test Engine and Aftertreatment Technologies

This section of the report describes the work performed under this Task. Individual efforts included the development and selection of the final test cycles used in the program, finalization and procurement of the test engine, and the selection of the pool of aftertreatment technologies that were considered under the screening efforts in Task 3. Each of these efforts is described separately below.

3.1.1 Test Cycles Selection

3.1.1.1 Primary Cycles

The primary cycles for this program were cycles established as certification procedures, and these primary cycles were used for calibration development and for demonstration of the final system in comparison to the 0.02 g/hp-hr target.

In accordance with the program proposal and with established emission certification procedures, the primary cycle of focus for this effort was the heavy-duty transient Federal Test Procedure (FTP). This cycle served as the primary development screening tool, and was also the primary metric for determining the emission level reached by the final emission system configuration. For this cycle, the development target was to reach a level below 0.02 g/hp-hr on the composite emission value. It was anticipated that reaching the required emission levels on the cold-start portion of the cycle would be representative of the primary technical challenge during this program. Table 42 summarizes projected cold-start and hot-start emission levels that were required to demonstrate the desired composite level. The target emission value was somewhat below 0.02 g/hp-hr, so as to provide some margin for measurement. It should be noted that the intent was to meet this target with an aged aftertreatment system. Therefore, the development targets for a fresh system were somewhat lower, to provide an aging margin.

**TABLE 42. INITIAL DEVELOPMENT TARGETS FOR DIESEL AGED
AFTERTREATMENT SYSTEM**

	Initial Target, g/hp-hr
Cold-FTP (1/7 th of composite)	0.06
Hot-FTP (6/7 th of composite)	0.009
Composite FTP	0.016

In addition to the cycles requested by ARB in the initial RFP, SwRI also determined that it would be necessary to demonstrate emission levels less than 0.02 g/hp-hr on the steady-state RMC-SET cycle. This was because the RMC-SET cycle was the primary cycle used to demonstrate compliance with GHG emission regulations for tractor engines. Given that this application was a key target for the heavy-duty engines evaluated in this program, an assessment of GHG emissions over the RMC-SET was critical for determining the impact of the final

system. The assessment would not be meaningful if the system did not also meet the 0.02 g/hp-hr level on the cycle, and therefore this cycle was added as a target to the program.

A secondary target cycle for this program is the World Harmonized Heavy-Duty Transient Cycle (WHTC), which was one of the primary tools used for emission certification in Europe. This cycle was requested by ARB as well, and it was chosen to represent a cycle in which the exhaust temperature remained at a lower average level than the FTP for a longer period. The desire was to demonstrate an emission level below 0.02 g/hp-hr for the WHTC as well. The WHTC includes a cold-start and hot-start phase, similar to the FTP, and it uses similar weighting factors to develop a composite number (i.e., 16% cold and 84% hot). Figure 97 shows a comparison of cold-start exhaust temperatures for the FTP versus the WHTC cycles. As can be seen in the chart, in the early portions of the cold-start (prior to 400 seconds), the engine stays below 150°C for a longer period. However, it should be noted that the WHTC duration was 1800 seconds, as compared to 1200 seconds for the FTP. The WHTC reached higher temperatures by the end of the cycle, prior to the ensuing hot-start cycle. In addition, the WHTC used only a 10-minute engine-off soak, as opposed to the 20-minute engine-off soak used for the FTP.

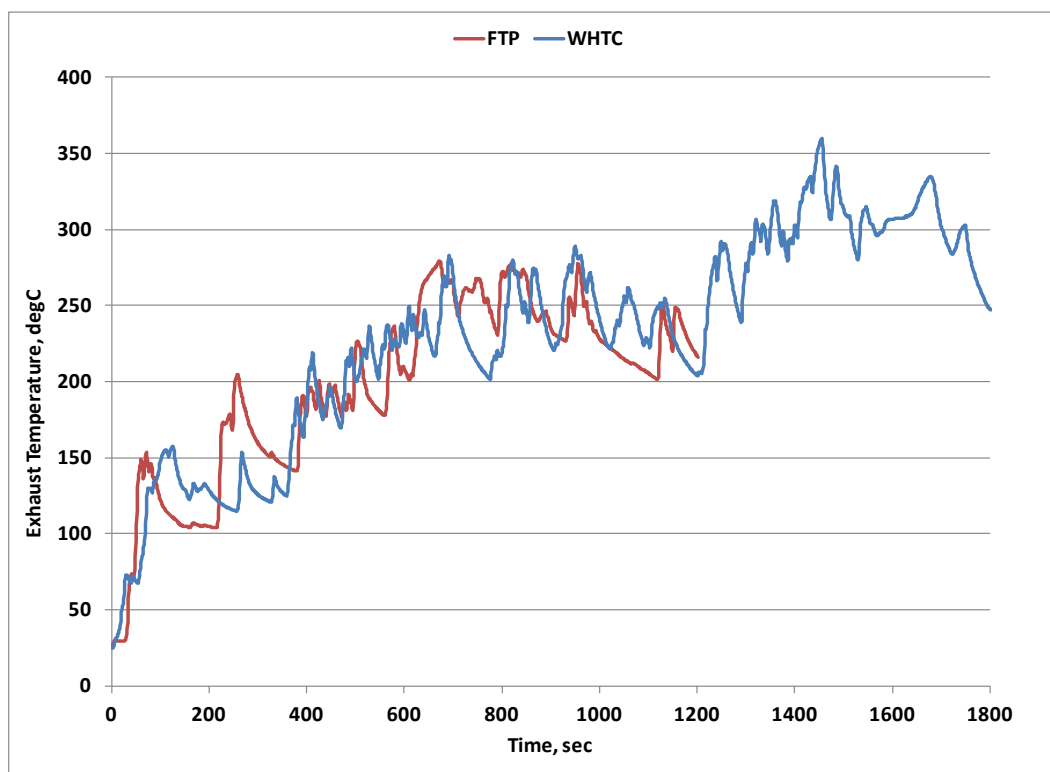


FIGURE 97. COLD-START EXHAUST TEMPERATURE COMPARISON FOR WHTC VS. FTP - PROGRAM ENGINE

Another secondary target cycle for this program was the California ARB Idle Test. This is a California-specific test designed to ensure a level of NO_x control during a sustained idle period. It consists of an FTP cycle warm-up, followed by two 30-minute idle periods. The first idle period was at a designated low idle speed (i.e., “curb idle), while the second 30-minute

period was at an elevated idle (no-load) speed of 1200 rpm. The current limit for this cycle is 30 g/hr average NO_x rate, integrated separately of each of the two 30-minute idle periods. While this was a cycle of interest, no specific limit was proposed as a target for the program. Therefore, the intent under the program was to examine the performance of the system, which was calibrated for the FTP and WHTC cycles on this ARB Idle cycle. It was anticipated that significantly lower levels would be observed than what was measured for the baseline engine on the idle test.

3.1.1.2 Additional Cycles

The diesel engine program used the same additional Vocational cycles that were used on the CNG engine. These cycles were the NYBC, Cruise-Creep, and OCTA Bus cycles. The details of these cycles were already described earlier in Section 2.1.1.2, and therefore the information will not be repeated here.

As noted earlier, these vocational cycles are intended for demonstration purposes only. There was no effort made to calibrate the performance of the emission system to improve performance on these cycles. Rather, the systems were taken as calibrated for the primary cycles, and the vocational cycles were run to demonstrate performance. This allowed comparison of the performance on these duty cycles with performance on the certification cycles.

The vocational cycles were also run as part of the baseline data generation for each engine, which allow for an initial comparison on current technology engines between certification cycles and these different field duty cycles.

A second-by-second schedule for each cycle is included in this report in Appendix A, in a normalized format. These cycles are meant to be de-normalized following the same process used for the FTP transient cycle, as described in 40 CFR Part 1065. In the case of the diesel engine, the idle points were run using the standard approach for a manual transmission tractor engine, which mean a target torque of zero at idle points.

3.1.2 40 CFR 1065 Compliance and Preconditioning Procedures

Characterization of the stock engine and final demonstration testing were conducted in transient capable test cells at SwRI that were fully compliant with the requirements outlined in 40 CFR Part 1065 for heavy-duty engine testing. SwRI maintains ten 1065-capable transient test cells equipped with full flow CVS dilution tunnels, including several cells, which are natural gas engine capable. When each engine was available for baseline characterization, SwRI would select an appropriate cell from among this pool of test cells to perform the stock engine characterization work.

SwRI is actively involved in numerous programs involving 1065 compliant emission measurements for both commercial and government clients. SwRI remains involved in the development and refinement of 1065 procedures as a participant on the Emission Measurement and Testing Committee (EMTC). SwRI has also performed confirmatory testing requiring 1065 compliance procedures on certified engines under contract to the U.S. EPA.

With regard to preconditioning procedures, SwRI recognizes that the performance of some of the aftertreatment technologies that were utilized in this program is sensitive to the near-term operational history prior to running of a test to document emissions for record. As a result, SwRI applied appropriate pre-conditioning procedures in order to improve the repeatability of the tests conducted to document emission performance during this program.

In 2014, SwRI completed a study of the effect of preconditioning procedures, conducted on behalf of the EMTC, and funded by the Truck and Engine Manufacturer's Association (EMA) [6]. Recommendations from this study were incorporated in draft modifications to 40 CFR Part 1065 that will be proposed in an upcoming notice of proposed rulemaking (NPRM). SwRI incorporated procedures consistent with those recommendations in this low demonstration program for CARB. Since that time, the preconditioning procedures have been finalized in 40 CFR Part 1065, and SwRI utilized the same approach in this program.

In addition, unless an experiment was specifically looking to measure the effects of active DPF regeneration on emissions, SwRI controlled the timing of active DPF regeneration so that it did not occur during test cycles, as was permitted under current draft 1065 procedures. Specific procedures were developed for the test engine as part of this baseline characterization task.

The final preconditioning approach used for this study was identical to what is currently outlined in 40 CFR Part 1065. For the FTP cycle, two successive preconditioning hot-start FTP cycles were run, with a 20-minute soak between them. After this preconditioning run, the engine was placed in cold soak overnight. This procedure was used for both baseline testing and for final demonstration tests. For the RMC-SET, a full RMC-SET cycle is run as a preconditioning, followed by the test for record, with no more than a 60-second dwell (at idle) between cycles. The ideal case for the RMC-SET is to run the preconditioning cycle and the test for record in a "head-to-tail" fashion, with no dwell between cycles. For the current program, RMC-SET tests were run with no dwell between the preconditioning cycle and the test for record.

It should be noted that considerable effort was expended to develop a dosing controller that would be able to reach stability within the framework of the standard preconditioning outlined for 40 CFR Part 1065. It was felt that this was important in order for the program results to be representative.

3.1.3 Test Engine

As part of the proposal submitted by SwRI in response to the initial RFP for this program, SwRI had secured the cooperation of Volvo as a partner for the diesel engine portion of the project. The initial plan within the proposal was to utilize a 2011 Volvo MD13 engine. SwRI already had an example of such an engine on-site, which had been utilized in a previous program (Phase 1 of the Advanced Collaborative Emissions Study or ACES program).

While this engine met the initial RFP requirement of being representative of a 2012 model year heavy-duty tractor engine, SwRI had several additional discussions with Volvo regarding the technology and options available for modifying the 2011 MD13 VGT engine. It

was agreed that a more up to date platform would be beneficial to the program in terms of providing additional flexibility in modifying the engine. In particular, the flexibility of the high-pressure common rail fuel injection system was considered important for the program. At the time of these discussions in late 2013, the most advanced production engine platforms Volvo had available were all targeted at the European (Euro VI) market. Volvo suggested the 2014 MD13TC engine as a better platform for the program. Initial test data from Volvo indicated that although the engine was technically certified for the Euro VI market, it would meet the U.S. emissions standards with regard to levels, and therefore should be representative from a baseline standpoint.

This suggestion from Volvo was based on two points. The first point was the additional development flexibility, which was a feature that had been requested by SwRI in support of the program. The MD13TC engine utilized cooled EGR, which was typical of a U.S. engine, and also incorporated a high pressure common rail fuel injection system with the capability to support multiple pilot and post injection events. It also had an intake throttle and an exhaust backpressure valve, and did incorporate in-exhaust hydrocarbon injection to support DPF regeneration, and potentially thermal management for this program as well. The previously planned 2011 MD13 engine utilized a less flexible electronic unit injection fuel system, as well as not incorporating any throttles.

The second point for the suggestion of the MD13TC engine was with regard to greenhouse gas emissions. Part of the ARB program target was to meet the NO_x target in “a manner consistent with the path towards meeting future GHG emission standards.” At the time of the initial discussions in 2013, EPA’s Phase I GHG standards were phasing in, and the Phase II targets were still being discussed at a high level, without any targets being set. Volvo indicated that the 2014 MD13TC engine was consistent with their plans at the time regarding meeting GHG regulations moving forward. Volvo indicated that the 2011 MD13 engine would not be very representative of any engine meeting even near term Phase I GHG targets. One indication of this was in the engine-out NO_x level, with the 2011 MD13 engine having engine-out NO_x at roughly 1.5 to 2 g/hp-hr. In contrast, the 2014 MD13TC engine was at an engine-out NO_x level of a little over 3 g/hp-hr, which was much more representative of current product meeting later stage Phase I standards. Therefore, it was suggested that the 2014 MD13TC engine would be a more representative test article than the 2011 MD13. Volvo indicated that plans at the time were to bring this engine technology to the U.S. towards the end of the Phase I GHG timeline.

One significant complicating factor with the choice of the MD13TC engine was that it uses a mechanical turbo-compound technology in the form of a second exhaust turbine to recover exhaust energy and transfer that energy directly to the crankshaft. This technology resulted in improved fuel economy; however, it also results in a significant drop in exhaust temperature as compared to a conventional turbocharger setup without the turbo-compound. Figure 98 shows a comparison of exhaust temperatures between the 2011 MD13 engine and the 2014 MD13TC engine over a cold-start FTP.

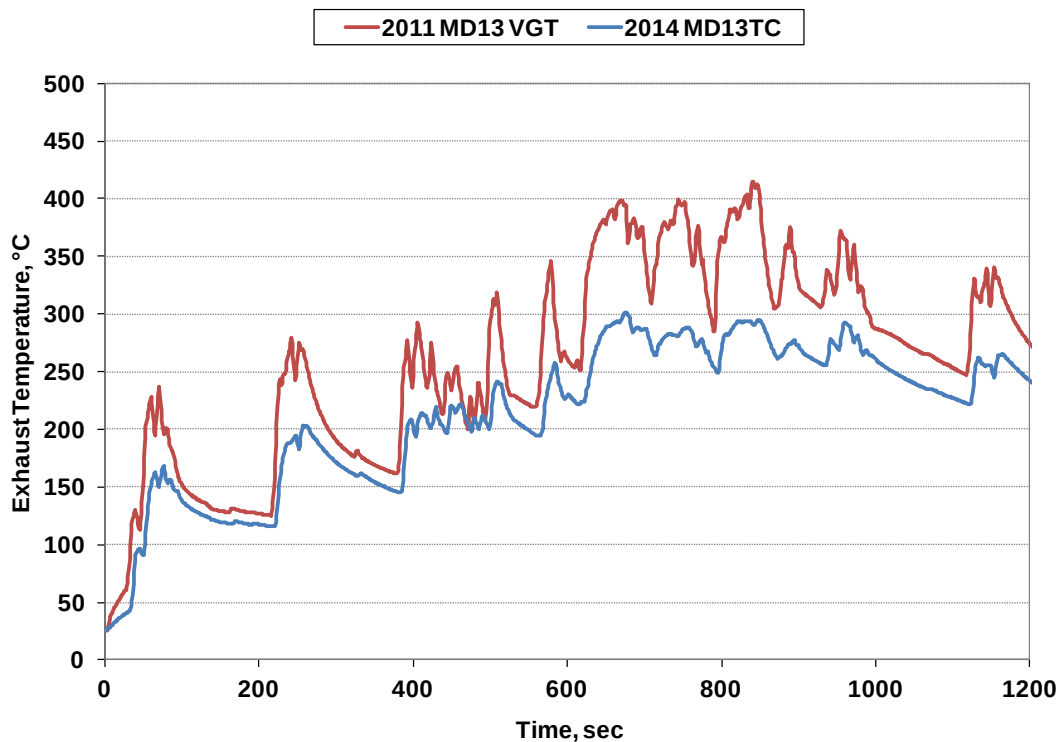


FIGURE 98. COLD-START FTP EXHAUST TEMPERATURE COMPARISON FOR VOLVO ENGINES

As can be seen in the chart, the exhaust temperature for the MD13TC engine is roughly 50 - 60 °C lower in the critical early phases of the FTP cycle. It was understood that this would present a significantly greater challenge for the aftertreatment system in reaching a 0.02 g/hp-hr target, likely requiring more energy input to reach the target. At the same time however, the fuel consumption and NO_x characteristics of the 2011 engine were such that the final overall system configuration might not be representative of a path towards future GHG emissions. Therefore, that engine might require considerable modification and calibration effort, which was not within the scope or available budget for the program.

Despite the challenge posed by the lower exhaust temperature, it was decided that the 2014 MD13TC engine would be a better overall choice for the program than the 2011 MD13 engine. It was felt that as part of the technology screening effort in Task 3, it would be possible to examine the relative level of complexity caused by the inclusion of the turbo-compound technology. The engine was new to production at that time, and due to several production delays, the MD13TC engine was ultimately delivered to SwRI in May of 2014 for initial installation and baseline testing, following initial checkouts at Volvo. Volvo also provided support with interface to the engine, and supported SwRI with calibration tools and access to allow for full authority control of the engine software. This allowed the flexibility to make any modifications necessary to the calibration, as well as to assume direct control of various actuators as needed to meet the program goals.

From the current vantage point at the end of the program in 2017, it is now apparent that this engine likely represents more of a “corner case” with regard to possible approaches to GHG emissions. Volvo has released a turbocompound version of this engine into U.S. production in 2017 for some applications, however much of the industry does not employ this technology. As such, the Volvo MD13TC engine likely represents closer of a “worst-case” platform with respect to exhaust temperature. In addition, the mechanical system is tightly integrated to the engine, and no means to bypass or modify the system was available in within the timeframe or scope of the program. Nevertheless, it is believed that this engine remains useful as a for demonstrating a worst-case level of effort that might be required to reach 0.02 g/hp-hr on a very challenging platform.

The 2014 Volvo MD13TC engine is shown in Figure 99. The engine was designed for use in a Class 8 Line Haul Tractor application. It has a nominal maximum power of 361 kW at 1477 rpm, a nominal peak torque of 3050 Nm at 1000 rpm. It should be noted that these speeds are somewhat lower than what was representative of U.S. Class 8 Tractor engines at the time. However, it was also understood that this kind of “downspeeding” was part of the strategy of many OEMs moving forward towards future GHG standards. Therefore, the engine was much more representative of current and near-term GHG technology.



FIGURE 99. 2014 VOLVO MD13TC ENGINE

It should be noted that the baseline engine incorporated a copper zeolite based SCR system, which was built into a “one-box” style aftertreatment system, wherein all of the catalysts are incorporated into a single, muffler-style assembly. This arrangement is very common in Euro VI applications, although there is no requirement to maintain such a design in this program.

For baseline testing, the aftertreatment was installed in a location representative of an actual on-highway truck application, using a transfer pipe that was fabricated by SwRI based on designs from Volvo. The SCR system incorporated an air-assisted urea dosing system, and it was planned to retain this production system due to superior atomization characteristics, which would aid in droplet evaporation and mixing at low temperatures.

3.1.4 Proposed Aftertreatment Technologies

As part of the initial proposal process for this program, SwRI secured the involvement of the Manufacturers of Emission Controls Association (MECA) as a partner in this program. As part of this commitment, MECA member companies agreed to supply advanced aftertreatment technologies for this program as an in-kind contribution. In addition, MECA as a whole agreed to participate by providing additional funding for technology screening, as well as for aging to be conducted later in the program.

For the majority of the aftertreatment system components, MECA members organized into technology teams, each of which was led by one of the major catalyst suppliers. Each team was responsible for specifying a range of technologies that would be supplied to the program. The catalyst supplier would also coordinate the substrate supply, canning, and development aging. SwRI supplied MECA members the data for the Volvo MD13TC engine to aid in the design of the systems. Each supplier put together an initial system design and strategy, including several suggested modifications to the system to try different technology approaches. It should be noted that while these teams were to be initially evaluated separately from each other, the final system configuration could incorporate elements from multiple teams, at the discretion of SwRI and ARB.

Throughout the program, the identity of the individual system suppliers was kept confidential, and the groups were referred to only by a generic Team letter designation that was assigned by SwRI as hardware arrived. SwRI was aware of the identity of the suppliers, and worked closely with all of the suppliers to aid in the design process. It was planned that this working relationship would continue throughout the program, with SwRI sharing data from technology screening with each supplier for their system hardware.

In addition to the primary teams, other individual MECA members provided aftertreatment technology in the form of system modifiers, energy input devices, sensors, and other technologies. SwRI coordinated with all of the suppliers to obtain a large pool of potential aftertreatment technologies.

The intent of this effort was to start with a large pool of possible approaches to reaching the 0.02 g/hp-hr target. This would allow the rapid screening of multiple approaches, with the goal of identifying not only a path to reaching 0.02 g/hp-hr, but also of selecting an approach that was the most advantageous in terms of impact on GHG emissions. In addition, considerations of system complexity, robustness, and packaging were all to be taken into account in the down-selection of the final configuration at the end of the technology screening phase of the program.

For the catalyst systems, suppliers were asked to provide four sets of samples. Two sets were provided to support the screening effort, one degreened and the other aged. Details of the aging process are discussed later in the report. A third set of parts was held in reserve for final aging in the event that those catalysts were down-selected for the final configuration. A fourth set of parts was available as a spare.

Following is a brief description of the technologies chosen to participate in the screening, as well as some of the considerations related to those technologies.

3.1.4.1 General Description of Systems

The aftertreatment systems were split into two broad categories, with a number of modifications possible to each of them. The first category was termed “Traditional” systems, and was designated to indicate system approaches that employed a conventional DPF (typically coated with a small amount of precious metal to aid in passive regeneration). The second category was termed “Advanced” systems, and indicated systems which were based around the use of an SCR-on-Filter approach, wherein an SCR catalyst is applied to the DPF. A basic schematic of each such system is given in Figure 100.

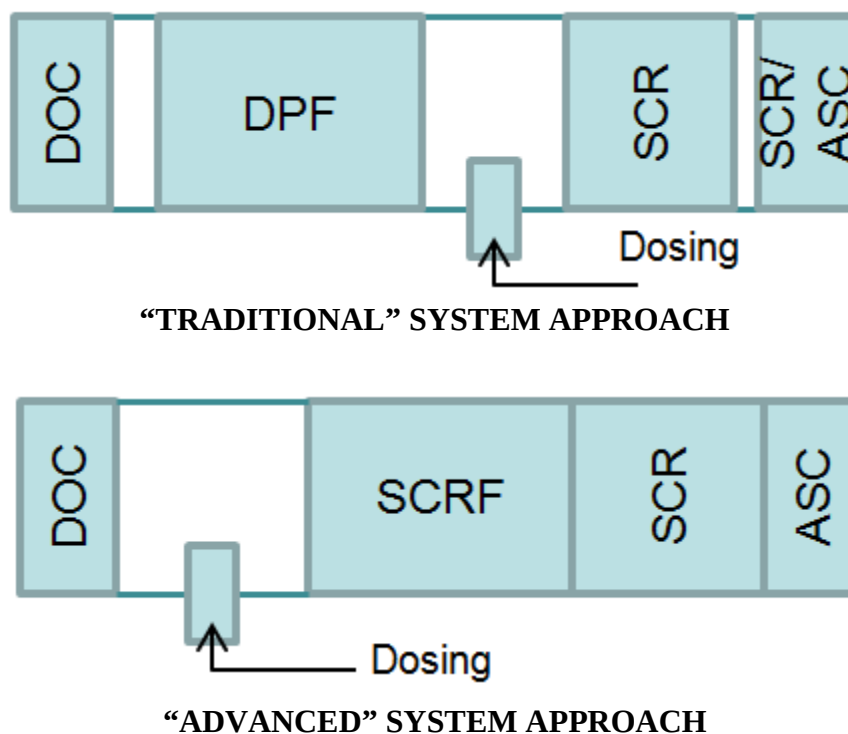


FIGURE 100. SCHEMATIC OF TWO SYSTEM CATEGORIES

The primary advantage of the “Traditional” system approach is the preservation of passive regeneration of the DPF at present levels, which would be a GHG advantage under most

normal system operation. However, the drawback to this approach was the large thermal mass of the DPF system upstream of the SCR, which delays the onset of dosing and catalyst light-off. Therefore, this approach would require significant energy input during cold-start in order to reach light-off early enough to reach the 0.02 g/hp-hr target. This energy input would be a GHG disadvantage. Several system modifiers could be applied to the “Traditional” approach to lower this barrier, such as heated dosing, low thermal mass substrates, and electrical heating, to name a few.

The primary advantage of the “Advanced” system approach was that with some SCR catalyst already on the DPF surface, the thermal mass of the filter was no longer a barrier to light-off. Therefore, less thermal energy input was needed to reach high efficiency quickly, which was a GHG advantage. However, the presence of SCR catalyst on the filter can have a detrimental effect on passive regeneration of soot accumulated on the filter. As a result, more frequent active regeneration events would be required in normal operation, which would be a GHG disadvantage. A number of different modifiers could also be applied to this system as well, again included heated dosing, multi-point dosing (which could help mitigate some of the regeneration issues), and other changes.

Other system options were also considered, such as placing the SCR catalyst upstream of the filter, which is typical of a light-duty approach. However, given the longer durability requirements of the heavy-duty application, as well as the resulting requirement for very frequent active regeneration events, this option was generally not considered as viable for this program. Although such a penalty could be mitigated by the use of multiple point dosing and an additional SCR catalyst downstream of the DPF, that approach was considered too complicated to be practical, in comparison to the SCRF-based approaches.

Some practical considerations were also considered in the initial system designs, such as packaging. While it might be advantageous to close couple the entire aftertreatment system to the engine with minimal distance, the requisite aftertreatment size for the heavy-duty application meant that such an approach would not be practical from a packaging standpoint. Therefore, any close-coupled components, if used, would have to be relatively compact.

A brief, conceptual description of the major technologies selected for screening in the program, and some of the issues related to them is given below on an individual basis. More detail is given in Section 3.3 TASK 3: Aftertreatment Technology Screening, on individual technologies. The focus of these descriptions is on NO_x control. Some form of DPF and DOC technology was assumed in all of these approaches.

A key point for all of the technologies offered was that they are all taken from either production or production intent hardware. In some cases, systems may have been developed to the point of commercialization and field trials, but may not have yet entered actual production due to changes in market demand. Therefore, all of the technologies considered in this program were at least feasible for production.

3.1.4.2 Catalyst Technologies

Selective Catalytic Reduction (SCR)

Ammonia-based SCR was still the primary de-NO_x technology used in this program. No other high efficiency technology was viable for the heavy-duty application from the standpoint of performance, cost, and durability. The other technologies applied in this program are generally all geared around either making the SCR work better or faster, or on controlling NO_x for a short period of time until the SCR has reached light off temperature.

Traditional NO_x adsorber technology, requiring periodic rich operation was not considered viable for this program due to known issues of cost, durability (primarily related to de-sulfation), complexity (due to rich operation), and GHG penalty.

All of the SCR technologies examined in this program were generally based around copper zeolite technology. Proprietary details of the formulation of the various catalysts in this program are not available for reasons of confidentiality. A variety of different options within that broad category were provided by the three different teams of MECA members.

SCR-on-Filter (SCRF)

While this technology was fundamentally similar to the other SCR technologies examined in this program, it differs in the application of the SCR catalyst directly to a diesel particulate filter substrate. This requires a number of modifications to the choice of substrate and washcoat in order to be successful. As discussed above, the advantage to this technology was more rapid SCR light-off because of not being downstream of the thermal mass of a DPF. There are also packaging advantages to this approach. These advantages can provide a GHG benefit compared to DPF-based systems.

The largest drawback of this technology was that the SCR reactions compete for NO₂ with the reactions for passive soot regeneration on the filter. Some of the formulation changes required for SCRF also can make passive regeneration less efficient. This must be compensated by more frequent active regenerations, which can be detrimental to GHG emissions. It was also possible that there may be durability implications related to the accumulation of ash in the filter, which may ultimately require ash cleaning to mitigate. While durability was an important consideration for this program, questions of ash cleaning methodology were outside the scope of this program.

The MECA suppliers provided several different examples of SCRF technology, and it was likely to be a key technology in many approaches to reaching 0.02 g/hp-hr NO_x levels.

Passive NO_x Adsorbers (PNA)

These technologies are a different approach to NO_x adsorber technology than the traditional NO_x adsorber catalysts, which require periodic rich operation in order to regenerate. In contrast, in a PNA, NO_x adsorption and desorption are based entirely on temperature. These devices can typically adsorb NO_x at very low temperatures, and many begin to release NO_x at moderate exhaust temperatures. Ideally, the release point would be above 200 °C where DEF dosing becomes much easier, but practically it was often lower than that. Additionally, a practically sized PNA often has a very limited storage capacity.

The primary purpose of a PNA was to hold on to a small amount of NO_x from the early portion of the cold-start, just long enough for the SCR to reach operating temperature, so that the NO_x can be reduced. Any NO_x released earlier was emitted. In some cases, the PNA may also perform the functions of a DOC at higher temperatures.

Some PNA technologies can be sensitive to sulfur, and may require periodic desulfation, although it may be possible to perform PNA desulfation during active DPF regeneration events. The MECA suppliers for this program offered multiple PNA technologies.

Ammonia Slip Catalysts (ASC)

Some form of ASC was a requirement for this program, for reasons similar to those which often require its use in current systems. This program will require a control strategy that maximizes the coverage of ammonia on the SCR catalyst surface(s), and such a strategy would result in unacceptable levels of ammonia slip without some additional controls. Therefore an ASC technology was provided by each of the MECA teams, each with a different approach to the ASC. Careful ASC design was required to maximize ammonia reduction, while at the same time avoiding the generation of N₂O, or the oxidation of that ammonia back into NO_x.

3.1.4.3 Dosing Technologies

The primary diesel exhaust fluid (DEF) dosing system used was provided with the engine as part of the baseline aftertreatment system. This dosing system was an air-assist approach, which provides for very good atomization characteristics that will help with evaporation and mixing at lower temperatures. However, MECA members have supplied a number of potential modifications to the dosing system.

Heated Dosing

In a heated dosing approach, an electrical heater was used to allow DEF to be used at a lower temperature than normal. In conventional systems, DEF dosing was typically limited to a minimum temperature of 180 °C, due to issue with evaporation and mixing below that. In some applications, limited dosing begins at temperatures as low as 165 °C, but this was only for a very short period of time. At such low temperatures, issues of deposit formation can also be very problematic.

Heated dosing allows for the introduction of DEF at lower temperature by using the heater, often in conjunction with another substrate, to provide a hot surface to allow for evaporation and thermal dissociation of urea while the bulk exhaust temperature was still too low. Sometimes this was also combined with a hydrolysis catalyst to further aid in the release of ammonia. In practical terms, this can lower the exhaust temperature require for DEF introduction to temperatures in the range of 130 °C. While the SCR catalyst may not necessarily be at peak efficiency yet at such lower temperatures, the lower temperature introduction of ammonia is still beneficial to system light-off.

Two approaches to heated dosing were supplied for the program. One approach was a full-flow approach, wherein the heater and system are installed in the full exhaust in line with other system components, as shown in Figure 101. A second approach was a partial-flow approach, where a small amount of exhaust was diverted to an off-line assembly, which incorporates the heating systems. The resulting ammonia laden gases are then re-introduced into the main exhaust stream upstream of the SCR. While the partial-flow approach was a bit more complex, it also offers the advantage of being able to direct the ammonia-laden gas to multiple locations relatively easily, which could aid in overall system efficiency. Both options were examined.

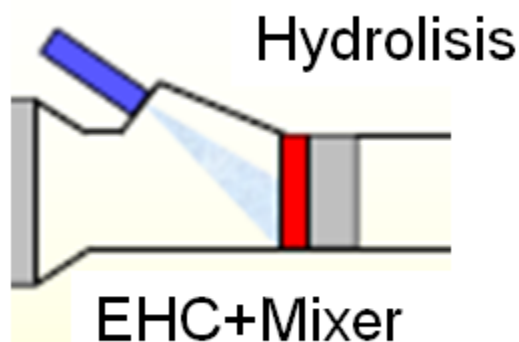


FIGURE 101. SCHEMATIC OF FULL-FLOW HEATED DOSING CONCEPT

Heated dosing requires additional power for the heater, although this requirement was generally two kilowatts or less. However, they have the advantage that they still utilize DEF, which allows continued use of the existing distribution infrastructure and dosing hardware.

Gaseous Ammonia

Another approach to lower temperature introduction of ammonia was to utilize direct ammonia injection. In the practical form of this system, ammonia is typically chemically stored in a solid form, and then the storage system is heated to release ammonia gas under pressure, which is then directed to the exhaust. The storage canisters would have to be periodically recharged. A gaseous ammonia system of this type was supplied by a MECA member as part of the program.

Direct ammonia injection allows lower temperature dosing by removing the issues of DEF evaporation, and the gaseous mixing was much easier than mixing and evaporation of DEF. In addition, hydrolysis was not needed to release ammonia. Gaseous ammonia can be introduced at very low temperatures, but from a practical sense, introduction below roughly 130 °C was not very beneficial, and could cause problems. In addition, it was relatively straightforward to direct the gas to multiple locations, which can help increase overall system efficiency. A small amount of heat was used to start the system, but the electrical power requirements are relatively small in this case.

Given that such a system typically uses a storage medium that is not based on DEF, the existing distribution infrastructure was not useable, and therefore a separate infrastructure would have to be created. This was not insurmountable, but it was a consideration from the standpoint of system complexity when down-selections were made. One possible approach to this was to utilize gaseous ammonia only during cold-start, and to use DEF once temperatures are sufficient (in the range of 180 °C and above). This helped mitigate infrastructure concerns and allowed recharge to potentially be a service item along the lines of an oil change. However, such an approach also increased overall system cost and complexity.

3.1.4.4 Heat Addition

Several approaches were possible for the addition of heat into the exhaust to accelerate catalyst light-off during cold-start, and different catalyst technology approaches required differing levels of heat input. Several methods of heat addition were already available from the baseline engine system, including engine re-calibration, or the use of hydrocarbon (HC) oxidation over a DOC to generate heat. HC can be introduced either via post-injection events, or through the use of the auxiliary HC injector (AHI) system which was supplied with the engine.

In addition to those methods, MECA members supplied two other approaches to heat addition. These include electrical heating and chemical heating via a burner.

Electrical Heating

Electrical heat addition is a technology that has been in existence for some time, although its use is not common in production for many mobile sources. Different approaches were supplied by MECA members, including both a heating element and an electrically heated catalyst (EHC), as depicted below in Figure 102. It should be noted that these systems are distinct from the heated dosing systems described earlier, because they are designed for direct heating of the bulk exhaust gas in order to increase catalyst temperature. Because of this, they tend to be larger systems requiring more power. Electrical heating systems benefit from flexibility, being able to generate heat nearly from key-on. In addition, they can be located near the components that require heat, allow for selective heating of only the desired components (such as an SCR downstream of a DPF). However, they are not as efficient in terms of energy usage as other approaches.



FIGURE 102. ELECTRICALLY HEATED CATALYST

To properly account for the GHG impact of these devices, the power consumption of any such system that was used had to be measured during testing. This power consumption was adjusted to practical alternator efficiency in order to predict the engine power requirement, and therefore fuel consumption, required to power the device.

For the purposes of this program, a practical limit of 5 kilowatts was considered for the size of any electrical heating systems. It was considered that below that limit, it was practical to incorporate such a device into a heavy-duty vehicle without major electrical system re-design, given that it would likely only operate for limited periods of time during cold-start. Above that limit, it was felt that considerable modification and cost would be required to support a larger power draw.

Exhaust Burner

Burners were used in production on diesel engines for heat generation directly in the exhaust. Typically, these were used in the past to support active DPF regeneration, as an alternative to HC dosing over a DOC. However, previous technology demonstrations have also shown the use of a burner for cold-start warm-up.

Burners benefit from being a highly efficient way to add heat to an exhaust system. Nearly all of the fuel energy consumed is available as heat, and that heat is generally directed very near the components that need it. As such, they are probably the most efficient means of adding heat to the exhaust.

For this program, several burner approaches were examined. Although it would technically not require a supplemental air source, a full-flow, in exhaust burner approach was ultimately turned down due to high thermal mass and issues with combustion stability. Instead, a side-flow, “mini-burner” approach was selected for this program, as depicted below in Figure

103. Such an approach benefits from the fact that it does not add significant thermal mass to the exhaust, which was important for cold-start. In addition, such an approach was generally more stable and easier to light when cold. It was also smaller and easier to package. The system selected was capable of provided roughly 10 kilowatts of heat to the exhaust.

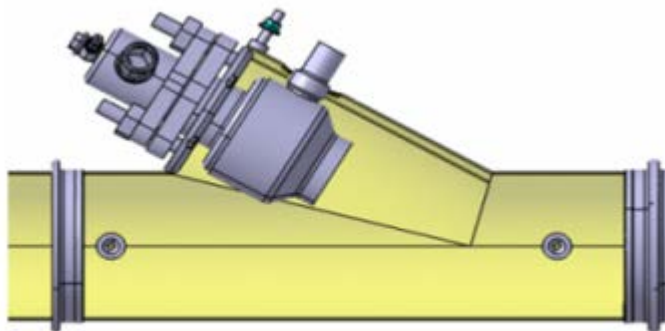


FIGURE 103. SCHEMATIC OF SIDE-FLOW MINI-BURNER

The primary drawback of a mini-burner approach was that it requires a supplemental source of combustion air. Several approaches were utilized in production to deal with this issue, with varying degrees of success. There were also considerations of system complexity that come with the use of a burner, and these were considered during the down-selection process.

3.1.4.5 Passive Heat Retention

These technologies generally comprised various modifications to the exhaust system, both on and off the engine, designed to help retain heat in the exhaust and prevent loss to the ambient environment. Several different technologies were proposed by MECA members for inclusion in the program, including:

- Air gap insulated, fabricated exhaust manifolds
- An air gap insulated transfer pipe from the engine to the aftertreatment
- Air gap insulated inlet and outlet cones incorporated into the catalyst canning

In addition, SwRI also utilized insulation and system configuration in an effort to minimize heat loss in the final system configuration. Although each of these measures has a small individual contribution to the overall system performance, they could in combination result in increased system efficiency. One key design point however, was that the benefits of any insulating concept have to be balanced against the potential increase in thermal mass of a given part, which could actually serve to slow down catalyst light off.

3.1.4.6 Exhaust Sensors

Improved control was an important part of the solution for any system configuration that targets 0.02 g/hp-hr. The high conversion efficiency demand for any such system requires more precision in system controls. Sensors provide a key input to those controls, and therefore it was important to use the best available sensor technologies to provide accurate measurements to the control system.

MECA members provided a number of different sensor technologies to the program including:

- Latest generation NO_x sensors for both the engine-out and tailpipe application
- Ammonia sensors
- Advanced, thermocouple-type temperature sensors which feature CAN-based communication

Incorporation of these sensors was important to reduce system variability and enhance the accuracy of the controls. All of the sensors provided for this program are either production or production-intent models.

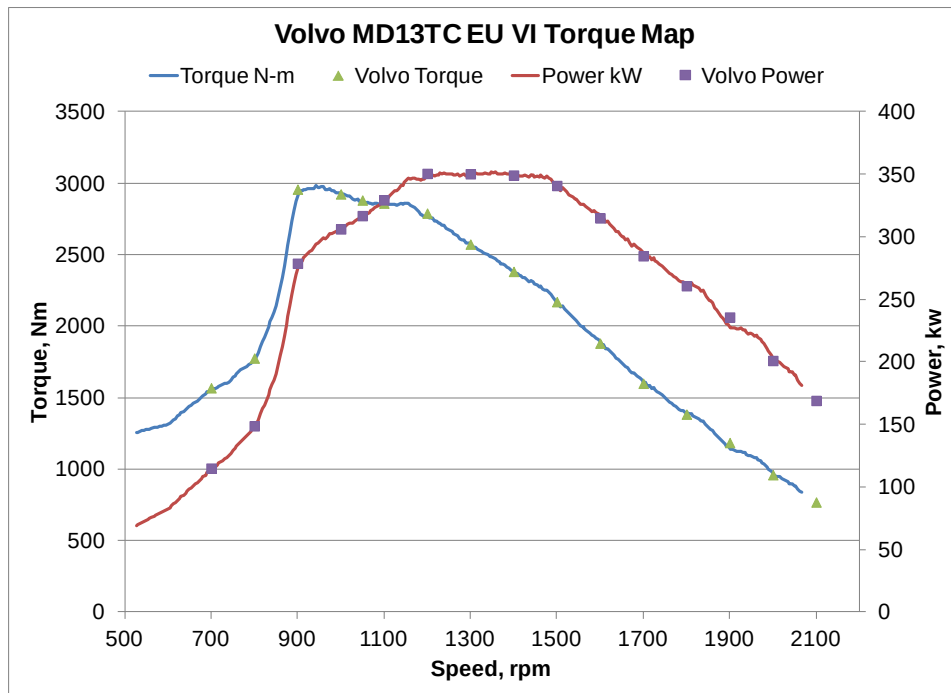
3.2 TASK 2: Engine Baseline and Ultra-Low NO_x Calibration

3.2.1 Overview

The objective of this task was to document the baseline engine and aftertreatment system performance over the regulatory and additional vocational test cycles. The baseline aftertreatment system was de-greened prior to testing. The baseline testing confirmed that the selected Euro VI engine and aftertreatment system met US 2010 emissions and established baseline GHG levels. Testing over the vocational cycles was also performed to validate the developed test cycles and to assess the low temperature emission control performance of the baseline system. The engine specifications are listed in Table 43 and the full load performance curves obtained at SwRI along with data provided by Volvo is shown in Figure 104. As shown, the engine operated as expected with a good performance match to Volvo's supplied data.

TABLE 43. 2014 VOLVO MD13TC ENGINE SPECIFICATIONS

Parameter	Value
Displacement	12.8 L
Bore x Stroke	131 x 158 mm
Rated Power	361 kW
Rated Speed	1477 RPM
Peak Torque	3050 Nm
Peak Torque Speed	1050 RPM
Fuel System	F2 Common Rail
Turbocharger	Fixed Geometry
Turbo-compounder	Mechanical
EGR System	Cooled, high pressure
Emission Certification	Euro VI
Application	Line-haul

**FIGURE 104. FULL LOAD PERFORMANCE OF VOLVO MD13TC**

3.2.2 Baseline FTP, RMC, WHTC, and CARB Idle Results

Baseline testing for the US heavy-duty FTP was composed of three sets of cold-start FTP test cycles. Each cold-start FTP was followed by three hot-start FTP tests with the proper twenty-minute soak time in between tests. The testing was performed in accordance with 40 CFR Part 1065 procedure and in a 1065-certified engine test cell. An emissions certification-grade diesel fuel was used for all diesel engine testing. The average composite FTP tailpipe emissions for the Volvo MD13TC engine rated at 361 kW can be seen in Table 44 below. The average was

determined from the three separate composite FTP test results and the corresponding standard deviation (SD) and coefficient of variation (CoV) was reported.

TABLE 44: BASELINE COMPOSITE FTP TAILPIPE EMISSIONS FOR VOLVO MD13TC

	Composite FTP Tailpipe, g/hp-hr					Composite FTP Tailpipe, ppm	
	NO _x	PM	NMHC	CO	CO ₂	NH ₃	N ₂ O
Average	0.140	0.001	0.000	1.000	547	0	0.03
SD	0.012	0.000	0.000	0.090	1.84		
CoV	8.5%	24%	88%	8.8%	0.3%		
US 2010 Standard	0.20	0.01	0.14	15.5	n/a		
SD % Standard	5.9%	2.5%	0.2%	0.6%	n/a	n/a	n/a

An RMC-SET was performed after each series of FTP tests for a total of three RMC-SET tests. The emission results from these tests are shown in Table 45. The tailpipe BSNO_x results for the cold and hot-start FTP and RMC-SET tests are shown graphically in Figure 105 with averages annotated. As shown, the baseline MD13TC engine calibration and one-box aftertreatment system met the US 2010 emission standards for heavy-duty on-road engines. In terms of GHG standards, the CO₂ results were below 2017 GHG levels as shown in Figure 106, where it should be noted that the Tractor (SET) standard would apply to this engine since it was a line-haul application.

TABLE 45: BASELINE COMPOSITE RMC-SET TAILPIPE EMISSIONS FOR VOLVO MD13TC

	Composite FTP Tailpipe, g/hp-hr					Composite FTP Tailpipe, ppm	
	NO _x	PM	NMHC	CO	CO ₂	NH ₃	N ₂ O
Average	0.080	0.002	0.003	0.020	458	0	0.05
SD	0.009	0.001	0.000	0.001	0.72		
CoV	11%	70%	9.0%	5.9%	0.2%		
US 2010 Standard	0.20	0.01	0.14	15.5	n/a		
SD % Standard	4.6%	13.6%	0.2%	0.0%	n/a	n/a	n/a

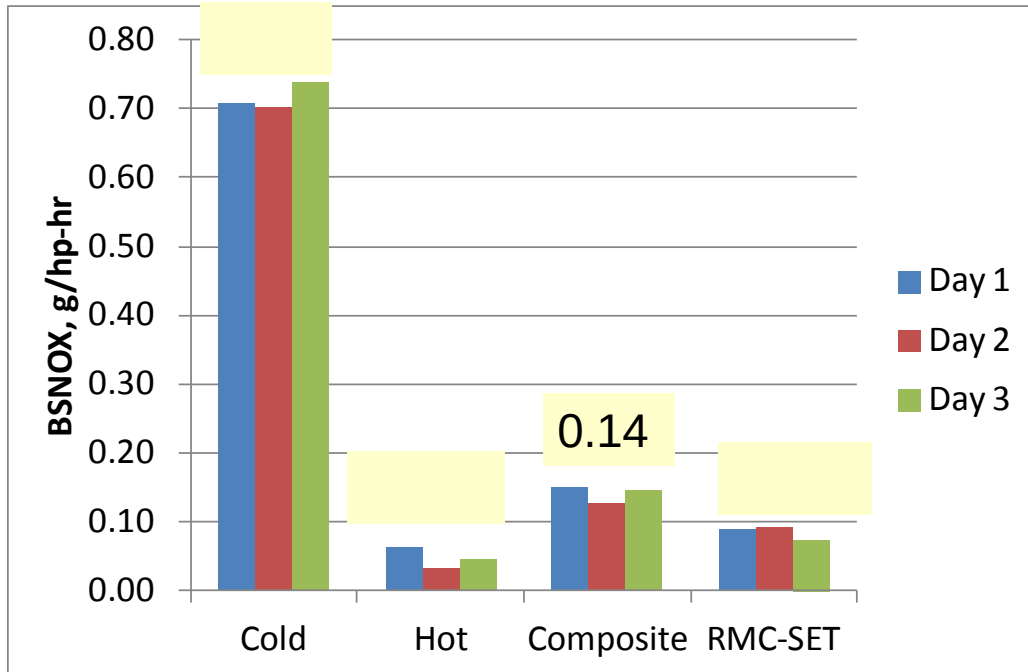


FIGURE 105. REGULATORY CYCLE TAILPIPE NO_x DATA FROM DIESEL BASELINE

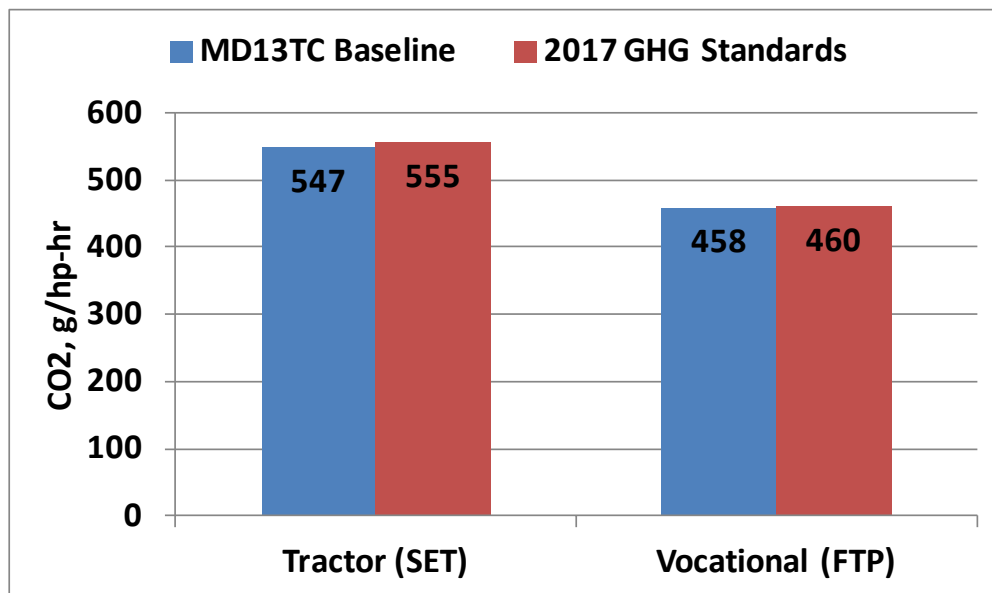


FIGURE 106. GHG RESULTS FROM DIESEL BASELINE

Because meeting the program ULN target would require significant improvement in cold-start NO_x control, it was of interest to review the cold-start FTP performance of the baseline engine and aftertreatment system. For this purpose, the key exhaust temperatures are shown in

Figure 107 along with the measured engine speed for cycle reference. This result illustrates the challenge of achieving early NO_x control with a conventional DOC+DPF+SCR system as the SCR inlet temperature didn't reach 180 °C until 550 seconds into the cycle due to the combination of low turbo-compounder outlet temperature (TC Out T) and the large thermal mass of the DPF. The 180 °C temperature was important since it corresponds to when sufficient urea evaporation can be achieved in the exhaust and when significant NO_x conversion can be achieved by SCR. The impact of this temperature history on tailpipe NO_x is shown in Figure 108. Moderate tailpipe NO_x control can be observed to begin around 400 seconds, but highly efficient NO_x control was not obtained until after 600 seconds, hence the resulting high cold-start FTP NO_x result. Additional insight into the baseline aftertreatment performance can be obtained by examining the accumulated tailpipe BSNO_x and NO_x conversion efficiency as shown in Figure 109. The time at which a cumulative BSNO_x of 0.07 g/hp-hr was reached is annotated in the figure and is shown to occur at 60 seconds. This value was important as it corresponded to the initial target for a cold-start FTP to achieve the ULN target of the program.

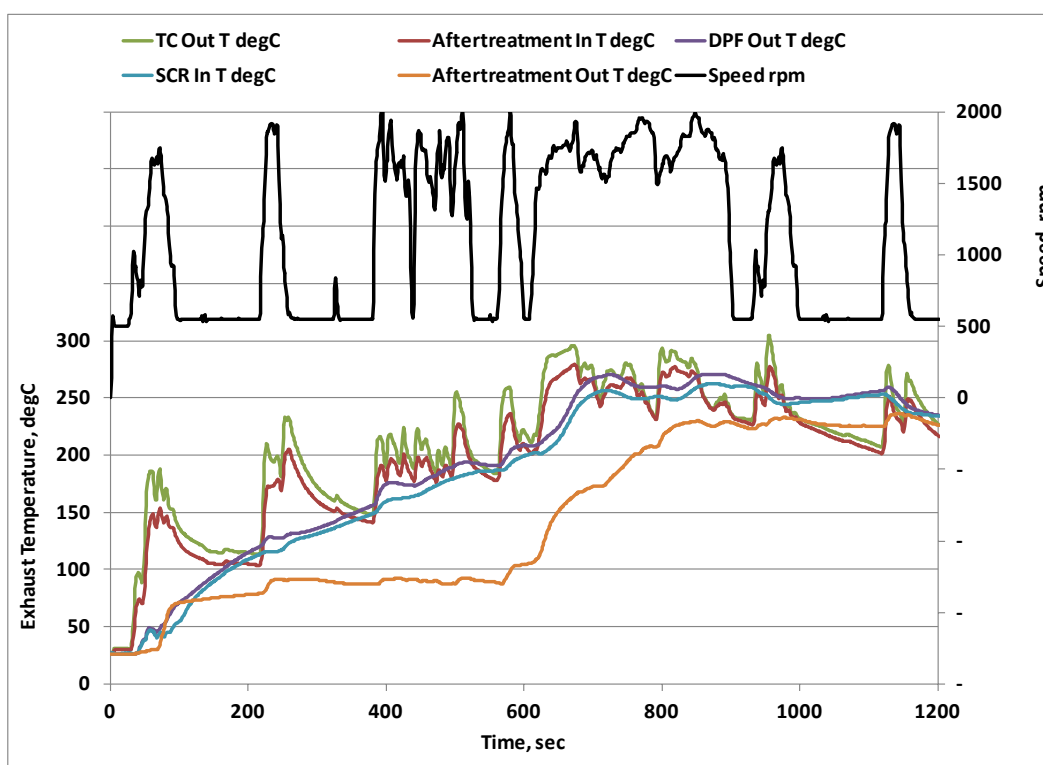


FIGURE 107. EXHAUST TEMPERATURES FOR DIESEL BASELINE COLD-START FTP

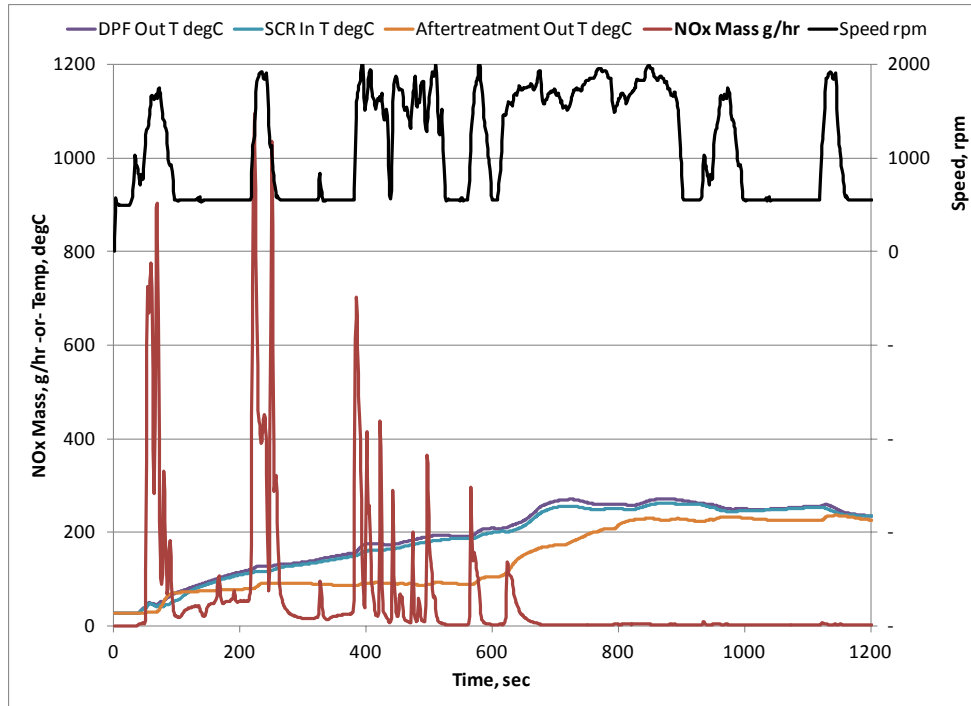


FIGURE 108. TAILPIPE NO_x FOR DIESEL BASELINE COLD-START FTP

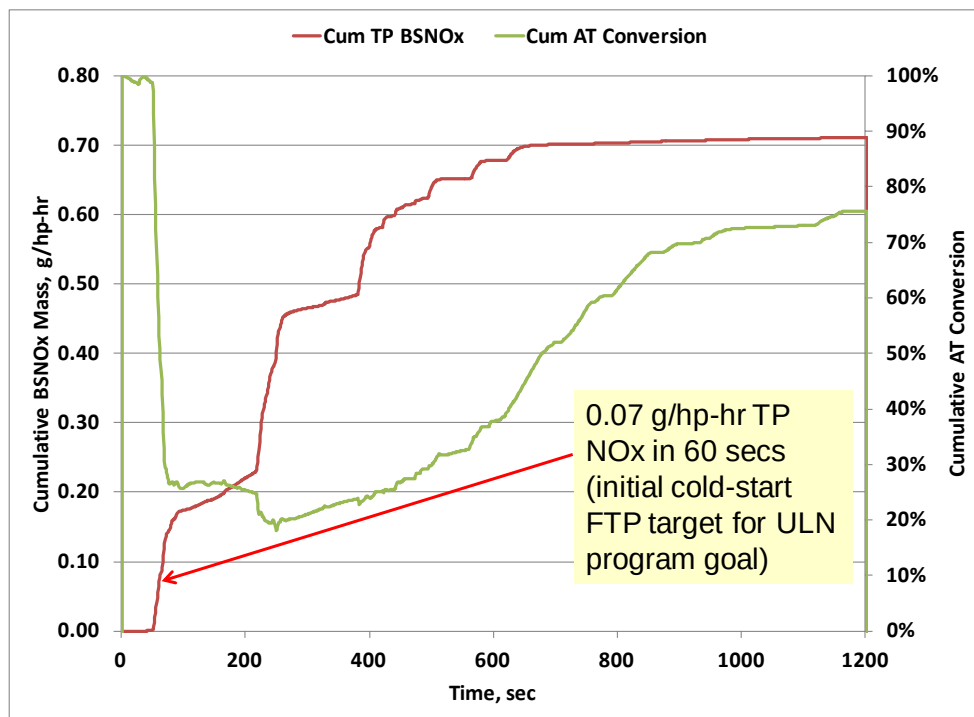


FIGURE 109. CUMULATIVE TAILPIPE BS NO_x AND CONVERSION EFFICIENCY FOR DIESEL BASELINE COLD-START FTP

Similar plots for a hot-start FTP are shown below in Figure 110, Figure 111, and Figure 112. As shown, some cooling of the aftertreatment occurred during the twenty minute soak period, however, little NO_x breakthrough was observed early in the cycle due to the high thermal mass of the aftertreatment devices. The impact of the long idle periods on aftertreatment cooling after the first and second accelerations was observed by reduced NO_x control especially during the early part of the third acceleration starting just before 400 seconds. The hot-start FTP cumulative tailpipe BSNO_x target for the ULN demonstration was set at 0.01 g/hp-hr. As shown in Figure 112, this limit was exceeded 390 seconds into the cycle.

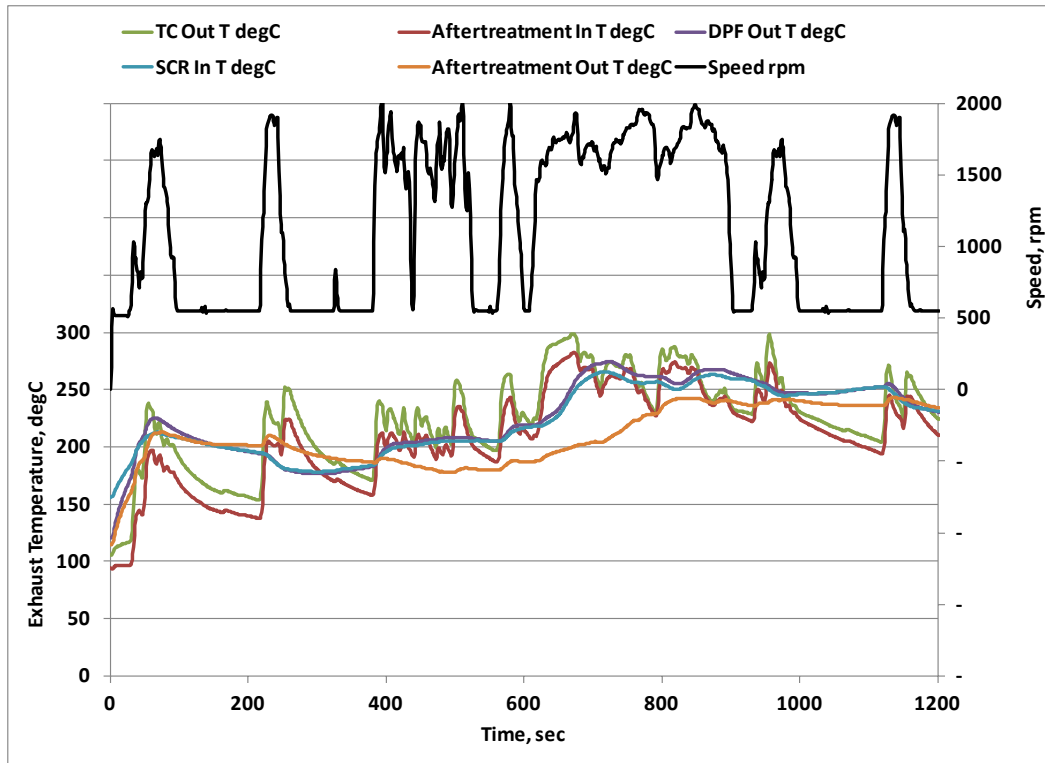


FIGURE 110. EXHAUST TEMPERATURES FOR DIESEL BASELINE HOT-START FTP

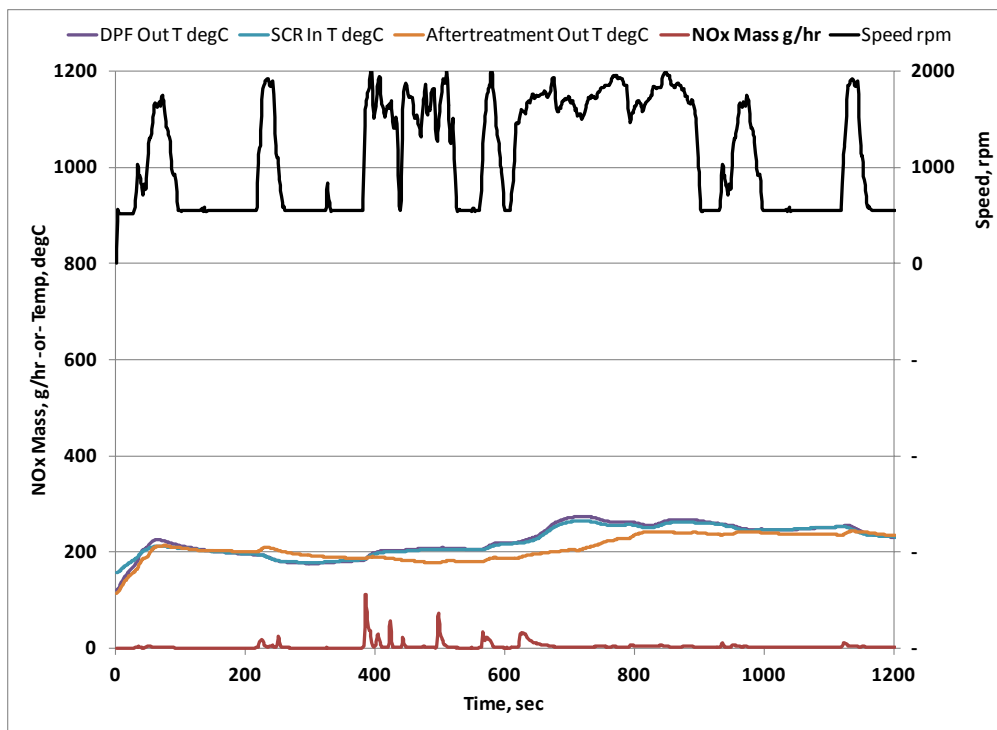


FIGURE 111. TAILPIPE NO_x FOR DIESEL BASELINE HOT-START FTP

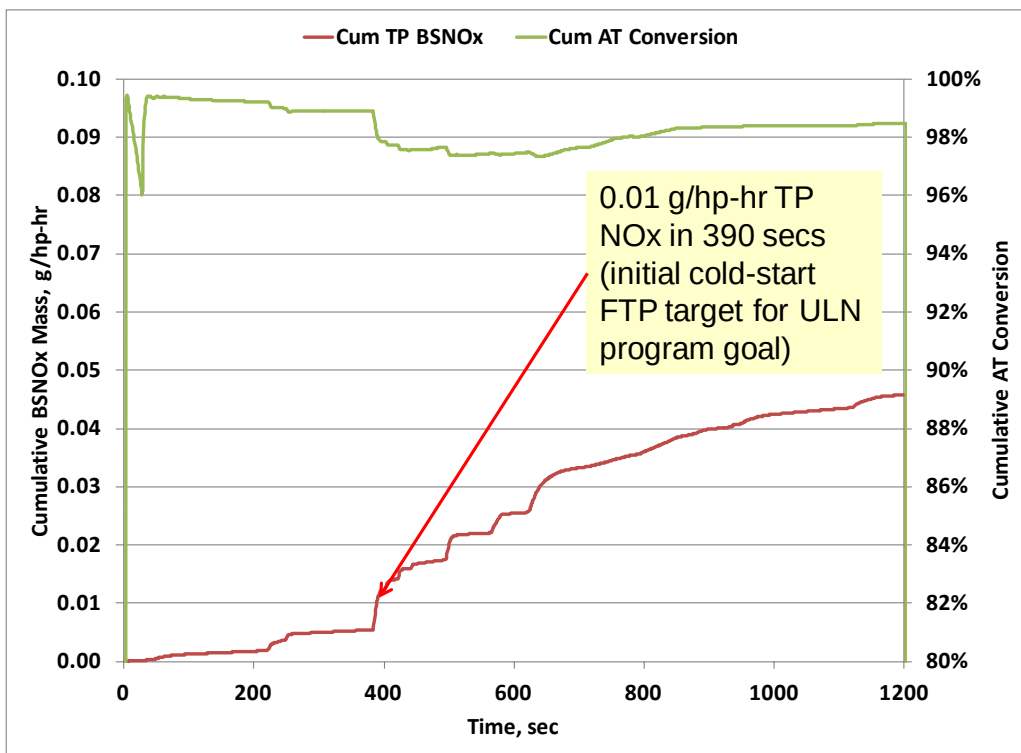


FIGURE 112. CUMALATIVE TAILPIPE BSNO_x AND CONVERSION EFFICIENCY FOR DIESEL BASELINE HOT-START FTP

Exhaust temperature and tailpipe NO_x traces measured for the baseline RMC-SET test cycle are shown in Figure 113 and Figure 114, respectively. As shown, even though the exhaust temperatures were consistently above 200 °C during this test cycle, significant NO_x breakthrough was observed during modes 2 (A100 point) and 8 (B100 point) which correspond to engine operation with high engine-out NO_x flow rates. Significant improvement in NO_x control was required to meet the ULN program target.

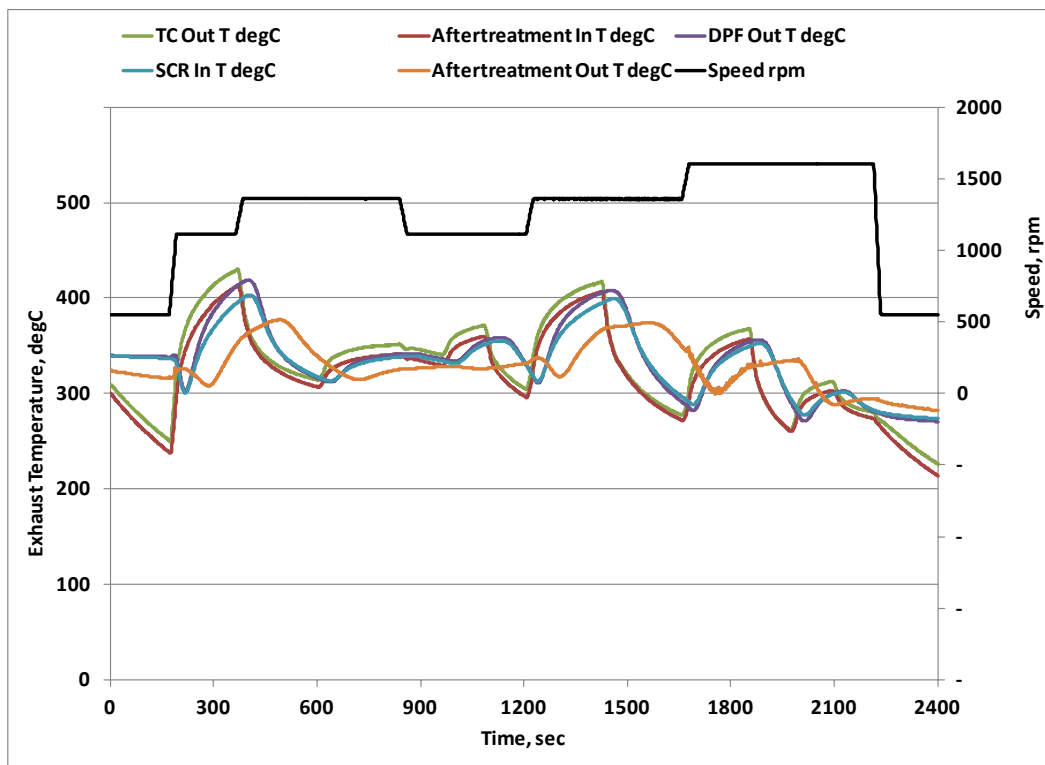


FIGURE 113. EXHAUST TEMPERATURES FOR DIESEL BASELINE RMC-SET

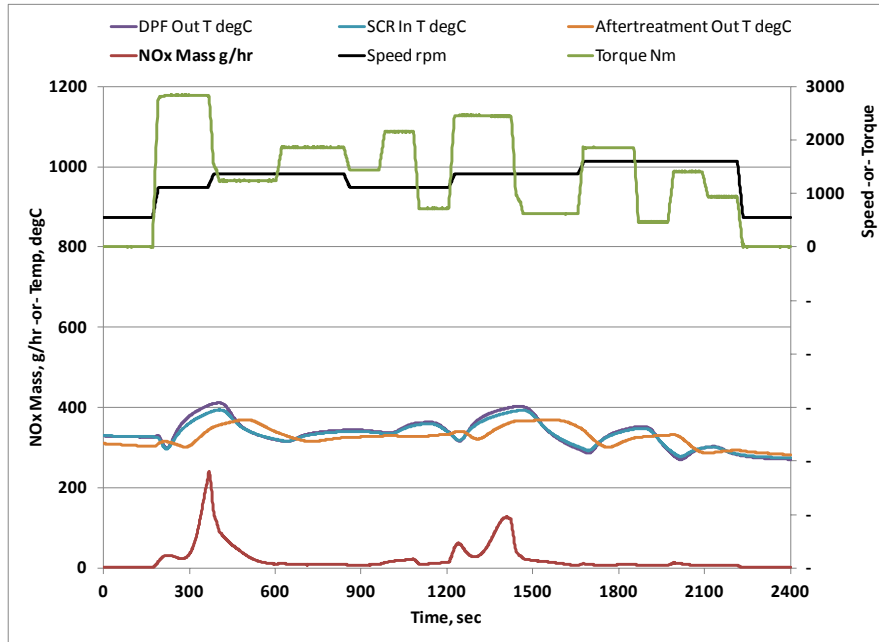


FIGURE 114. TAILPIPE NO_x FOR DIESEL BASELINE RMC-SET

The engine-out BSNO_x levels during the FTP tests were around 3 g/hp-hr and the transient composite aftertreatment conversion efficiency was 95% (75% for cold, 98% for hot). The engine-out BSNO_x for the RMC-SET was around 2.6 g/hp-hr. The engine-out PM levels were 0.2, 0.1 and 0.03 g/hp-hr for the cold and hot FTP, and RMC-SET, respectively.

Baseline testing over the WHTC was also performed over triplicate test sequences, each comprised of a single cold-start followed by three hot-start tests with the proper ten minute soak time in between tests. Measurement procedures in 40 CFR Part 1065 procedure were followed and the testing was performed in the same 1065-certified engine test cell. Cycle denormalization followed the protocols outlined in the Economic Commission for Europe (ECE) Regulation No 49 (R49) procedure for the WHTC. The average composite WHTC tailpipe emissions can be seen in Table 46, below. The results listed were obtained from the cold-start and an average of the three hot-starts. Results are shown in g/hp-hr, even though the WHTC is normally regulated in g/kW-hr.

TABLE 46: BASELINE COMPOSITE WHTC TAILPIPE EMISSIONS FOR VOLVO MD13TC

	WHTC Tailpipe, g/hp-hr				
	NO _x	PM	THC	CO	CO ₂
Cold	0.492	0.0014	0.001	1.45	501.4
Hot Average	0.049	0.0009	0.002	0.18	484.1
Composite	0.111	0.0010	0.002	0.36	486.5
Euro VI Standard	0.46	0.01	0.16	4.0	

Engine-out NO_x levels on the WHTC were at a level of 3.5 g/hp-hr (or 4.5 g/kW-hr) and transient composite NO_x aftertreatment efficiency was 96.7% (84% for cold and 98.5% for hot).

Baseline results for the CARB extended idle test are summarized in Table 47 below. The values given are averages for the entire 30 minute idle period in each case. Continuous data for the two idle modes is shown in Figure 115. It should be noted that the data for record was preceded immediately by an FTP hot-start test, per the options in the CARB idle test procedure. NO_x conversion is maintained at first until the aftertreatment system runs out of heat and stops dosing DEF. There is some continued conversion from stored ammonia until temperature becomes too low during the low idle, although this eventually fades and conversion at the end is very low. Still this is enough to easily comply with the 30 g/hr tailpipe limit. The higher idle does not actually meet the full requirement, but given that this is actually a Euro VI calibrated engine that was not required to comply with this particular test, that does not indicate any particular problem with the engine.

TABLE 47. BASELINE CARB IDLE TEST RESULTS FOR VOLVO MD13TC

Test Mode	Tailpipe NO _x Rate	Engine-Out NO _x Rate	NO _x Conversion
	g/hr	g/hr	%
Low Idle – 550 rpm	11.7	46.2	75%
PTO Idle – 1100 rpm	53.1	56.5	20%
Current CARB Idle Standard	30		

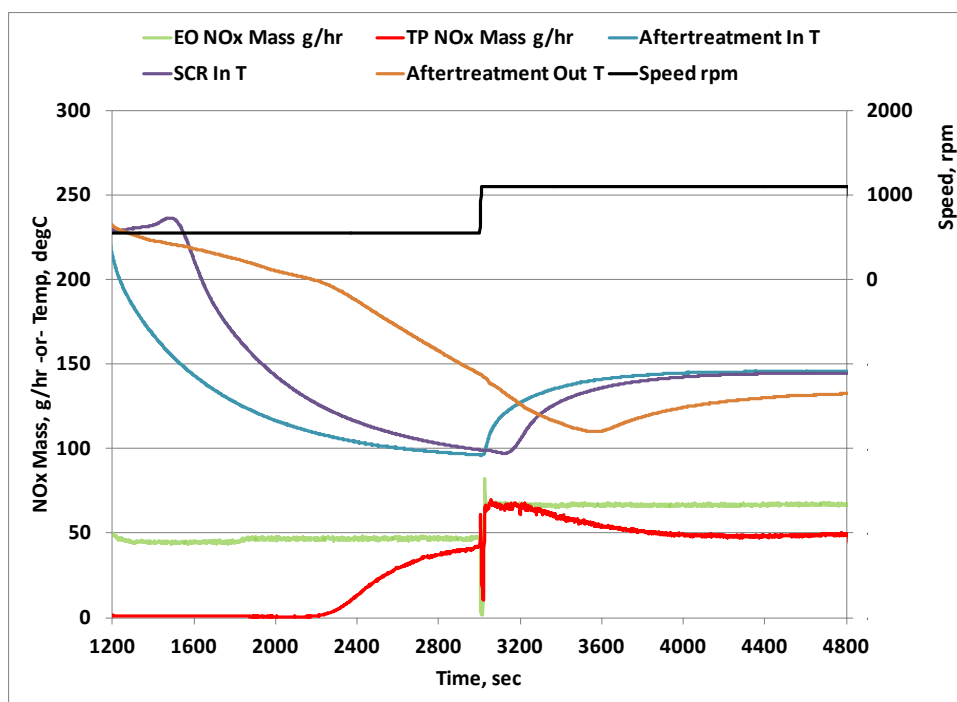


FIGURE 115. CONTINUOUS NO_x AND TEMPERATURE DATA FOR BASELINE CARB IDLE TEST

3.2.3 Baseline Vocational Test Cycle Results

As discussed in Section 3, the intent of the vocational cycles was to examine how well the reduction of emissions to 0.02 g/hp-hr on the certification cycles might translate to operation on other, potentially more challenging duty cycles from the field. For comparison purposes, testing with the baseline engine calibration and aftertreatment system was performed over the three selected vocational test cycles. The results for each cycle are presented in the following sections.

3.2.3.1 NYBC x 4 Test Cycle

The intent of the NYBC cycle was to evaluate the emission characteristics during highly transient operation with severe short-duration power spikes and sustained low temperature operation. The average engine power during the cycle was 17 kW. Cycle pre-conditioning consisted of engine warm-up, a preparation NYBC x 4 cycle followed by a 30-minute idle period prior to the NYBC x 4 cycle for record. Following this procedure with the baseline engine and aftertreatment system, exhaust temperature traces after the DPF, before the SCR and after the SCR as well as tailpipe NO_x mass flow rates are shown in Figure 116. As shown, the inlet temperature to the SCR decreased significantly during the idle period leading to high tailpipe NO_x during the power spikes. The magnitude of the NO_x spikes reduced as the cycle progressed due to the SCR system slowly warming up. The cycle-averaged engine-out NO_x was around 6 g/hp-hr and the tailpipe was 2.4 g/hp-hr with an average NO_x conversion efficiency of 62%.

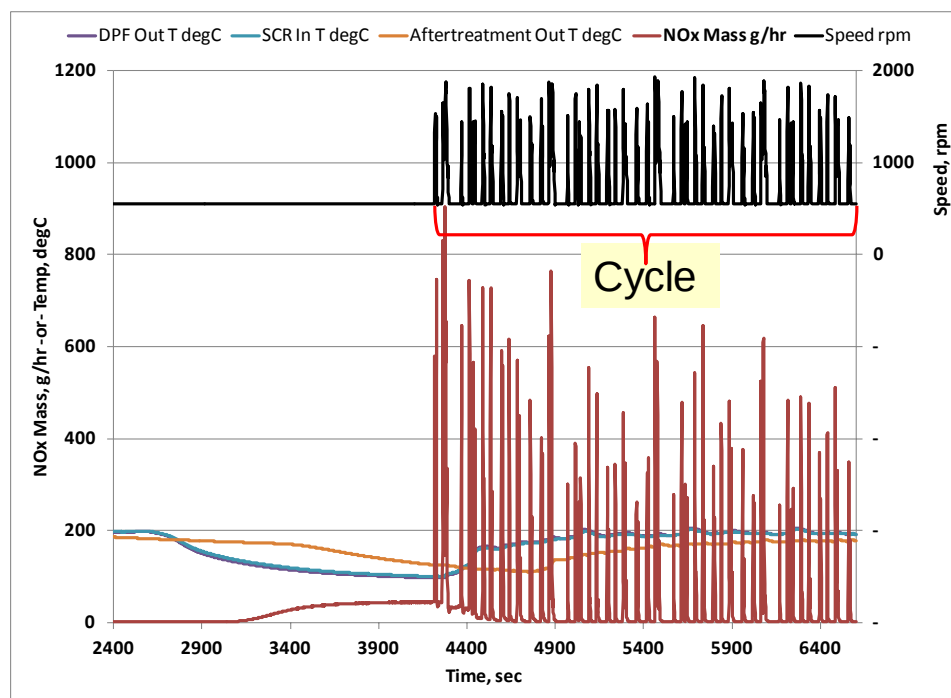


FIGURE 116. NYBC X 4 CYCLE EXHAUST TEMPERATURES AND NO_x FOR DIESEL BASELINE

3.2.3.2 Cruise+Creep x 10 Cycle

The intent of the Cruise+Creep cycle was to evaluate the emission characteristics during sustained light load operation and assess the ability of the aftertreatment system to maintain heat following the Cruise portion of the cycle. Cycle pre-conditioning consisted of engine warm-up prior to the Cruise+Creepx10 cycle for record. Following this procedure with the baseline engine and aftertreatment system, the resulting exhaust temperature traces measured after the DPF, before the SCR and after the SCR as well as tailpipe NO_x mass flow rates are shown in Figure 117. As shown, exhaust temperatures during the cruise portion of the cycle were well above 200 °C and consequently, high NO_x conversion efficiency was obtained at the start of the creep portion. The baseline system maintained good NO_x control for roughly half of the creep cycles after which NO_x slip was observed to begin and worsen as the cycle progressed.

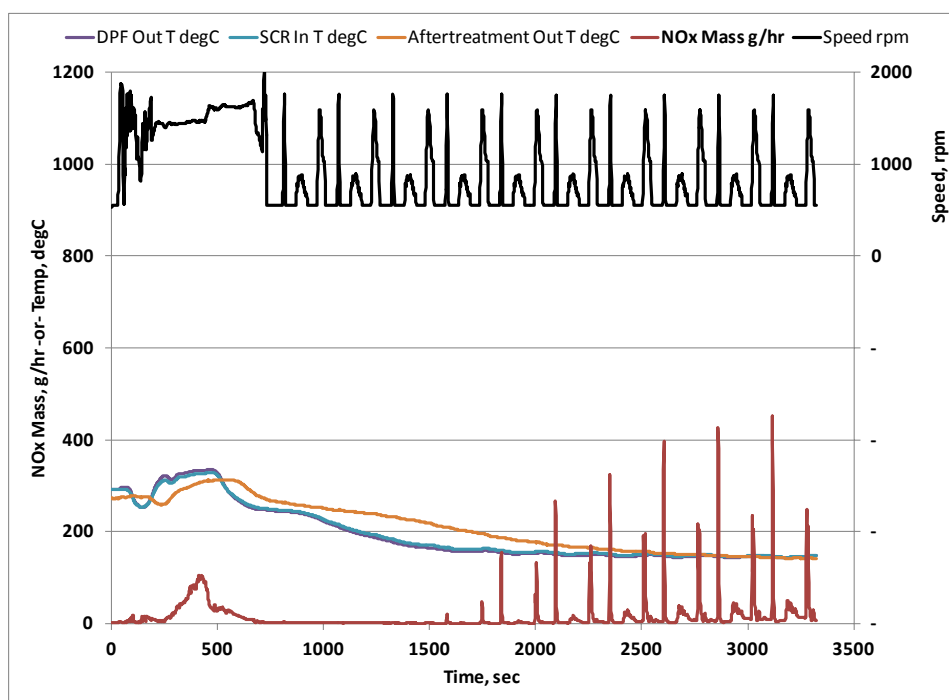


FIGURE 117. CRUISE+CREEP X 10 CYCLE EXHAUST TEMPERATURES AND NO_x FOR DIESEL BASELINE

3.2.3.3 OCTA Bus Cycle

The intent of the OCTA bus cycle was to evaluate the emission characteristics during a realistic vocational cycle for California. The cycle was based on transit bus data with less aggressive transients than the FTP cycle and had an average cycle power of 53 kW. Cycle pre-conditioning consisted of engine warm-up and a prep OCTA bus cycle prior to the OCTA bus cycle for record. Following this procedure with the baseline engine and aftertreatment system, the resulting exhaust temperature traces measured after the DPF, before the SCR and after the SCR as well as tailpipe NO_x mass flow rates for both the prep and cycle for record are shown in Figure 118. As shown, exhaust temperatures during the cycle for record were consistently above 200 °C and consequently, a high NO_x conversion efficiency of 99.4% over the cycle was

achieved. The cycle average BSNO_x results were 3.8 g/hp-hr for engine-out and 0.02 g/hp-hr for tailpipe.

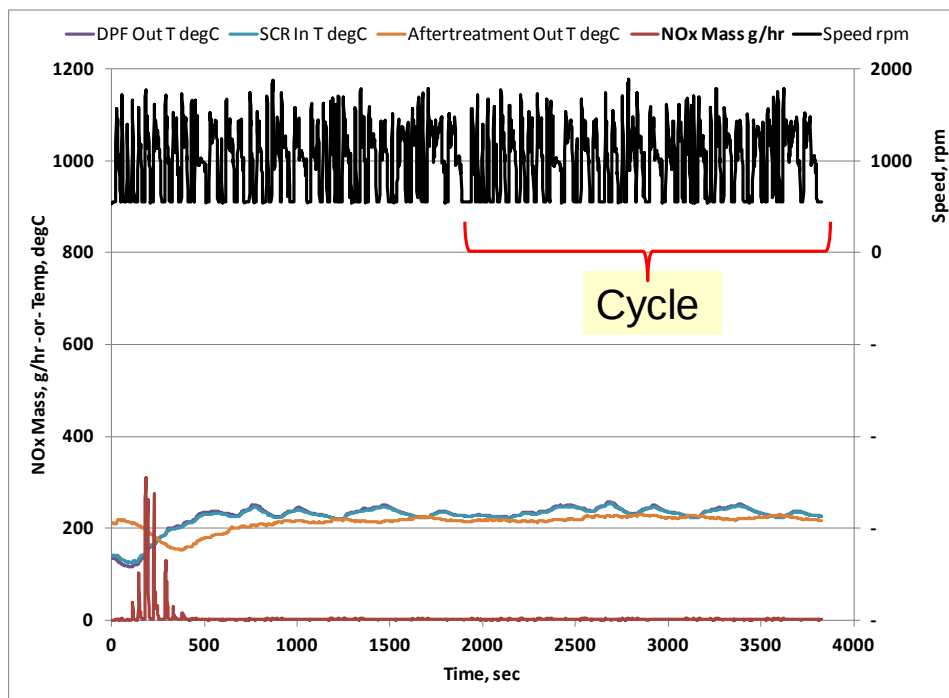


FIGURE 118. OCTA BUS CYCLE EXHAUST TEMPERATURES AND NO_x FOR DIESEL BASELINE

3.2.4 Cold-Start Engine Calibration

This task focused on exploring the capabilities of the stock engine hardware to simultaneously reduce engine-out NO_x emissions and increase exhaust gas temperature without incurring a significant fuel penalty during SCR warm-up following a cold-start on the FTP cycle. The effectiveness of the engine-based measures was assessed at several steady-state engine-operating conditions that were representative of the FTP test cycle. These results were used to guide the development of revised cold engine calibrations. The resulting exhaust temperature, flow rate and emission traces obtained for a cold FTP with the revised cold engine calibration were utilized in the screening task for performance assessment of the advanced catalysts provided for the program.

The engine was provided with an open ECU, which was interfaced with ATI Vision software. This interface enabled manual control of fueling and air-handling actuators through an override function as well as access to various calibration tables. In addition, the engine was provided with provisions to allow installation of a cylinder pressure transducer in one cylinder. Therefore, a Kistler 6045A pressure sensor was installed and crank-angle-based cylinder pressure was used during this task to monitor combustion quality during both steady-state and transient engine testing.

3.2.4.1 Baseline FTP Results and Steady-State Test Point Selection

For the engine calibration task, the majority of the effort was focused on the early portion of the cold-start FTP since little to no catalytic NO_x control was available when the SCR was cold. To illustrate this issue, baseline cold-start FTP results are shown in Figure 119. This figure shows engine speed in the top chart, engine-out exhaust gas (measured after the turbo-compounder), exhaust gas at the SCR inlet and engine coolant temperature in the middle chart, and cumulative engine-out and tailpipe NO_x mass in the bottom chart. From the cumulative NO_x results, good catalytic control of NO_x was achieved after 500 seconds from the start of test cycle, which corresponded to when the SCR inlet temperature approached 200 °C. As mentioned previously, the engine-out temperature was relatively low compared to traditional engines due to the turbo-compounder.

Therefore, the goal of the engine calibration task was to leverage the available engine measures to increase engine-out temperature and reduce engine-out NO_x emissions early in the cold-start FTP. The engine measures available on the test engine included:

- Cooled high-pressure-loop EGR
- Multiple in-cylinder injections (7th injector available)
- Intake throttling
- Idle speed control

For this purpose, engine operation during the first 525 seconds of the FTP was used to determine suitable steady-state test points for subsequent engine calibration investigations. The coolant temperature was included in the FTP test results to point out that the engine coolant temperature starts at approximately 25 °C and was below 50 °C for over half of the 525-second window selected.

Since coolant temperature can affect in-cylinder combustion characteristics, especially when using moderate levels of cooled EGR, which were planned for NO_x reduction, the calibration investigations were conducted at low engine coolant temperature by using a blocked open thermostat and lab heat exchangers to maintain low coolant temperature during engine calibration development testing.

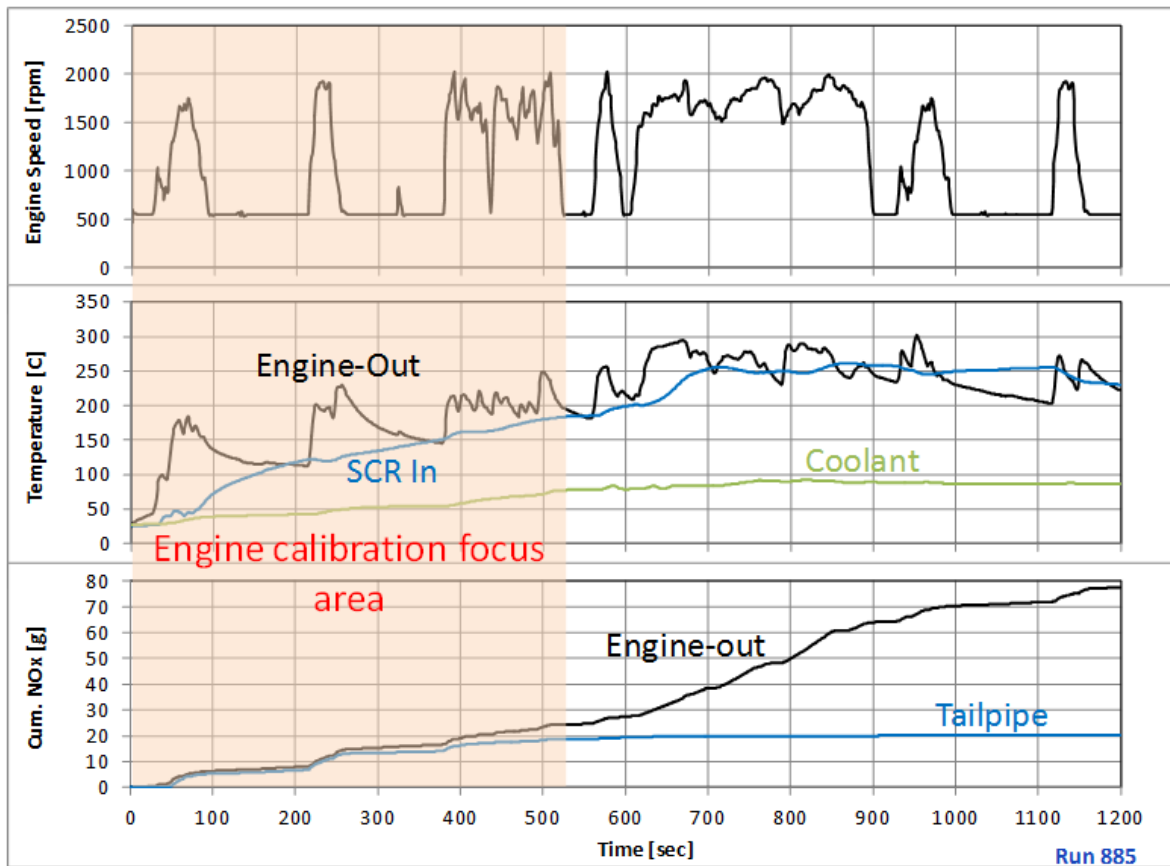


FIGURE 119. BASELINE COLD-START FTP RESULTS WITH ENGINE CALIBRATION FOCUS AREA HIGHLIGHTED

A total of eight steady-state test points were selected as illustrated in Figure 120, which shows a scatter plot of engine speed versus load recorded during the first 525-seconds of the FTP cycle. The target engine speed and load settings for the steady-state test points are also listed in Table 48. The next section presents the results of the baseline calibration as well as after exercising the available engine measures at these engine conditions.

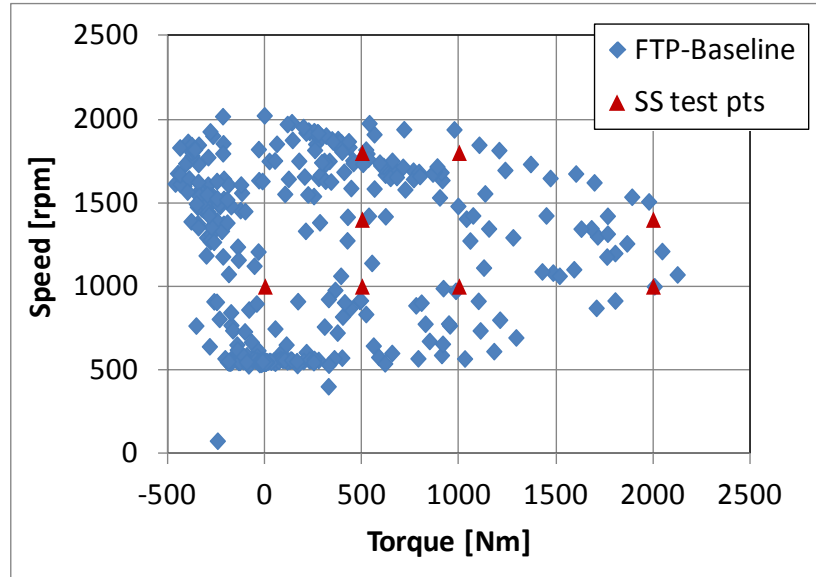


FIGURE 120. ENGINE SPEED AND LOAD POINTS FROM BASELINE FTP ALONG WITH SELECTED STEADY-STATE TEST POINTS FOR CALIBRATION STUDIES

TABLE 48. TARGET SPEED AND LOAD SETTINGS FOR SELECTED STEADY-STATE TEST POINTS

Test Point	Engine Speed	Torque
[-]	[RPM]	[Nm]
1	1000	0
2	1000	500
3	1000	1000
4	1000	2000
5	1400	500
6	1400	2000
7	1800	500
8	1800	1000

3.2.4.2 Steady-State Evaluations for Revised Cold Calibration Development

The first step in the cold calibration development was to document the baseline engine operation at the selected test points. This testing was performed at low coolant temperature as mentioned previously. Three modes of baseline operation were available. The first mode corresponds to what was used for around the first 300 seconds of the cold-start FTP, and is referred to subsequently as the “Normal Cold Map.” It should be noted that no EGR was used in this mode to avoid potential condensation of the exhaust gas in the EGR cooler due to the low coolant temperature. The second baseline engine mode was an elevated exhaust temperature calibration and was used after the normal cold map during baseline cold-start FTP operation. For the purposes of this study, this mode is referred to as high exhaust temperature operation and uses the label “Hi Exh Temp Map” in presented results. The baseline operation in this mode uses EGR as the coolant temperature was generally high enough to avoid condensation. However,

engine tests were conducted both with and without EGR in order to examine the effect of EGR on NO_x at forced low engine coolant temperature. Although not demonstrated in this program, the durability concern associated with using EGR at low coolant temperatures could be addressed by employing an EGR cooler by-pass loop.

Enabled by the F2 common rail fuel system on the test engine, the injection pattern used by the baseline calibration in the high exhaust temperature mode for all of the selected test points consisted of three injections: 1) pilot, 2) main and 3) close post. A relatively new strategy used mostly by light-duty diesels to increase exhaust gas temperature is to employ multiple close post injections with appropriate spacing to ensure adequate combustion of the post injections. Therefore, the effect of adding a second post injection to the high exhaust temperature settings was also investigated at several test points. The cylinder pressure measurement was essential for verifying combustion quality for the post injections. The two injection patterns are illustrated in Figure 121. It should be noted that when a second post injection was added, the engine torque increased so the main injection quantity had to be reduced in order to maintain the target engine load.

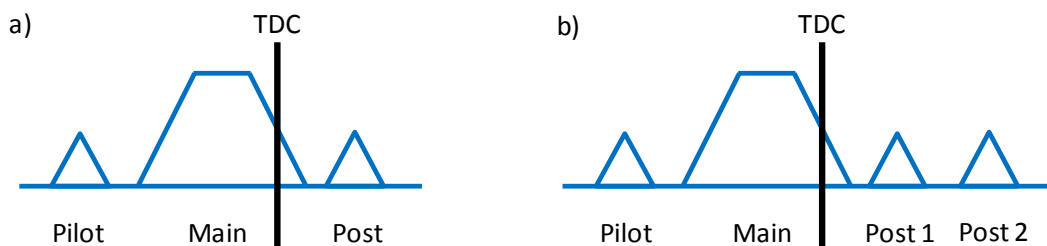


**FIGURE 121. INJECTION PATTERNS USED DURING CALIBRATION INVESTIGATIONS:
A) SINGLE POST, B) DOUBLE POST**

Based on the results obtained from the investigations described above, the stock engine fueling and air-handling calibration tables used during high exhaust temperature operation were modified to create a new cold calibration referred to as “Cold Cal 1.” Engine tests were conducted at the selected steady-state test points with the new calibration to document the corresponding exhaust temperature, NO_x and fuel consumption. In summary, steady-state engine tests were conducted at the selected test points with up to five different calibration strategies, which are labeled in the plots as:

1. “Normal Cold Map” – Baseline operation mode for first 300 seconds of cold-start FTP.
2. “Hi Exh Temp Map” – Baseline calibration for elevated exhaust temperature operation and used after normal cold map. Baseline operation was with EGR, however these tests were conducted without EGR so the impact of EGR on NO_x could be assessed.
3. “Hi Exh Temp Map+EGR” – Baseline calibration for elevated exhaust temperature operation and used after normal cold map. EGR rate included baseline settings plus increased level

4. “Adding 2nd Post Inj” – Same as 3, but a second post injection was added and the quantity was varied to assess the impact on exhaust temperature and fuel consumption.
5. “Cold Cal 1” – Resulting engine calibration developed for cold-start FTP which utilizes double post injections and increased EGR.

For brevity, only results obtained at test points 1, 2, and 7 for the different calibration modes are presented in detail in the following sections. A summary was then provided to compare the baseline operation to the final cold cal 1 map for all test points.

3.2.4.3 Steady-State Test Results Obtained at Test Point 1: 1000 RPM, 0Nm

In addition to the initial 24 second idle period at the beginning of the heavy-duty FTP, there are two prolonged periods of idle of nearly two minutes each within the selected 525-second window (see Figure 119). Therefore, it was of interest to investigate the potential exhaust temperature and energy flow improvements available by simply increasing the engine idle speed from the baseline value of 550 RPM to 1000 RPM. Engine data was recorded at the baseline idle (referred to by “BI”) and elevated idle speed (referred to as “EI”) while in the normal cold map mode. At the elevated idle speed, additional data was acquired after changing to the elevated exhaust temperature mode with EGR and then after adding a second post injection (which corresponds to the final Cold Cal 1 map). All testing was conducted with low coolant temperatures (between 25 and 30 °C). The resulting exhaust flow rates, turbo-compounder out temperature and exhaust energy increase over the baseline case are shown in Figure 122.

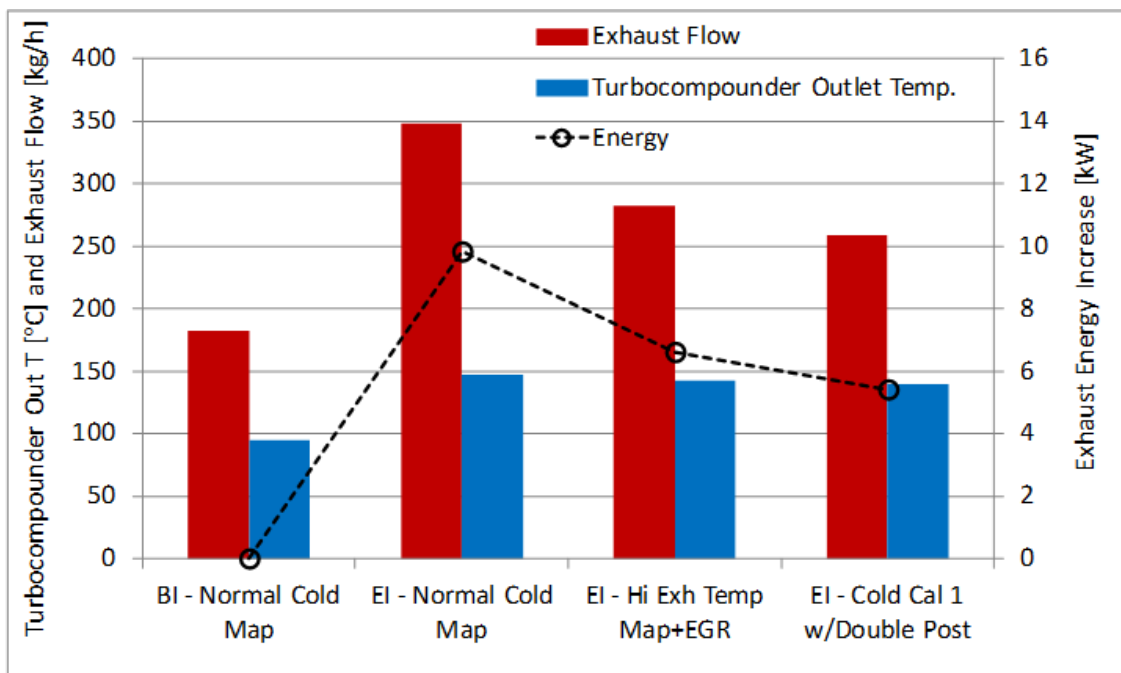


FIGURE 122. TEMPERATURE, EXHAUST FLOW AND ENERGY RESULTS AT IDLE

As shown, simply increasing the idle speed resulted in a significant increase in the exhaust energy (10 kW over the baseline idle condition) due to the combined effect of increased exhaust gas flow rate and temperature. However, changing to the baseline high exhaust temperature mode or Cold Cal 1 operation did not result in further increases in exhaust gas temperature and resulted in a reduction in exhaust flow rate and corresponding energy. The corresponding engine-out NO_x, EGR rate and fuel flow results presented in Figure 123. The exhaust flow reduction was largely due to the addition of EGR and the final Cold Cal 1 map had slightly increased EGR compared to that of the baseline high exhaust temperature mode. A higher level of EGR was needed to mitigate the increase in NO_x mass flow rate caused by the elevated idle speed operation. As shown, the final Cold Cal 1 tuning resulted in a similar NO_x mass flow rate as the baseline idle under normal cold map operation. However, the required fuel flow rate more than doubled so it was clear that there was a fuel penalty associated with elevated idle operation.

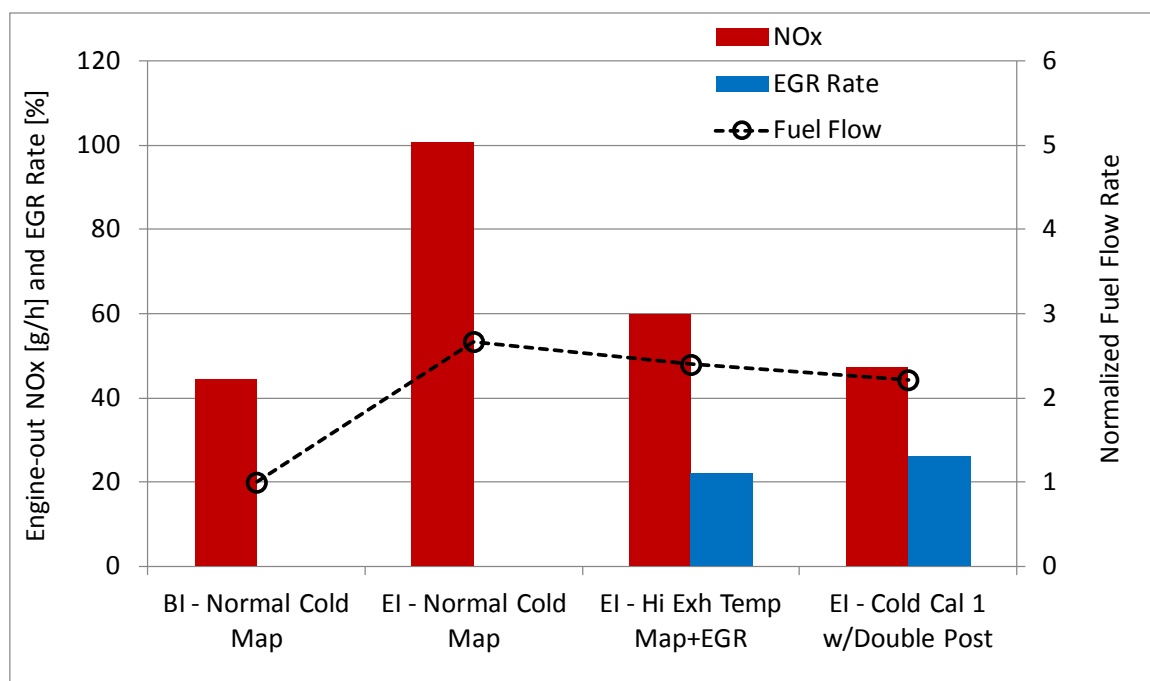


FIGURE 123. ENGINE-OUT NO_x, EGR RATE AND FUEL FLOW RATE RESULTS AT IDLE

3.2.4.4 Steady-State Test Results Obtained at Test Point 2: 1000 RPM, 500 Nm

Similar engine tests were conducted at 1000 RPM, 500 Nm under low coolant temperatures (maintained around 30 °C). However, in addition to documenting the baseline elevated exhaust temperature operation with and without EGR, the effect of increasing the EGR rate during this engine mode was investigated. At the highest EGR setting, the effect of adding a second post injection was then examined, and finally, the resulting Cold Cal 1 operation was documented. The corresponding normalized BSFC results and engine-out NO_x mass flow rates versus turbo-compounder out temperatures for these evaluations are shown in Figure 124.

As shown in the top chart, the exhaust gas temperature increased by more than 50 °C with a 5% fuel penalty when the operation was changed from the normal cold map to the high exhaust temperature mode. Adding EGR had little impact on the temperature or fuel consumption. Further increases in temperature and fuel consumption were obtained by using the double post injection strategy. The resulting Cold Cal 1 operation provided a 130 °C increase in exhaust gas temperature with a 16% increase in fuel consumption over the baseline normal cold map operation at this engine condition. In terms of NO_x, both baseline operating modes without EGR had high NO_x mass flow rates of over 300 g/h. When EGR was added, the NO_x was reduced to below 100 g/h with a final cold cal 1 NO_x flow rate of 65 g/h.

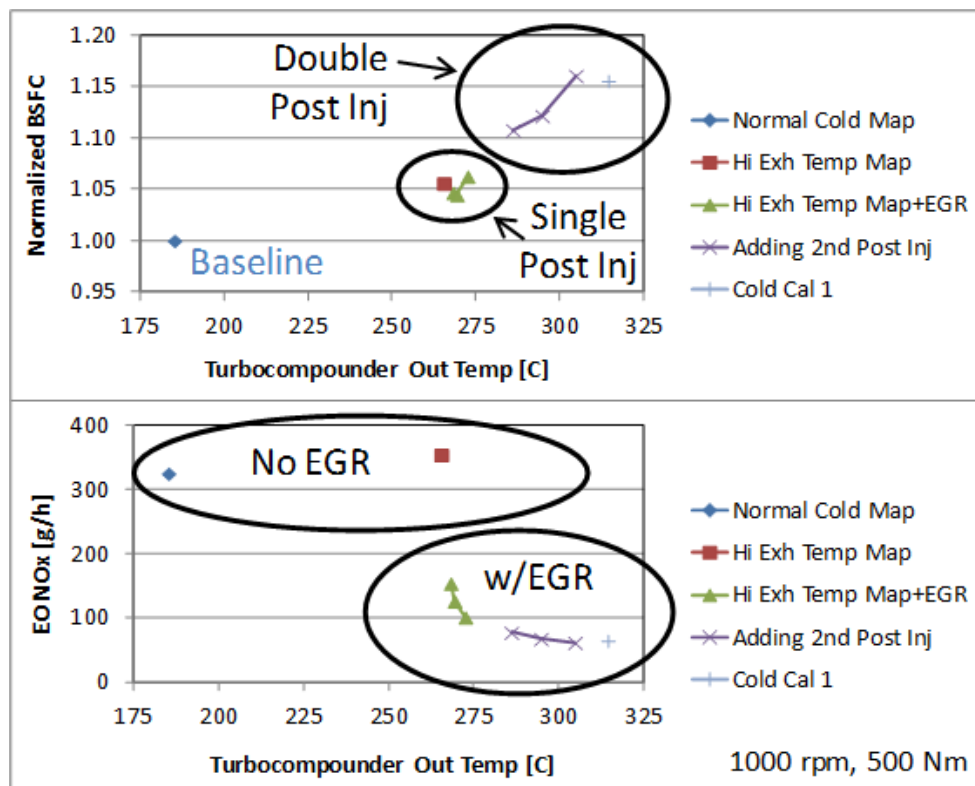


FIGURE 124. STEADY-STATE CALIBRATION TUNING RESULTS OBTAINED AT TEST POINT 2 (1000 RPM, 500 NM)

3.2.4.5 Steady-State Test Results Obtained at Test Point 7: 1800 RPM, 500 Nm

The same series of experiments were conducted at 1800 RPM and 500 Nm under cold coolant temperature conditions (maintained around 35 °C). The corresponding normalized BSFC results and engine-out NO_x mass flow rates versus turbo-compounder out temperatures are shown in Figure 125.

As shown in the top chart, neither the exhaust gas temperature nor the BSFC increased at this engine condition when the operation was changed from the normal cold map to the high exhaust temperature mode. However, as shown in the bottom chart, the NO_x emissions

increased significantly when no EGR was used. Adding EGR reduced the NO_x as expected, but caused the exhaust temperature to decrease by nearly 20 °C. The fuel consumption was not negatively impacted with EGR in the elevated exhaust temperature mode. As before, the addition of a second post injection resulted in increased exhaust temperature at the expense of increased fuel consumption. However, for the post injection quantities tested, only a marginal fuel consumption penalty was obtained at the highest temperature. It is also interesting to point out that NO_x was reduced as the post injection quantity was increased. This was due to the fact that as the post injection quantity was increased, the main injection quantity was reduced so that more of the combustion occurred later in the expansion stroke which reduces peak in-cylinder temperatures and NO_x formation at the expense of thermal efficiency. Finally, the resulting Cold Cal 1 operation provided a 50 °C increase in exhaust gas temperature with a 4% fuel penalty over the baseline normal cold map operation at this engine condition. The NO_x mass flow rate was reduced by 73% from the baseline.

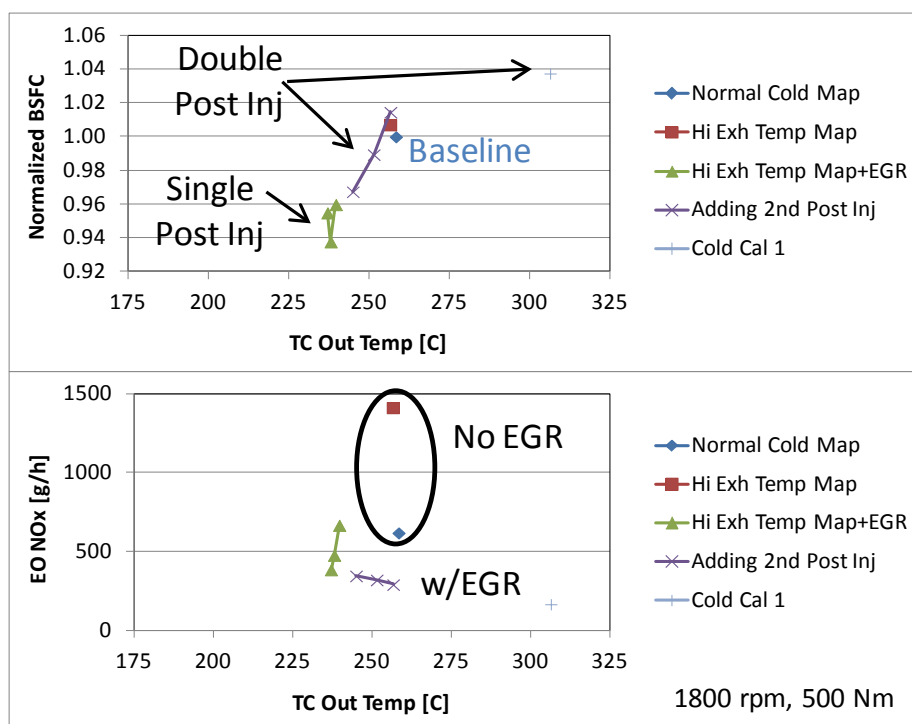


FIGURE 125. STEADY-STATE CALIBRATION TUNING RESULTS OBTAINED AT TEST POINT 7 (1800 RPM, 500 NM)

3.2.4.6 Summary of Steady-State Cold Calibration Tuning

To summarize the results of the final revised calibration map, a comparison table for the selected steady-state evaluation test points is provided in Table 49, which lists the corresponding turbo-compounder out temperatures and engine-out NO_x mass, flow rates for the baseline normal cold map and Cold Cal 1. Also included is the BSFC penalty for the Cold Cal 1 relative to the baseline cold calibration operation.

TABLE 49. SUMMARY OF STEADY-STATE CALIBRATION TUNING AT TEST POINTS 1-8

Test Point	Engine Speed	Torque	Calibration	TC Out Temperature	Engine-out NOx	Normalized BSFC
[-]	[RPM]	[Nm]	[-]	[°C]	[g/h]	[-]
1	1000	0	Baseline ⁽¹⁾	95	44.3	1.0 ⁽²⁾
			Cold Cal 1	139	47.3	2.2 ⁽²⁾
2	1000	500	Baseline	185	325	1.00
			Cold Cal 1	314	65.0	1.16
3	1000	1000	Baseline	246	572	1.00
			Cold Cal 1	369	198	1.04
4	1000	2000	Baseline	329	1495	1.00
			Cold Cal 1	358	695	0.98
5	1400	500	Baseline	201	485	1.00
			Cold Cal 1	306	110	1.12
6	1400	2000	Baseline	372	1682	1.00
			Cold Cal 1	357	631	0.95
7	1800	500	Baseline	258	619	1.00
			Cold Cal 1	306	167	1.04
8	1800	1000	Baseline	286	725	1.00
			Cold Cal 1	301	268	0.90

(1) Baseline idle speed of 550 RPM

(2) Normalized fuel flow rate

3.2.4.7 Transient Evaluations of Revised Cold-Start Engine Calibration

This section presents the evaluation of the revised cold calibration over the cold-start FTP cycle. Two sets of revised cold calibration results are reported. The difference between the two results is the idle speed used for the first 400 seconds of the FTP cycle as tests were conducted with both the base idle (BI) and elevated idle (EI) speeds. The engine speed profiles for these two cases are shown in Figure 126 for the first 600 seconds of the FTP cycle. The idle speed is different for the two cases until after 379 seconds.

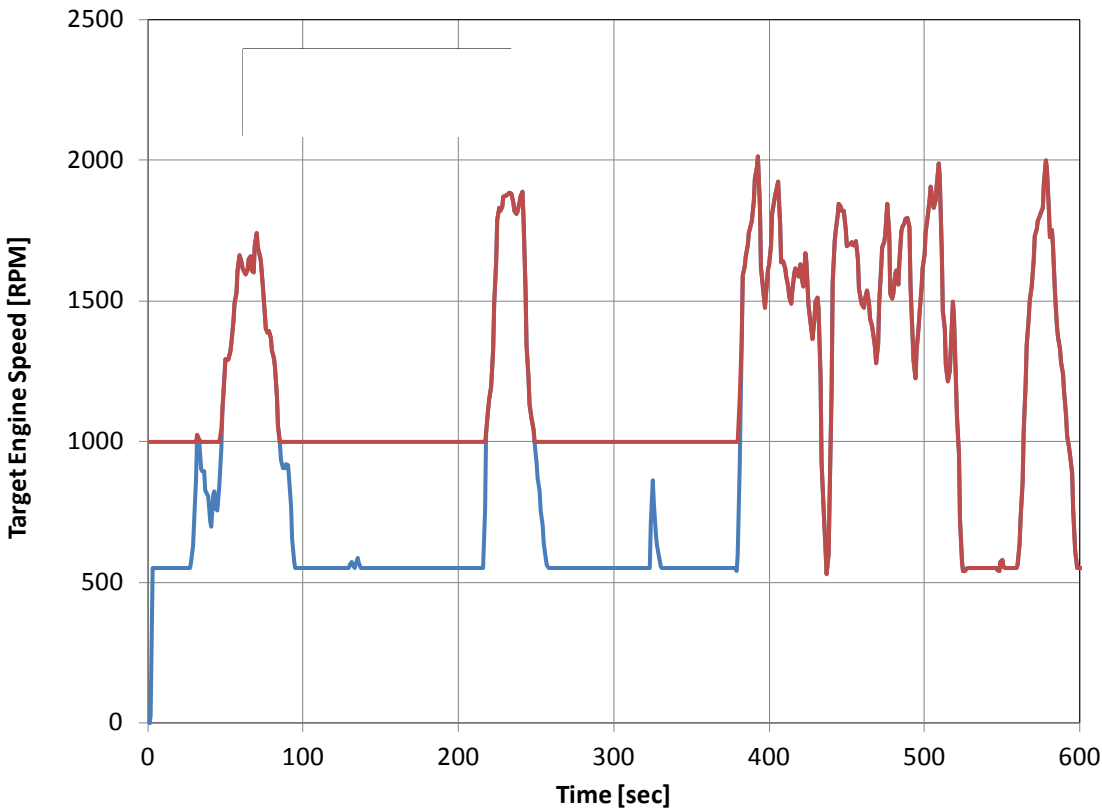


FIGURE 126. TARGET FTP ENGINE SPEED PROFILES FOR BASE AND ELEVATED IDLE TESTS

Although the heavy-duty FTP was 1200 seconds in duration, test results from the first 600 seconds of the cycle are shown in the following plots since the window of focus was the first 525 seconds. It was expected that by 525 seconds into the cycle (or earlier), sufficient NO_x control would be achieved by the selected aftertreatment system so that the engine operation could be returned to baseline control. Three sets of cold-start FTP results are presented: 1) Baseline, 2) Cold Cal 1 with BI and 3) Cold Cal 1 with EI. It should be noted that all tests were conducted without exhaust aftertreatment devices and the exhaust restriction was set to the OEM specification using an exhaust valve. The engine speed and turbo-compounder outlet (T/C out) temperature traces for the three sets of FTP tests are shown in Figure 127. The time when the engine calibration control was returned back to baseline is annotated in the chart by the green dashed line labeled “Cal change”. Engine calibration control was achieved by utilizing a scripting functionality within ATI Vision. For this task, a timer was used for calibration control since the testing was performed without aftertreatment. The calibration control logic was planned to be modified to rely on exhaust temperature inputs for calibration map switching control.

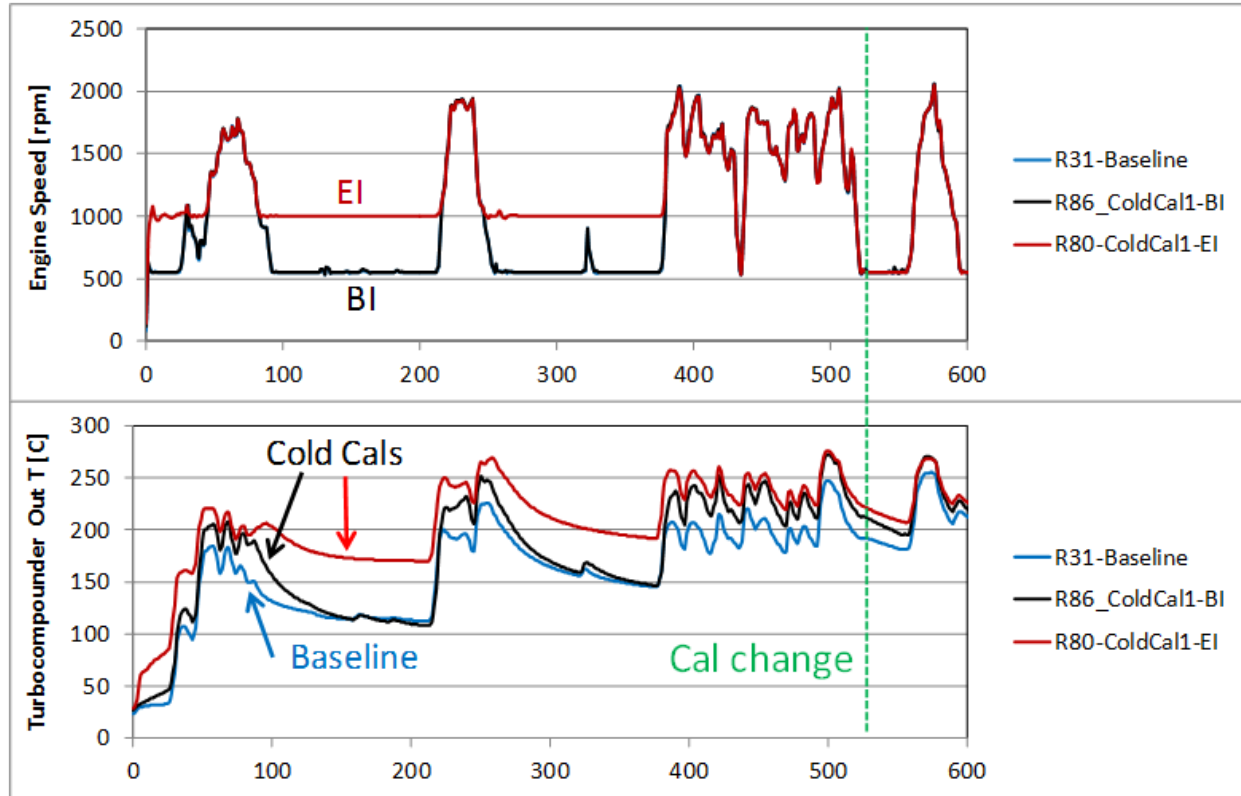


FIGURE 127. COLD-START FTP RESULTS: ENGINE SPEED AND EXHAUST TEMPERATURE COMPARISON

The benefit of the elevated idle operation in increasing exhaust gas temperature after the turbo-compounder was apparent with a 50 °C temperature increase measured during the idle periods. For the cold cal 1 operation with base idle, an increase in exhaust gas temperature of around 25 °C was observed during the off idle periods. The instantaneous and cumulative engine-out NO_x emissions are shown in Figure 128. Cold Cal 1 was effective in reducing engine-out NO_x early in the cycle, which was critical for achieving low tailpipe NO_x since the aftertreatment was ineffective until light-off was reached. In terms of cumulative NO_x, both variations of the Cold Cal 1 provided a significant NO_x reduction over the baseline calibration with a slightly higher cumulative NO_x for the elevated idle case. These results are summarized in Table 50 where cumulative results for the first 525 seconds are provided for turbo-compounder out exhaust energy and NO_x. In addition, the cycle BSFC and brake-specific particulate matter (BSPM) results are included.

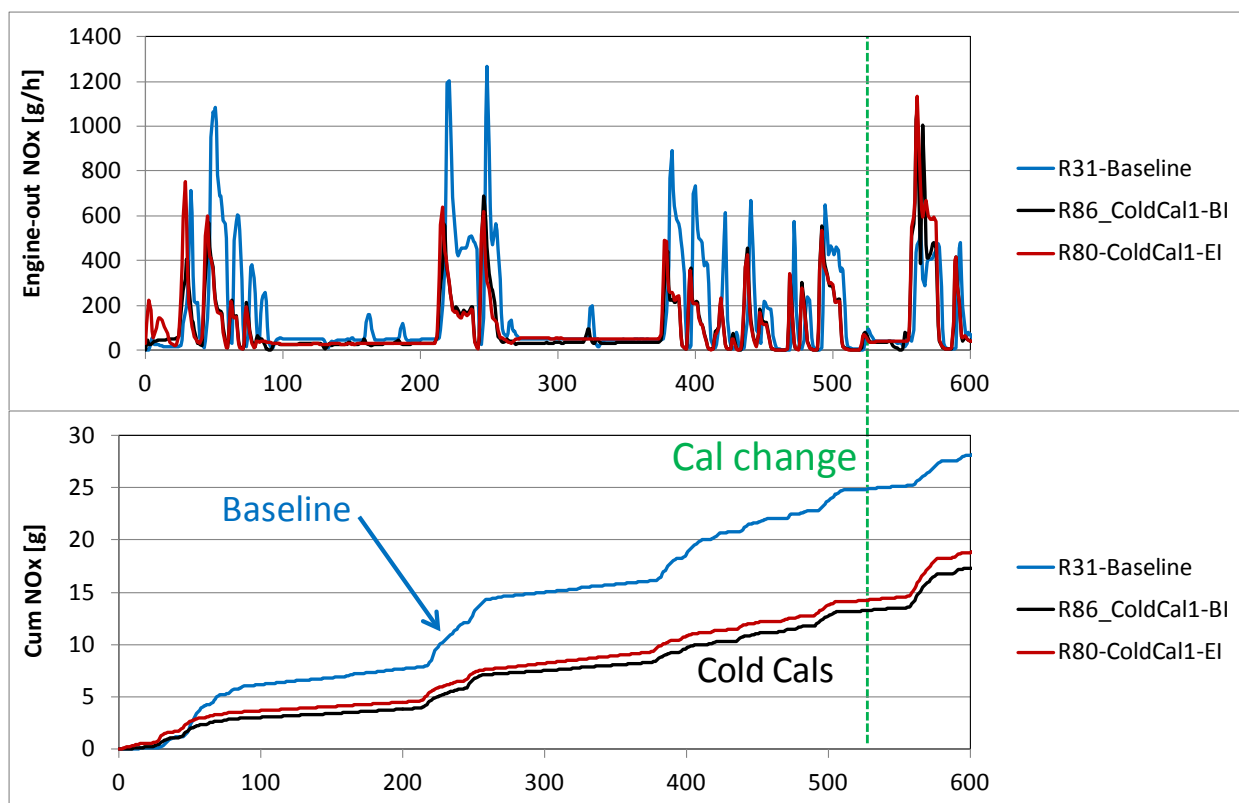


FIGURE 128. COLD-START FTP RESULTS: INSTANTANEOUS AND CUMULATIVE ENGINE-OUT NO_x COMPARISON

TABLE 50. COLD-START FTP EMISSIONS SUMMARY FOR ENGINE CALIBRATION TASK

Run Number	Engine Calibration	Cumulative T/C Out Energy (0-525 sec)	Cumulative Engine-out NO _x (0-525 sec)	Cycle BSFC	Cycle BSPM
[-]	[-]	[MJ]	[g]	[g/kW-h]	[g/HP-h]
31	Baseline	31.4	24.8	241	0.19
86	Cold Cal 1 – BI	26.9	13.3	239	0.22
80	Cold Cal 1 – EI	34.0	14.2	247	0.20

The impact of increased EGR used for Cold Cal 1 was reflected in the reduced cumulative exhaust energy for the base idle case due to a reduction in exhaust flow rate. However, the effectiveness of the EGR for NO_x reduction was evident. No change in cycle BSFC was observed for the base idle case of Cold Cal 1, however a 2.5% increase in cycle BSFC was obtained for the elevated idle case, which was consistent with the steady-state test results reported earlier. In terms of cycle BSPM, no increase was measured for either Cold Cal 1 case. The measured exhaust gas temperatures, exhaust flow rates, and emissions from these two Cold Cal 1 results were used for assessing the performance of the advanced catalyst systems with the Hot Gas Transient Reactor (HGTR) system.

3.2.4.8 Evaluation of Increased EGR During First Acceleration of FTP – Cold Cal 2

During catalyst screening activities conducted in Task 3, it became clear that reaching SCR system light-off temperature in the very early portion of the cold-start (i.e. before 90 seconds of operation) would be very challenging, even with significant thermal management. Therefore, further investigation of the practical limit of engine-out NO_x reduction available, and the associated penalties with using higher levels of EGR during the first acceleration, was of interest. As a first step, the EGR valve position history during this period of the test cycle was reviewed to see if the Cold Cal 1 EGR tables needed to be revised. During this review process, a discrepancy between the expected and actual EGR commands was discovered, especially during periods of rapid pedal increases. An example of this behavior is shown in Figure 129 where engine speed and accelerator pedal position traces are shown in the top plot and actual and expected EGR valve commands are shown in the bottom plot for a portion of the first acceleration during Run 80. The expected EGR valve command was interpolated from the Cold Cal 1 EGR map using the recorded engine speed and pedal inputs.

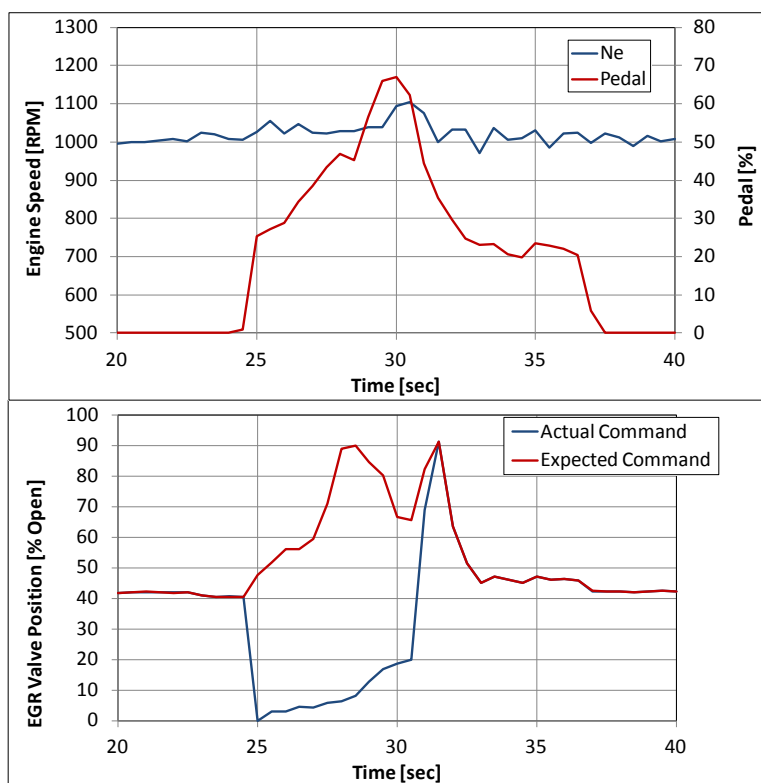


FIGURE 129. EXAMPLE OF EGR VALVE COMMAND DISCREPANCY DURING RAPID PEDAL INCREASE (FROM RUN 80)

As shown, the actual EGR valve command was significantly lower (even closed) than the expected command for a significant portion of the period of pedal increase. This behavior was discussed with Volvo who subsequently informed SwRI that this was normal as it was part of its transient engine control logic. Volvo advised SwRI on how to change the amount of EGR valve closing during this type of operation and after several iterations of EGR parameter manipulation,

an EGR command schedule that provided a significant NO_x reduction was obtained and is referred to as Cold Cal 2. A comparison of the EGR valve commands and corresponding engine-out NO_x emissions for Cold Cals 1 and 2 with elevated idle operation are shown in Figure 130 for the same period of FTP operation presented previously. As shown, a significant NO_x reduction was obtained when the EGR valve closing was limited. It should also be noted that the increased EGR level utilized in Cold Cal 2 had a measureable impact on the torque response as shown in Figure 131.

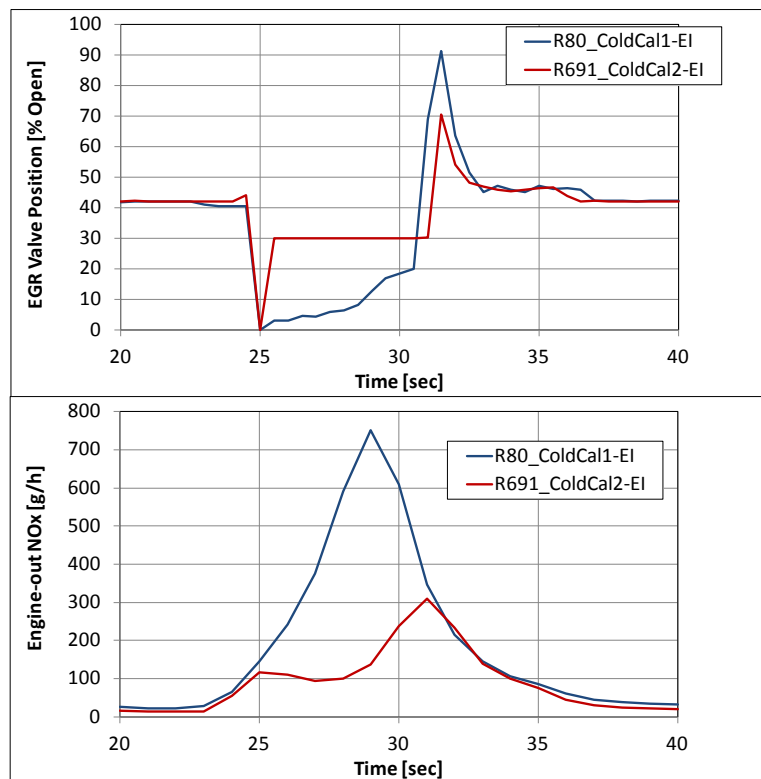


FIGURE 130. EGR VALVE COMMAND AND NO_x COMPARISON BETWEEN COLD CALS 1 AND 2

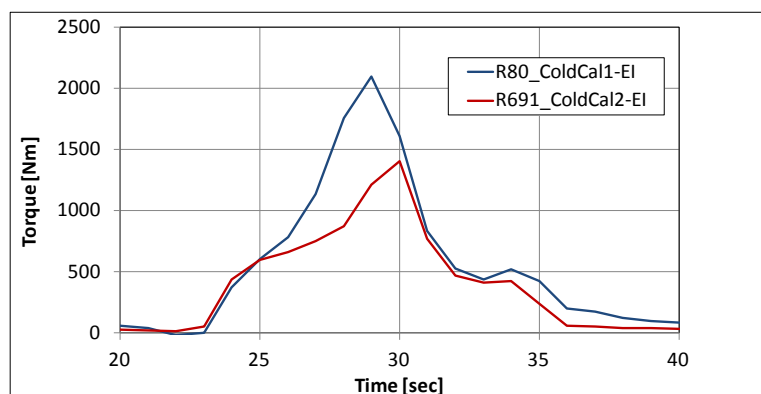


FIGURE 131. TORQUE RESPONSE COMPARISON BETWEEN COLD CALS 1 AND 2

As a reminder, the objective of this exercise was to quantify the maximum NO_x reduction potential and corresponding penalties associated with increased EGR operation during the first acceleration. For this purpose, cold-start FTP tests with both base and elevated idle speeds for the first 400 seconds were conducted using Cold Cal 2 EGR control parameters during the first acceleration (24 < time < 85 seconds) and Cold Cal 1 for the rest of the cycle until reverting to the base calibration at 525 seconds. The results obtained with these calibrations are shown in Table 51. The effectiveness of the Cold Cal 2 can be readily assessed by the cumulative NO_x mass computed up to 100 seconds.

TABLE 51. COLD-START FTP EMISSIONS SUMMARY FOR ENGINE CALIBRATION TASK WITH COLD CAL 2 RESULTS ADDED

Run Number	Engine Calibration	Cumulative Engine-out NO _x (0-100 sec)	Cumulative Engine-out NO _x (0-525 sec)	Cycle BSFC	Cycle BSPM
[-]	[-]	[g]	[g]	[g/kW-h]	[g/HP-h]
31	Baseline	6.2	24.8	241	0.19
86	Cold Cal 1 – BI	3.0	13.3	239	0.22
684	Cold Cal 2 – BI	1.9	11.0	247	0.37
80	Cold Cal 1 – EI	3.7	14.2	247	0.20
691	Cold Cal 2 – EI	2.6	12.0	256	0.33

As shown, the increased EGR in Cold Cal 2 was successful in reducing NO_x in the first acceleration with an approximate 33% reduction in cumulative NO_x after 100 seconds of the test cycle. However, additional fuel penalties between 3 and 4% and significant PM increases were incurred. In addition, the use increased EGR beyond Cold Cal 1 levels was found to cause short periods of rich operation, which was incompatible with some of the PNA technology supplied for the program. Ultimately, for this engine, the decision was made to utilize PNA technology, and therefore Cold Cal 2 was not utilized.

3.2.4.9 Comments on Additional Cold-Start Engine Measures

As stated previously, the available engine measures to increase engine-out temperature and reduce engine-out NO_x emissions early in the cold-start FTP were utilized in the revised cold engine calibration. These engine measures included cooled high-pressure-loop EGR, multiple in-cylinder injections, intake throttling and idle speed control. The engine measures were limited to those readily available due to program budget and time constraints. However, it is worth mentioning that additional measures were reported in the literature, and showed benefits in terms of increased exhaust gas temperature with reduced fuel penalty and reduced NO_x. Some of these alternative engine measures include variable valve actuation (VVA), EGR cooler by-pass, cylinder de-activation, and thermal barrier coatings. Also, because the ULN program engine turbocharger was fixed geometry, the amount of EGR that could be used to reduce engine-out NO_x during the cold-start FTP was limited. This limit was due to engine torque response considerations and because some advanced aftertreatment devices (i.e. PNA) were not tolerant of rich exhaust gas. In fact, a considerable amount of tuning of the smoke limiting tables

was done to prevent rich operation, which was found to occur with the base calibration early in the cold FTP.

3.3 TASK 3: Aftertreatment Technology Screening

This task of the program focused on screening various aftertreatment system configurations and technology enabling options. The primary objective of technology screening was to evaluate combinations of "Advanced" and "Traditional" technology systems and optional modifiers to assess the potential ULN performance of various combinations of technologies and strategies. All technologies evaluated were production or production intent devices. The goal was to rank combinations of technology with a high probability to achieve ULN emissions levels. The study was organized into two parts; "Traditional" technology and "Advanced" technology configurations. The results are presented as both cold mass emissions and composite. An additional goal of this task was to develop the Integration Control and Software logic for dosing and supplemental heating approaches.

The data was collected to enable ranking of the technologies and systems for the technology down selection of the system to be used in the final demonstration. The elements considered in ranking the technologies included:

- NO_x potential performance achieved
- Fuel economy impact of solution
- Durability
- Complexity
- Cost impact

The baseline engine provided a good example of current technology control using a typical aftertreatment emissions configuration consisting of DOC-DPF-SCR. The baseline engine emissions and overall catalyst efficiency on each cycle is shown in Table 52.

TABLE 52. BASELINE NO_x ENGINE EMISSIONS AND CONVERSION EFFICIENCIES

Test	BSNO _x [g/hp-hr]		NO _x Conversion Efficiencies [%]
	Engine-out	Tailpipe	
Cold	2.82	0.715	74.7
Hot	2.98	0.047	98.4
Composite	2.96	0.140	95.2

Under an Ultra-low NO_x (ULN) emissions control strategy, the cold-start emissions become a primary point of focus, as well as maintaining superior hot start and high space velocity control. To achieve ULN composite emissions levels, the cold-start FTP emissions must be very low (targeted less than 2.7 g for this engine), on the order of current technology hot-start emissions. The Hot-Start control strategy must achieve very high catalyst efficiency for the

whole cycle, (emitting less than approximately 0.2 g accumulated over the entire hot portion test cycle for this engine). Achieving composite ULN mass emissions of 0.02 g/hp-hr requires a more than 90% reduction from the current regulated level. Figure 132 illustrates the allowable hot-start to cold-start NO_x tradeoff that must be achieved to reach levels below ULN.

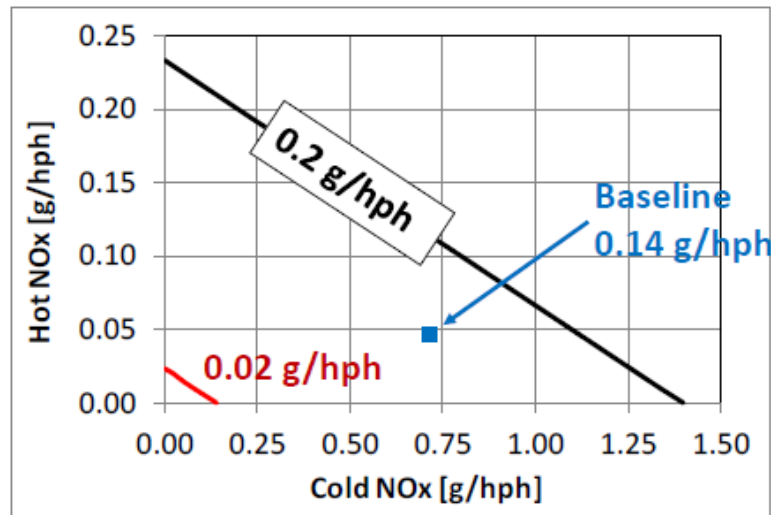


FIGURE 132. HOT-START TO COLD-START TAILPIPE NO_x MASS EMISSION TRADE-OFF TO ACHIEVE VARIOUS TARGETED COMPOSITE EMISSION LEVELS

The calibrations and elements employed in a ULN strategy can be grouped into two basic parts:

1. Reduced time to catalyst light-off
 - Modified catalyst configurations
 - Supplemental heat and/or distributed heat
 - Engine calibration for increased exhaust temperature
 - Potential consideration to Phase II Green House Gas (PII GHG) approaches
2. Reduce engine-out NO_x until catalyst was hot enough to provide good Tailpipe NO_x control
 - More aggressive engine-out NO_x reduction at low coolant temperature
 - NO_x storage catalyst systems (PNA or close-coupled light-off SCR)

Figure 133 and Figure 134 show examples of measured tailpipe NO_x emissions from the baseline engine compared to an ULN example.

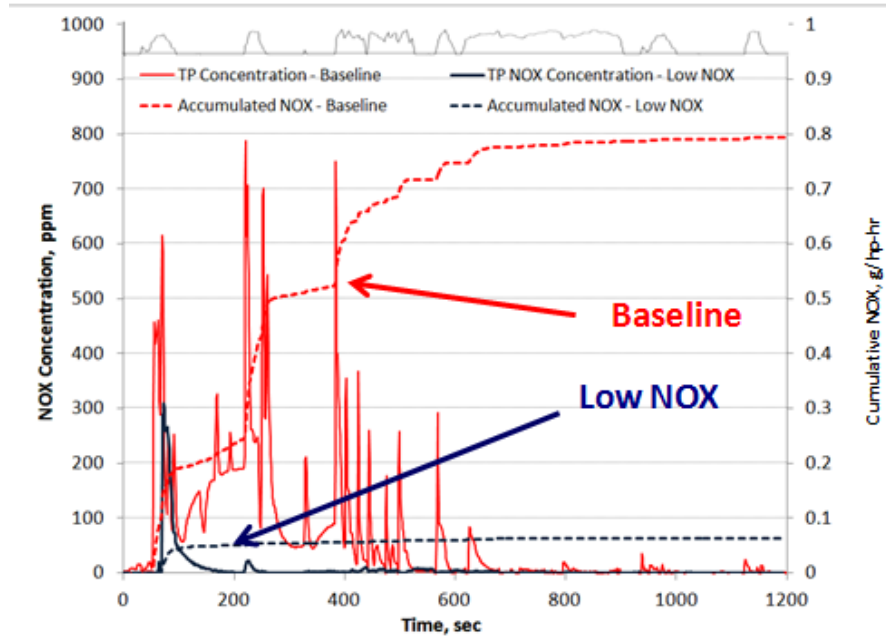


FIGURE 133. BASELINE COLD-START FTP TAILPIPE NO_x EMISSIONS COMPARED TO AN ULTRA-LOW NO_x EXAMPLE

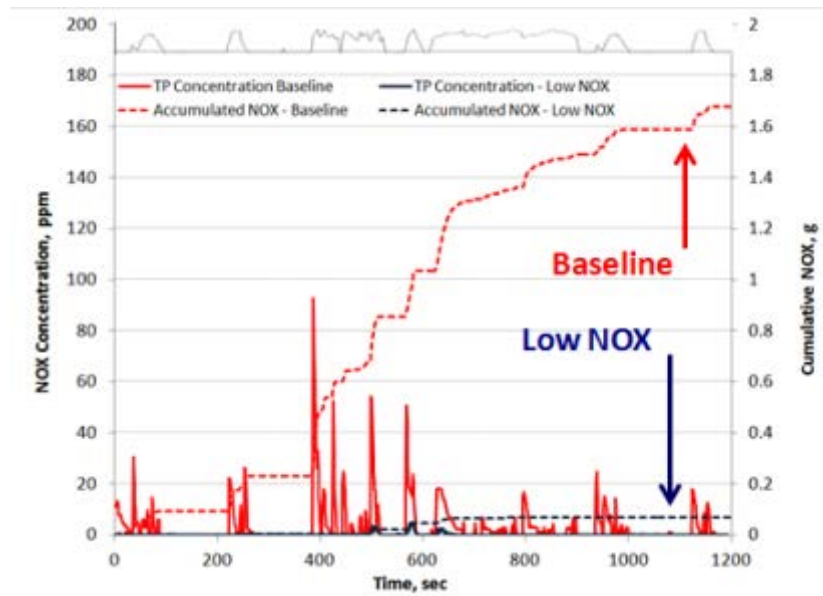


FIGURE 134. BASELINE HOT-START FTP TAILPIPE NO_x EMISSIONS COMPARED TO AN ULN EXAMPLE

There are many approaches that can be leveraged to raise the exhaust gas temperature into the catalyst, each approach costs energy and has an associated efficiency. Figure 135 shows an overview of modes of operation that can result in low exhaust temperature being delivered to the catalyst, some active thermal management approaches to address these modes, and some technologies that can be leveraged in strategies to raise the exhaust temperature. The

temperature management strategies are loosely grouped into engine-based and emissions system-based approaches. (Refer to the NOMENCLATURE for interpretation).

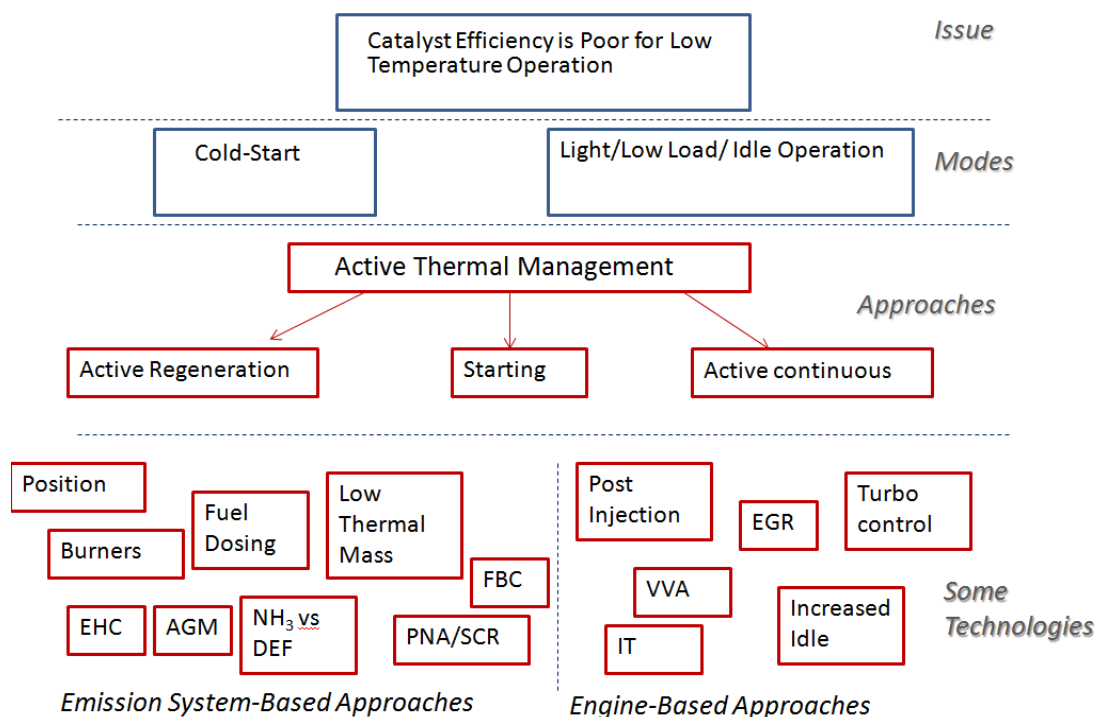


FIGURE 135. OVERVIEW OF OPERATING MODES THAT RESULT IN LOW TEMPERATURE OPERATION AND SOME TECHNOLOGIES THAT CAN BE UTILIZED TO INCREASE EXHAUST ENERGY

3.3.1 Aftertreatment Systems and Options Screened

Many different aftertreatment catalysts and optional emissions reduction enabling components were provided for this program. The preliminary goal of this portion of the study was to develop controls for and to evaluate the NO_x reduction capability of various combinations of aftertreatment components and alternate dosing and supplemental energy options to assess the feasibility of achieving ULN emission levels using production and near-production technologies. Some of the components and options that were evaluated during the screening included:

- **Low Thermal Loss/Mass Components**
 - Air gap exhaust manifolds
 - Air gap transfer pipes
 - Catalyst packaging
 - Catalyst positioning
 - Thin wall substrates
- **Advanced Technology Components**
 - SCR on Filter (SCRF)

- Passive NO_x Adsorber (PNA)
- Light-Off SCR (LO SCR)
- Advanced technology washcoats
- **Traditional Technology Components**
 - Diesel Oxidation Catalyst (DOC)
 - Diesel Particulate Filter (DPF)
 - Selective Catalytic Reduction(SCR)
 - Ammonia Slip Catalyst (ASC)
- **Dosing Options**
 - Compact mixer/doser
 - Full flow heated dosing
 - Partial flow heated dosing
 - Gaseous NH₃ injection
- **Supplemental Energy Options**
 - Electrically Heated Catalyst (EHC) (2-6 kW)
 - Diesel fueled mini-burner (5-20 kW)
 - EHC assisted catalytic oxidation

This section discusses various system configurations, optional performance modifiers and the controls developed and applied during screening. The two primary goals of this work were to rank the technologies and combinations for NO_x reduction potential and to evaluate their potential fuel economy impact.

3.3.1.1 Dosing Options and Controls Approach

The dosing and control strategies for each system were tailored according to the specific needs of the system under test, however the time allotted for tuning was very short and the results do not necessarily represent best performance possible if further effort was expended. The catalyst systems were initially preconditioned by exposing the system to elevated temperature (600 °C) for 15 minutes, and then stabilizing the NH₃ storage at 250 °C and an ammonia and NO_x ratio (ANR) of 1.2 until tailpipe (TP) NO_x efficiency achieved 99%, followed by two hot-FTP tests. Subsequent testing consisted of running one cold- and two hot-FTP tests per day during strategy development. During the work, 1-2 configurations were screened each week. All testing was conducted on aged catalysts. The systems for screening were aged under accelerated thermal conditions (no additional oil consumption) either on-engine or in oven.

The production DEF dosing system was utilized throughout the entire program for all configurations that leveraged DEF injection. The production system was an air assisted, solid cone injector designed to be sprayed along the centerline of the exhaust gas flow. A low thermal mass perforated swirl type mixer was utilized during the screening exercise. A schematic of the dosing configuration and spray are provided in Figure 136.

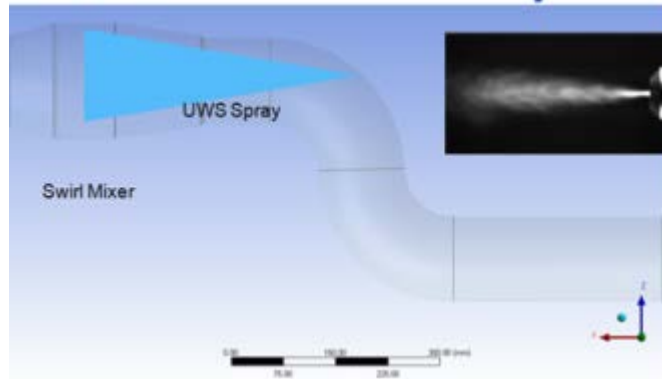


FIGURE 136. STOCK DEF INJECTOR AND DOSING LAYOUT IN EXHAUST

There were four basic DEF dosing approaches considered during this program, including:

- Traditional air assisted dosing
- Full flow heated dosing (HD1)
- Partial flow heated dosing (HD2)
- Gaseous ammonia injection

Figure 137 provides an overview of the dosing approaches considered.

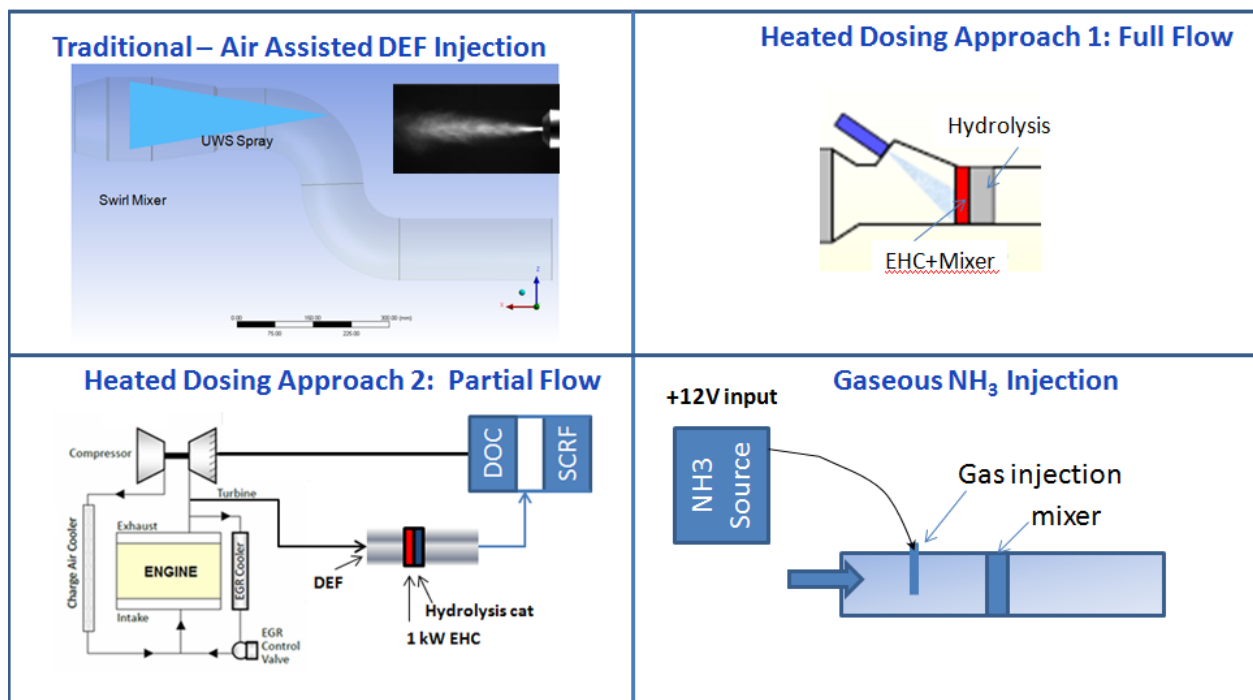
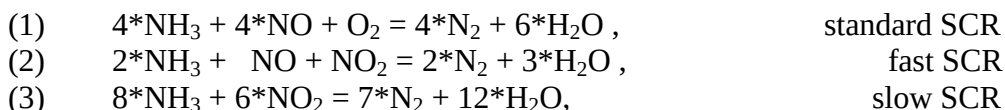


FIGURE 137. DEF DOSING APPROACHES CONSIDERED

The lower temperature threshold for injection of DEF was predominantly governed by the temperature required for evaporation of the water-based solution and the hydrolysis of DEF to NH₃ gas. This lower temperature threshold limit was around 170 °C for start of injection and 200 °C for full dosing. Since heated dosing systems employ heated evaporation surfaces and a hydrolysis catalyst, they enable lower temperature injection of DEF. The advanced SCR technologies in this program utilized Cu-Z catalysts that displayed some conversion efficiency below 170°C, so enabling lower temperature NH₃ injection should improve NO_x conversion efficiency under cold-start conditions. The SCR catalytic reduction of NO_x was governed by three primary reactions:



Since diesel engine exhaust was heavily weighted toward NO, the standard reaction and the fast reaction are the primary reactions that take place within the SCR, where the fast reaction dominates at colder temperatures. The balance between the fast reaction and the standard reaction was governed by the conversion efficiency of NO to NO₂ across the DOC for the SCR or an SCR in a typical installation position. Therefore, approaches that heat the DOC (enhancing NO-NO₂ conversion) can also act to improve NO_x efficiency through both supplemental heating and modification of the NO-NO₂ balance.

The full flow heated dosing system (HD1) utilized was a 2 kW EHC located upstream of a hydrolysis catalyst. The control strategy developed for HD1 activated the EHC at ‘key-on’ and continued supplying energy to the device until the SCR catalyst inlet temperature exceeded 190 °C. In practice, the EHC could be deactivated at this point, however, for screening the HD1 system was maintained on for a fixed period of time to enable system to system comparison. The primary benefit provided by the heated dosing system was that it enabled lower temperature dosing. Typically the SCR catalyst was capable of effectively reducing NO_x emissions below 170 °C exhaust temperature, however, DEF cannot be effectively evaporated and decomposed to form NH₃ (the active NO_x reduction chemical) at exhaust temperatures lower than 170 °C. Because HD1 provides a heated evaporation surface combined with a hydrolysis catalyst, DEF dosing can be initiated when the SCR inlet temperature exceeds 130 °C, thus making HD1 a low temperature-enabling device.

The partial flow heated dosing system (HD2) utilized a portion of exhaust gas pre-turbo charger, which then passed over a 1 kW EHC/ hydrolysis catalyst integrated with the stock dosing nozzle in a small off-side chamber. This gaseous NH₃ stream could then be directed into the exhaust upstream of the SCR catalyst in a traditional system or upstream of the SCR in an advanced technology system. Since the feed gas stream utilized pre-turbine exhaust, the gaseous NH₃ stream also contained particulate matter and could not be directed downstream of the filter catalyst in either configuration. Time did not permit evaluation of this device under screening. It was decided that both heated dosing systems would provide near equivalent results, but should a split heated dosing configuration be needed under final demonstration, that HD2 would be employed.

The gaseous ammonia system was a production device that stored NH_3 in solid form in canisters. The release of NH_3 was facilitated by heating the cylinder to produce a pressurized gaseous NH_3 stream. This was a clean stream of NH_3 and could be introduced at any point in the exhaust system. The canisters contained a finite amount of stored NH_3 , and therefore, to minimize canister change interval, this system was only utilized during cold-start. The strategy employed when using the gaseous NH_3 system was to begin dosing at 130 °C and then to transition to liquid DEF injection at 190 °C.

3.3.1.2 Supplemental Energy Options and Control Approach

The second set of optional aftertreatment performance modifiers involved exhaust energy management through the utilization of supplemental heat generation devices located in or on the exhaust system in close proximity to the catalyst. These devices included electrical heaters, fuel burners, and electrical heaters coupled with fuel oxidation over a catalyst.

All supplemental heat devices were enabled at key-on. After start was detected, a coolant and exhaust temperature check was performed to determine if the catalyst system was above or below its light-off temperature. If it was detected that the temperature of the catalyst system was below the temperature required for high conversion efficiency, the supplemental heating device was activated for a minimum period of time defined by the temperature level (essentially determining if the system was in cold- or hot-start condition) and energy was added based on temperature needs of the system. The strategies employed for screening were based on fixed inputs, this allowed system performance to be compared based on similar system inputs. The strategies were programmed to run for 550 seconds, as this was the same timing applied to the engine calibration. In application, the strategies would be tuned based on measured thermal energy of the systems, and time of application would be ideally reduced.

Each device varied in total energy output available. The goal was to accelerate catalyst light-off as much as feasible for the given device, therefore, the total power input to the exhaust varied by device being utilized. Figure 138 shows the four supplemental heating devices considered in this program:

- Diesel fueled mini-burner (MB)
- Electrically heated catalyst (EHC)
- EHC assisted catalytic fuel combustion
- Full flow heated dosing (HD1)

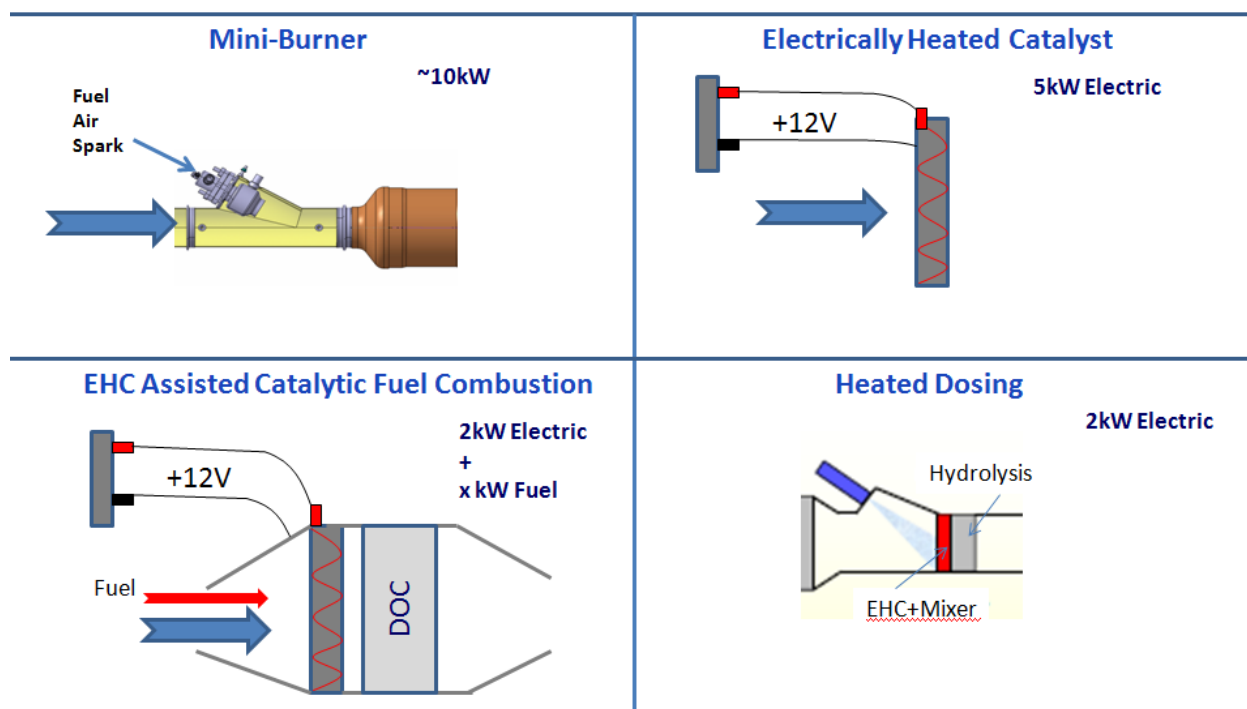


FIGURE 138. SUPPLEMENTAL HEAT ADDITION OPTIONS CONSIDERED

The diesel-fueled mini-burner (MB) was saddled on the exhaust (not submerged into the full flow) with its own fuel, air, and ignition source. The air source was designed to be belt driven, however, the system as tested was driven with a variable frequency drive. The fuel system had its own pump and metering valve. This device was programmed to activate and control the energy output to achieve a desired temperature (250-350 °C) at the SCRF inlet. The mini-burner was applied with a variable energy demand control algorithm that adjusted the energy output from 8 to 20 kW depending on the SCR catalyst inlet temperature. When the MB was applied, liquid DEF injection (no heated dosing assist) was used and the minimum SCR inlet temperature for dosing was adjusted back to 170 °C. This device was originally designed for DPF regeneration. The MB itself was not sized large enough to facilitate full flow regeneration, but rather, it was designed to elevate the DOC temperature to levels that would enable fuel dosing and oxidation over the DOC to add the remaining energy needed to raise the exhaust temperature to sufficient levels for DPF regeneration.

Two electrically heated catalysts (EHC) were evaluated in the program, 5 kW and 6 kW. All EHCs were full flow devices that utilized modulation of 24V power to modify the power of the device. These devices were activated at key-on, and operated until the first SCR catalyst inlet temperature exceeded 190 °C (approximately 400 seconds).

EHC assisted catalytic fuel oxidation utilized a 1 kW EHC coupled to a metallic DOC that was formulated for fuel oxidation. This device was originally intended to add energy upstream of the DOC to enable fuel oxidation over the DOC to elevate the exhaust temperature to levels necessary for carbon oxidation during DPF regeneration (similar in application to the MB). Only preliminary evaluations targeted at cold-start energy addition were conducted with this device, but this device was considered to provide significant potential output, similar to the

energy output of the MB. The calibration effort was considered to be more involved than the MB, but the hardware complexity and durability considerably less. The control strategy involved activating the EHC either with pre-heat or at key-on, waiting for the DOC to reach fuel oxidation temperatures, and then activating in-exhaust fuel dosing.

Distributed heat was also evaluated as a supplemental heating option, and was achieved by installing a 5 kW electric heater after the DPF, upstream of the dosing system along with HD1, the power to each device was modulated for a total of 5 kW of electric energy. The dosing control strategy and activation duration was the same as for HD1.

3.3.1.3 Aftertreatment Component Configurations

MECA member companies provided the catalysts and components. Each component was canned and flanged to allow modular construction enabling various configurations and options to be tested. The systems were organized into two basic subsets; advanced technology systems or traditional technology systems. The traditional technology systems consisted of a DOC-DPF-SCR and the NO_x reduction performance was modified using alternate dosing options or the addition of supplemental heat. The advanced technology systems contained catalyst components that varied from the traditional technologies, such as PNA and SCRF. There were over 500 different possible combinations of catalysts, options and test cycles from the components that were received. The experimental screening exercise was conducted over a 20-week period, so the number of approaches to be physically tested was reduced to 33 via an analytical screening process. Analytical screening consisted of a combination of modeling, engine data, and supplier information, to look at the potential of various technology combinations, and to narrow the test plan to only the most promising approaches and avoid duplication of effort. The selections were chosen to encompass a wide array of combinations to enable a broad picture of technology trends to meet ULN. Figure 139 depicts the advanced technology configurations with options that could have been tested.

Advanced Technology

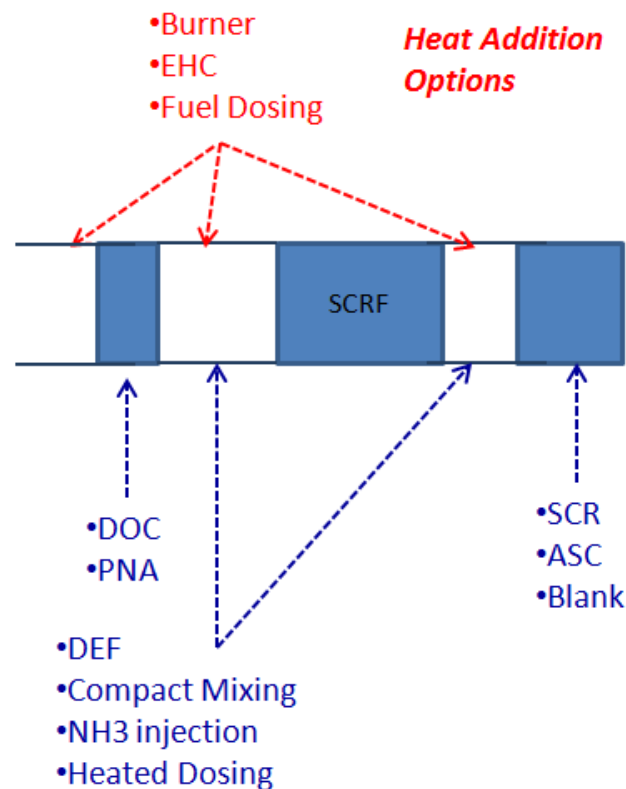


FIGURE 139. ADVANCED TECHNOLOGY CONFIGURATION WITH OPTIONS

A potential advantage of the advanced technology configuration is that it allows close coupling of SCR catalyst, which potentially reduces the warm up time and energy requirement to achieve effective NO_x control. However, competition for NO_2 between the SCR fast reaction and passive soot oxidation of the PM filter may reduce the passive regeneration capability of the SCRF filter and require more frequent active regeneration.[7][8] This results in higher fuel penalties and potentially higher Infrequent Regeneration Adjustment Factors (IRAF).

One major advantage of the traditional system is that it maximizes passive regeneration of the DPF through the use of NO_2 , and there is a large body of knowledge and experience with the technology contained in the system. The biggest disadvantage is that placing the SCR after the DPF results a large amount of thermal mass upstream of the SCR, which increases the amount of time required to achieve catalyst light-off and thus effective NO_x control. Figure 140 depicts the traditional technology configurations with options that could have been tested.

Traditional with Options

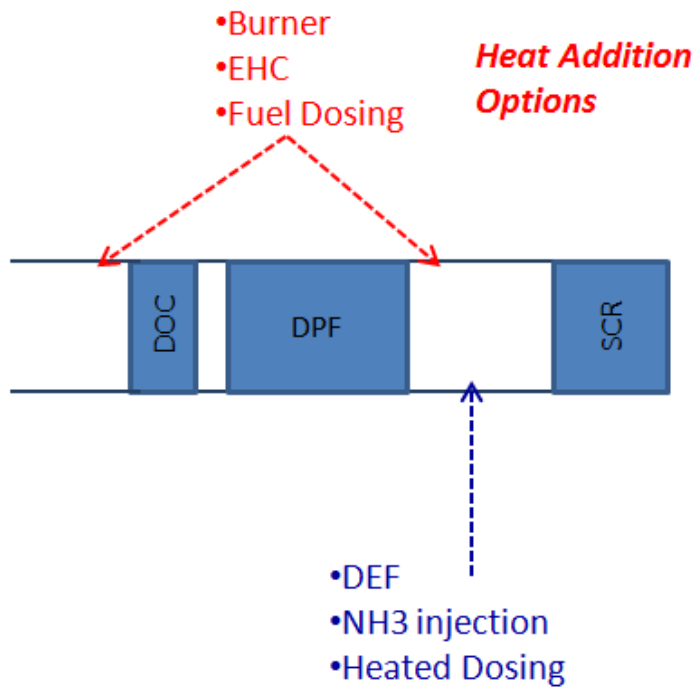


FIGURE 140. TRADITIONAL TECHNOLOGY CONFIGURATIONS WITH OPTIONS

Table 53 provides the typical size range of components tested and compares those to the production emissions system for reference. This table shows that emissions systems designed for ULN trend toward larger volume SCR catalysts. This results in reduced catalyst space velocity, increased NH₃ storage capacity, and reduced aging impact.

TABLE 53. TYPICAL CATALYST VOLUMES

	Catalyst Volumes			
	DOC (L)	DPF SCRF (L)	SCR/ASC (L)	Total (L)
Traditional Technology	13	22	26	61
Advanced Technology	13	26	26	65

All systems were canned in a ‘modular’ fashion to enable reconfiguration of the catalyst and optional components. Figure 141 shows the typical layout of the systems tested. Each system included the following requirements:

- All components clamped using a ‘standard’
- Allows all components to be interchanged
- NO_x sensors at EO, mid-bed and TP
- Temperature and Sample at inlet and outlet of each component and mid-bed SCR
- NH₃ sensor mid-bed SCR or SCRF out
- All cones air gap
- All systems connect to same air gap down pipe

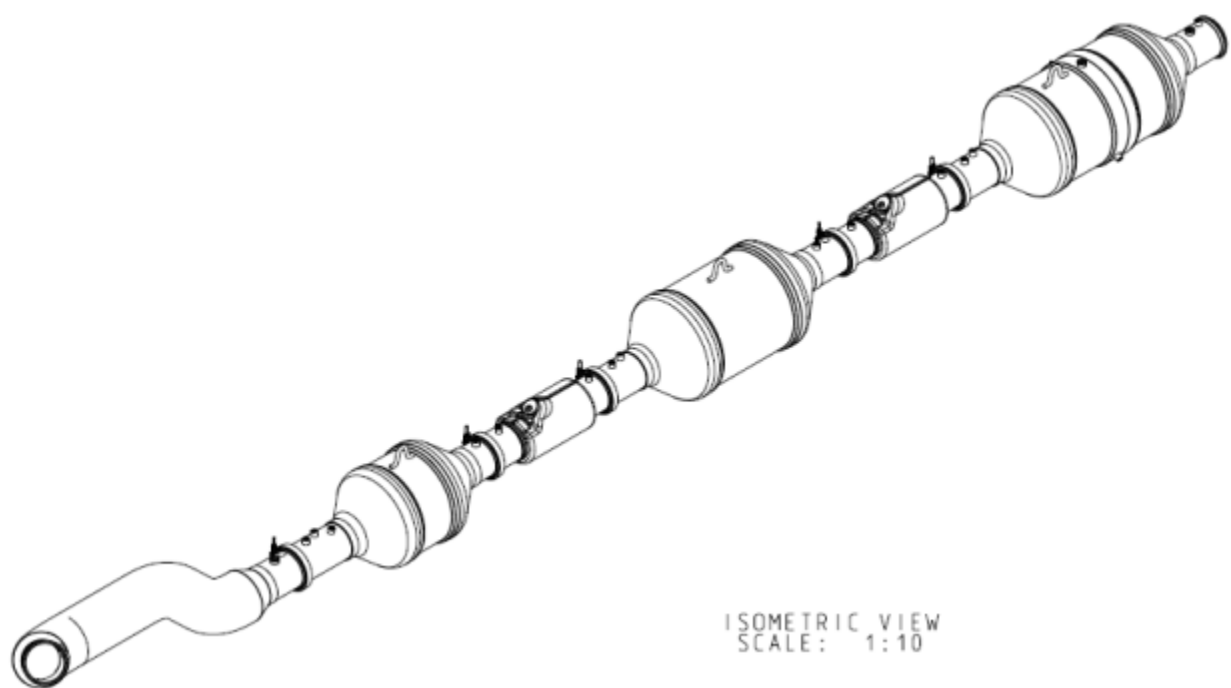


FIGURE 141. EXAMPLE LAYOUT OF AFTERTREATMENT FOR SCREENING EXERCISE

3.3.2 Transient Reactor Bench

The screening studies were performed using SwRI’s full size transient gas reactor (FOCAS® Hot Gas Transient Reactor (HGTR™)) to provide precise control of the relevant exhaust gas components enabling accurate comparisons between the various emissions system configurations.

The HGTR is a computer-controlled, burner-based, continuous flow reactor system designed to duplicate the lean exhaust conditions produced by medium-duty to line-haul size truck engines. The HGTR is a fully transient, full size reactor system. Unlike typical small core

gas reactor benches, which use bottled gas to simulate exhaust conditions, the HGTR produces a continuous exhaust flow through combustion of fuels and compounds, producing an exhaust gas composition that replicates the array of gaseous species found from the combustion of diesel fuel in an engine. The exhaust gas conditions are generated through independent, model-based control and allow any combination of mass flow, temperature, NO_x , H_2O and O_2 concentration within the window of operation. The HGTR is primarily used for catalyst performance evaluation and screening, multi-dimensional mapping, control model calibration, engine/catalyst calibration integration, and engine cycle simulations, and can be applied to individual catalysts or complete exhaust aftertreatment systems. A schematic of the system is shown in Figure 142.

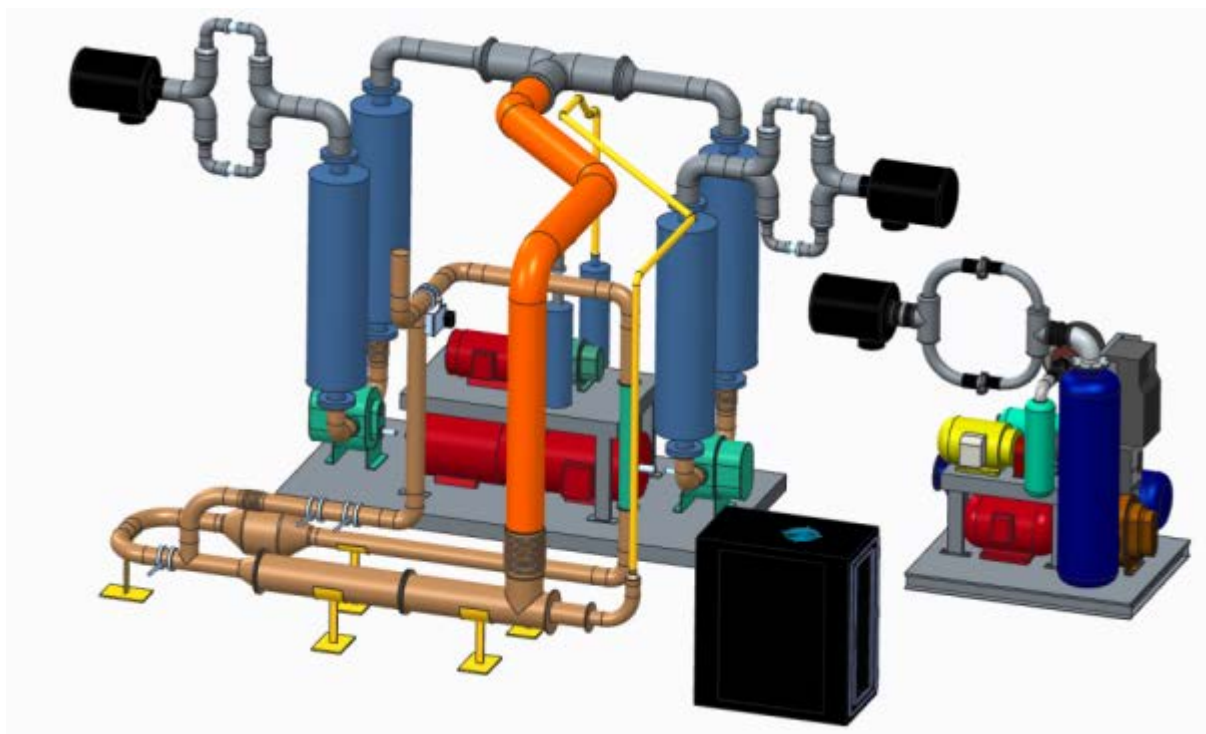


FIGURE 142. SCHEMATIC OF TRANSIENT REACTOR BENCH

The first task in the screening study was to use the reactor to simulate the baseline FTP cycle from the Volvo Engine. During this task, the engine out exhaust gas temperature, flow and NO_x concentration were simulated. Figure 143 shows a comparison of these parameters measured over the cold-start FTP cycle between the engine and the HGTR system. The tailpipe NO_x mass emissions between the engine and the HGTR are shown in Figure 144.

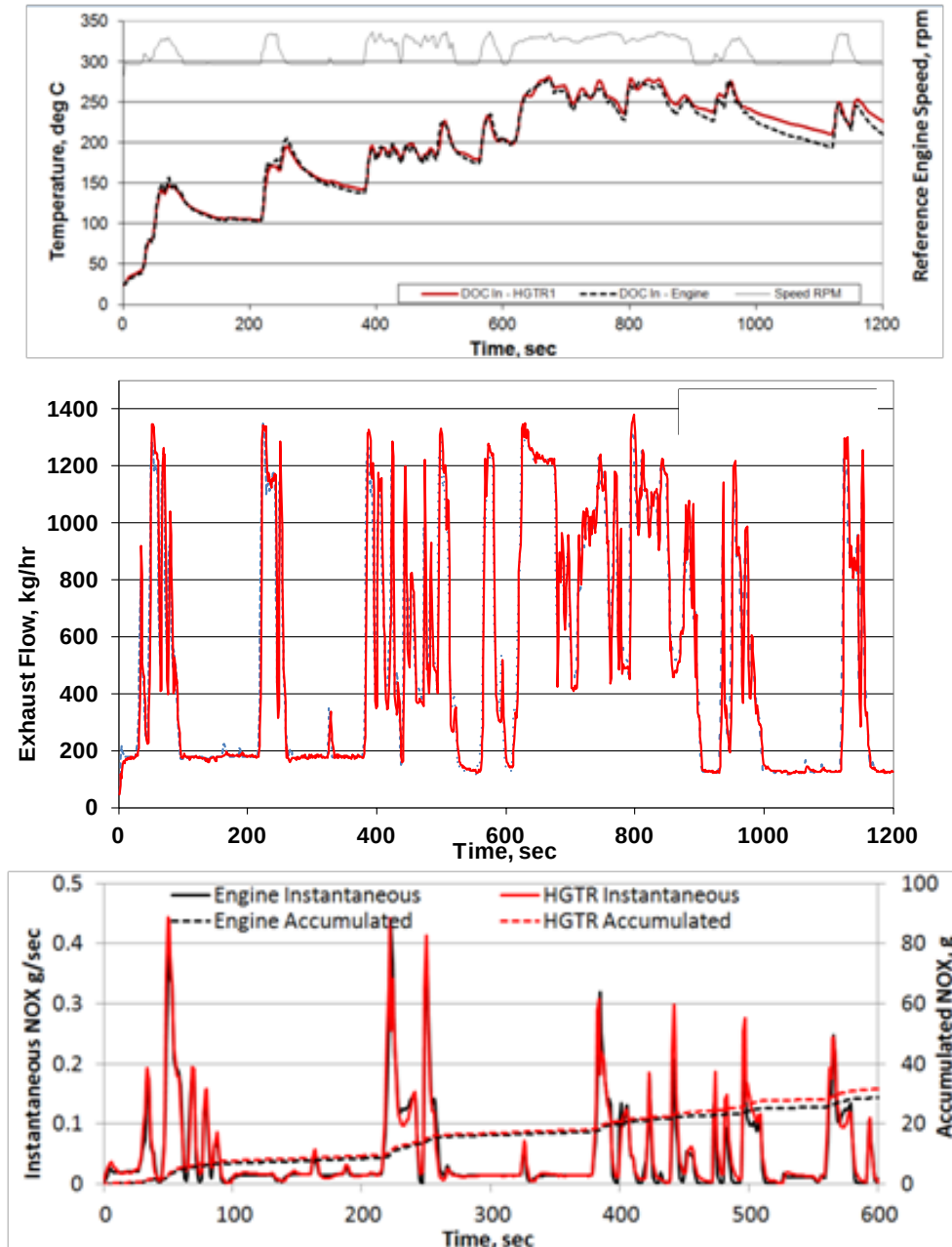


FIGURE 143. COMPARISON OF BASELINE EXHAUST GAS CONDITIONS BETWEEN THE ENGINE AND THE HGTR

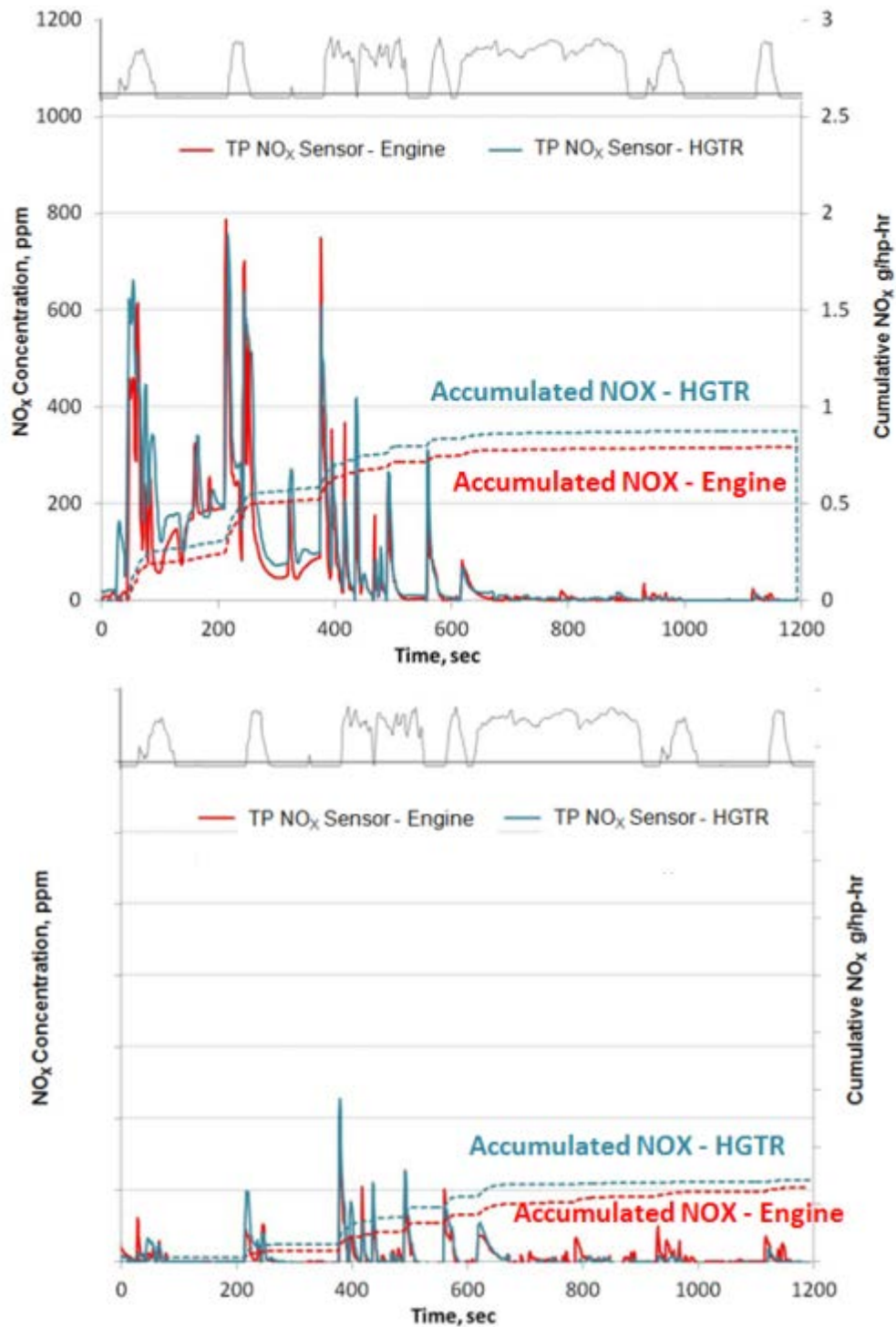


FIGURE 144. BASELINE TAILPIPE NO_x EMISSIONS FROM THE STOCK ATS; TOP SHOWS THE COLD-START CYCLE, BOTTOM SHOWS THE HOT-START CYCLE

3.3.3 Aftertreatment Integration Controller

Since the stock Aftertreatment Control Module (ACM) did not support optional equipment, or modified dosing strategy development, a stand-alone integration controller was developed during screening to enable the control of dosing and supplemental heating options and to allow a dosing control model to be integrated and developed. The controller was designed to work with the aftertreatment system, thus enabling it to be transferred to the engine along with the aftertreatment systems for final calibration and demonstration portion of the program. This allowed all control strategies developed during screening to be directly leveraged, thereby avoiding duplicate controls development or calibration on the engine. Figure 145 shows a schematic overview of the Integration Controller Function.

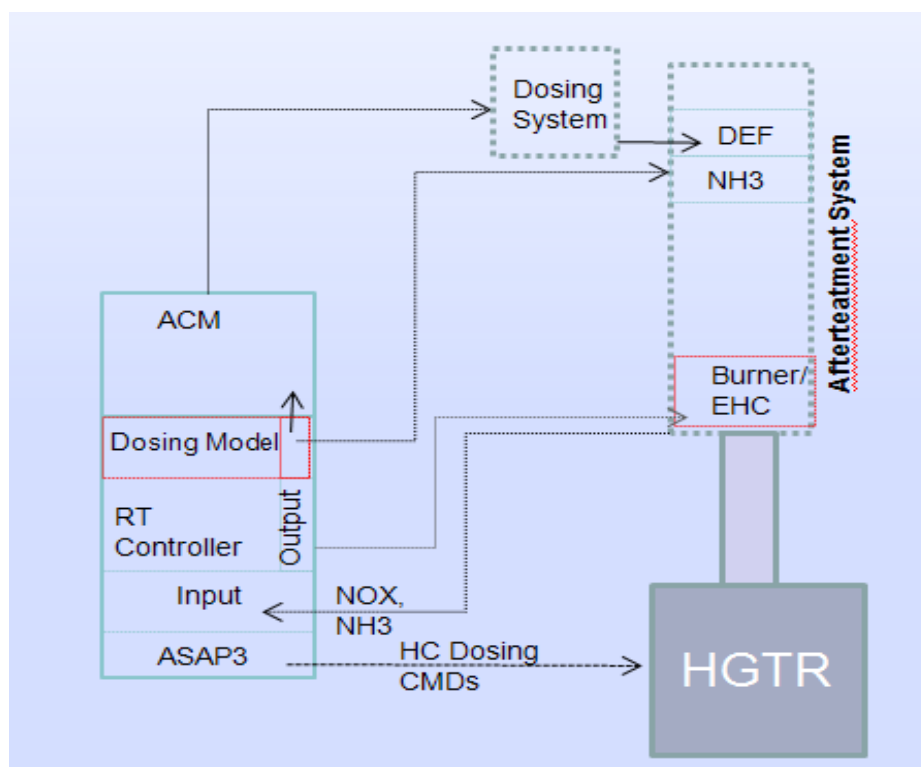


FIGURE 145. SCHEMATIC OF INTEGRATION CONTROLLER FUNCTION

3.3.4 Traditional Technology Configurations

One major advantage of the traditional system is that it maximizes passive regeneration of the DPF through the use of NO_2 , and there is a large body of knowledge and experience with the technology contained in the system. The biggest disadvantage is that placing the SCR after the DPF results a large amount of thermal mass upstream of the SCR, which increases the amount of time required to achieve catalyst light-off and thus effective NO_x control.

The first set of screening evaluations explored traditional technology aftertreatment systems (ATS). These systems included a DOC-DPF-SCR catalyst array, positioned in the conventional current heavy-duty architecture with the DPF upstream of the SCR catalyst. Two

sets of hardware were evaluated, the production emissions system and an improved traditional system that utilized low temperature performance washcoats and low thermal mass substrates.

The production emissions system (DOC-DPF-DEF-SCR) was studied under four combinations of calibration and supplement heat addition:

- Baseline calibration
- Cold Engine Calibration 1 – elevated idle (Cold Cal 1)
- Baseline calibration + mini-burner (MB) heat addition
- Cold Cal 1 + MB

Applying the Cold Cal 1 engine calibration to the production ATS, resulted in a reduction of tailpipe NO_x from 0.14 g/hp-hr to 0.09 g/hp-hr composite. This reduction was due largely to the reduction of engine-out NO_x emissions by 40% during the catalyst warm-up period. Figure 146 shows a comparison of the instantaneous and accumulated NO_x between the baseline and the Cold Cal 1 engine calibration on the stock ATS. Figure 147 provides a comparison of DEF dosing between the two tests. During screening, a simple temperature activated real-time ammonia to NO_x ratio (ANR) with mid-bed ammonia (NH₃) compensation was employed. It was hypothesized that this strategy could be more repeat-controlled and more quickly tuned between the systems to promote more consistent results for system evaluations. The impact of the elevated exhaust temperature and flow (increased energy) of Cold Cal 1 calibration achieved a slight advantage that can be seen as earlier DEF dosing compared to the baseline (achieving dosing temperatures about 75 seconds sooner). In addition to the reduced NO_x calibration, the earlier dosing also acted to help reduce tailpipe NO_x.

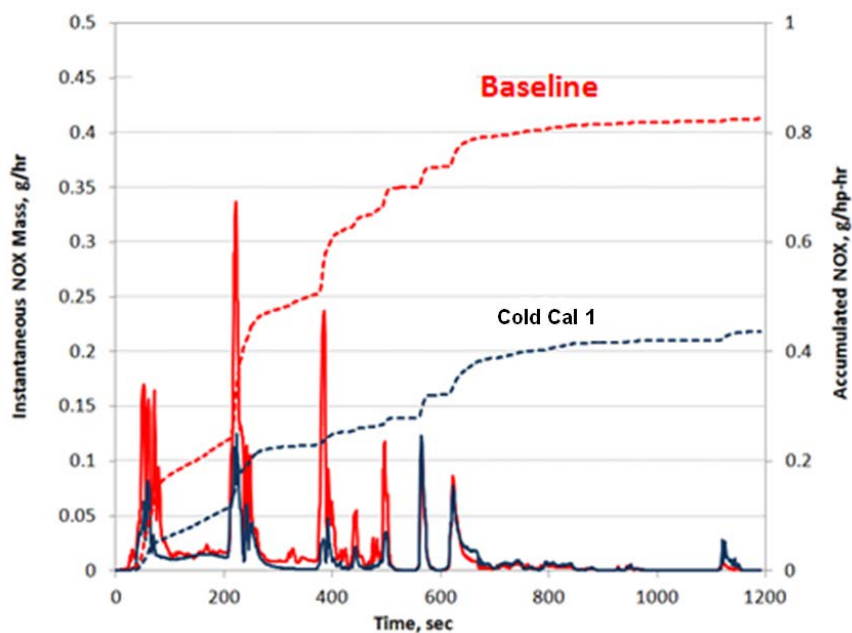


FIGURE 146. TAILPIPE NO_x EMISSION COMPARISON BETWEEN THE BASELINE ENGINE CALIBRATION AND COLD CAL 1 FOR THE STOCK EMISSIONS SYSTEM

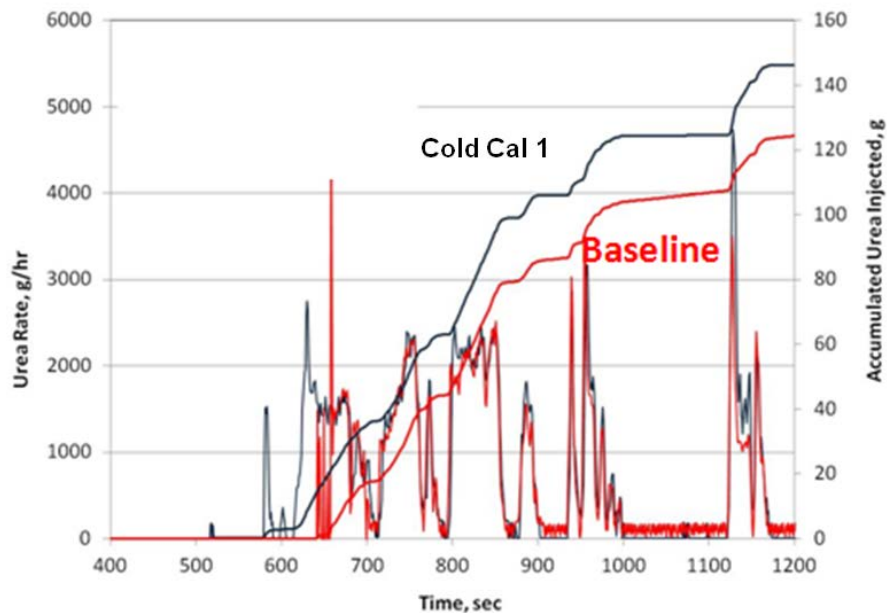


FIGURE 147. MEASURED INSTANTANEOUS AND ACCUMULATED DEF DURING THE BASELINE AND COLD CAL 1 COLD-START FTP CYCLES

Applying a small diesel burner (with variable energy from 5-20 kW) upstream of the catalyst array (MB+DOC+DPF+DEF+SCR), but using the baseline engine calibration reduced the composite tailpipe NO_x emissions to approximately the same level (0.09 g/hp-hr) as applying the Cold Cal 1 engine calibration. However, the NO_x reduction was achieved using a very different approach (supplemental heat as opposed to engine calibration), and the lower NO_x result was largely due to the accelerated catalyst warm-up time and reduced time to dosing. During cold-start, the mini-burner calibration utilized 5 MJ of additional fuel energy and 0.35 MJ of parasitic loss (from the belt driven air pump) which corresponds to 2.6% fuel penalty over the cold-FTP. The resulting heat addition brought the SCR inlet temperature up to over 200 °C significantly faster (i.e., 400 seconds faster) than the stock system without the heat addition. Both approaches (MB and Cold Cal 1) resulted in a 2.6% fuel economy penalty on the cold-start (about 0.4% fuel penalty on a composite FTP) – equivalent fuel penalty for equivalent NO_x reduction.

The final comparison applied Cold Cal 1 engine calibration and the MB to the stock system. The combination of both the MB and Cold Cal 1 reduced the tailpipe NO_x emission by an additional 5.4 g, resulting in a total fuel penalty of 5.1 % over the cold-FTP (0.78% combined penalty over the composite FTP). The emitted tailpipe NO_x level was approximately 5 grams over the cold-FTP test (resulting in 0.06 g/hp-hr composite), which was substantially above the sub-2.7 gram level needed for ULN. Figure 148 provides a comparison of the measured SCR inlet temperature for the Cold Cal 1 test to the same calibration, but with the addition of the MB. Figure 149 shows a comparison of the measured DEF dosing for the MB+Cold Cal 1 configuration to the baseline, where the start of dosing was triggered when SCR catalyst inlet temperatures exceeded 170 °C for both tests.

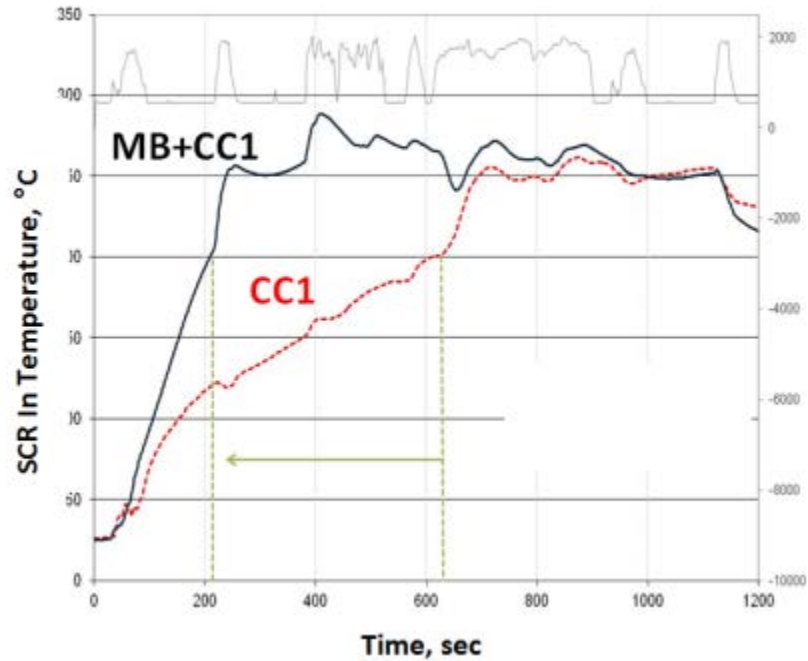


FIGURE 148. SCR CATALYST INLET TEMPERATURE FOR THE ULN COLD CAL 1 CALIBRATION ON PRODUCTION ATS COMPARED TO SAME CONFIGURATION WITH ADDITION OF A MB DURING CATALYST WARM UP PERIOD

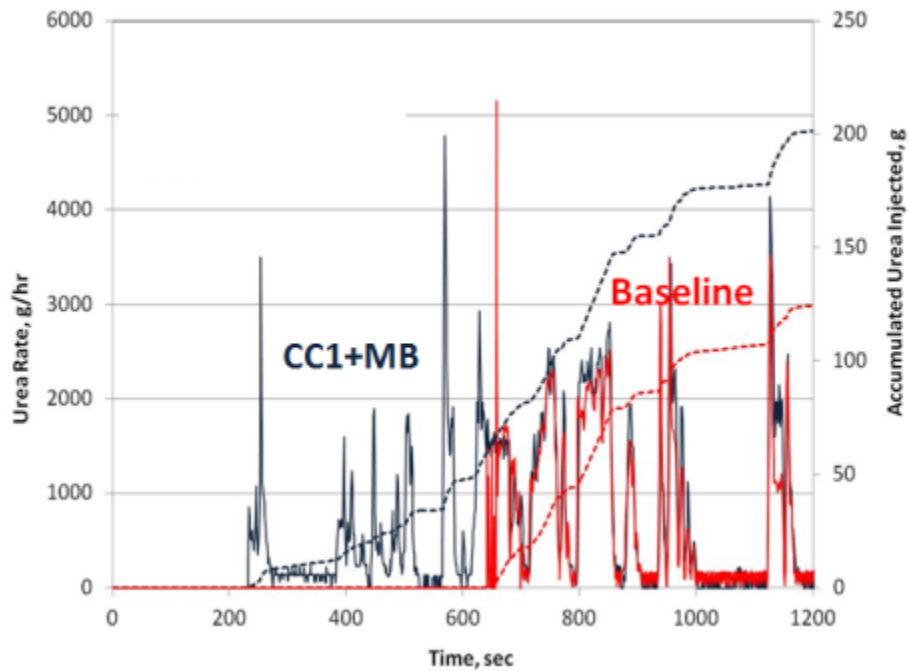


FIGURE 149. MEASURED DEF DOSING FOR BASELINE ENGINE CALIBRATION ON PRODUCTION ATS COMPARED TO COLD CAL 1 CALIBRATION WITH ADDITION OF A MINI BURNER DURING COLD-START

These results highlight the potential reductions that can be realized by applying engine calibration and supplemental heat, without any further modifications to the current aftertreatment or engine technology. Figure 150 provides a summary of the NO_x emission results obtained utilizing the production emissions system. The graph shown in this figure represents the backdrop for the comparison discussion presented in this study. The y-axis is composite FTP NO_x potential (recall the results are generated using transient exhaust gas simulation). The x-axis is loosely laid out from left to right beginning with simple DEF injection (no supplemental in-exhaust energy addition) on the left, moving to advanced DEF injection (options that reduce the temperature threshold required for DEF dosing) or small heat additions and then finally to the far right, solutions that leverage high levels (≥ 5 kW) of supplemental energy addition. Figure 151 shows the measured instantaneous NO_x mass emission and accumulated mass for all four stock ATS tests.

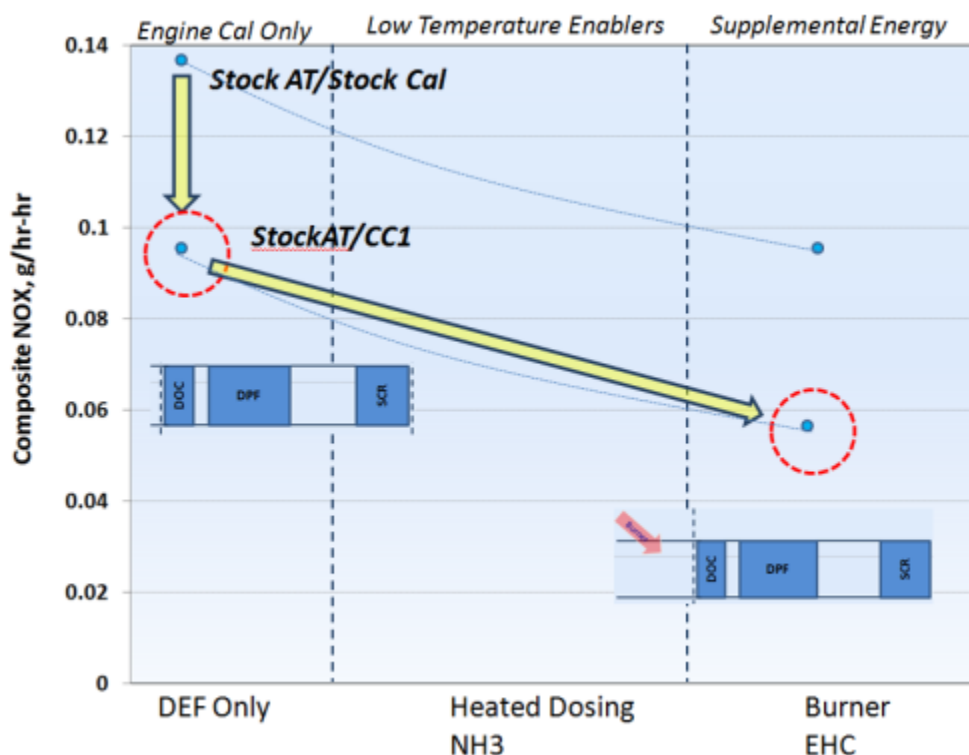


FIGURE 150. COMPOSITE NO_x POTENTIAL OF PRODUCTION ATS WITH MODIFIED ENGINE CALIBRATION AND SUPPLEMENTAL HEAT ADDITION

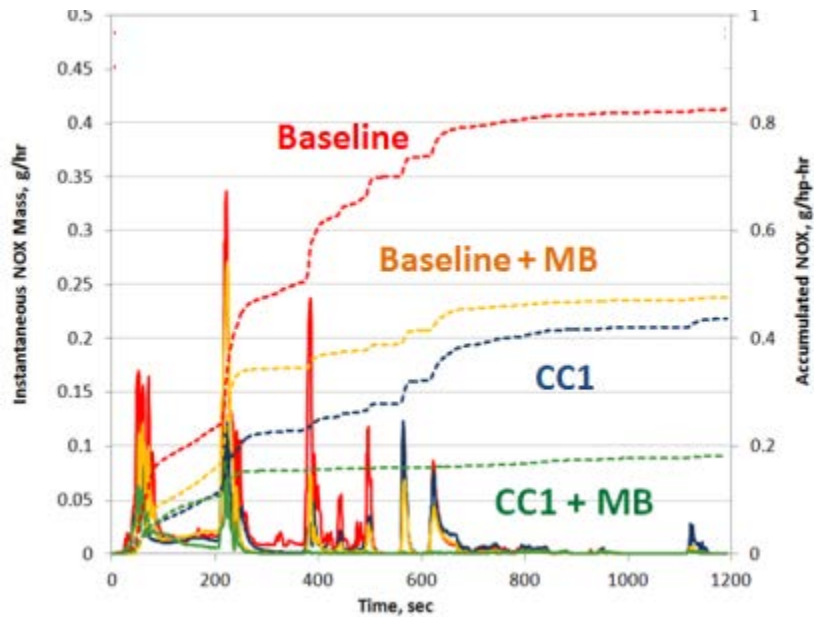


FIGURE 151. COMPARISON OF INSTANTANEOUS AND ACCUMULATED TAILPIPE NO_x EMISSIONS FOR PRODUCTION ATS TESTS

The next traditional system evaluated represented a high performance system designed for best NO_x performance by utilizing low thermal mass substrates and advanced washcoats. This system was referred to as ‘improved traditional technology’, and the performance was assessed utilizing heated dosing (1), distributed heat (2), and supplemental heat from the MB (3). Figure 152 shows a schematic layout of the configurations tested. There were two basic configurations that utilized electrical energy, the first utilized HD1 to enable low temperature dosing, the second included HD1 plus an additional EHC at the outlet of the DPF for a total energy input of 5 kW. The MB configuration utilized the same energy addition control approach and calibration as the stock traditional system.

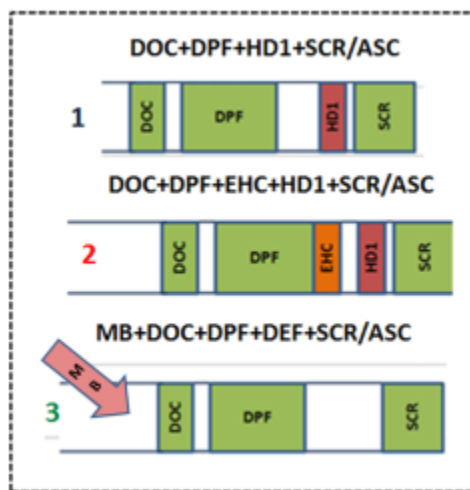


FIGURE 152. CONFIGURATION OF TRADITIONAL TECHNOLOGY SYSTEMS TESTED

In the absence of any supplemental heat addition, the temperature measured in front of the SCR catalyst did not exceed 200 °C for well over 500 seconds into the cold-start cycle. During this period of the cold-start, the engine emitted 19 grams of NO_x, which greatly exceeded the target 2.5 grams for a cold-start cycle for an ULN application. Therefore, to achieve ULN both reduced SCR light-off time (to less than 200 seconds) and NO_x emission management prior to SCR light-off would be required. Reducing SCR light-off time for a cold-start was achieved by increasing the exhaust energy flow rate into the SCR.

Figure 153 shows the measured SCR inlet temperatures and accumulated tailpipe NO_x mass emissions over the cold-FTP (Cold Cal 1 was used for all remaining screening evaluations) for the three configurations tested. This figure shows that as energy input into the ATS increased, tailpipe NO_x decreased. The reduction in tailpipe NO_x emission was due to the reduction in time to dosing and higher NO_x efficiency earlier in the cycle as energy input was increased. It should be noted that both heated dosing and distributed heat utilized a system that enabled dosing at lower temperatures (130 °C), the MB configuration began dosing at 170 °C. The time to dosing for the MB configuration compared to the production system was reduced to 150 seconds from 550 seconds.

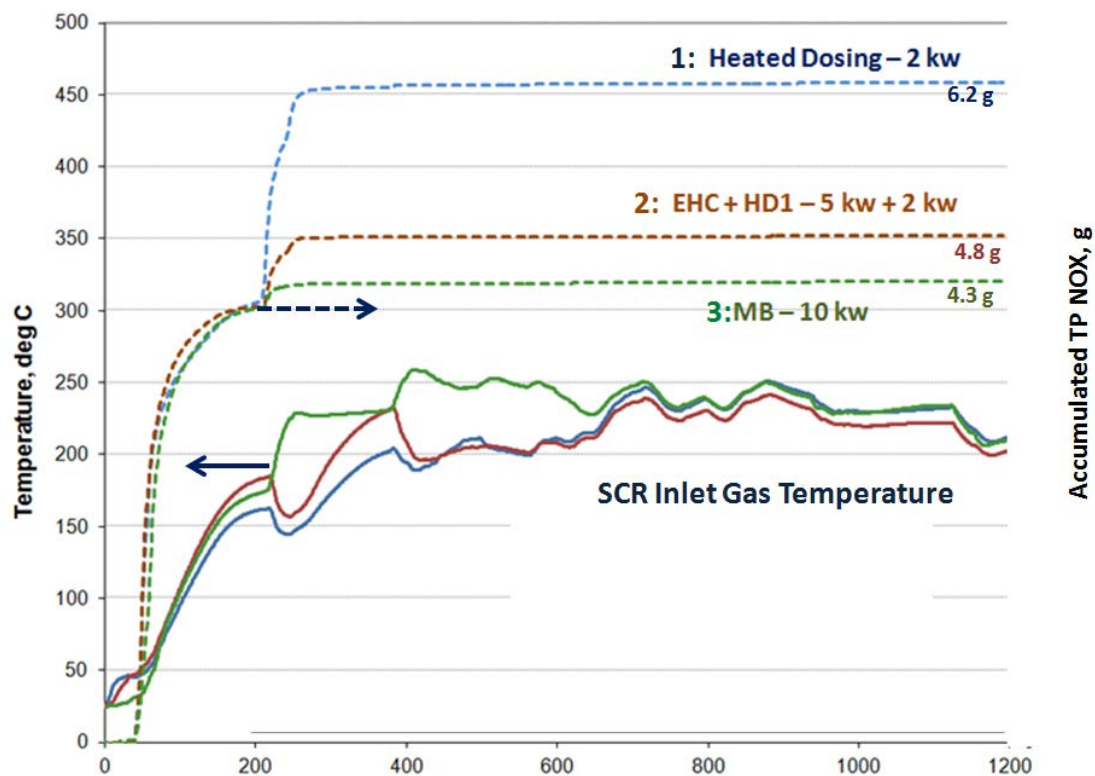


FIGURE 153. IMPROVED TRADITIONAL TECHNOLOGY SYSTEMS WITH MODIFIERS

Figure 154 shows the potential tailpipe composite FTP NO_x emission for the three improved traditional technology configurations tested, charted along with the performance measured from the production ATS. This figure shows the potential improvement gained by reduced thermal mass substrates, improved washcoat technology and the addition of

supplemental energy input and lower dosing temperature enablers on a traditional configuration system. The improved technology system with the application of a MB demonstrated composite NO_x potential very close to the ULN threshold.

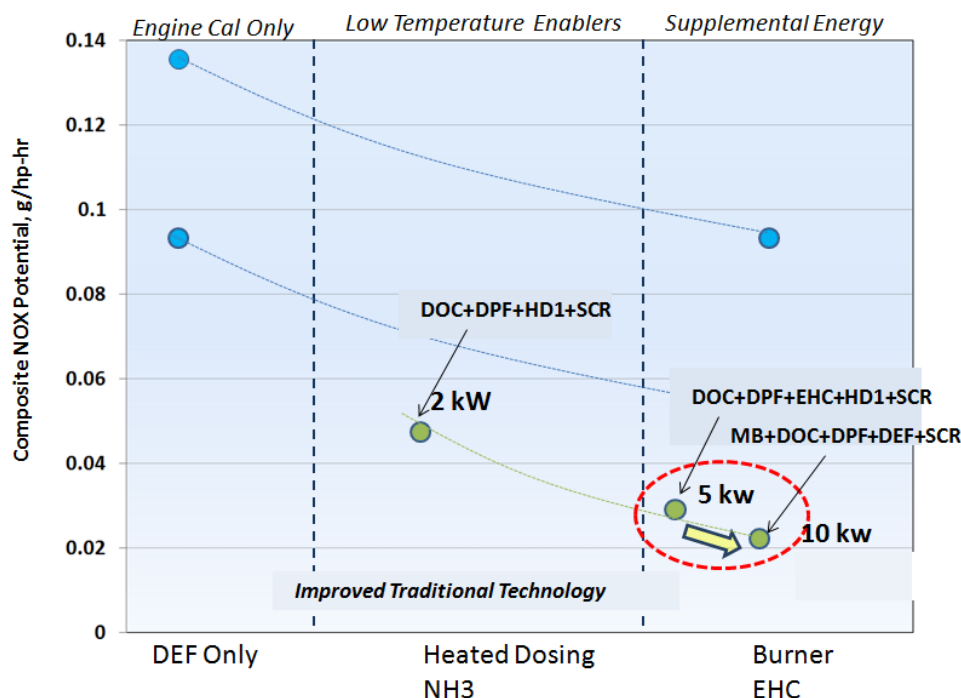


FIGURE 154. COMPOSITE TAILPIPE NO_x POTENTIAL FOR IMPROVED TRADITIONAL TECHNOLOGY SYSTEM WITH MODIFIERS

3.3.5 Advanced Technology Configurations

The advanced technology configurations all included an SCRF, which is a dual function device that combines the SCR functionality of traditional SCR catalyst and the PM filtering functionality of conventional DPFs. This configuration provides an opportunity to locate the SCR catalyst closer to the engine and with reduced thermal mass upstream of the NO_x reduction system compared to the traditional configuration. There were two basic groups of advanced technology systems evaluated. The first group included a DOC as the first catalyst; the second group included a PNA (with combined DOC functionality) as the first catalyst in the array.

For the first set of advanced technology systems, the configurations tested are shown in Figure 155. The HD1 and MB were controlled using the same approach as was employed for the traditional technology configuration evaluations.

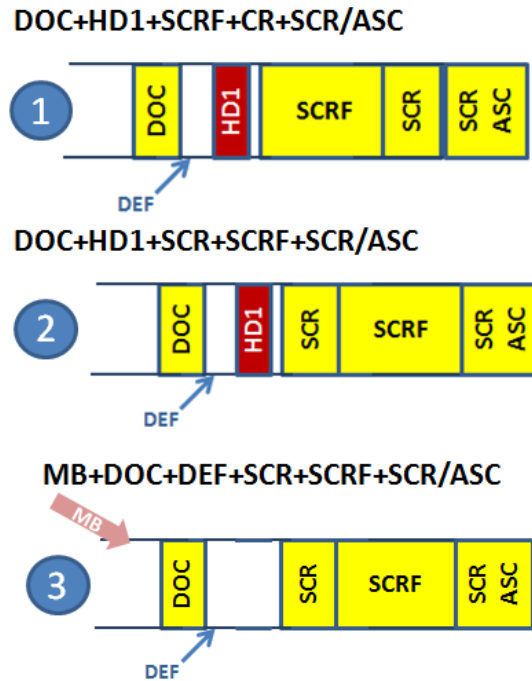


FIGURE 155. DOC BASED ADVANCED TECHNOLOGY CONFIGURATIONS TESTED

Figure 156 shows the measured SCR inlet exhaust gas temperature for configurations 1 and 3. From these data, it can be seen that the time to reach dosing temperatures for both systems was less than 100 seconds, and compared to the traditional technology configuration these data demonstrate the impact of positioning the first SCR catalyst closer to the engine in the ATS (thereby reducing the upstream thermal mass). This graph shows that both configurations performed similar in the early portion of the cycle, but that high efficiency NO_x control was realized earlier for the burner-assisted configuration. The improved performance was attributed to the additional thermal energy provided by the burner, which improves catalyst efficiency during the second acceleration.

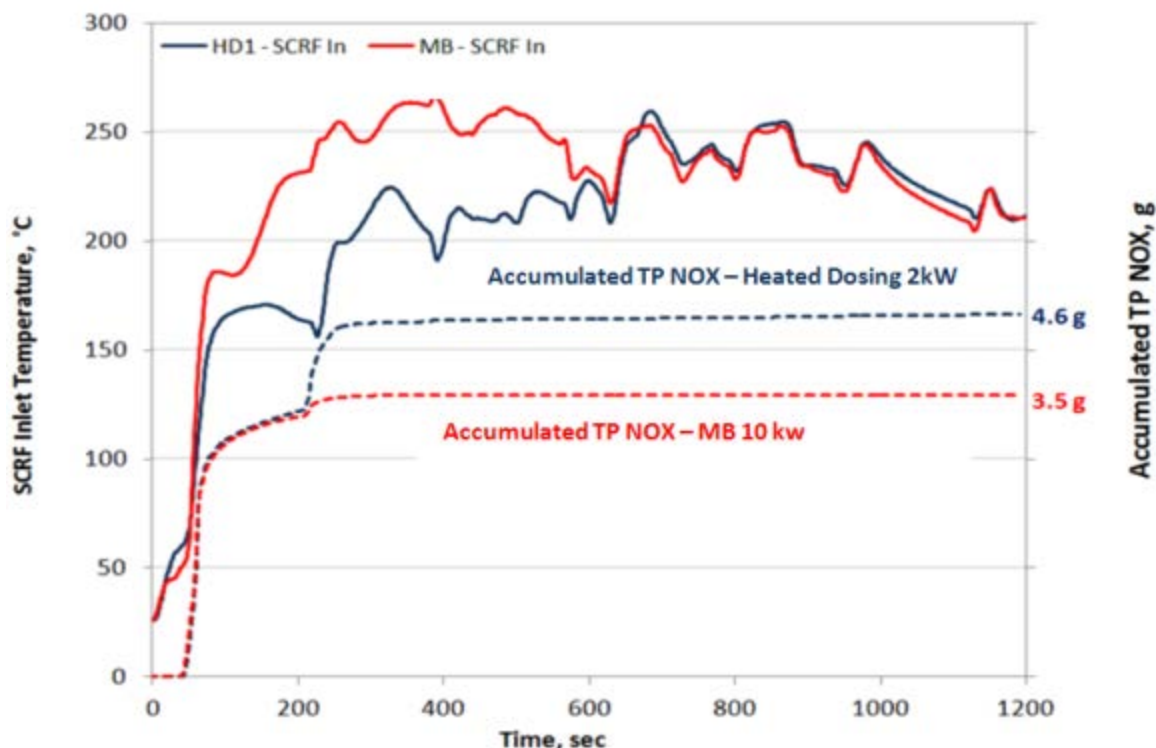


FIGURE 156. MEASURED SCRF INLET GAS TEMPERATURE AND ACCUMULATED TAILPIPE NO_x MASS EMISSIONS OVER THE COLD-FTP FOR THE DOC BASED ADVANCED TECHNOLOGY SYSTEM

Figure 157 provides a comparison the tailpipe composite NO_x potential for the DOC based advanced technology configurations tested. The data show that positioning an SCR catalyst upstream of the SCRF provides a slight advantage. This advantage is due to the higher surface area and lower thermal mass of the SCR catalyst, which produces a slight NO_x conversion efficiency advantage over the SCRF. However, it should be noted, that positioning an SCR catalyst upstream of the SCRF will further reduce the passive soot regeneration capability of the filter and may lead to a further increase in active regeneration frequency. Utilizing HD1 and an SCRF the composite NO_x emissions were reduced to below 0.04 g/hp-hr. The use of a MB upstream of the DOC and standard DEF injection reduced the potential composite NO_x emission to a level slightly below the ULN threshold.

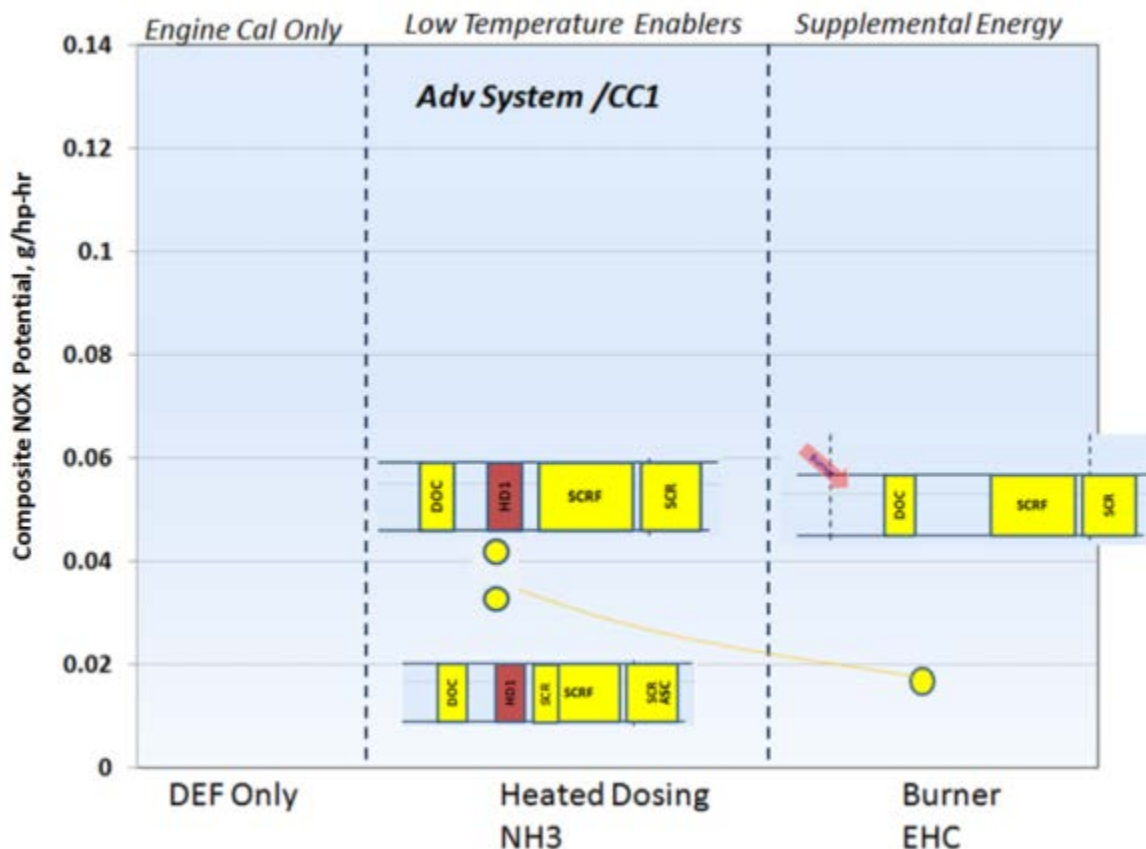


FIGURE 157. TAILPIPE COMPOSITE NO_x POTENTIAL FOR THE DOC BASED ADVANCED TECHNOLOGY CONFIGURATIONS TESTED

The second set of advanced technology configurations evaluated included a PNA as the first catalyst in the array. The PNA was designed to adsorb NO_x at low temperatures, and then thermally desorb NO_x as the exhaust gas temperature increased to a level commensurate with effective NO_x control via SCR conventional methods (<200 °C). No special preconditioning cycles were executed to intentionally expose the PNA to elevated temperatures to completely remove NO_x stored on the PNA. Upon completion of the initial system preconditioning, testing consisted of executing one cold- and two-hot start FTP tests per day and then cold soaking. Figure 158 shows the advanced technology configurations tested utilizing the PNA. The MB was not evaluated upstream of the PNA as this would defeat the low temperature NO_x storage function of the device.

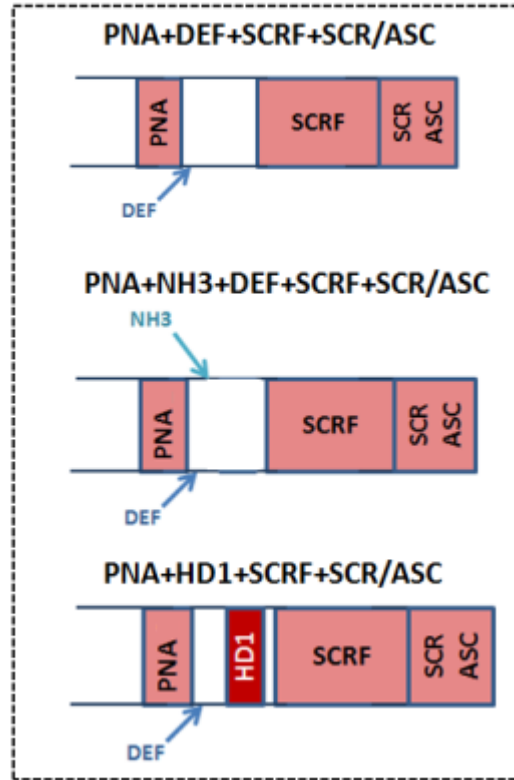


FIGURE 158. PNA BASED ADVANCED TECHNOLOGY CONFIGURATIONS TESTED

Figure 159 shows a comparison of measured SCR inlet temperature using DEF only injection to heated dosing (HD1). HD1 provided some thermal benefit during the idle portions of the test, as was evident from the elevated temperatures during the idle segments, but the primary advantage that HD1 provided was lower temperature dosing (130 °C). The bottom portion of the graph shows the thermal energy realized at the catalyst compared to the energy input. The red dotted line represents the total energy required to drive HD1 (includes mechanical engine efficiency to produce the energy and alternator efficiency for a total electrical efficiency of 22%). The real electrical energy delivered to the heater was slightly less than 1MJ and that energy was transferred to the catalyst as thermal energy with a very high efficiency.

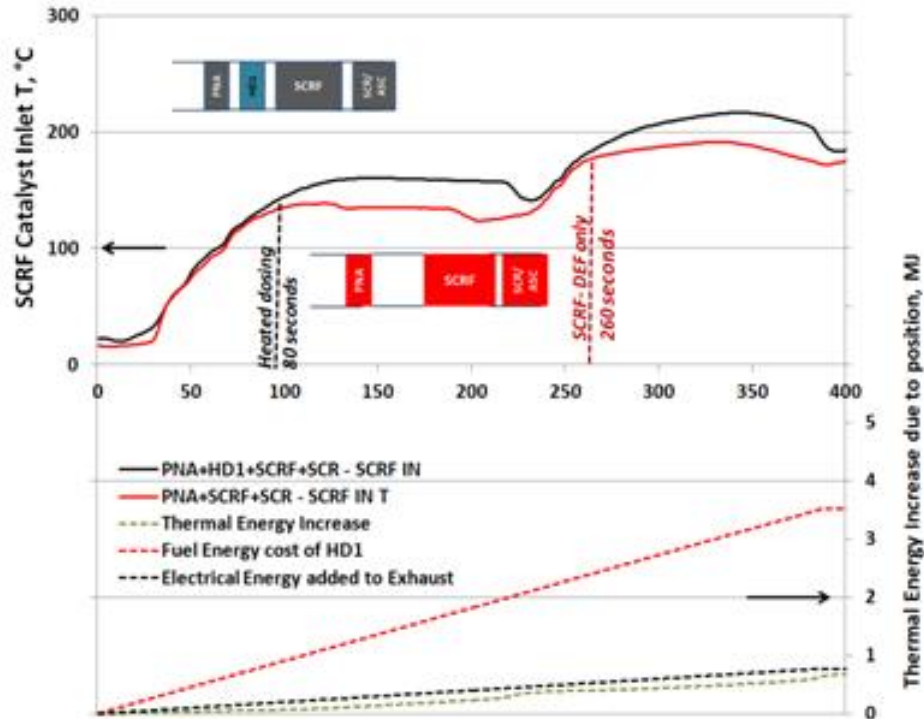


FIGURE 159. COMPARISON OF PNA-BASED ADVANCED TECHNOLOGY SYSTEM UTILIZING DEF INJECTION ONLY AND UTILIZING HEATED DOSING

Gaseous NH_3 injection was facilitated by utilizing a commercially available, solid NH_3 storage system that was designed for use on heavy-duty trucks. Gaseous NH_3 injection was only used during the cold-start portion of the cycle, and then the reductant injection was switched back to liquid DEF injection once sufficient exhaust temperature had been reached (190°C). Heated dosing (HD1) involved using a 2 kW electrically heated catalyst upstream of a hydrolysis catalyst submerged in the full flow of exhaust. When utilizing this system, the electric heater was switched off once sufficient temperature had been reached to enable standard DEF injection.

Both of these systems were used as low temperature enablers during cold-start operation, and NH_3 injection, similar to HD1, dosing was initiated when the SCRf inlet temperature reached 130°C . Figure 160 shows that the exhaust temperature measured for standard DEF injection and gaseous NH_3 injection were similar (since no additional heat was added to the exhaust, and gaseous NH_3 injection was only used until standard DEF injection was initiated). The advantage of the 2 kW EHC utilized in HD1 can be seen, particularly at idle conditions when the exhaust flow was low.

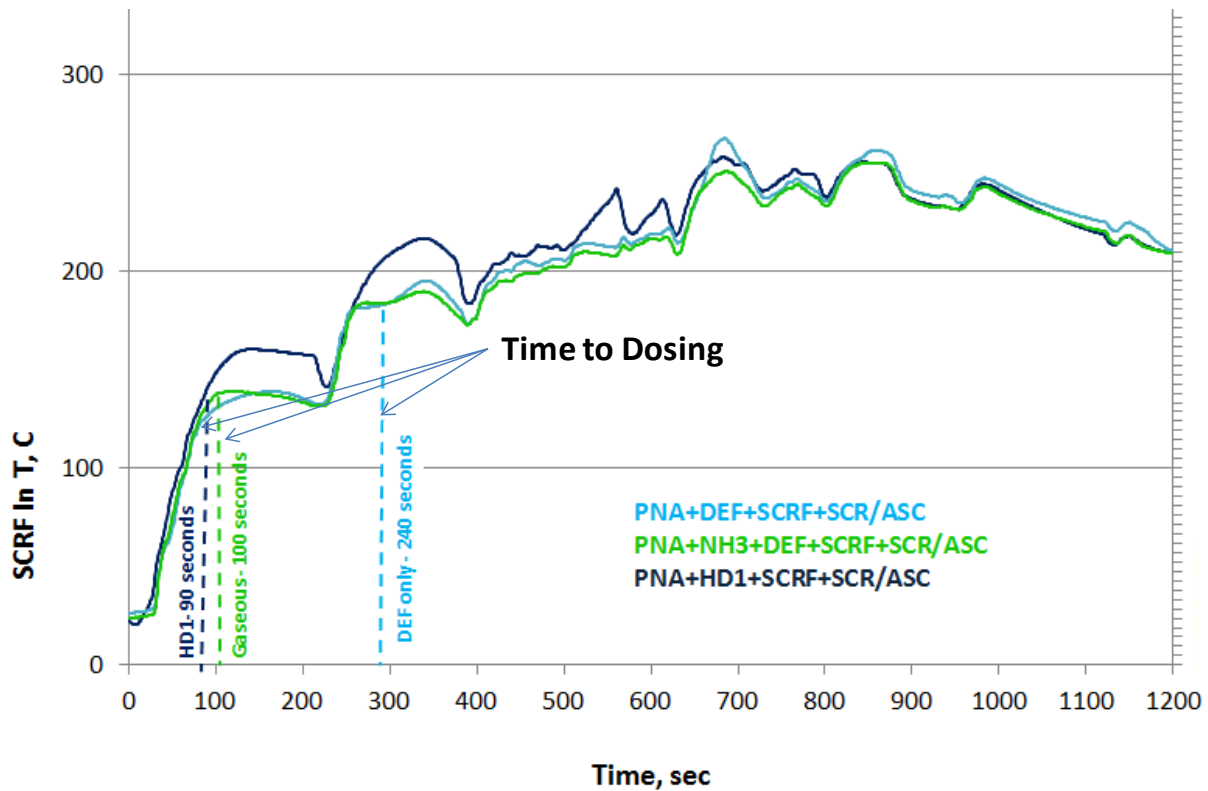


FIGURE 160. EXHAUST GAS TEMPERATURE INLET TO THE SCR FOR STANDARD DEF APPROACH AND FOR HEATED DOSING AND GASEOUS NH₃ INJECTION

Figure 161 shows a comparison between the measured accumulated tailpipe NO_x for DEF injection only compared to the HD1 and gaseous NH₃ injection. This is a very interesting comparison because it shows that the tailpipe NO_x mass emissions for all three configurations were similar during the cold portion of the cycle (before dosing was initiated). Since both HD1 and NH₃ injection can begin dosing at 130 °C a NO_x reduction advantage was realized over DEF injection at the point that dosing was initiated, however, it also shows that there was no real difference between HD1 and NH₃. This indicates that HD1 was effective at achieving evaporation the liquid DEF and hydrolysis to NH₃ at these low temperatures and that both the heated dosing and the gaseous NH₃ systems produced an equivalent effect. By utilizing HD1 or NH₃ injection, the time to dosing was reduced to about 80 seconds from 240 seconds (for the configuration using DEF only), and the impact on tailpipe NO_x was a reduction of composite NO_x potential to 0.03 g/hp-hr compared to 0.05 for the DEF only approach.

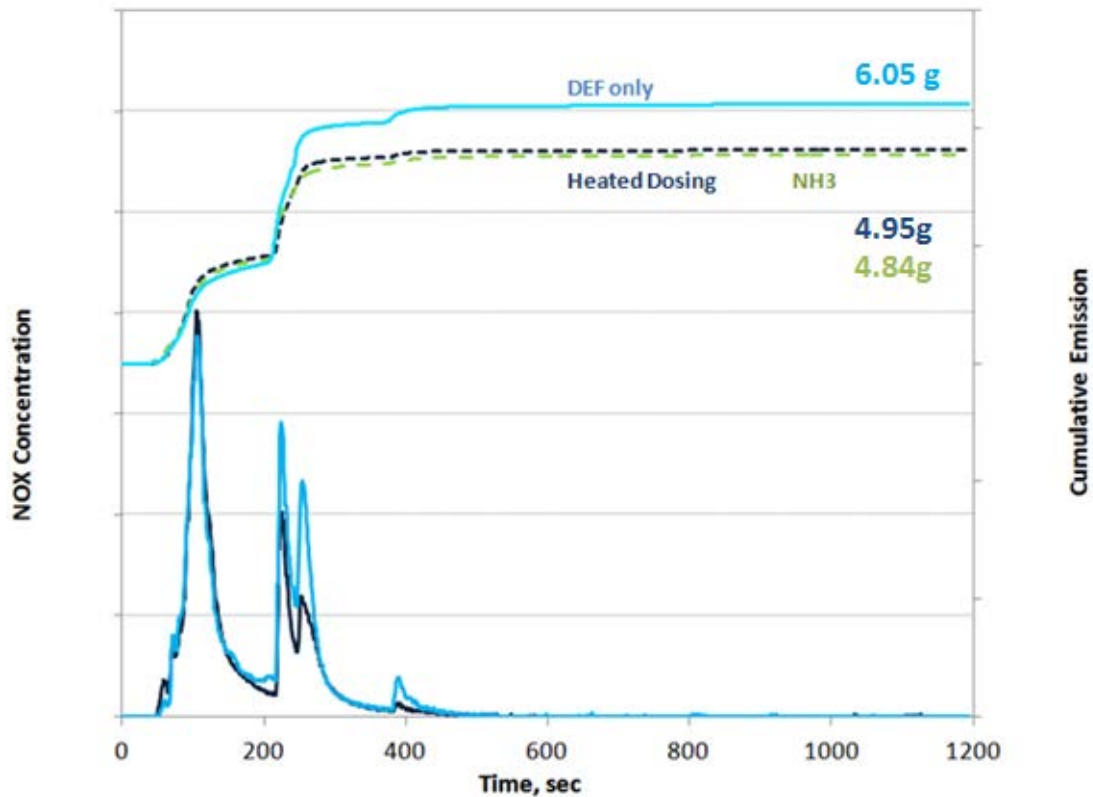


FIGURE 161. CONTINUOUS AND ACCUMULATED TAILPIPE NO_x OVER A COLD-FTP FOR THE PNA BASED ADVANCED TECHNOLOGY SYSTEM

Figure 162 shows a comparison of the potential tailpipe composite NO_x emissions measured for all three configurations tested along with the DOC based advanced technology systems. These data show an improvement over the traditional technology with DEF only reaching the 0.05 g/hp-hr range (compared to 0.09 for the stock system on the Cold Cal 1 calibration). The yellow markers show the results for configurations with a DOC at the front, while the pink markers indicate results for configurations with a PNA at the front. The bright pink marker represents the performance of an improved technology PNA (PNA2) for the PNA+HD1+SCRF+SCR configuration. PNA2 was received late in the screening work and provided improved capacity and release compared to PNA1 (the light pink markers).

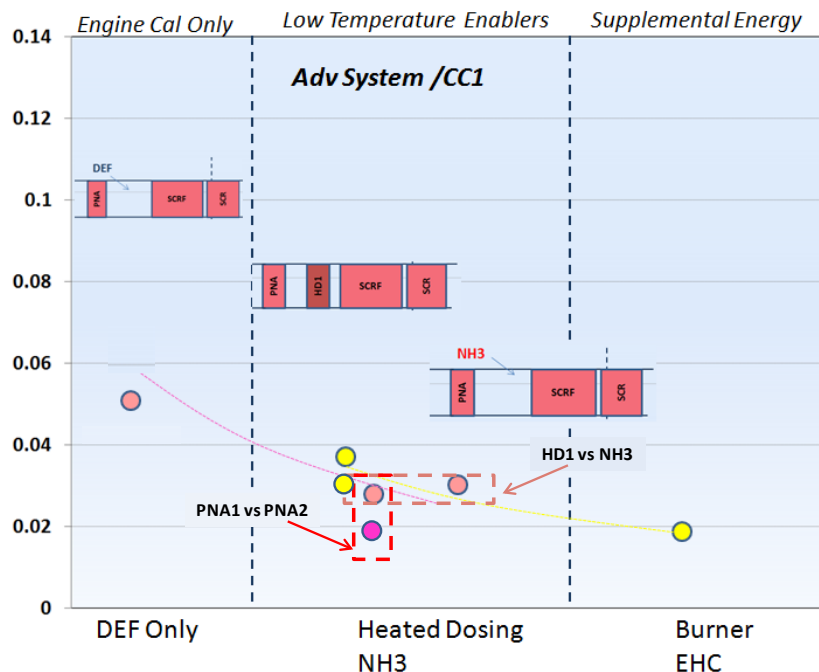


FIGURE 162. TAILPIPE NO_x POTENTIAL FOR THE PNA BASED ADVANCED TECHNOLOGY SYSTEMS

3.3.6 Enhanced Configurations

Figure 163 provides an overview comparison of the results from the initial screening work, organized by technology approach. It was observed that there were many configurations that showed good potential of achieving close to the ULN level, but that further reductions in NO_x emissions were needed to reach below the ULN threshold. The plateau was attributable to the NO_x mass produced by the engine before the SCR catalyst system reached dosing temperatures. Since this engine utilized a turbo-compounder (TC) as a fuel economy improvement approach and the TC was positioned upstream of the catalyst system with no option to bypass the device during cold-start, the catalyst inlet temperature was about 50-75 °C lower during cold-start than would be realized by an engine that did not utilize a TC. It was anticipated that many of the configurations in the 0.02-0.03 g/hp-hr range may have performed below the ULN threshold if this engine did not employ a TC or if a means to bypass the TC during cold-start could have been employed. However, since modifying the TC was not an option for this program, additional, more aggressive, early heating strategies were developed to accelerate high efficiency catalyst performance.

In Figure 163, several different colors are utilized to denote the different configurations. The blue markers are for the stock aftertreatment system, while the green markers are for the traditional (DPF-based) configurations that utilized the updated program hardware. The yellow markers denote SCRF-based configurations with a DOC, while the pink markers indicate SCRF-based configurations with a PNA.

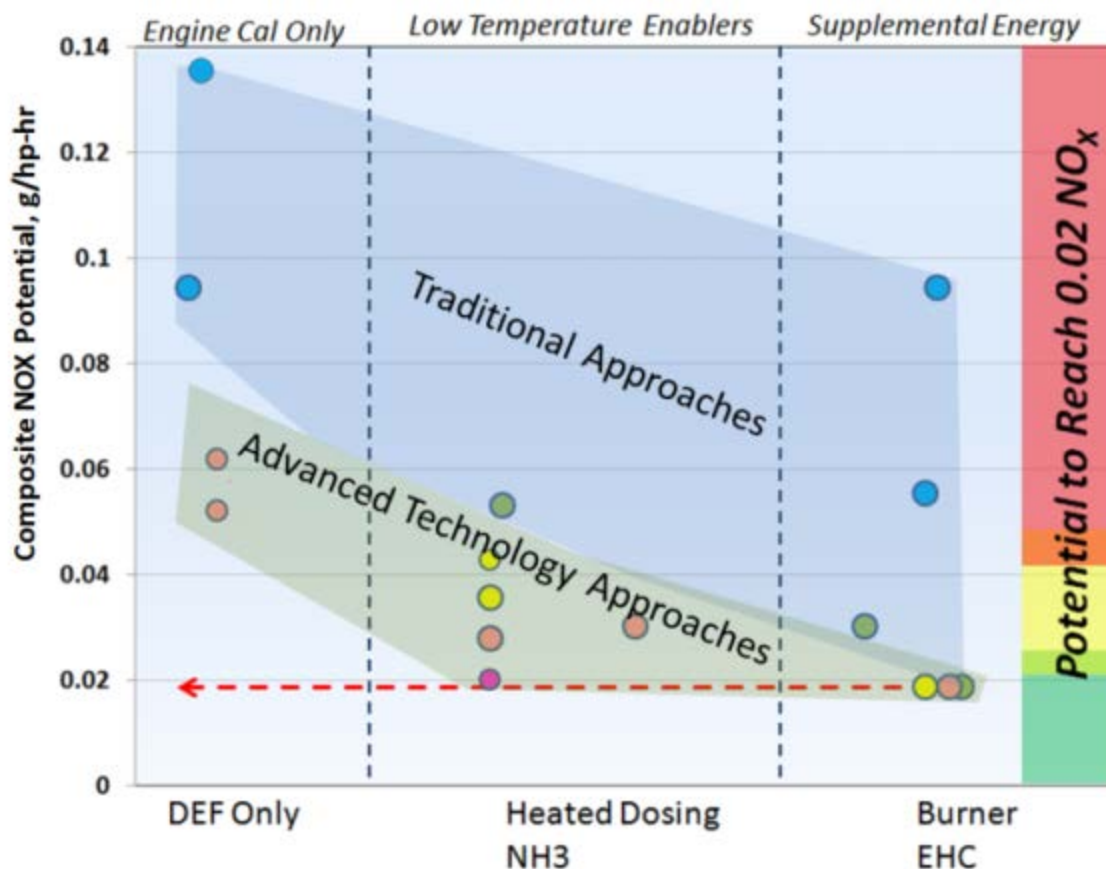


FIGURE 163. SUMMARY OF EARLY SCREENING RESULTS FOR POTENTIAL COMPOSITE TAILPIPE NO_x ON TC-ENGINE

3.3.6.1 Light-Off SCR (LO SCR)

Catalyst positioning and low thermal mass substrates potentially lower the energy required to achieve temperatures required for high catalyst conversion efficiency by reducing the thermal mass in front of the first SCR catalyst. The first enhanced emissions control approach proposed the utilization of a new concept in SCR control - the SCR light-off catalyst (LOSCR). This concept employed an additional section of SCR catalyst positioned as the most upstream element in the catalyst array. This approach was proposed to overcome the thermal mass of other upstream catalysts and reduce the energy input required to achieve light-off of the first SCR catalyst during cold start operation.

To highlight the potential catalyst positioning alone, the exhaust temperature for three different first SCR catalyst positions was examined. Figure 164 shows three first SCR catalyst positions for both advanced and traditional technology configurations that would be reasonable solutions for heavy-duty applications.

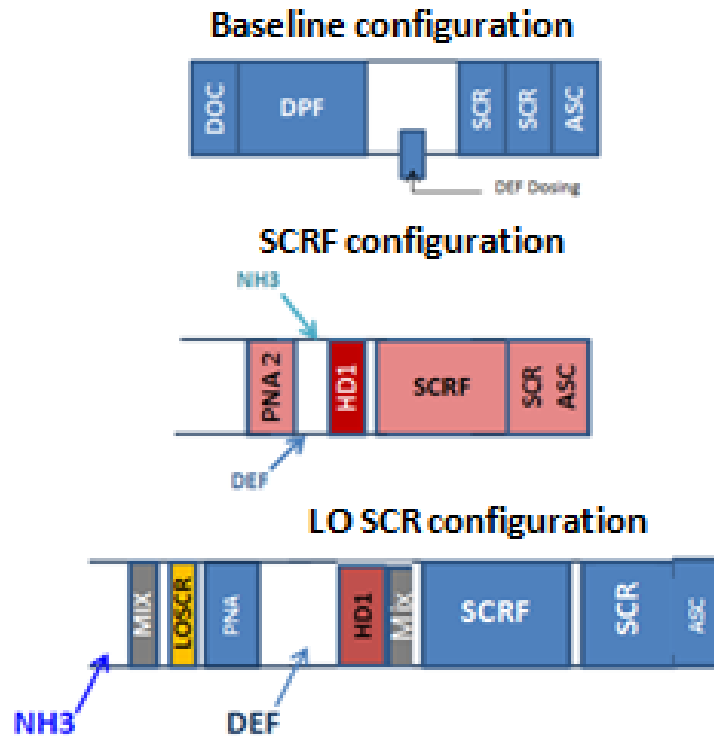


FIGURE 164. TESTED FIRST SCR CATALYST POSITIONS

Figure 165 shows the measured exhaust gas temperature into the first SCR catalyst for each of these configurations and the amount of energy that would be required to increase each of these configurations to 200 °C for 400 seconds after cold-start. The vertical dashed lines denote the time at which various configurations reach the point where dosing begins. It should be noted that because there are heat loss pathways upstream of the first SCR catalyst, the real energy required to achieve this temperature would increase by the heat losses incurred upstream of the catalyst. The baseline configuration would require 5MJ, the SCRF configuration would require 3MJ, and the LO SCR configuration 1MJ.

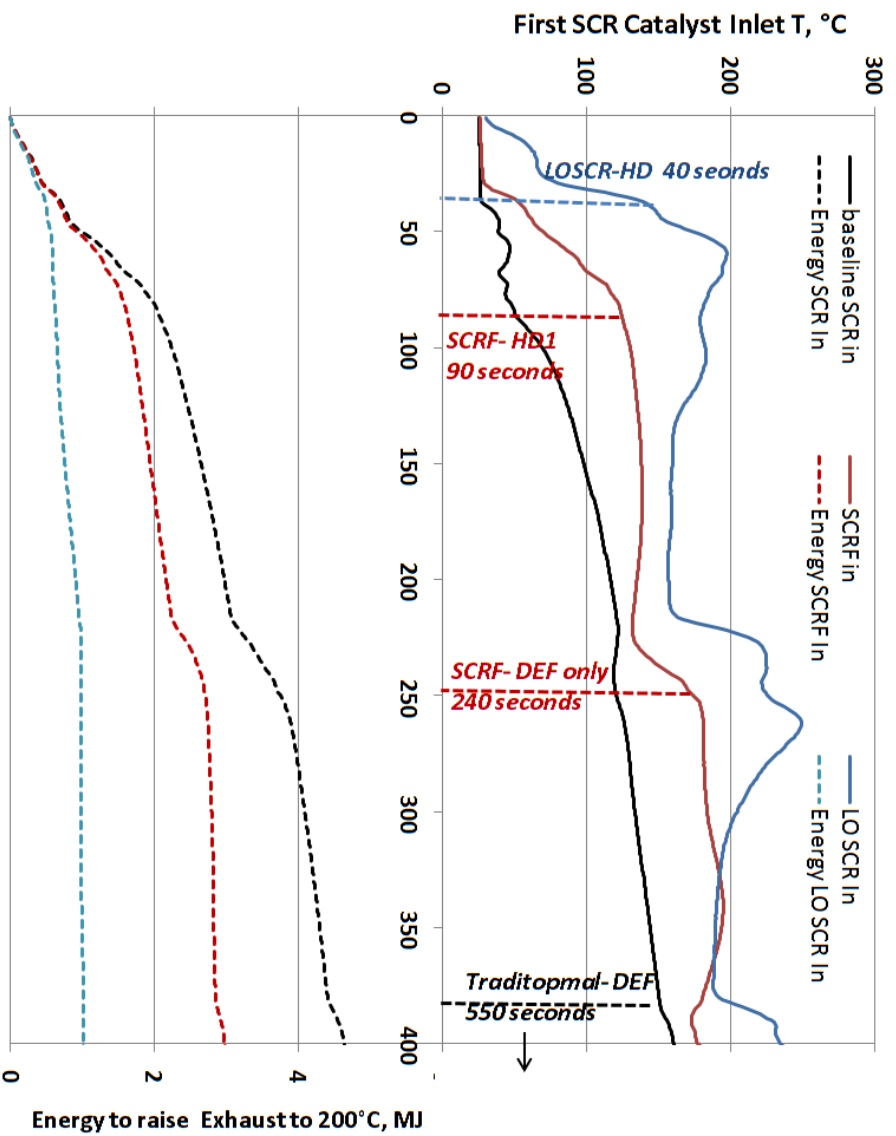


FIGURE 165. MEASURED EXHAUST GAS TEMPERATURE INTO FIRST SCR CATALYST AND THEORETICAL ENERGY (NO HEAT LOSS) REQUIRED TO REACH 200 °C DURING FIRST 400 SECONDS AFTER COLD-START

Figure 166 shows a comparison of the measured first SCR inlet exhaust gas temperature over the cold-FTP for several PNA+SCRf advanced technology configurations (the other configurations details were outlined in Figure 118).

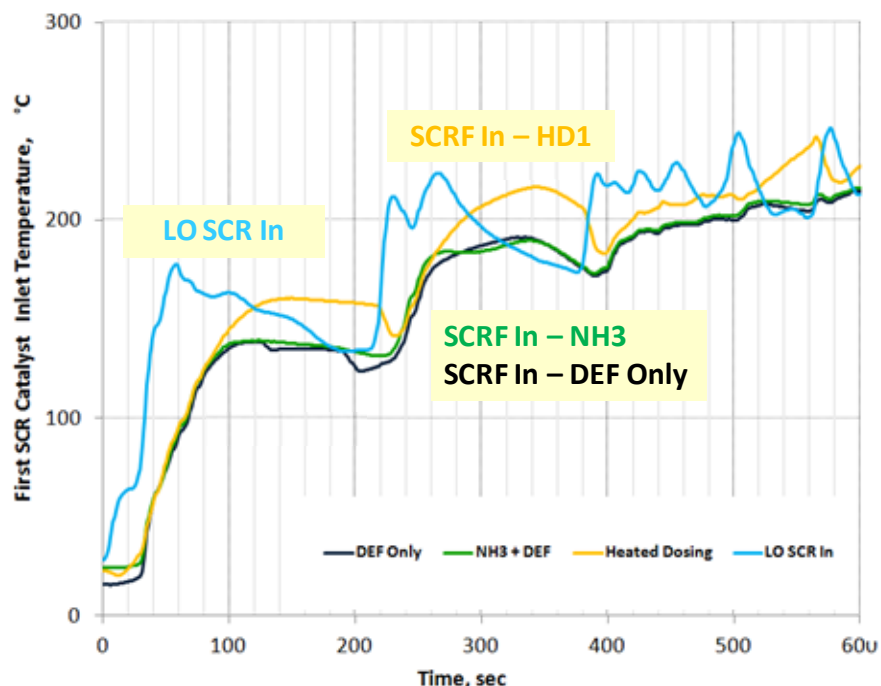


FIGURE 166. FIRST SCR CATALYST INLET TEMPERATURE COMPARING LO SCR TO SCRF CONFIGURATION

Under cold conditions the SCR catalyst relies heavily on the fast SCR reaction ($2\text{NH}_3 + \text{NO} + \text{NO}_2 = 2\text{N}_2 + 3\text{H}_2\text{O}$) and since the engine-out exhaust was predominantly NO there was concern that the LO SCR might have very low efficiency. However, the purpose of this catalyst was not to achieve very high efficiency control, but to trim the system NO_x enough that the early NO_x accumulation could be reduced to levels to make ULN more achievable. Additionally, if the LO SCR catalyst could reduce the input NO_x , and a PNA was utilized downstream, then the LO SCR would also act to reduce the NO_x mass storage requirement in the PNA and should help to reduce the effective NO_x flux through the PNA, potentially reducing NO_x breakthrough on hard accelerations. A preliminary test was conducted to examine the potential effectiveness of the LO SCR under the standard SCR reaction ($4\text{NH}_3 + 4\text{NO} + \text{O}_2 = 4\text{N}_2 + 6\text{H}_2\text{O}$). Figure 167 shows a comparison of the low temperature NO_x efficiency for a range of exhaust mass flows typically encountered on the FTP cycle (a moderate acceleration) for a feed stream of exhaust that consisted of 90% NO. This figure shows very good NO reduction for flow rates corresponding to idle conditions, and some efficiency for moderate acceleration conditions for temperatures below 180°C were achievable.

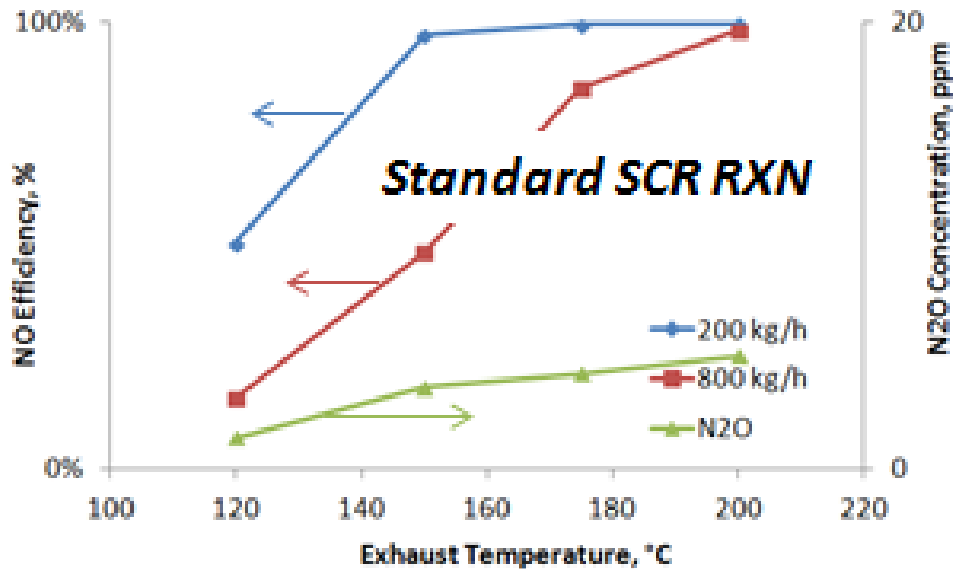


FIGURE 167. LOW TEMPERATURE NO_x CONVERSION EFFICIENCY OF LOSCR UNDER STANDARD SCR REACTION FOR IDLE AND MODERATE FLOW AND N₂O AT IDLE CONDITIONS

Figure 168 compares the measured tailpipe instantaneous and accumulated NO_x, and accumulated N₂O for NH₃+LOSCR+PNA+HD1+SCRF+SCR compared to PNA+HD1+SCRF+SCR. This figure shows that utilizing the LOSCR and split dosing reduced the tailpipe NO_x emissions during the early portion of the cycle compared to heated dosing alone. The dosing strategy used for the LO SCR involved starting gaseous dosing at 100 °C at an ANR of 1.0, and continuing until the SCRF reached 160°C. The strategy then reduced the LOSCR ANR to 0.4. The control requires two NO_x sensors (at engine out and PNA out) and the dosing balance was clearly complex. The reduction was likely to be a combination of some NO_x reduction across the LO SCR, in addition to an effective increase in PNA capacity due to a reduced NO_x feedstream. An additional benefit to the LOSCR was that N₂O emissions are reduced. Since N₂O was largely formed from nitrates formed from NO₂ during DEF dosing under cold operation, the LOSCR also had the potential to reduce N₂O formation since the reaction over that device was predominantly NO based. The composite tailpipe NO_x emission for the LOSCR configuration with PNA2 was 0.017 g/hp-hr, which was below ULN threshold.

The LOSCR formulation was Cu-Ze, which performs well at lower temperatures, however, this formulation was also susceptible to sulfur poisoning, and being the first catalyst in the array, may not be exposed to exhaust temperatures sufficient to desulfate the catalyst. This was a potential issue with this configuration, and alternate formulations or desulfation approaches were considered.

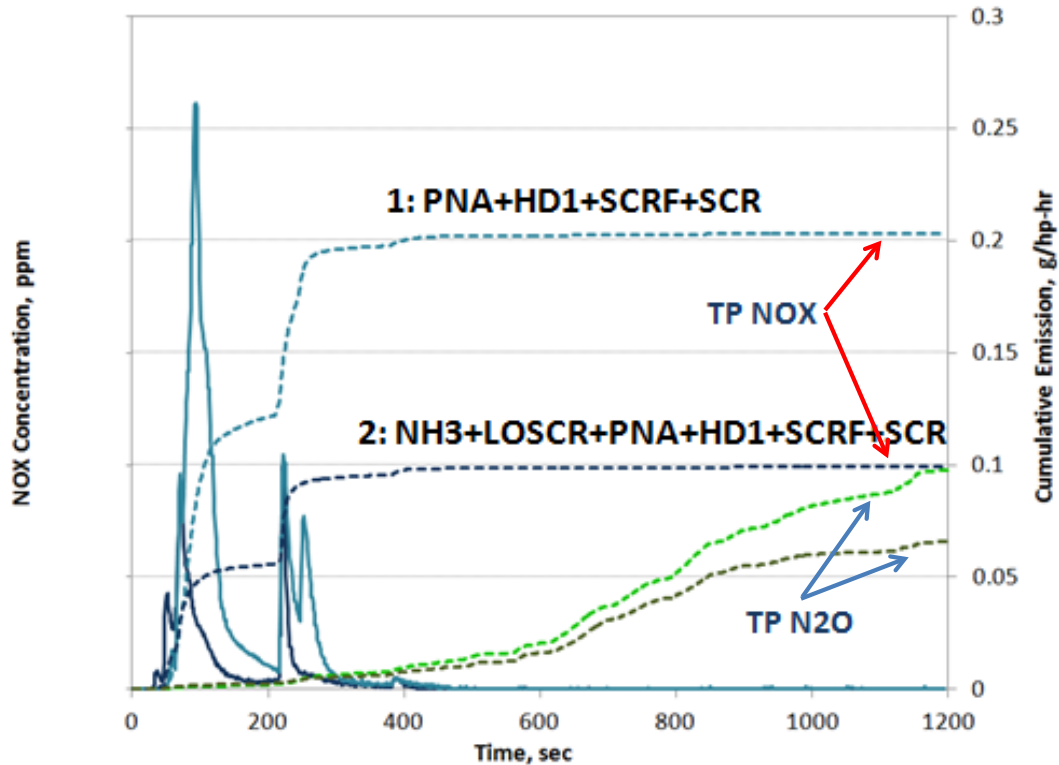


FIGURE 168. TP NO_x AND N₂O FOR PNA BASED ADVANCED TECHNOLOGY CONFIGURATION WITH AND WITHOUT LOSCR

3.3.6.2 MB Placement

In this study, the MB was considered a dual-purpose device. It can be utilized for cold-start assist, but also for active DPF PM regeneration. In the typical configuration, the MB was placed upstream of the DOC to heat the DOC to enable fuel oxidation and increase exhaust temperature during active regeneration events. An alternate configuration with the MB placed downstream of the DOC or PNA was considered to accelerate first SCR catalyst warm up during cold-start. If the PM filter was an SCRF, then the MB could still be used to assist regeneration, but the heat during warm up and regeneration would be directly applied to the SCRF catalyst, additionally, the MB alone may not be sufficient to reach regeneration temperatures at off idle conditions.

The first comparison explored the use of the MB upstream of the DOC in a traditional system (to enable use for both catalyst light-off and for regeneration), upstream of the DOC in an advanced technology configuration and downstream of the PNA in a second advanced technology configuration. The positioning in the advanced technology system (upstream of the DOC and downstream of the PNA) allows an assessment of the impact of the thermal mass of the first catalyst. For this work, the same MB calibration was applied to each system; each system was supplied with an additional 4MJ of energy over the cold start. Figure 169 shows the three MB based systems that were compared. Figure 170 shows a comparison of the fuel and air run by the MB for the three different runs.

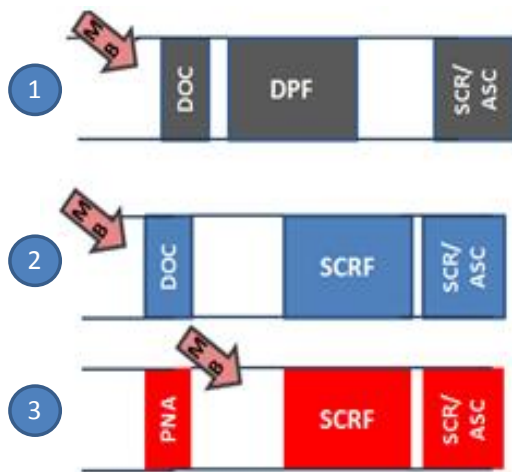


FIGURE 169. TRADITIONAL AND ADVANCED TECHNOLOGY CONFIGURATIONS COMPARED DURING MB POSITIONING COMPARISON

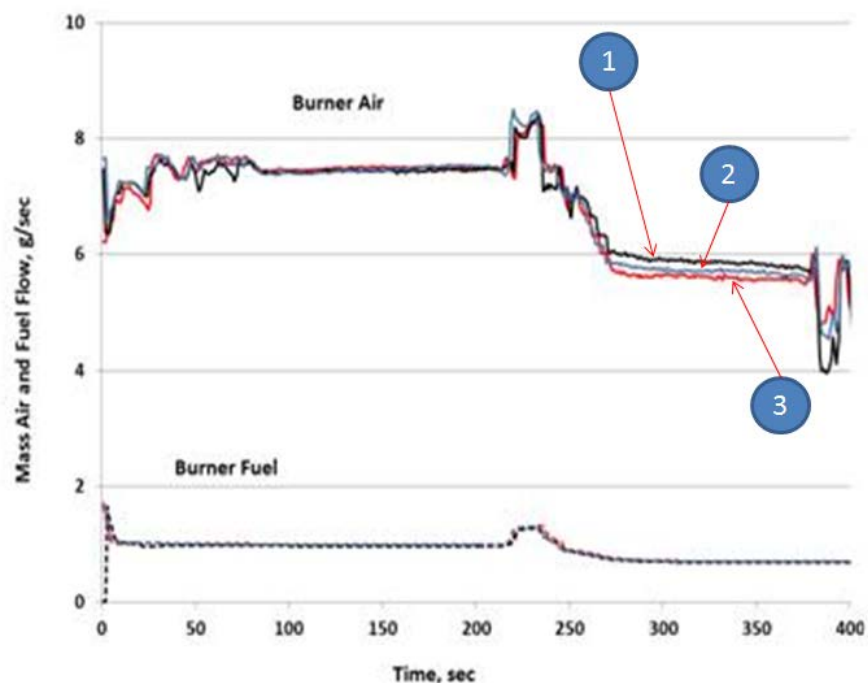


FIGURE 170. FUEL AND AIR DELIVERED TO MB DURING THREE SEPARATE COLD-START FTP TESTS, UTILIZING THE SAME MB CALIBRATION

Figure 171 shows the measured exhaust temperature inlet to the first SCR catalyst for each run as well as the tailpipe NO_x accumulated mass emissions. Both advanced technology systems showed substantial reduction in tailpipe NO_x mass emissions compared to the traditional technology approach. Comparing the performance of the MB+DOC+DPF+SCR versus the MB+DOC+SCRF+SCR, the impact of the upstream thermal mass of the DPF can be observed, and the primary difference in the tailpipe NO_x between the two configurations was due to the

reduced time to dosing in the advanced technology system. Comparing the MB+DOC+SCRF+SCR to PNA+MB+SCRF+SCR it can be seen that the temperature profiles are similar, but with the downstream MB showing a slight thermal advantage over the MB upstream of the DOC.

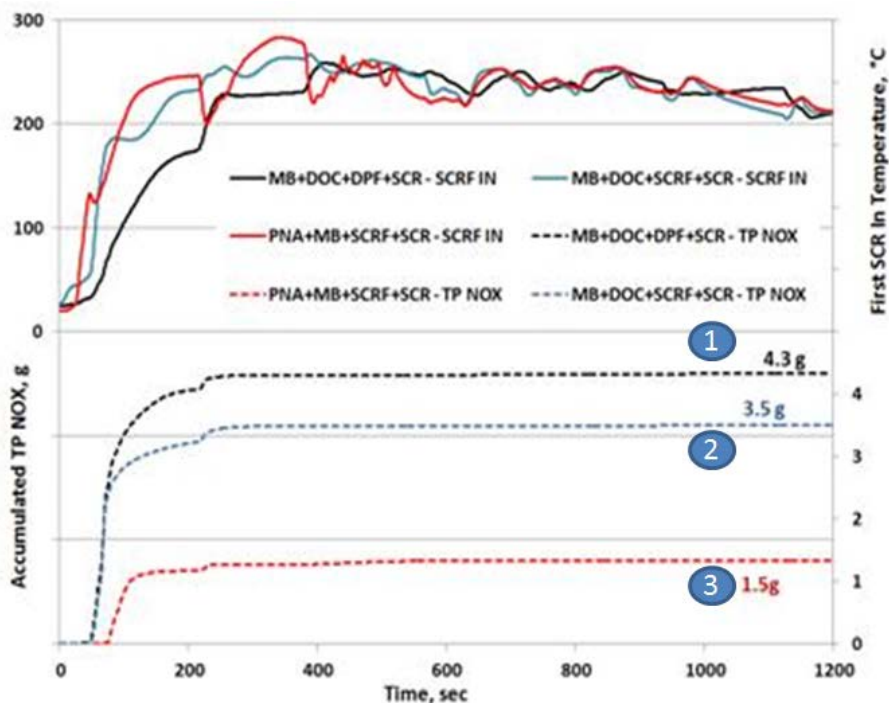


FIGURE 171. MEASURED EXHAUST GAS TEMPERATURE UPSTREAM OF THE FIRST SCR CATALYST FOR BOTH TRADITIONAL AND ADVANCED TECHNOLOGY CONFIGURATIONS

However, the tailpipe NO_x for the PNA+MB+SCRF+SCR configuration shows substantial reduction over the MB+DOC+SCRF+SCR configuration. Figure 172 shows the measured DOC and PNA out accumulated NO_x (NO_x mass into SCRF) and accumulated thermal energy increase (over a baseline/no heat addition advanced technology configuration). This figure shows that positioning the mini-burner after the first catalyst provides a slight thermal advantage compared to upstream of the DOC, but that the main advantage in the PNA configuration was due to the reduced NO_x levels at the inlet to the SCRF due to NO_x adsorption on the PNA during the catalyst warm up period. This figure shows that 4.1 MJ of fuel energy were added during the first 400 seconds, but only 3.1 MJ of thermal energy was measured at the catalyst inlet due to thermal heat losses to the DEF mixer and the evaporation of DEF.

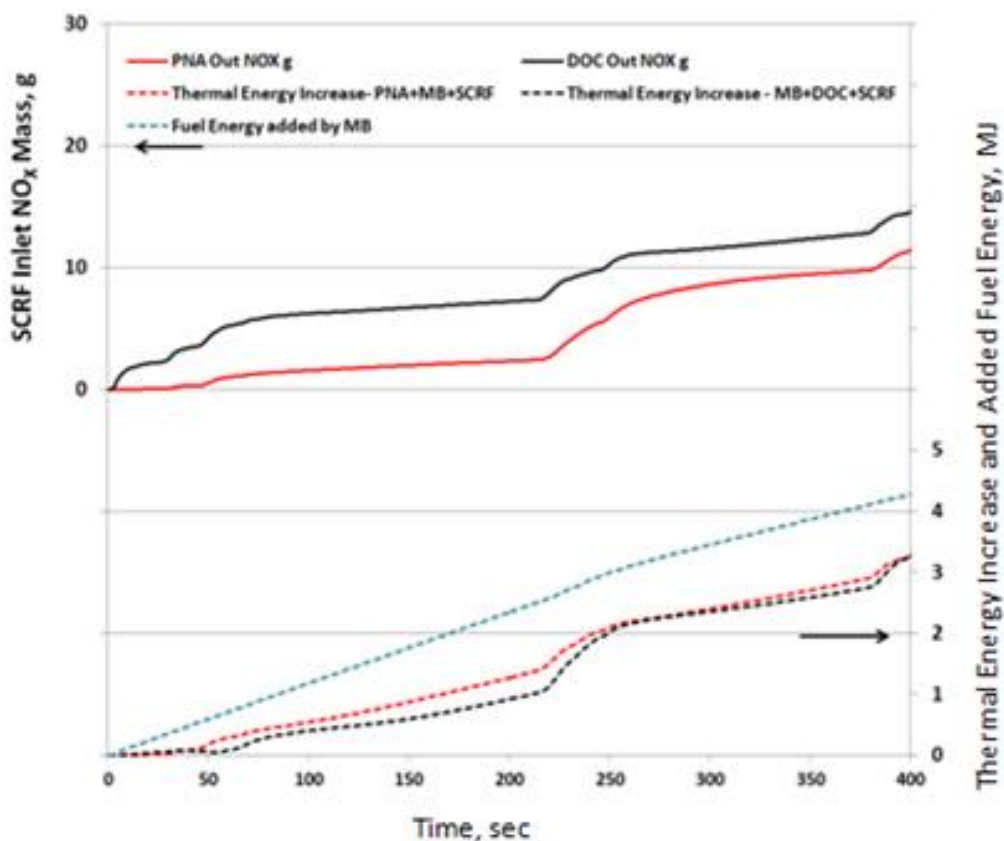


FIGURE 172. SCR F CATALYST INLET NO_x AND INJECTED FUEL ENERGY AND THERMAL ENERGY FOR ADVANCED TECHNOLOGY CONFIGURATIONS

Figure 173 shows the impact of the two advanced technology configurations on accumulated tailpipe NO_x and N₂O mass emissions. The PNA+MB+SCR+SCR configuration reduced the tailpipe composite NO_x emissions very close to 0.01 g/hp-hr. The N₂O emissions for both configurations are equivalent since both are still leveraging DEF dosing into the SCR.

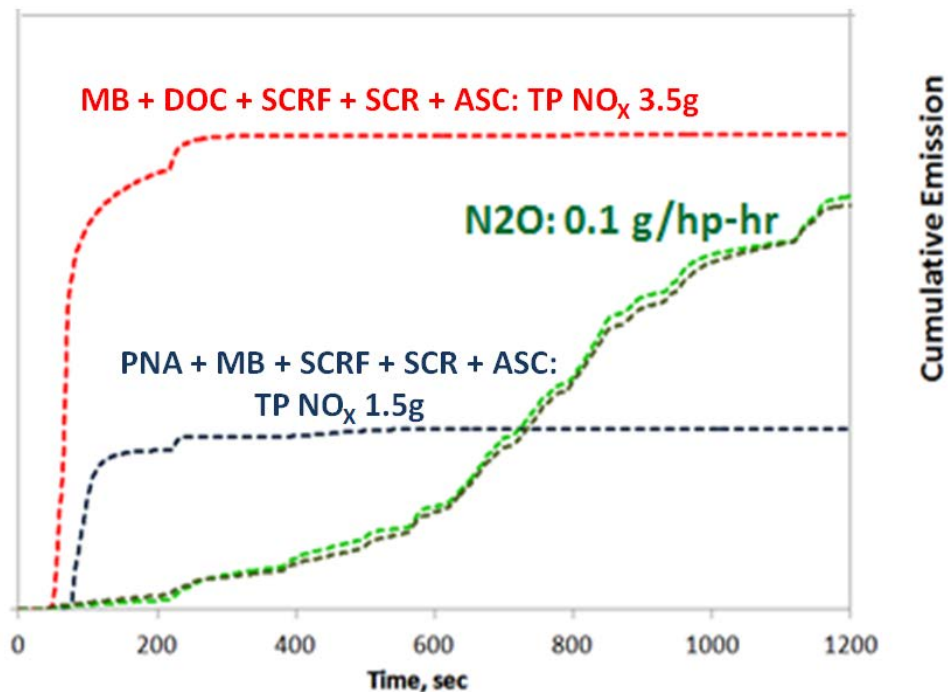


FIGURE 173. TAILPIPE NO_x AND N₂O ACCUMULATED MASS EMISSIONS FOR ALTERNATE MB LOCATION

3.3.6.4 Summary of Advanced Technology Configurations

Figure 174 shows a comparison of first SCR catalyst inlet temperature measured for various advanced technology configurations. The configurations shown are:

- (1) DEF Only: PNA+DEF+SCRF+SCR
- (2) HD1: PNA+HD1+SCRF+SCR
- (3) NH3: PNA+NH3+DEF+SCRF+SCR
- (4) LO SCR: LO SCR+PNA+SCRF+SCR
- (5) MB-1: MB+DOC+DEF+SCRF+SCR
- (6) MB-2: PNA2+MB+DEF+SCRF+SCR

This figure provided an excellent summary of the thermal differences observed by the different configurations of an advanced technology approach.

Figure 175 shows a summary of the instantaneous and accumulated tailpipe NO_x emission for the six configurations. Again, the primary advantage in moving from higher tailpipe NO_x to lower was a combination of reduced time to dosing for higher supplemental energy additions and NO_x control during cold-start (here due to PNA).

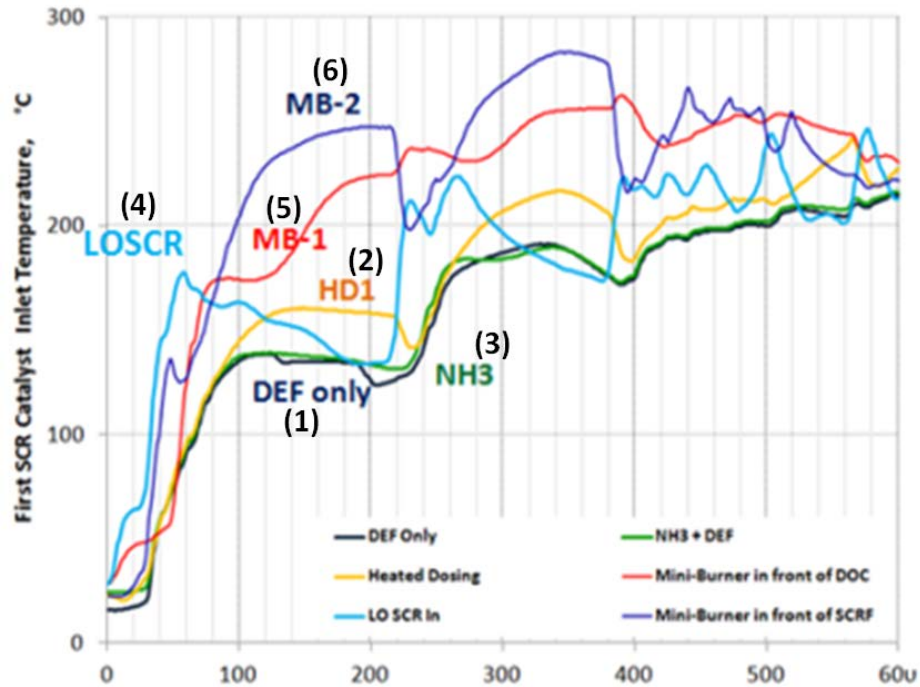


FIGURE 174. FIRST SCR CATALYST INLET TEMPERATURE DURING COLD FTP FOR VARIOUS ADVANCED TECHNOLOGY CONFIGURATIONS

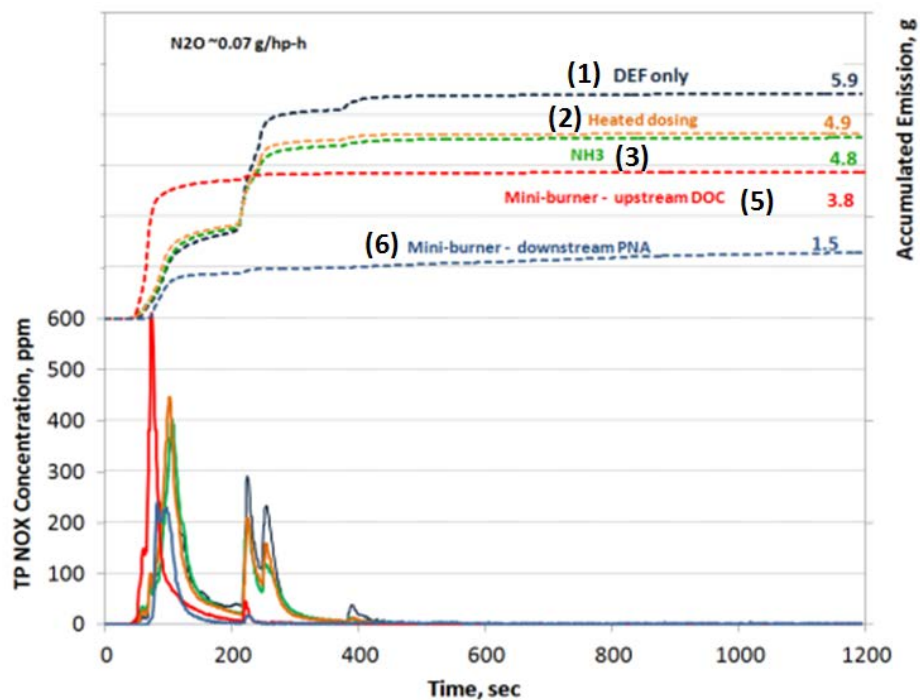


FIGURE 175. TAILPIPE NO_x EMISSIONS DURING COLD FTP FOR PNA-BASED ADVANCED TECHNOLOGY SYSTEM WITH VARIOUS THERMAL MANAGEMENT STRATEGIES

3.3.7 Impact of SCRF Regeneration on Fuel Consumption and GHG Emissions

As noted earlier, SCRF was a key technology for many of the configurations that showed the potential to reach NO_x levels below 0.02 g/hp-hr. It has been found that the application of SCRF can have a negative impact on passive regeneration due to competition between SCR and regeneration reactions [7][8]. This will cause an increased need for active regeneration, resulting in increased fuel consumption. This was observed in the current program, although the increase could potentially be mitigated somewhat by catalyst formulation or the use of multiple points of urea dosing.

In order to make an accurate determination of the impact of the final configuration in fuel consumption and GHG emissions, it was therefore important to make an assessment of how much additional demand for active regeneration will occur on this engine as a result of the use of SCRF. To that end several experiments were run in order to provide information needed to enable this calculation. It should be noted that these projections are estimates based on data available at the time.

One set of experiments involved looking at the soot oxidation behavior of a loaded filter. In these experiments, the filter was soot loaded to 6 grams/liter and weighed to confirm the loading level. The engine was then run for 1500 seconds at a given temperature (e.g. 250, 300, 400, 450°C) and 850 kg/hr exhaust flow rate. Differential pressure was monitored, and the filter was reweighed after the experiment to confirm the amount of soot mass lost. Experiments were conducted using a DOC+DPF as a control and with the SCRF (using the upstream PNA as the DOC) both with and without DEF dosing. The results of these experiments are summarized in Figure 176.

They indicate little or no passive soot oxidation on any systems below 300 °C, and then an increasing level of soot oxidation on the DPF as expected above 400 °C. The SCRF without dosing showed a small drop in soot oxidation in comparison at high temperatures, likely due to the lack of precious metal on the filter. However, once the dosing was turned on, there was a significant loss of passive soot oxidation, with the data indicating very little passive regeneration activity. This data was matched with soot loading experiments conducted on clean filters, which confirmed very little passive soot oxidation at DEF dosing rates needed for ULN levels.

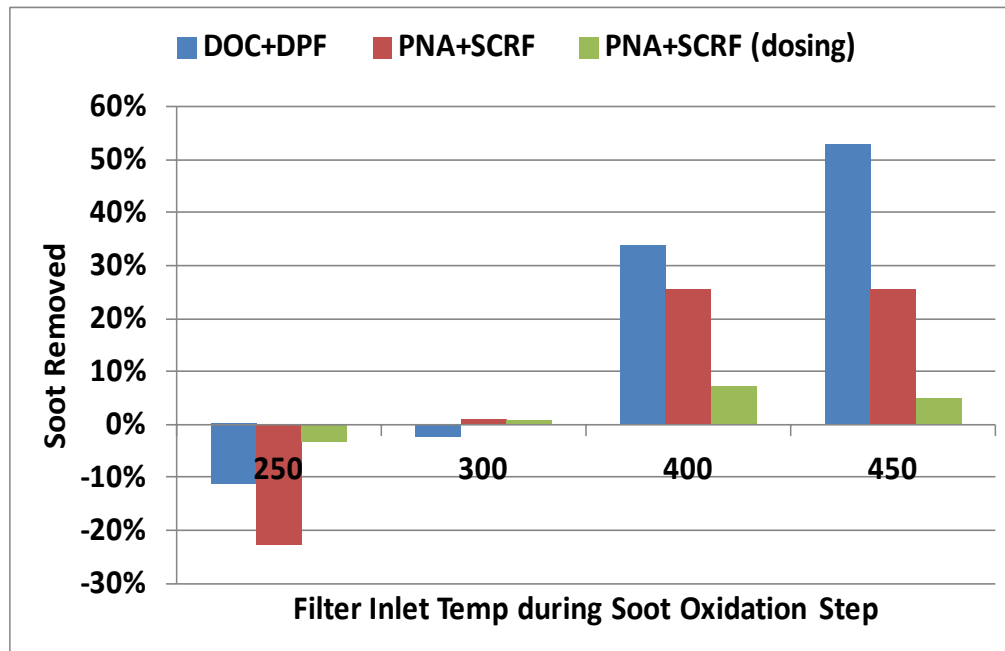


FIGURE 176. SOOT REGENERATION RESULTS FOR DPF VERSUS SCR CONFIGURATIONS

This impact was not significant on the FTP cycle, wherein the average temperature on the SCR was only 230°C, so that significant passive regeneration was not observed on either the DPF or the SCR. However, on the higher temperature RMC-SET cycle, the impact was significant. This suggests that the impact of SCR technology on relative active regeneration frequency was dependent on the duty cycle. For this program, it was necessary to calculate relative regeneration frequency values for both the FTP and RMC-SET cycles, in order to assess the impact of the technology in the context of Phase 2 GHG regulations. A final, field cycle based number was needed in order to finalize the aging cycle for the parts to be used in the final demonstration testing.

In the final configuration, SCR regeneration was accomplished in a manner similar to most current Class 8 heavy-duty engines, with in-exhaust injection of diesel fuel used to generate an exotherm over the upstream DOC (or PNA). In order to support this calculation, regeneration experiments on soot loaded SCR were used to quantify the efficiency of conversion of fuel energy to heat, which was generally found to be on the order of 94% for the PNA+SCR system.

The following data were utilized in the final calculations:

- filter inlet PM data (shown below in Table 54)
- field data histograms from the engine manufacturer
- test cycle RMC-SET and FTP cycle temperature data

TABLE 54. FILTER INLET PM EMISSIONS (DOWNSTREAM OF SYSTEM DOC)

DPF-In PM Data, g/hp-hr		
	Baseline	Updated Calibrations
Cold-FTP	0.16	0.16
Hot-FTP	0.065	0.040
RMC-SET	0.020	0.015

Based on comparison of the temperature histograms, it was determined that the field data could be best represented by weighting the FTP and RMC cycles by 65% and 35%, respectively. In addition, the cycle temperature and flow data was used to establish the amount of fuel needed on each cycle to raise the SCRf inlet temperature to the requisite 600 °C for successful active regeneration. A target soot loading level of 6 g/liter was used for DPF calculations, while a lower level of 5 g/liter was used for the SCRf. The slightly lower level for the SCRf was chosen at a level wherein SCR conversion would not be impacted over the FTP cycle.

Based on all of these data, final regeneration frequencies were calculated as shown in Table 55. It should be noted that a somewhat longer regeneration event was required to ensure complete regeneration on the SCRf. It should also be noted that the baseline field cycle frequency was based on data from the manufacturer, while the FTP and RMC frequencies are based on measurements made using the engine at SwRI and a program DPF. Overall, it was estimated that active regeneration frequency will nearly double. It should be noted there are technology options that could potentially help mitigate some of this penalty, including different SCRf formulations, or the implementation of a multi-point DEF dosing system.

TABLE 55. PREDICTED REGENERATION FREQUENCY FOR BASELINE DPF AND SCRf CONFIGURATIONS

	Baseline		SCRf with updated engine	
FTP	every 33 hours	1.3%	every 40 hours	1.7%
RMC	every 96 hours	0.4%	every 36 hours	1.9%
Field	every 40 hours	1.0%	every 39 hours	1.7%
Active Duration	25 min - 575°C		40 min - 600°C	

Based on the active regeneration frequencies given above, and on the measured fuel required for regeneration on the two cycles, the overall penalty for increased SCRf regeneration on this engine was calculated to be 0.4% on the FTP, and 0.3% on the RMC-SET. To get these numbers, total regeneration fuel requirements were calculated for both baseline and SCRf cases by multiplying the amount of additional fuel needed for a cycle in which regeneration occurs by the total regeneration frequency. The penalty shown is the difference between these the baseline and SCRf values, shown as a percentage of the baseline fuel consumption on the cycle. These values are added to the measured data from the test cell in order to determine the final fuel consumption impact of the ULN configuration. It must be noted that these numbers are closely linked with the particular hardware, engine, and calibration choices made in this program.

3.3.8 Technology Ranking

In February 2016 the Ultra-Low NO_x Diesel System technology screening results were peer reviewed at a CARB Program Advisory Group technology symposium for the CARB Low

NO_x program. Composite and real time emissions and performance data from the screening of the various technologies, technology options and configurations were reviewed. The screening exercise was conducted on a full size transient gas reactor (HGTR) which enabled a large number of systems to be screened and ranked for their NO_x control potential in a relatively short period of time. A summary of the aftertreatment technologies and engine calibrations considered under this program and their composite NO_x potential realized on this engine are summarized in Figure 177. Figure 178 summarizes the measured FTP composite NO_x potential of the various systems evaluated using the Cold Cal 1 engine calibration simulation.

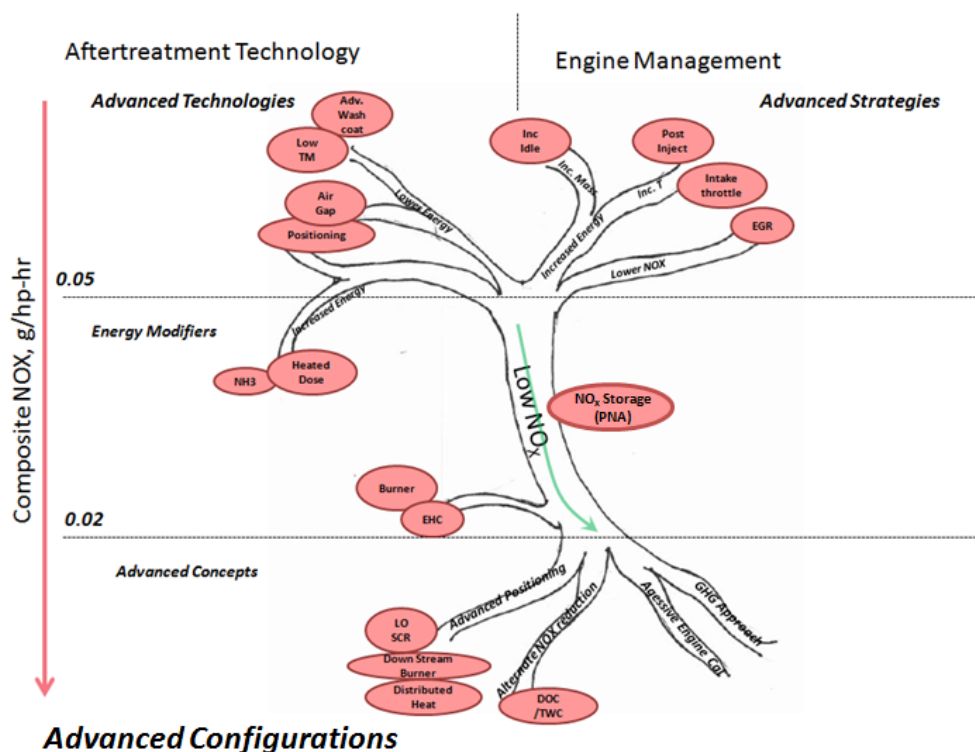


FIGURE 177. AFTERTREATMENT TECHNOLOGIES AND ENGINE CONTROL APPROACHES AND THEIR CUMULATIVE COMPOSITE NO_x POTENTIAL ON TEST ENGINE

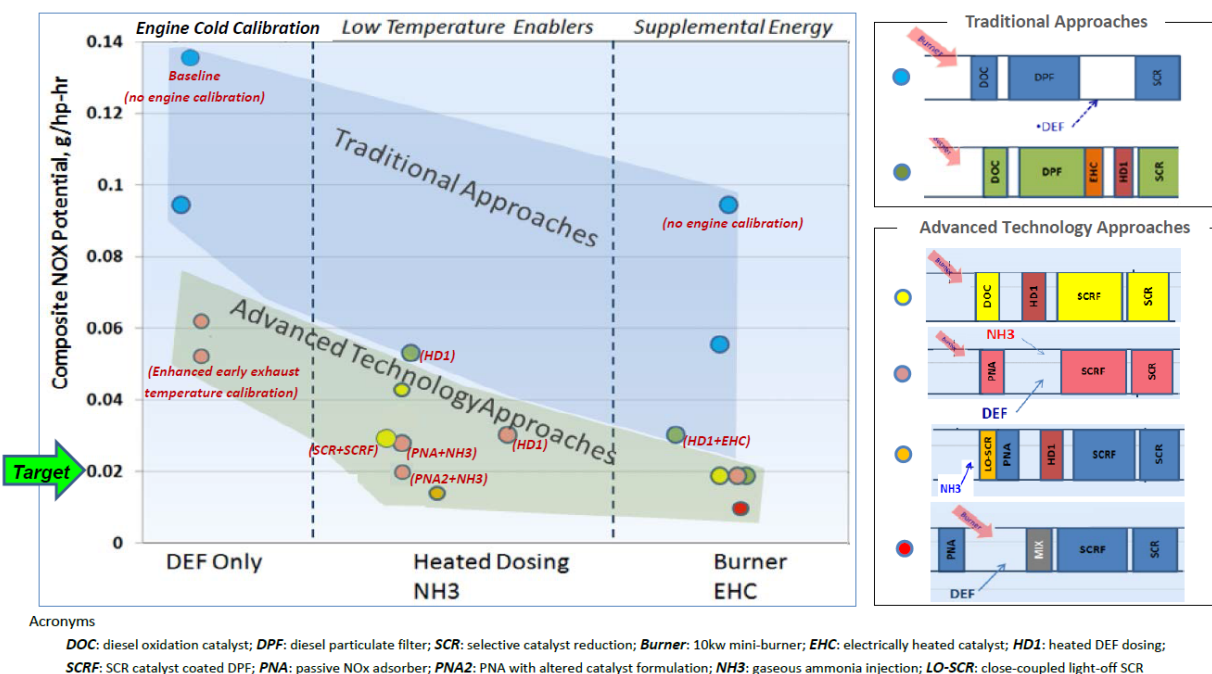


FIGURE 178. SUMMARY OF COMPOSITE ULTRA-LOW NO_x POTENTIAL OF VARIOUS TECHNOLOGY CONFIGURATIONS

To reach ULN composite emissions levels, significant cold-start FTP emission reductions (on the order of current technology hot-start emissions) must be achieved as well as very high conversion efficiencies for the entire hot-start cycle. A key part of obtaining the necessary cold-start emission reductions was reducing the time to achieve SCR light-off. Increased exhaust energy was needed to obtain rapid SCR light-off and was provided by engine measures and direct in-exhaust heat addition in the form of electric heaters or burners. Each approach had a fuel consumption increase versus energy increase trade-off.

To reduce the fuel penalty realized by in-exhaust thermal management many aspects were considered. The elements that affected total energy addition and potential fuel from an in-exhaust thermal management strategy included: catalyst positioning, positioning of supplemental heat, leveraging of low temperature dosing enablers, and devices designed to reduce SCR inlet NO_x mass during catalyst warm-up period

The screening exercise identified many characteristics that were common to the configurations that were able to achieve low NO_x performance. These characteristics and some of the technologies that enabled these performance features included:

- Ability to begin dosing within 60-150 seconds
 - Lower temperature dosing ability
 - Heated dosing or gaseous NH₃ injection
 - Light-off SCR
 - Reduced time to dosing by addition of high levels of supplemental heat
 - Mini-burner or catalytic fuel combustion

- Low temperature NO_x suppression until the first SCR catalyst reached light-off temperature
 - Passive NO_x adsorber
 - Engine calibration

The results of the screening exercise and a qualitative assessment of the technologies and configurations were used to rank the configurations that enabled low NO_x performance. The ranking was broken down into five subgroups:

1. Potential Composite NO_x performance
2. Potential Green House Gas Impact
3. Potential Durability
4. Complexity
5. Additional Cost

Members of MECA and EMA that participated as part of the Low NO_x Program Advisory Group were given the opportunity to assess and rank the technologies and configurations. This section summarizes the collective assessment of potential Low NO_x technologies and rankings of the technology combinations. The final ranking served as the guideline for selection of the combinations to be evaluated and to undergo final calibration on the engine, progressing to the final diesel system demonstration. The configurations that were considered and ranked, grouped by traditional or advanced technology approach, are shown in Figure 179. Refer to the NOMENCLATURE for interpretation.

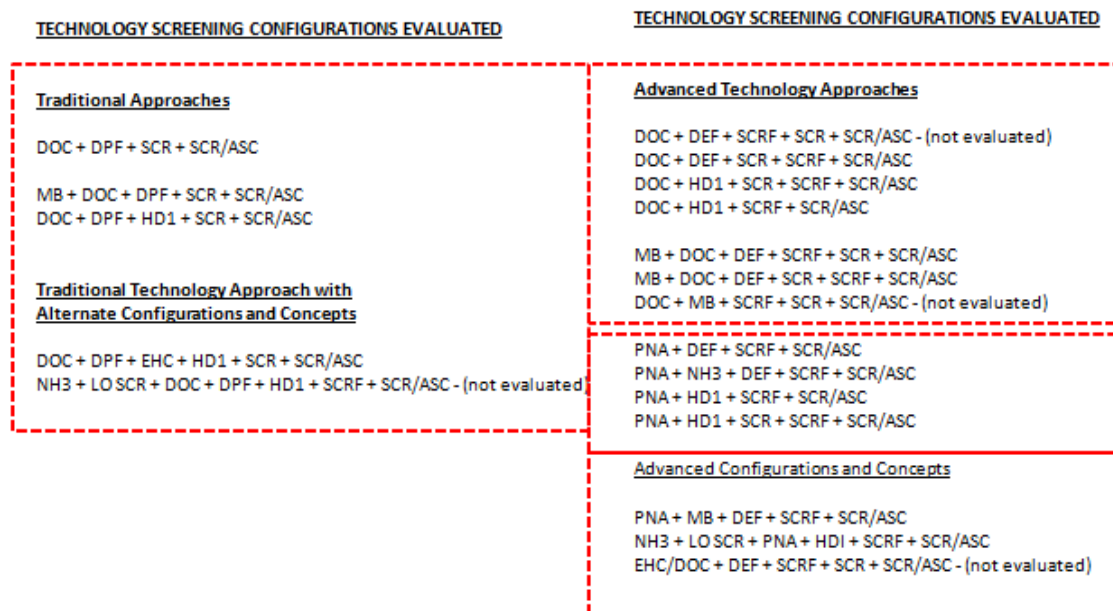


FIGURE 179. TECHNOLOGY CONFIGURATIONS CONSIDERED AND RANKED UNDER SCREENING TASK

3.3.8.1 NO_x Performance Ranking

The composite NO_x potential of each technology configuration was used to rank the technology combinations. Those technologies that had a high potential to meet the <0.02 g/hp-hr target were ranked green, those in the 0.025-0.04 range were ranked yellow, and those above 0.05 were ranked red. Table 56 shows the technologies ranked green and yellow. Although it was felt that the calibration effort for the technologies that ranked yellow would exceed the allowable effort for this program, it was felt that they should also be considered highly viable, particularly in applications that did not include a turbo compound (resulting in higher cold-start exhaust gas temperatures and potentially less energy to achieve catalyst light-off).

TABLE 56. TECHNOLOGY RANKING TABLE - FTP COMPOSITE NO_x POTENTIAL

System	Composite NO_x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + MB + DEF + SCRf + SCR/ASC	0.01				
NH3+LO SCR + PNA + HD1 + SCRf + SCR/ASC	0.016				
PNA2 + HD1 + SCRf + SCR/ASC	0.018				
MB + DOC + DEF + SCR + SCRf + SCR/ASC	0.019				
MB + DOC + DEF + SCRf + SCR + SCR/ASC	0.018				
DOC + MB + SCRf + SCR + SCR/ASC - (not evaluated)	////////// //				
EHC/DOC + DEF + SCRf + SCR + SCR/ASC - (under evaluation)	///				
MB + DOC + DPF + SCR + SCR/ASC	.025				
EHC/DOC + DPF+ HD1 + SCR + SCR/ASC - (not evaluated)	////////// ///				
PNA + HD1 + SCRf + SCR/ASC	0.029				
PNA + NH3 + DEF + SCRf + SCR/ASC	0.031				
NH3 + LO SCR + DOC + DPF + HD1 + SCR+ SCRf + SCR/ASC (not evaluated)	////////// ///				
DOC + DPF + EHC + HD1 + SCR + SCR/ASC	0.033				
Base engine, stock calibration: 4852 g					
Base engine, CC1: 4973 g					

Other concepts that can improve performance of technology: Turbo-Compound bypass, EGR cooler bypass, Close-coupled LO SCR placement, canning to reduce heat loss

Note: Green considered viable for ULN on current engine, Yellow considered viable for ULN on non-turbocompound engine

3.3.8.1 Fuel Economy Penalty

The potential fuel economy impact of each configuration was assessed based on the sum of the engine calibration penalty, the penalty associated with the supplemental energy added to accelerate catalyst light-off and any penalty associated with increased regeneration frequency compared to the baseline system.

The potential fuel addition requirement of applying each technology or engine calibration was estimated and is shown in Table 57. Additional fuel equivalent was measured directly for the MB fuel consumed, and estimated for electrical devices and parasitic losses using assumed electrical and mechanical efficiencies. All strategies were assumed to be maintained for 500 seconds. The assumptions used in these calculations were:

- Electrical efficiency: 44% for mechanical efficiency * 50% generator efficiency = 22% net efficiency
- Burner assumed 2kW parasitic/mechanical losses for air pump
- SCRF increased regeneration penalty

The potential fuel economy (FE) impact to both the cold start FTP (CFTP) and the composite FTP are also shown in the table.

TABLE 57. FUEL ECONOMY IMPACT OF VARIOUS CALIBRATIONS, HEAT ADDITION OPTIONS AND TECHNOLOGIES THAT IMPACT PASSIVE REGENERATION

	Consumed Additional Electrical Energy MJ	Parasitic losses MJ	Consumed Additional Fuel Energy MJ	Total Additional Energy MJ	Fuel Equivalent g	Potential FE Impact to CFTP	Potential FE Impact to Composite
Baseline					4944	0.0%	0.0%
CC1-EI					5067	2.5%	0.4%
<i>Supplemental heat and dosing options</i>							
Mini-Burner		0.8	4	4.8	130	2.6%	0.38%
EHC - 5kw	2.5			2.5	254	5.1%	0.73%
HD1 - 2kw	1			1	101	2.1%	0.29%
HD2 - 1kw	0.5			0.5	51	1.0%	0.15%
EHC+DOC - 2kw	1		1.75	2.75	141	2.8%	0.41%
NH3 injection	0.2			0.2	20	0.4%	0.06%
SCRF- additional regeneration penalty							0.40%

Ultimately, the total fuel economy penalty was assumed to be a combination of the strategies and technologies applied. Figure 180 summarizes the calculated potential composite fuel economy penalty and tailpipe NO_x of each approach. Figure 181 breaks the potential composite fuel penalty down into grams of additional fuel calculated for each contributing component in the configuration. Table 58 shows the system ranking including the potential fuel economy penalty for the top ranked systems.

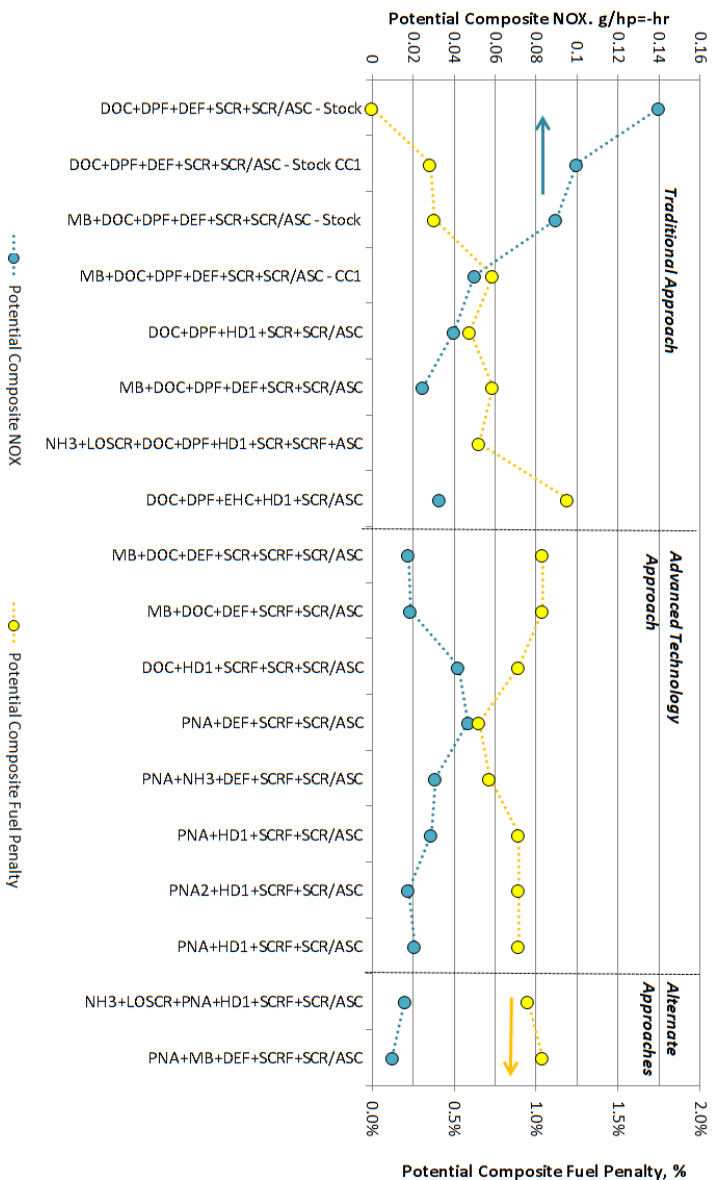


FIGURE 180. COMPOSITE NO_x POTENTIAL AND FUEL ECONOMY PENALTY OF VARIOUS TRADITIONAL AND ADVANCED TECHNOLOGY COMBINATIONS

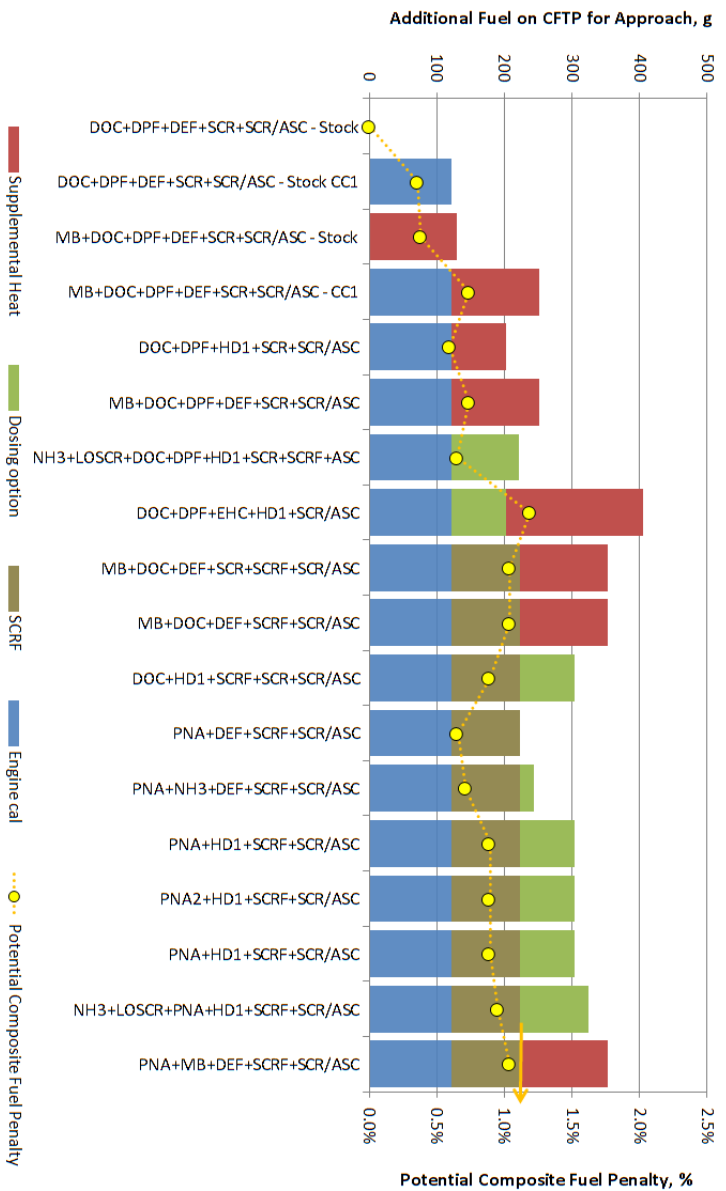


FIGURE 181. POTENTIAL ADDITIONAL COLD-START FUEL CONSUMPTION AND COMPOSITE FUEL ECONOMY PENALTY OF VARIOUS TRADITIONAL AND ADVANCED TECHNOLOGY COMBINATIONS

TABLE 58. TECHNOLOGY RANKING TABLE - FUEL ECONOMY IMPACT

System	Composite NO_x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + MB + DEF + SCRF + SCR/ASC	0.01	1.04			
NH3 + LO SCR + PNA + HDI + SCRF + SCR/ASC	0.016	0.95			
PNA2 + HD1 + SCRF + SCR/ASC	0.018	0.9			
MB + DOC + DEF + SCR + SCRF + SCR/ASC	0.019	1.04			
MB + DOC + DEF + SCRF + SCR + SCR/ASC	0.018	1.04			
DOC + MB + SCRF + SCR + SCR/ASC - (not evaluated)	//////////	1.04			
EHC/DOC + DEF + SCRF + SCR + SCR/ASC - (under evaluation)	///	1.05			
MB + DOC + DPF + SCR + SCR/ASC	0.025	0.74			
EHC/DOC + DPF + HD1+ SCR + SCR/ASC - (not evaluated)	//////////	0.98			
PNA + HD1 + SCRF + SCR/ASC	0.029	0.9			
PNA + NH3 + DEF + SCRF + SCR/ASC	0.031	0.72			
NH3 + LO SCR + DOC + DPF + HD1 + SCR+SCRF + SCR/ASC (not evaluated)	//////////	0.65			
DOC + DPF + EHC + HD1 + SCR + SCR/ASC	0.033	1.2			
Base engine, stock calibration: 4852 g					
Base engine, CC1: 4973 g					

Composite Fuel Penalty Potential is Additional Fuel for all options:

0.4% COLD CAL 1 + 0.3% SCRF (if used) + dosing strategy + supplemental heat strategy

Note: Green considered viable for ULN on current engine, Yellow considered viable for ULN on non-turbocompound engine

3.3.8.2 Durability, Complexity, and Additional Cost

Durability, complexity and additional cost rankings were subjective. Durability, complexity and cost concerns of all elements of the emissions system that were not traditional technology or were additions to a base 2010 technology system (including active regeneration devices) were assigned a rating from 0-10, where 0 is best. Table 59, Table 60, and Table 61 summarize the feedback received by the participating members for durability, complexity and cost. There were four participating EMA members and four participating MECA members. The comments for each device have been combined into one statement and summarized. The ranking for each participating member, identified as MECA or EMA are shown along with the SwRI ranking and the average of all scores. The ranking for each technology configuration was the sum of the average rating for all the technologies used in configuration.

TABLE 59. TECHNOLOGY RANKING TABLE - DURABILITY RATING

	SwRI	EMA-1	EMA-2	EMA-3	EMA-4	MECA-1	MECA-2	MECA-3	MECA-4	Ind. Average	<i>DURABILITY</i>
Device	Rating										Notes
Passive NO _x adsorber	4	9	8	3	5	7	4	4	2	5.5	Durability not well known. Adsorption capacity can be notably reduced due to thermal aging and sulfur poisoning. Desulfation, related LNT technology already common in light duty production
SCR on Filter	3	8	6	3	6	2	3	3	4	4.3	Impact of ash on efficiency and ash cleaning procedure not well known The heat from regeneration can have multiple negative impacts to SCR and filter element designs, which impacts system performance and durability. Risk of increased thermal aging of the SCR wash coat, due to e.g. drop to idle during soot regeneration. Existing Cu SCR formulations are robust, SCR on Filter already in LD production so real world experience expanding.
LO-SCR	2	7	5	2	5	2	2	5	5	3.8	Oil poisoning may impact performance. Poisoning is a high risk from fuel and oil quality issues. Difficult to receive sufficient engine out temperature to de-sulfate the LO-SCR, risk of permanent sulfur poisoning. Sulfation will be a concern – also, NO only performance will degrade more than NO/NO ₂
Mini-Burner	6	6	9	7	4	7	6	6	6	6.4	Possible coking issues. Many potential equipment malfunction pathways
EHC assisted Catalytic Fuel Combustion	4	5	8	4	6	5	4	5	4	5.1	Durability of washcoat, fouling of DOC Aging and stress on the washcoat is also an unknown. Not well known durability over time for the connections and insulations (risk of short cut etc). Washcoat adhesion concerns with thermal cycling, Resistance vs time unknown
Dual Point Dosing	1	2	5	2	3	1	1	3	2	2.3	Possible corrosion of NH ₃ switching valve More components give higher chance to breakdown of parts. Increased failure rate relative to single point dosing without improved component reliability. Not well known durability over time for the connections and insulations (risk of short cut etc). Discreet injectors eliminates switching valve concern
Full Flow Heated Dosing	1	1	6	2	6	7	1	4	4	3.5	Heated element can reduce urea deposit potential Catalyst damage after long times of heating and exposure to gas flows is a concern. Not well known durability over time for the connections and insulations (risk of short circuit)
Partial Flow Heated Dosing	3	0	7	3	4	3	3	5	5	3.5	System packaging to create a durable system is a concern. Not well known durability over time for the connections and insulations (risk of short circuit etc). Diagnostics more of a concern than actual durability
5kw EHC			3	3	5	4	3	4	5	3.7	Fast heat-up could lead to thermal stress on the wash-coat. Durability of electrical system is a concern.
Gaseous NH ₃	1	3	7	2	1	7	1	7	3	3.6	Not well known durability over time for the technology.

TABLE 60. TECHNOLOGY RANKING TABLE - COMPLEXITY RATING

	SwRI	EMA-1	EMA-2	EMA-3	EMA-4	MECA-1	MECA-2	MECA-3	MECA-4	Ind. Average	
Device	COMPLEXITY										
	Rating										Notes
Passive NO _x adsorber	2	1	8	3	7	7	2	2	1	4	Desulfation may be required. Requires development of PNA model. Controls are challenging as there is no way to measure storage / sulfation interaction. Needs to secure regenerative status at key off (e.g. after run, gives fuel penalty) otherwise risk of defeat device. OBD? Advanced control and diagnostic strategy is required
SCR on Filter	2	0	4	3	4	2	2	2	4	3	May reduce passive regeneration. Must be diagnosed as both SCR and DPF. Competing reactions for NO2 between NOx reduction and passive regeneration. Still requires downstream SCR. Refinement of active regeneration model.Reduces the passive regeneration, may need to use dual point additive dosing. 2nd NOx sensor needed for diagnostics. Advanced control and diagnostic strategy is required
LO-SCR	2	5	6	2	6	3	3	4	5	4	Development of dosing strategy required. Dual point dosing required. Additional sensors required for system level diagnostics. Desulfation, if Cu-SCR, in addition to dual point dosing. N2O/NOx control due to NH3 slip to downstream DOC – need LO-SCR / AMOX. Sulfur regeneration maybe complex. Huge complexity across broad range of applications on vehicle for space claim, may not be feasible. Novel diagnostic strategy needs to be developed. Ensure space in the vehicle.
Mini-Burner	6	8	9	7	4	8	6	6	7	7	Additional control system. Fuel, spark, air subsystems. Control complex. Additional control system required. Diagnostics required for each subsystem. System maintenance drives as much control challenge as catalyst needs
EHC assisted Catalytic Fuel Combustion	5	9	8	5	3	7	5	5	3	6	Involved dosing strategies for cold-start to balance activity, slip and deposit formation. Control moderate. Controls complexity, CO2 impact ,additional ECU needed & OBD. Complex energy management strategy for HC control
Dual Point Dosing	2	2	6	2	5	4	2	5	5	4	Additional control and calibration with injection point and rate determination and strategy for splitting DEF flow. Controls moderate. Strategy optimization up front. In use no more challenging than dual leg system. Additional controls complexity, urea deposit concerns Advanced NH3 storage control and diagnostics for increased sensor and actuator set required.
Full Flow Heated Dosing	1	3	6	2	2	2	1	3	3	3	Control of heating element. Additional control system required. Controls for the heating and diagnostics are needed.
Partial Flow Heated Dosing	3	4	8	3	4	3	3	5	6	4	Additional controller required, Controls complex. Flow control makes it slightly more challenging than full flow heated dosing. Reduces the engine performance and cost fuel during warm driving at least 0.2-0.4% not mentioned in presentation material. SCR on filter only? Otherwise . Gas feed from turbine inlet needs to be modulated and controlled, engine performance impact? , OBD Controls for the heating and diagnostics are needed.
5kw EHC		6	6	3	2	2	3	3	4	4	Requires additional alternator. Need to know when to turn off (drop-to-idle type risk)
Gaseous NH ₃ injection	4	7	7	4	6	8	4	5	7	6	Cartridge change required, Infrastructure is non-existent for cartridge-based system. Additional mass inherent in dual reductant system. Gas dosing metering and diagnostics are complex. Weight and size of the ammonia dosage/storage system and addition component installations complicate vocational chassis designs. The life time of the cartridge could be questionable

TABLE 61. TECHNOLOGY RANKING TABLE - ADDITIONAL COST RATING

	SwRI	EMA-1	EMA-2	EMA-3	EMA-4	MECA-1	MECA-2	MECA-3	MECA-4	Ind. Average	ADDITIONAL COST
Device	Rating										Notes
Passive NO _x adsorber	1	8	9	3	6	8	2	2	4	4.8	Replaces DOC in traditional system Additional precious metals will be needed
SCR on Filter	1	0	3	3	2	0	1	1	2	1.4	Replaces DPF in traditional system. Part cost may drop but development costs would be higher due to new controls and regeneration/dosing strategy.
LO-SCR	2	1	4	2	3	3	2	5	2	2.7	Can be zone washcoated on DOC or added as close coupled catalyst. Requires dual point dosing. Add. NO _x sensor?
Mini-Burner	7	6	8	7	3	8	7	6	5	6.3	Belt driven air pump, fuel pump and metering, spark, controller. Controls complex. Additional components, controls and OBD.
EHC assisted Catalytic Fuel Combustion	3	7	7	5	4	5	3	4	5	4.8	Electronic control and upgraded cables and generator. In-exhaust injection (if not already available).
Dual Point Dosing	1	2	6	2	4	3	1	6	4	3.2	Additional valving, plumbing and mixing.
Full Flow Heated Dosing	2	3	6	2	5	5	2	3	4	3.6	EHC with hydrolysis catalyst. Upgraded cables and generator.
Partial Flow Heated Dosing	4	4	8	3	6	6	4	5	7	5.2	EHC with hydrolysis catalyst. Upgraded cables, plumbing changes at turbo inlet.
5kw EHC	3	5	7	3	4	4		3	4	4.1	Higher amp output may require two alternator/generators
Gaseous NH ₃ injection	5	9	6	4	6	9	5	6	5	6.1	Second dosing system if only used during cold-start/ cold operation. Additional mixing.

3.3.8.3 Final Ranking for Technology Down Selection

Under Task 4 of the program, one of the technology configurations was to undergo final calibration on engine and demonstration at the conclusion of the program. The final ranking scores from the screening exercise for composite NO_x potential, potential fuel penalty, durability, complexity and cost were assembled ordered the systems in recommended order to consider on the engine. The recommend order of the systems to be evaluated, as determined from the screening results, is shown in Table 62. The order was established by first considering the systems with the highest potential to achieve ULN on the engine platform used in the program, then by lowest potential fuel penalty impact (assuming CO₂ increase to be the primary indicator of greenhouse gas impact). Although durability, complexity and additional cost were all important factors, due to program timing considerations ULN potential and calibration effort were weighted heavily in the ranking order and final decision.

TABLE 62. FINAL TECHNOLOGY RANKING TABLE

System	Composite NO _x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + HD1 + SCRF + SCR/ASC	0.02	0.9	8/13.3	5/10	4/9.8
NH3 + LO SCR + PNA + HD1 + SCRF + SCR/ASC (HD1)	0.016	0.95	12/20.7	11/20.7	11/12.5
EHC/DOC + DEF + SCRF + SCR + SCR/ASC - (underevaluation)	///	1.05	7/9.4	7/9	4/6.2
PNA + MB + DEF + SCRF + SCR/ASC	0.01	1.04	13/16.2	10/13.1	9/12.5
MB + DOC + DEF + SCR + SCRF + SCR/ASC	0.019	1.04	9/10.7	8/10	8/7.7
MB + DOC + DEF + SCRF + SCR + SCR/ASC	0.018	1.04	9/10.7	8/10	8/7.7
DOC + MB + SCRF + SCR + SCR/ASC - (not evaluated)	//////////	1.04	9/10.7	8/10	7/7.7
MB + DOC + DPF + SCR + SCR/ASC	0.025	0.62	6/6.4	6/7	7/6.3
EHC/DOC + DPF + HD1 + SCR + SCR/ASC - (not evaluated)	//////////	0.98	5/8.6	6/9	5/8.4
PNA + HD1 + SCRF + SCR/ASC	0.029	0.9	8/13.3	5/13	4/9.8
PNA + NH3 + DEF + SCRF + SCR/ASC	0.031	0.72	8/13.4	8/13	7/12.3
NH3 + LO SCR + DOC + DPF + HD1 + SCR + SCRF + SCR/ASC (not evaluated)	//////////	0.65	4/15.2	9/16	10/12.4
DOC + DPF + EHC + HD1 + SCR + SCR/ASC	0.033	1.2	2/7.2	2/7	6/7.7
Base engine, stock calibration: 4852 g					
Base engine, CC1: 4973 g					

Note: Green considered viable for ULN on current engine, Yellow considered viable for ULN on non-turbocompound engine

3.4 TASK 4: Final System Integration and Ultra-low NO_x Demonstration

Under this task, the final system configuration was tested to demonstrate low NO_x emission levels achieved. Final demonstration tests were conducted using aged system components. As with the baseline emission measurements, all of the test cycles selected under Task 1.1 were run in triplicate to document final emission levels. All final demonstration tests were conducted in accordance with 1065 procedures, and employed finalized preconditioning sequences determined during Task 4.1. It was anticipated that the preconditioning sequence was similar to that used for baseline testing under Task 2.1. In addition to the key program cycles specified under Task 1.1, SwRI also evaluated final system performance on two additional vocational cycles specified by ARB.

The primary measurements for the final demonstration were tailpipe emissions of NO_x, NO, NO₂, NH₃, and N₂O. SwRI also measured tailpipe emissions of PM, THC, NMHC, CH₄, CO, and CO₂. The primary method of gaseous emission measurement was dilute continuous measurement, with the exception of NH₃ and N₂O, which was measured in the raw tailpipe exhaust. PM measurement was done via double-dilution utilizing the full-flow CVS dilution tunnel.

3.4.1 Aftertreatment Aging Approach

A key part of the demonstration target was that the system must demonstrate emissions using aged components. The aging was intended to be representative of full useful life, which was 435,000 miles for a heavy heavy-duty on highway application (generally about 11,000 hours of operation). However, the program does not contain sufficient scope, time, or funding to actually age parts on engine all the way to full useful life. Therefore, an alternative approach had to be used to develop parts, which are as representative as possible within the scope constraints of the program. As a result, part of the initial technology selection involved coming up with an appropriate methodology for catalyst aging to reach this target.

Early in the process development, it was realized that there were actually two different aging targets for different phases of the program. Therefore, the process was split into two phases. The first phase, which was designated Development aging, was intended to produce parts relatively quickly in order to support the Technology Screening effort under Task 3. The second phase, which was designated Final Aging, was intended to produce the final demonstration parts which would be utilized for the emissions demonstration at the end of Task 4. These two different phases had different goals, and would be supported by different funding mechanisms. The base program did not have any dedicated budget allocated to aging. A basic aging methodology was used as the starting point for both Screening and Final aging protocols, and then was modified as needed to reach the targets for two protocols.

3.4.1.1 Basic Aging Approach

Given the time constraints, it was necessary for the aging protocol to incorporate some means to accelerate aging, since it was not feasible to run roughly 11,000 hours. The approach that was proposed by SwRI utilized a protocol that was developed under a cooperative research

program that was run at SwRI, which was titled the Diesel Aftertreatment Accelerate Aging Consortium (DAAAC)[5]. In that program, considerable effort was expended to develop and correlate an aging protocol to actual field aged parts. The resulting DAAAC methodology was useable by SwRI in support of other programs. In addition, the DAAAC protocol has been used as the basis for development of aging protocols by the JRC for heavy-duty catalyst aging in Europe, as well as by ARB for the development of a protocol to age aftermarket DPF parts prior to emission demonstration testing.

The DAAAC protocol includes a method to transform field data into equivalent engine aging protocols. This method was based on an Arrhenius rate equation to assess thermal aging exposure, and was similar in principal to the methodology employed by U.S. EPA in the Standard Bench Cycle (SBC) protocol that is used for light-duty accelerated aging.

SwRI obtained the field duty cycle data from Volvo for the MD13TC engine, and this data was used as the basis for the DAAAC calculations. Given the technologies chosen, an aging factor for a copper zeolite SCR catalyst was used for the calculation. In addition to the field data, Volvo also provided information on DPF regeneration frequency, and the temperatures expected for an oxygen-based regeneration. This information was all utilized in the DAAAC calculation to derive an appropriate aging exposure. The calculation result is illustrated below in Table 63. The calculation show a field temperature histogram for the base engine, as well as the amount of time that would generate the equivalent heat load at 600°C. For most temperatures the equivalent time is near zero, which is due to the exponential nature of the heat load calculations.

TABLE 63. DAAAC AGING CALCULATIONS

Temperature	Average	Time	Equivalent
Bins	Temperature	at	Time at max.
°C	Kelvin	Temperature	Temperature
<150	423	864	0.001
150-200	448	216	0.001
200-250	498	628	0.030
250-300	548	529	0.207
300-350	598	102	0.233
350-400	648	1	0.010
600	873	24	24.000
etc	Total time	2364	
Equivalent time at		873	24.482

Desired aging temperature = 873 K
600 °C

This table calculates equivalent aging time at different temperatures.

If the peak aging temperature is 873

24.482 hours at 873 K
113 hours at 873 K

As can be seen in the table, the equivalent aging was dominated by the DPF regeneration events at 600°C. The remaining operating time contributes very little to overall aging from a hydrothermal standpoint. Based on the time represented by the field data histogram of 2,364 hours, and a 40mph average speed in application (resulting in 10,875 hours for full useful life), a total aging time of 113 hours at 600°C was determined. This essentially represents a full useful life of exposure to DPF regeneration. The starting point for the basic aging approach was therefore to expose the system to the equivalent of a full useful life of DPF regenerations.

While this approach covers hydrothermal aging, it does not account for chemical aging due to exposure to lube oil components. This component of aging was dealt with differently for the two different aging protocols. The implementation of this basic approach for each of the phases of aging is discussed below separately.

3.4.1.2 Development aging

The target for development aging was to develop parts that were somewhat representative of full useful life aging, but that were all aged in a consistent manner in order to allow a proper comparison between different technologies. Under the screening in Task 3, the performance of aged parts and de-greened parts would be compared in order to assess the relative sensitivity of a given part to aging. That sensitivity would be considered as part of the down-selection process. Therefore, the real goal was to ensure that a valid comparison of parts could be made.

At the same time, development aging was to be provided by all of the individual suppliers for their hardware. This meant that a large number of parts needed to be produced, many of which would not be selected for the final demonstration. As a result, it was necessary to limit the level of effort, while at the same time produce parts to enable a valid comparison.

As a result of these objectives, the basic approach to aging was adjusted in several ways. First, it was determined that chemical aging would not be part of the development aging. Each technology might react differently to chemical poisoning requiring different approaches, which would take significant time to determine and implement. In addition, the positioning of components in the system also has a significant effect on exposure to lube oil components, and the final configuration would not be known at the start of screening. Some specific effects, such as sulfur sensitivity could also be examined during the screening process. Finally, representative chemical aging was generally very time consuming and expensive, and might not be of significant aid to the down-selection process. Therefore, chemical poisoning could be excluded from the Development aging.

In addition, it was determined that a consistent process would be used for all parts, and that this process would be based on the thermal aging characteristics already calculated for the base approach. While a final configuration might change the regeneration frequency, this was not yet known at the start of screening. Therefore, the base approach would be used, with some modifications depending on the parts being aged. Temperatures were also increased somewhat in order to shorten times and account for other possible issues. For most of the catalysts, this meant exposure to 625 °C for 100 hours. However, in the case of SCRF components, where regeneration might result in higher temperature exposure and regenerations might be more

frequent, it was decided that these components would be aged 100 hours at 650 °C instead to represent this added exposure. This same exposure was also used for any PNA components given that they would also be exposed to higher temperatures given their upstream position and possible function generating the regeneration exotherm.

For Development aging, it was decided to allow both oven aging and engine aging to prepare the aged screening parts. In the case of oven aging, it was determined that the aging would be done in air containing roughly 10% steam to provide sufficient water content. In the case of engine aging, system components would be mounted as intended in use, and HC injection over the upstream DOC would be used to control temperature at the DOC outlet to the desired target. In both cases, the de-greened parts would use the same conditions but would be run for only 5 hours. Each manufacturer was allowed to determine which of these two approaches they would use.

3.4.1.3 Final Aging

For the Final Aging, the primary target was to be as representative as feasible of full useful life for the final system configuration. The basic DAAAC-based methodology would still be used, which meant that aging time and temperature would still be based on active regeneration events. However, there are several key differences in the implementation of the final aging, as compared to the Development aging described earlier.

The first difference was that the final number of hours, and the exposure temperature would be determined based on the actual regeneration characteristics of the final system. As part of the screening work, testing would be performed to compare the regeneration frequency of the final system components to a baseline DOC-DPF configuration. These tests would include soot loading and oxidation rate determinations, including DEF dosing where appropriate (such as for an SCR component). These tests would be used to derive an appropriate regeneration frequency and temperature for the system. If that frequency was higher than the base engine frequency of roughly 1%, then the aging hours at temperature would be increased appropriately. In the event that no change was observed between the final configuration and the baseline configuration, then a 1% frequency would be utilized.

Second, the final aging would be conducted on engine only. The complete system would be used, and DEF would be dosed during aging as appropriate for high conversion NO_x reduction. Rather than a continuous steady-state temperature exposure, temperature would be cycle through individual regeneration events using system components. As a result, HC-dosing would be used over the appropriate system DOC component to create the exotherm required to reach the target regeneration temperature. The duration of individual regenerations would likely be roughly 20-30 minutes at temperature, not include the ramp time. In between regenerations, a lower temperature condition would be run that was representative of average in-use temperatures. In essence, a full useful life of regeneration events were ran in succession. Additional high temperature exposures are required for other components, such as desulfation events, these were also included in the final aging protocol.

Given the timing and the ongoing development occurring on the Volvo MD13TC engine, that engine was not used for final aging. Instead a mule engine at SwRI was run, but at conditions representative of the Volvo program engine. The mule engine used was a modified 2009 Cummins ISX 15-liter engine. The engine was modified in accordance with the DAAAC protocol in order to increase oil consumption by a factor of three over the base engine. This modification allowed for some acceleration of oil exposure, while still maintaining a representative mechanism of exposure and poisoning.

For the aging protocol, it was planned that minimum of 1,000 hours would be run. The 1000 hour duration was determined to allow for both realistic thermal aging and cycling and as much oil exposure as possible, while still being manageable within the program scope and timeframe. This would cycle between regeneration and non-regenerating conditions. It was anticipated that this would result in more time in a non-regenerating condition. However, in the event of very frequent regeneration events, at least a 50:50 balance of the two conditions would be maintained. Aging would be extended beyond 1,000 hours if needed to maintain this balance and reach the target amount of high temperature exposure hours. Given the DAAAC increased oil consumption rate, it was anticipated that the aftertreatment system would be subjected to 3,000 hours of equivalent oil exposure, roughly 28% of full useful life. This was roughly equivalent to 120,000 miles of oil exposure.

Details for the final aging protocol were developed only after the system configuration was finalized, and experiments were run to determine the SCRF regeneration method and frequency. These details are discussed later in the report, as is the actual conduct of the Final Aging.

3.4.2 Engine Integration and Testing of Final Candidate Aftertreatment Systems

As discussed at the end of the Screening section of the report, the final output from screening was a ranked list of candidate systems which showed the potential to reach 0.02 g/hp-hr. These options were listed in order of preference as a result of the ranking process. The next step in the program was to integrate and test these candidate technologies on the Volvo MD13TC engine. The systems were tested in the order of preference listed in the ranking table.

There were several common elements to all of the candidate systems. These elements were required due to the very low exhaust temperature profile of the MD13TC engine, as a result of the turbo-compound system used for waste heavy recover. These common elements included:

- A multi-bed SCR system consisting of an SCR-on-Filter (SCRF) followed by a flow-thru SCR catalyst
- A passive NO_x adsorber (PNA) for low temperature NO_x storage. The PNA also serves the functions of a traditional DOC in this system, including generation of the exotherm needed for regeneration of the filter (via supplemental fuel injection using in the exhaust).
- A dual-layer Ammonia Slip Catalyst (ASC).

Additional modifiers were added to these common elements as discussed for each system below.

3.4.2.1 Packaging Changes for Final Configurations

Prior to the start of this testing, several modifications were made to the basic system package, in an effort to optimize the system better from a thermal and packaging standpoint. The SCR system packaging was altered from its original form in order to reduce system mass and also to reduce thermal losses. These modifications are shown in Figure 182 and Figure 183 showing the system before and after the changes. Several end-cones and sections of piping were removed from the system to create a better package.

To facilitate the use of the ammonia sensor in this package, it was necessary to make a further modification to the system in order to allow for an accurate sample of the exhaust gases to be taken across the 13-inch diameter of the catalysts face, while using a sensor that protrude less than 1 inch into the catalyst can. A static probe assembly was designed, fabricated, and installed in the front of the SCR catalyst, downstream of SCRF. This probe was designed to sample exhaust gases from across the face of the catalyst. Those gases exit the probe assembly at the top via a gap in the back of the wider section that surrounds the NH_3 sensor probe. In this way, the gases are forced to flow across the sensor. It was found that NH_3 sensor signal using this arrangement showed good correlation with FTIR readings sampled via a similar multi-holed probe arrangement in a used in several different orientations. This allowed the sensor to have a signal useable for controls. This probe assembly is shown in Figure 184, which also shows the extended length production temperature sensor used at this position.



FIGURE 182. MODULAR PACKAGING OF SCR SYSTEM CATALYSTS FOR SCREENING

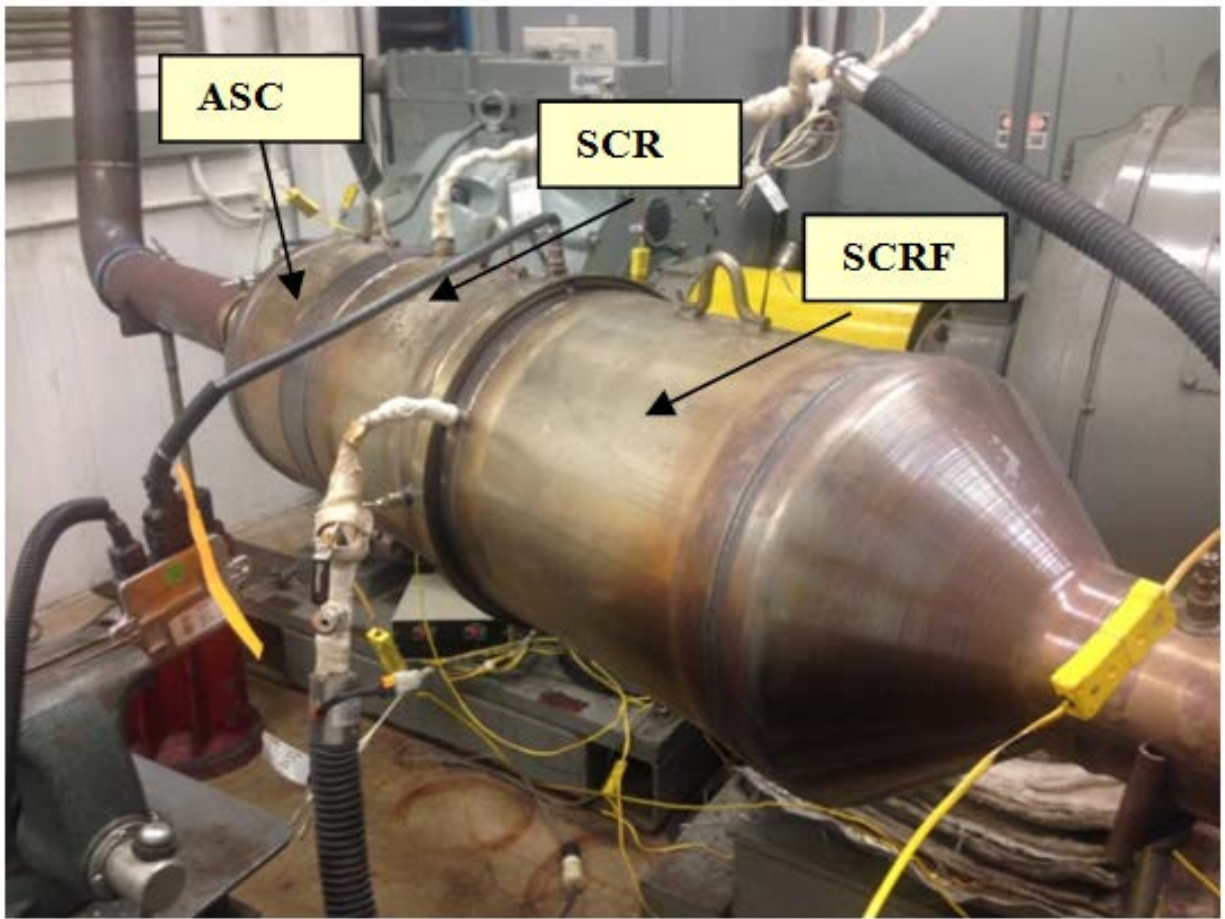


FIGURE 183. FINAL MULTI-BED SCR SYSTEM PACKAGE



FIGURE 184. SCR CATALYST INLET SHOWING NH_3 SENSOR PROBE (AND PRODUCTION TEMPERATURE SENSOR)

3.4.2.2 Dosing System and Final Mixing Configuration

The DEF dosing system used for this program was the same as the production system utilized on the Volvo MD13TC baseline engine. This was an Albonair air-assisted dosing system. The air-assisted system was retained due to its superior atomization characteristics, which allowed it to generate a very fine spray distribution, with a Sauter Mean Diameter (SMD) near 30 microns and a relatively narrow droplet size distribution. Given the focus on cold-start and low temperature conversion it was determined that this approach would be the best choice for low temperature droplet evaporation.

The DEF system was paired with a compact mixer that was specifically designed to mount the Albonair nozzle. Figure 185 shows the mixing section of the final configuration in the test cell. The mixer was designed to work with the relatively narrow cone angle and high exit velocity of the Albonair nozzle. It promoted mixing primarily via interaction of the spray with

turbulent exhaust gas, thus minimizing contact with the walls at low temperatures. For some configurations employing the heated dosing system, this mixer was placed in front of the electrical heating element and hydrolysis substrate. A downstream swirl mixer was used to ensure complete gas phase mixing prior to entering the SCRF inlet. This configuration is shown in Figure 185. In cases where this hardware was not employed and the distances were shorter, this mixer was paired with a diffuser cone at the SCRF inlet to provide the mixing and distribution required for very high NO_x conversion rates. This configuration is illustrated in Figure 186. Although the final package was relatively compact, further development could be conducted to improve the overall thermal package and reduce heat loss through the mixer further, as well as to reduce overall system backpressure.

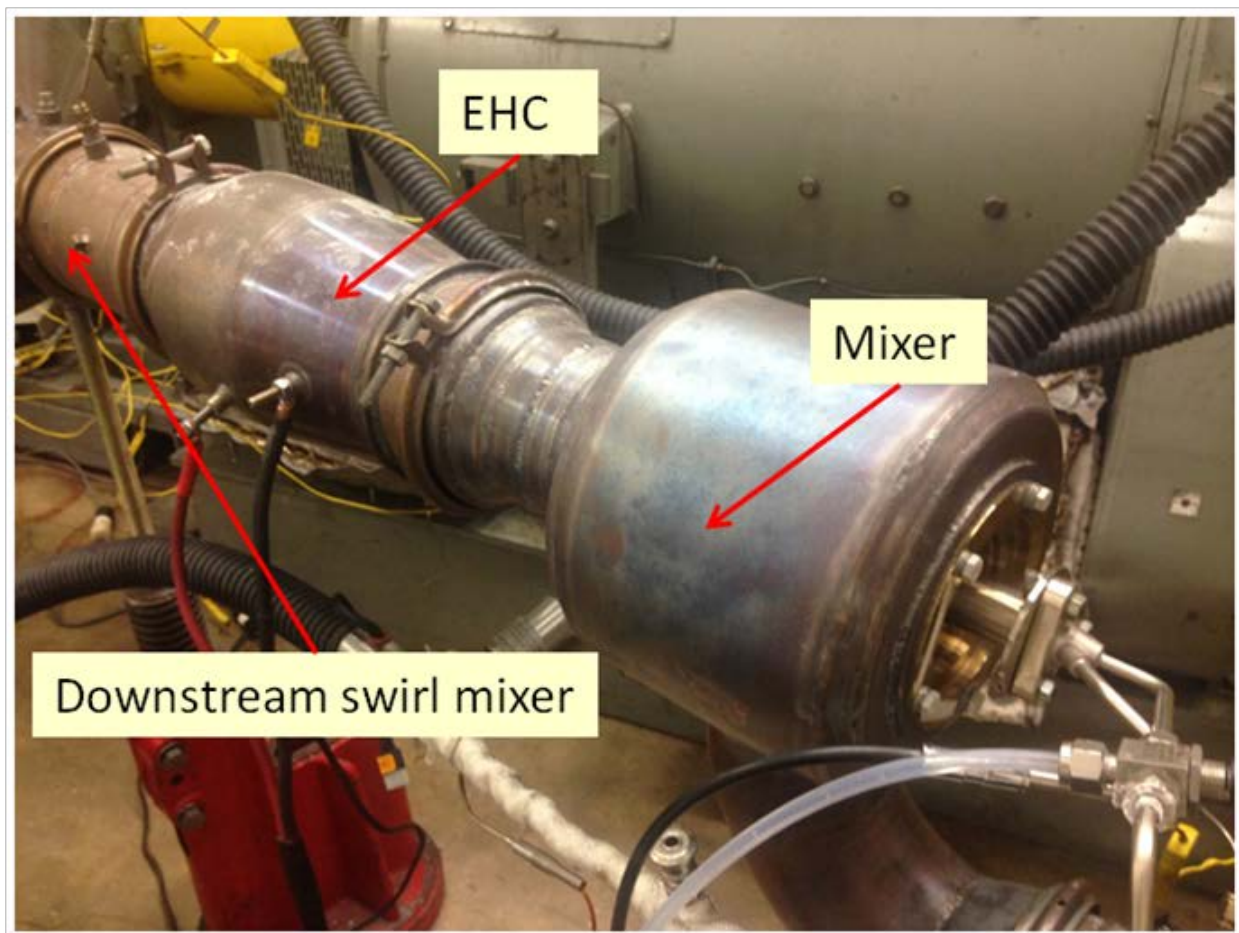


FIGURE 185. MIXER INSTALLED UPSTREAM OF ELECTRICALLY HEATED CATALYST

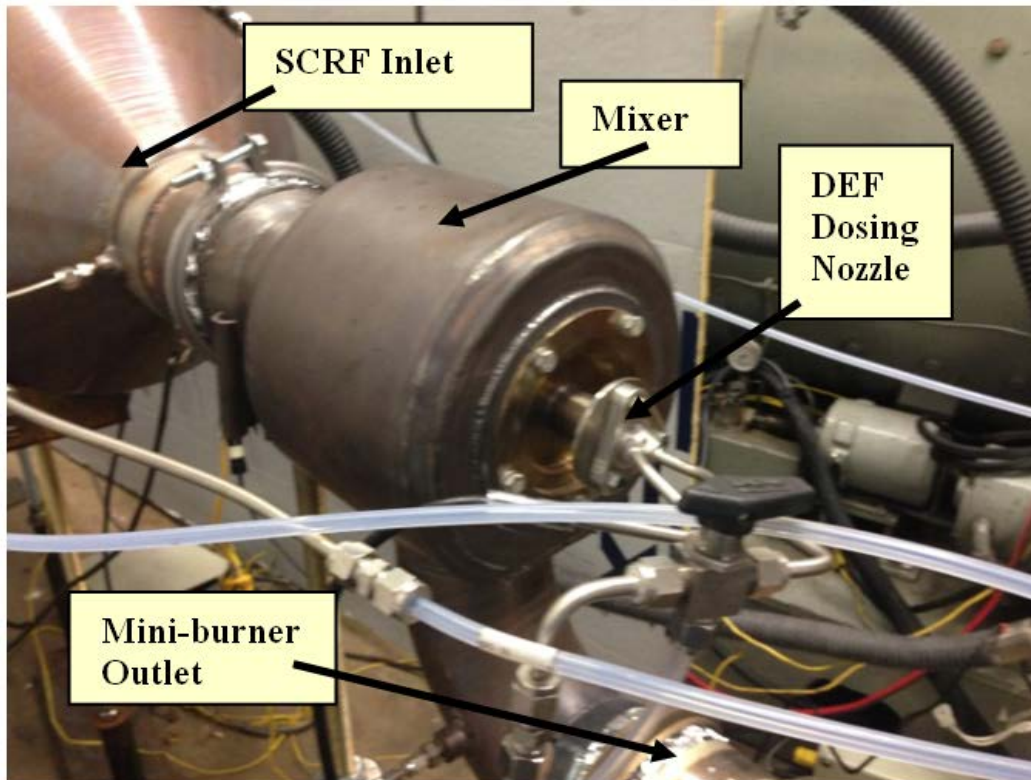


FIGURE 186. MIXER INSTALLATION AFTER MINI-BURNER WITH SHORTER DISTANCE TO SCRF INLET

3.4.2.3 Dosing Controls Approach

Two different controls approaches were used over the course of the Task 4 effort. For the initial testing of different configurations that prior to the final down-selection, the same controls approach that was applied during screening was utilized. After the final configuration was selected, a more advanced model-based control strategy was implemented with models calibrated specifically to the chosen SCRF and SCR catalysts. Each of these approaches is described briefly below.

3.4.2.3.1 Initial Dosing Controls Approach for Screening and Early On-Engine Down-selection

The initial dosing control approach on engine evaluations was based on a combination of a fixed ANR schedule and feedback from the NH_3 sensor located between the SCRF and SCR catalysts. This NH_3 sensor was utilized as part of an “ammonia braking” function, in which it would reduce dosing to lower levels if the measured value exceeded certain thresholds and was not rapidly decreasing. While this approach was suitable for comparing parts and assessing performance, it was not flexible enough to deal with all of the different cycles that would eventually be run during the demonstration. Each cycle would require a custom schedule, which is not realistic. In addition, careful preconditioning would be needed for each different duty cycle, which is not appropriate for demonstration testing. However, this control was sufficient to assess the performance of different systems over cold-start and hot-start FTP tests.

3.4.2.3.2 Final Model-Based Dosing Controls

The final controls approach utilized an advance, model-based control strategy, which is described in more detail below. This model-based controller was used for all of the final demonstration tests on all cycles. A calibration was developed and tuned using FTP and RMC cycles, and then that calibration was utilized without modification for nearly all other cycles. It should be noted that a slightly different calibration tune was utilized for the WHTC cycle, however it was felt that this was appropriate, given that the final calibration of any production system would be optimized for the regulatory cycles appropriate to the target market. A schematic of this approach is given in Figure 187.

The final controller has two primary elements:

- A feed-forward controller which utilizes a model-based ammonia coverage observer to manage ammonia across the SCR catalysts
- A feedback (closed-loop) controller which utilizes the signal from a mid-bed ammonia sensor to adjust and correct the model state

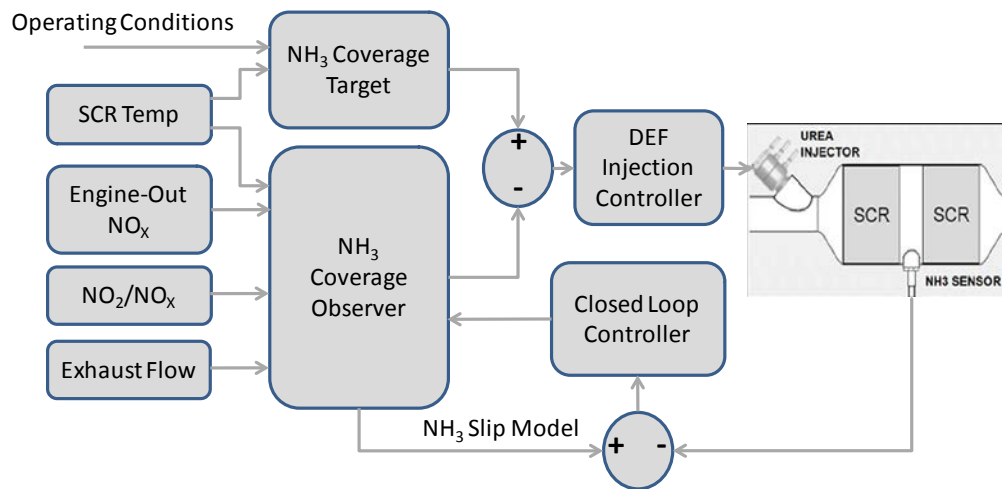


FIGURE 187. SCHEMATIC OF MODEL-BASED DOSING CONTROLLER

The primary sensor inputs for the controller are shown in Figure 188, which shows the system diagram for the final down-selected configuration with all of the sensors in the system.

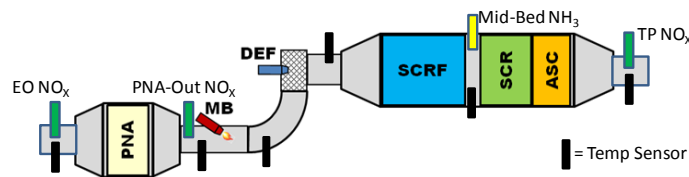


FIGURE 188. AFTERTREATMENT SYSTEM DIAGRAM WITH SENSORS

The key sensor inputs for the controller are:

- An engine-out NO_x sensor. This sensor is primarily required for OBD of the PNA, but it is utilized in cold-start to drive dosing prior to the release of NO_x from the PNA
- A PNA-out NO_x sensor, which serves as the primary SCR system inlet NO_x measurement.
- An NH₃ sensor located at the SCRF outlet. This is the primary real-time feedback sensor used by the controller
- A tailpipe NO_x sensor, which would be required for OBD, but can also be utilized for long-term adaptive update of the dosing controller, especially with regard to the downstream SCR state. This function was not utilized within the current demonstration program, given the short time scale of the laboratory testing.
- Temperature sensors at the following locations
 - o PNA Inlet and Outlet
 - o SCRF Inlet and Outlet (which was also the SCR Inlet)
 - o Tailpipe (ASC outlet)

The two SCR catalysts in the system had very different performance characteristics in terms of ammonia storage and NO_x reduction. In addition, the SCRF and the downstream SCR were managed to achieve different objectives. As a result, a separate coverage observer was used for each catalyst. The SCRF had significantly lower storage capacity per unit volume. Therefore, despite being twice the size of the downstream SCR, the SCRF represented only about 40% of the total ammonia storage capacity of the system. The location of the NH₃ sensor downstream of the SCRF allowed the sensor to have a more timely response to system changes and made it more useful for feedback, as compared to a tailpipe location.

The primary target for the control of the SCRF was to maintain good coverage of ammonia across the catalyst, but also to achieve a stable, manageable level of ammonia slip that to supply ammonia to the downstream SCR catalyst. The primary target for control of the SCR was to maintain a stable level coverage across the catalyst, but also to prevent coverage from being excessive to avoid excessive levels ammonia slip that could not be managed by the downstream ASC.

The basic control approach was the use the coverage observer as a virtual feedback sensor to manage ammonia coverage, as illustrated in Figure 187. The actual structure of the coverage observer is in the form of a 1-D model, which is actually a series of “cells,” each of which is a 0-D kinetic model of a portion of the catalyst. A number of these cells are connected in series in order to allow for monitoring of both the total ammonia storage and the axial profile of storage across the catalyst. A schematic of this concept is shown below in Figure 189. The observer also contains a thermal model to predict temperature at intermediate locations. The inlet and outlet conditions for the model were measured, and all intermediate conditions were tracked by the model internally. The model used for the SCR controller utilized seven cells for each catalyst substrate, although the model was designed to be scalable so that the number of cells could be adjusted as needed to more or fewer cells. As mentioned earlier, a separate observer was used for the SCRF and the SCR. While temperatures between the catalysts were measured, the gas inputs from the SCRF to the SCR were tracked by the model.

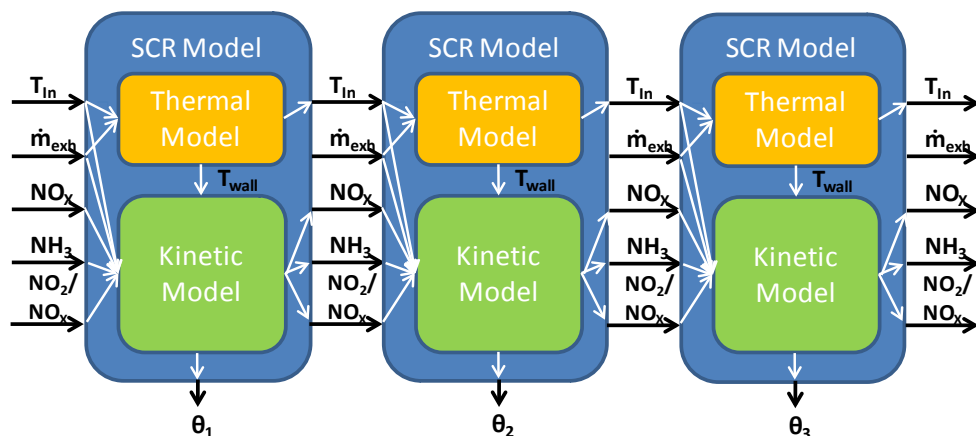


FIGURE 189. SCHEMATIC OF SCR CATALYST MODEL WITH MULTIPLE CELLS

The reaction rates constants of the model were calibrated using a series of experiments on small catalysts cores that were conducted using a synthetic gas bench at SwRI called the Universal Synthetic Gas Reactor (USGR). Additional experiments were performed on the full-size catalysts (especially for the SCRF) using the Hot-Gas Transient Reactor (HGTR) facility at SwRI. In practice, it was planned that the models could be calibrated using only core tests on the USGR. Separate calibration experiments were conducted on the SCRF and the SCR, and a different set of reaction rate constants and storage capacity parameters were developed for each of these catalysts.

In this model, ammonia storage was tracked in the form of a coverage ratio, θ , which was expressed as the ratio between the currently stored ammonia and the maximum storage capacity of the system (which was set based on the measured storage capacity at 200°C at an inlet ANR of 1.2). The storage capacity was determined via a series of temperature programmed desorption (TPD) experiments for each catalyst.

For the controller, NO_2 - NO_x information at the SCRF inlet was predicted by an empirical model of the PNA system, based primarily on catalyst temperature sensor measurements. This model was calibrated using a separate series of experiments.

The actual coverage control function was implemented as a “mean priority controller,” with the controller targeting a mean coverage value for each catalyst. Individual model cells are also weighted to define a desired profile. The mean value targets form the primary calibration input for the controller. In addition, an upper and lower bound value was generated from the mean values, and these are used by a bound manager function in a more aggressive manner to try to prevent regions of the catalyst from either emptying or storing excessive amounts. A schematic of this approach is shown in Figure 190.

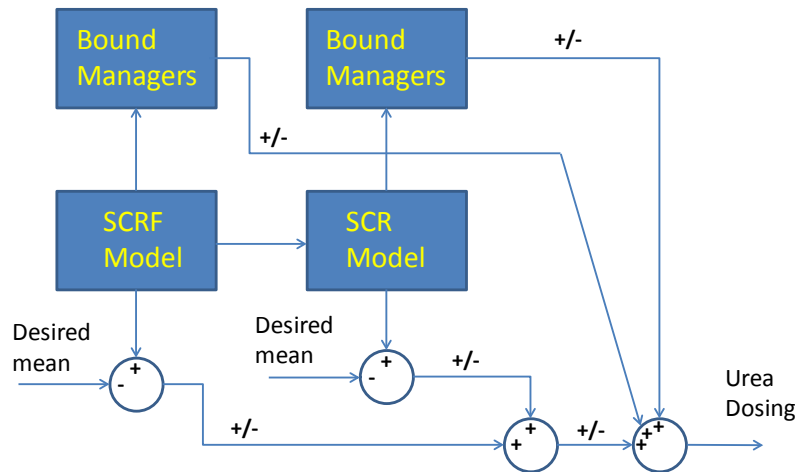


FIGURE 190. SCHEMATIC OF AMMONIA COVERAGE CONTROL

The NH_3 sensor feedback for the SCRf and tailpipe NO_x sensor feedback for the SCR were implemented as functions that correct the state of the appropriate coverage observer, based in comparison between the models predicted value and the sensor value. A schematic of this function is shown in Figure 191. This comparison was used to generate an “innovation” term, which was applied to the model state. It should be noted that in the case of the tailpipe NO_x sensor, this requires the implementation of an ammonia slip detection function in order to deal with the cross-sensitivity of the NO_x sensor to ammonia. This requirement, and the slow response of the tailpipe location to system inputs due to the amount of upstream catalyst, would require that the NO_x innovation function be implemented on a longer time scale, more suitable as an adaptive learn function. As noted earlier, this function was not utilized for the current program, given the short timeframe of the laboratory demonstration.

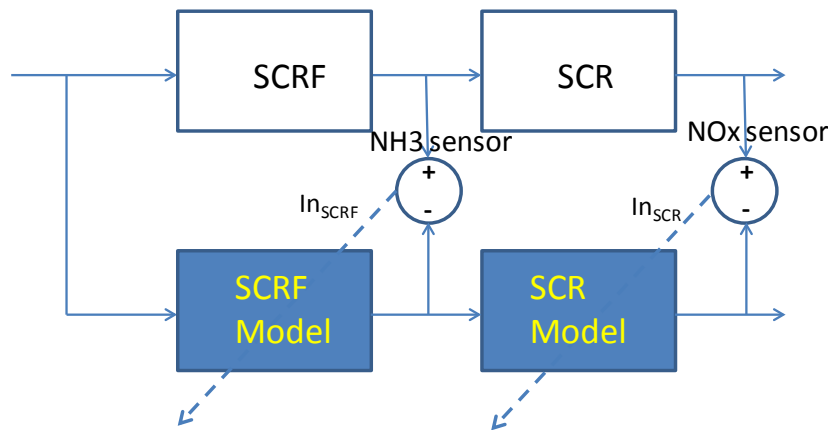


FIGURE 191. SCHEMATIC OF SENSOR FEEDBACK CORRECTION APPROACH

The controller stores the state of both the coverage observers on engine shut-down, and then reloads that state at key-on and engine start. This function was essential to allow the models to track storage ammonia accurately over time. At present, no adjustments are made to the stored coverage states while the engine was off.

The final controller was calibrated initially using a series of steady-state experiments and step tests in the engine cell, and then was further tuned over the target cycles, including the FTP, RMC, and WHTC cycles. An example of the dynamic behavior of the SCR controller over the FTP cycle is given below.

Figure 192 shows the average coverage over both the SCRF and the SCR over the course of the cycle. As can be seen, the SCRF coverage function was much more dynamic, and it was also calibrated to use a much higher amount of its capacity. This was a result of the need for the SCRF to supply ammonia to the downstream SCR.

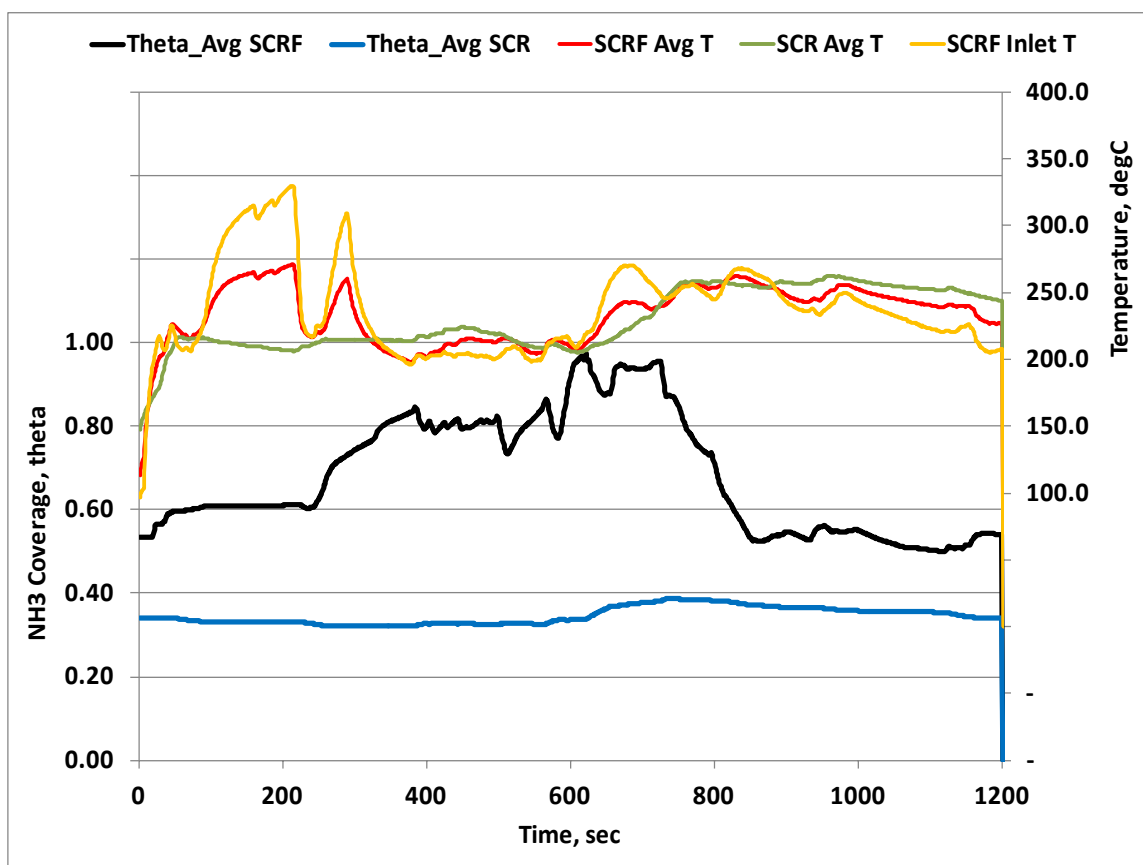


FIGURE 192. AVERAGE AMMONIA COVERAGE AND TEMPERATURE OVER HOT-START TRANSIENT FTP

Figure 193 shows the dynamic behavior of the coverage profile on the SCRF over a hot-FTP cycle. The NH_3 sensor feedback signal is also shown in this figure. Early on, at low temperature, the controller was targeting ammonia coverage at higher levels, which could only occur from the front of the SCRF where the DEF injector was located. As temperature increased, the controller began to reduce coverage, but also a wave of ammonia began to move through the catalyst axially from front to back. This emerged as increased ammonia slip at the SCRF outlet, and the NH_3 sensor indicated a large spike in ammonia that had to be managed. The controller responded by reducing dosing drastically, resulting in a rapid drop in storage at the front, while the ammonia wave was depleted by incoming NO_x . When storage levels were

sufficiently reduced and the NH_3 sensor signal returned to normal levels, the controller began to increase dosing again to ensure that coverage was maintained.

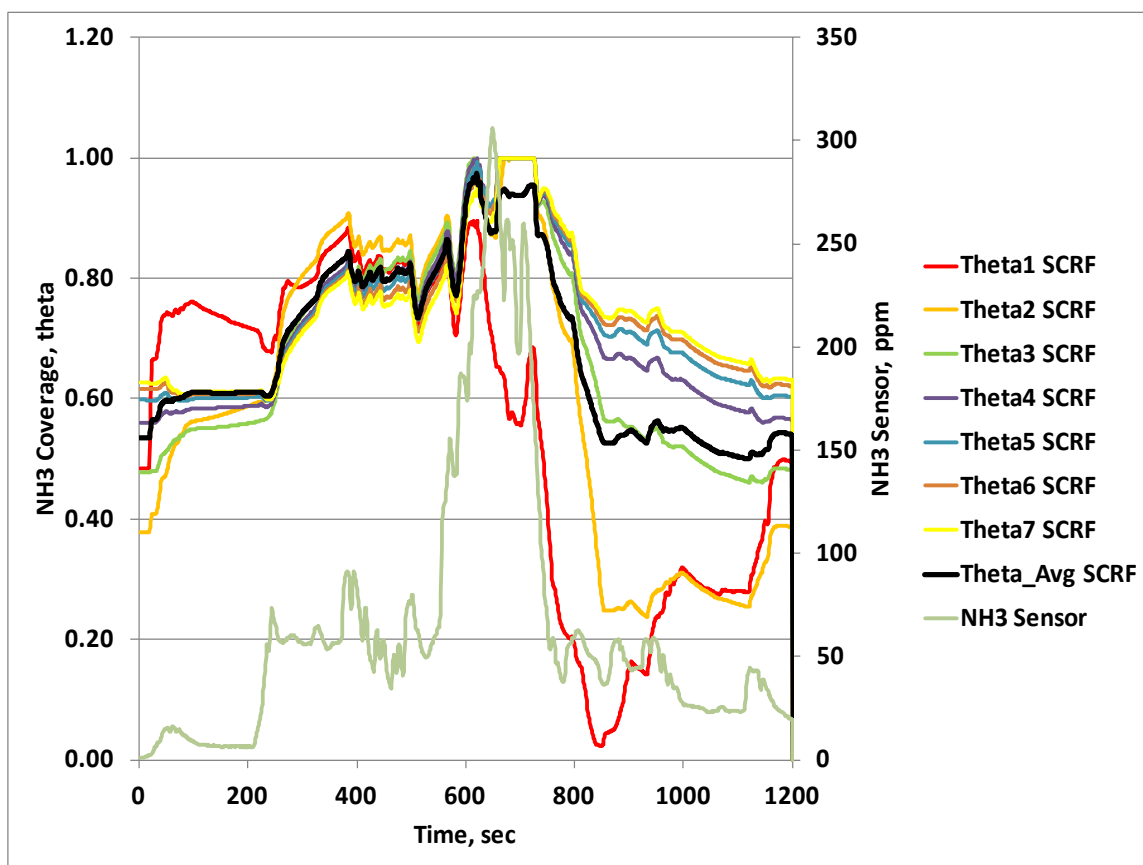


FIGURE 193. COVERAGE PROFILE OF THE SCRf CATALYST OVER HOT-START TRANSIENT FTP CYCLE

The result of this controller behavior on final dosing is shown in Figure 194, in comparison to base “stoichiometric DEF demand.” Stoichiometric DEF demand was calculated based on system inlet NO_x data, assuming an ANR of 1. Early in the cycle, the controller was “over-dosing” to achieve the desired coverage target. As the temperature increased, a wave of ammonia propagated through the catalyst, and dosing was reduced, most notably in the 600 to 900 second range. Later in the cycle, the controller again increased dosing over the ANR 1 level to maintain coverage. The overall DEF injection for this particular cycle was very close to an ANR of 1.

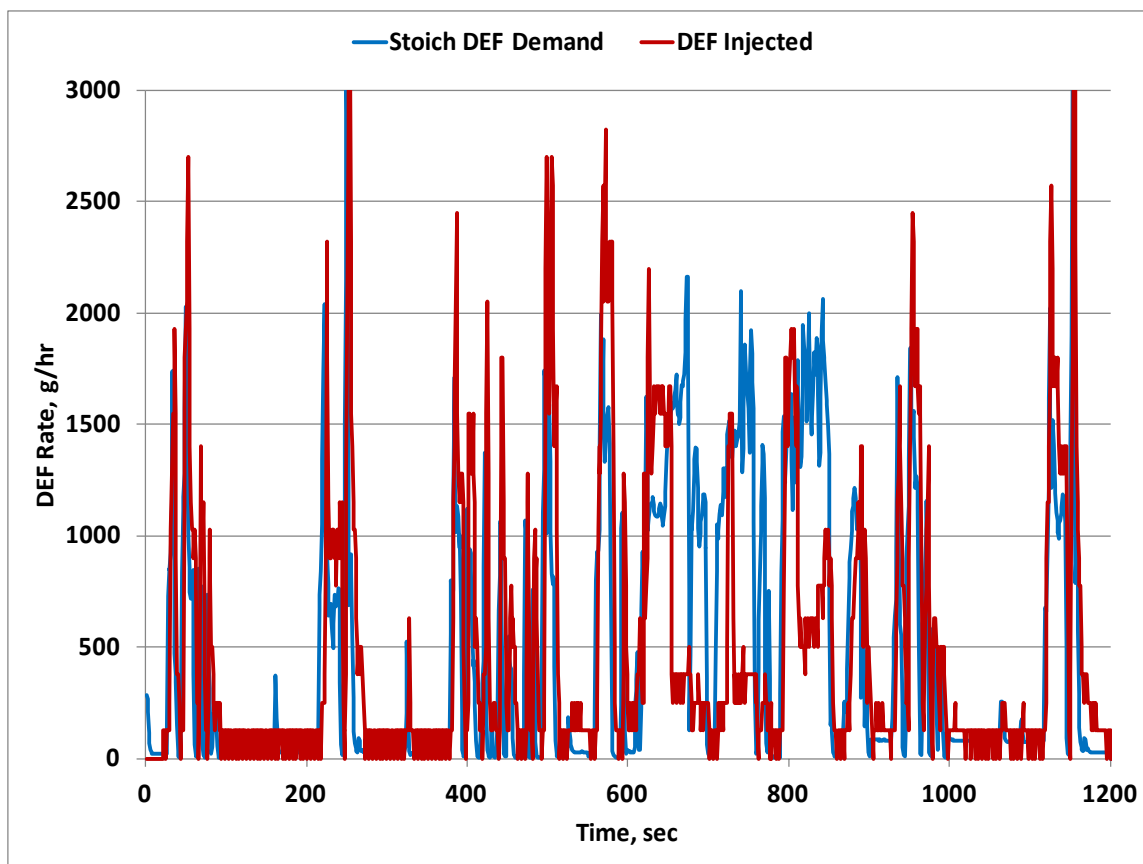


FIGURE 194. DEF DOSING RATE OVER HOT-START TRANSIENT FTP COMPARED TO STOICHIOMETRIC DEMAND (BASED ON ANR 1 AND SYSTEM INLET NO_x), AVERAGE CYCLE

An important feature of the final controller was that it was able to manage ammonia coverage to achieve high NO_x conversion under normal operation. Even following a high temperature event, such as an RMC cycle or a filter regeneration, the controller was able to re-establish the ammonia coverage needed within the normal two FTP cycle preconditioning tests that are permitted in 40 CFR Part 1065. No special preconditioning procedures are needed beyond these normal cycles in order to prepare the system for a cold-start FTP. This behavior is illustrated in Figure 195 which shows DEF dosing behavior during the first hot-start preconditioning run following a high temperature event (in this case an RMC cycle). Because coverage was significantly below targets, the controller increases dosing rapidly in order to re-establish ammonia coverage. The overall DEF injection over the cycle in this case was close to an ANR of 1.5.

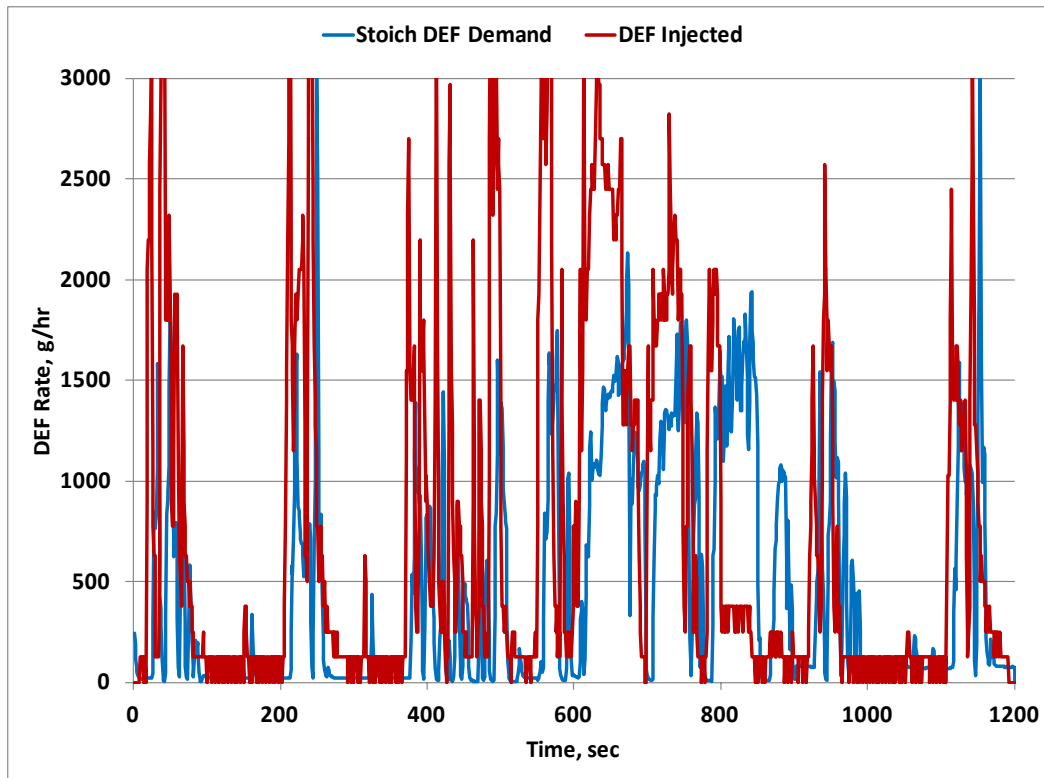


FIGURE 195. DEF DOSING RATE OVER HOT-START TRANSIENT FTP COMPARED TO STOICHIOMETRIC DEMAND, FOLLOWING HIGH TEMPERATURE EVENT

3.4.2.4 Final Candidate System Configuration 1 – PNA + HD1 + SCRf + SCR + ASC

The first configuration tested consisted of a PNA upstream for low-temperature NO_x storage, followed by Heated Dosing System 1 (the full-flow heated dosing system), to enable low temperature DEF introduction, followed by the multi-bed SCR system discussed earlier. This configuration had indicated composite emission levels of 0.018 g/hp-hr during screening when using the second-generation PNA formulation (designated in screening as PNA2). A schematic of Configuration 1 is shown in Figure 196.

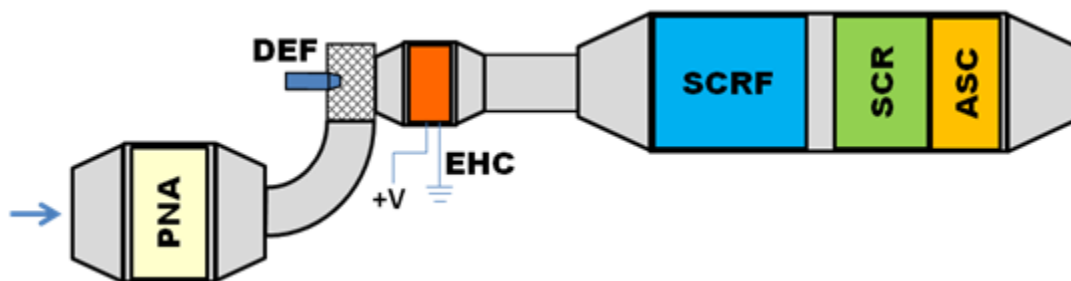


FIGURE 196. FINAL CANDIDATE CONFIGURATION 1 – PNA+HD1+SCRf+SCR+ASC

It should be noted that for the initial test configuration, the HD1 system utilized a heater capable of 2kW at 24 volts. The actual measured power draw for the HD1 heater was 1.8 kW when it was turned on. The primary purpose of this heater was to provide a heated surface to allow the injection of DEF at temperatures as low as 130°C. However, it did also provide a small amount of heat to the exhaust.

Given that this was the first configuration tested, a considerable amount of effort was invested in the initial system integration and start-up. Initial test results indicated cold-start FTP levels of roughly 0.15 g/hp-hr, and hot-start levels of roughly 0.015 g/hp-hr. From this base point, additional efforts were put into modification of the engine calibration in order to reduce early cold-start NO_x levels, and also on the hot-start calibration to minimize cool-down in the early idle portions of the test when aftertreatment temperatures could cool below the optimal operating point.

Figure 197 shows an example of a modified cold-start calibration that was attempted in an effort to reduce NO_x further early in the cycle, before the aftertreatment reached full operating temperature. These modifications were initially successful in reducing cold-start tailpipe levels, however after some continued work, it was noted that tailpipe NO_x began to deteriorate from run to run.

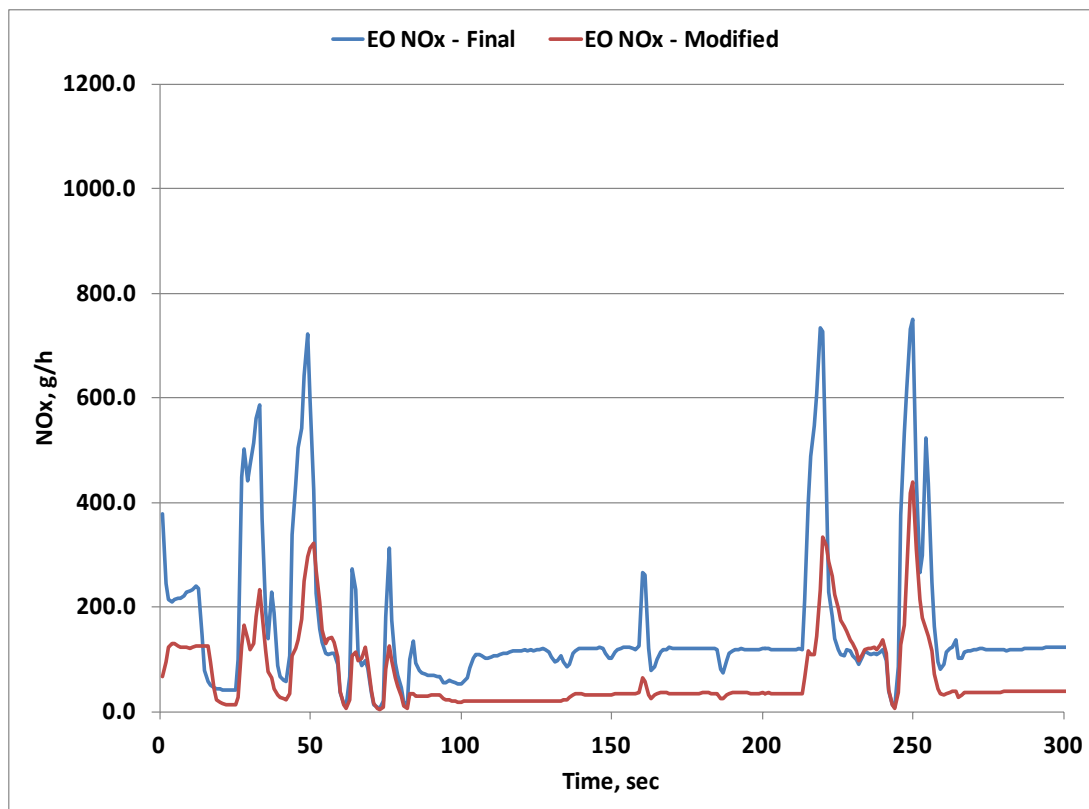


FIGURE 197. MODIFIED NO_x CALIBRATIONS EARLY IN ENGINE OPTIMIZATION – CONFIGURATION 1

Although the modified calibration was successful in reducing NO_x, it also resulted in the brief periods of rich or near-rich operation during transient accelerations. It should be noted that this same behavior was observed on the baseline engine, and it was necessary to remove that behavior due to the sensitivity of the PNA to these events. As seen in Figure 198, the modified calibration resulted in brief spikes of engine-out CO, indicate such operation.

It should be noted that this behavior was the result of the combination of factors, including the limits of the engine architecture to maintain transient air-fuel ratio with its fixed geometry turbocharger and turbo-compound, and the need to maintain adequate transient torque response. The constraints associated with the PNA meant that these excursions could not be allowed in order to maintain robust system performance over time. Therefore, further engine calibration changes had to be halted, and engine-out NO_x on the cold-start was essentially fixed at a level of roughly 2.7 g/hp-hr.

It should be noted that a different engine architecture using the variable geometry turbocharger would have allowed more flexibility to maintain air-fuel ratio during transients, and in turn allowed lower NO_x levels during this crucial early part of the cold-start. In addition, an aftertreatment strategy that did not utilize a PNA would allow more flexibility in the engine calibration.

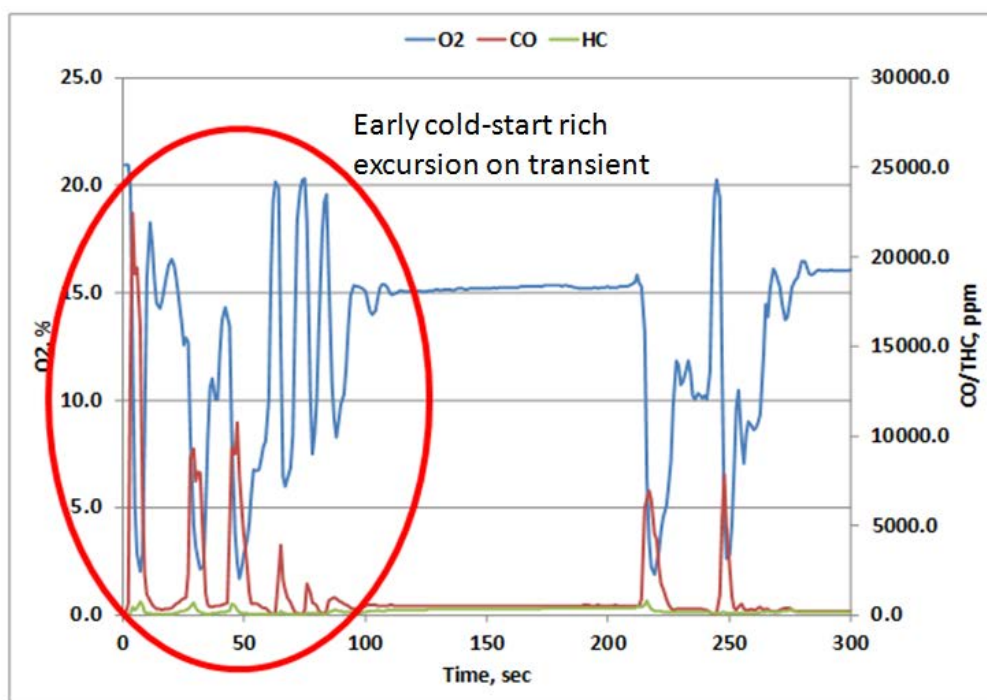


FIGURE 198. EARLY COLD CYCLE OXYGEN AND CO LEVELS WITH MODIFIED ENGINE CALIBRATION – CONFIGURATION 1

However, given the low exhaust temperatures associated with the turbo-compound on the MD13TC engine, the PNA was required for the aftertreatment system to be able to achieve 0.02 g/hp-hr, and therefore the constraints had to be accepted.

It was initially planned that little or no thermal management would be needed for the hot-start FTP cycle. However, due to the low exhaust temperatures with the turbo compound engine, aftertreatment temperatures were observed to fall below temperature required for continued dosing around the area of the 200-400 second segment of the FTP. In addition, those temperatures also fell just low enough to cause a slight drop in aftertreatment conversion efficiency utilizing stored ammonia. This behavior is illustrated in Figure 199. This normally resulted in small NO_x breakthroughs in this same area of the cycle, as shown in Figure 200. Tailpipe NO_x levels were on the order of 0.03 g/hp-hr as a result of these breakthroughs, therefore some amount of thermal management was needed for the hot-start FTP.

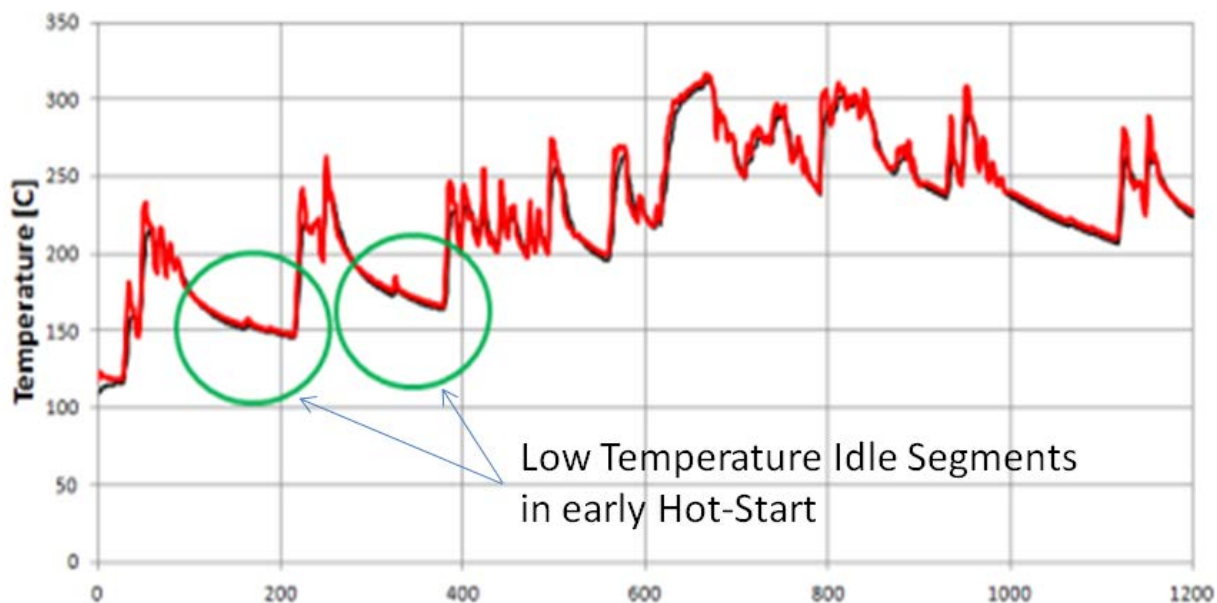


FIGURE 199. HOT-START FTP CYCLE TEMPERATURES UPSTREAM OF DEF DOSING POINT AND THE SCR INLET – CONFIGURATION 1 WITHOUT THERMAL MANAGEMENT

Some of this thermal management could be achieved via minor modifications to the hot-start calibration, but in this configuration, it was also found that the EHC could be used even at only the 1.8kW level, in order to provide sufficient heat to mitigate these issues. This combination of elements allowed hot-start FTP levels of 0.01 g/hp-hr to be achieved, as shown in Figure 201. A hot-start FTP emission level at or below 0.01 g/hp-hr as required for the system to be able to meet a composite level of 0.02 g/hp-hr. However a small impact on CO₂ was also observed in this case of about 0.8%. It was likely that this penalty could be reduced with further calibration effort.

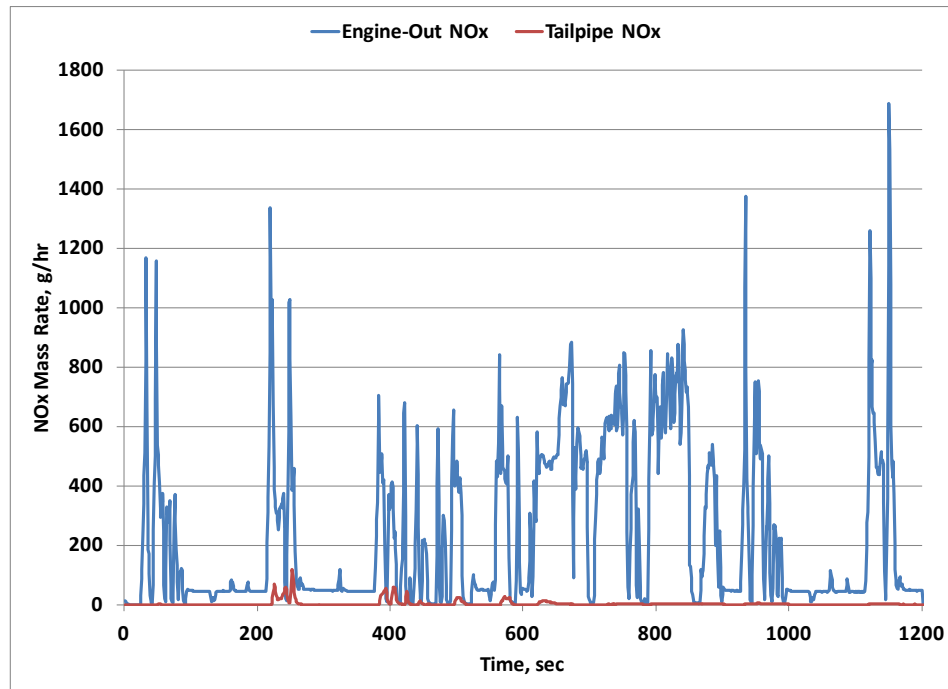


FIGURE 200. HOT-START FTP NO_x FOR CONFIGURATION 1 WITHOUT THERMAL MANAGEMENT IN EARLY CYCLE

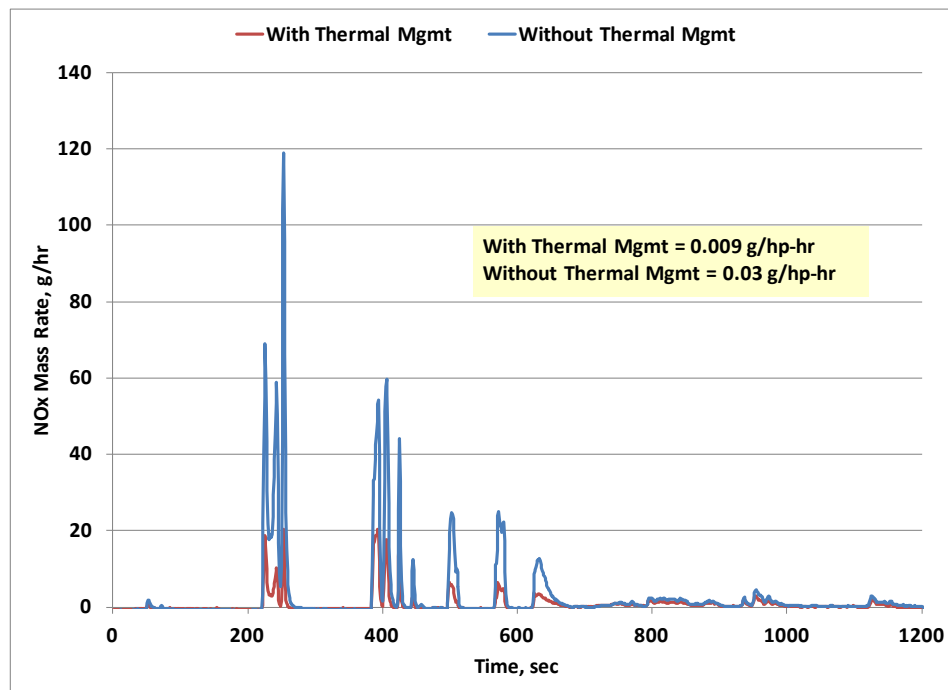


FIGURE 201. COMPARISON OF HOT-START FTP TAILPIPE NO_x WITH AND WITHOUT EHC FOR CONFIGURATION 1

The final calibration NO_x results achieved for this configuration with HD1 operating at 1.8 kW, are given in Table 64. Cumulative cold-start NO_x emissions for this configuration are

shown in Figure 202. Just over 4 grams of NO_x are emitted over the cold-start FTP, while a total of 2 grams are required to reach the design target. Much of this can be seen to occur near the 200 second mark in the cycle, during the second acceleration event.

This configuration was able to reach levels just under 0.03 g/hp-hr with the Development aged parts. The net CO₂ impact for the cold start, including both the engine calibration and the 1.8kW EHC was 4.6%, and on the hot-start it was about 0.8%. Therefore, the composite FTP CO₂ impact for this system was 1.5%.

TABLE 64. FINAL CANDIDATE CONFIGURATION 1 - FTP CYCLE NO_x, G/HP-HR (DEVELOPMENT AGED)

	Tailpipe	Engine-Out	AT Conversion
Cold-Start	0.152	2.7	94.3%
Hot-Start	0.009	2.9	99.7%
Composite	0.029	2.9	99.0%

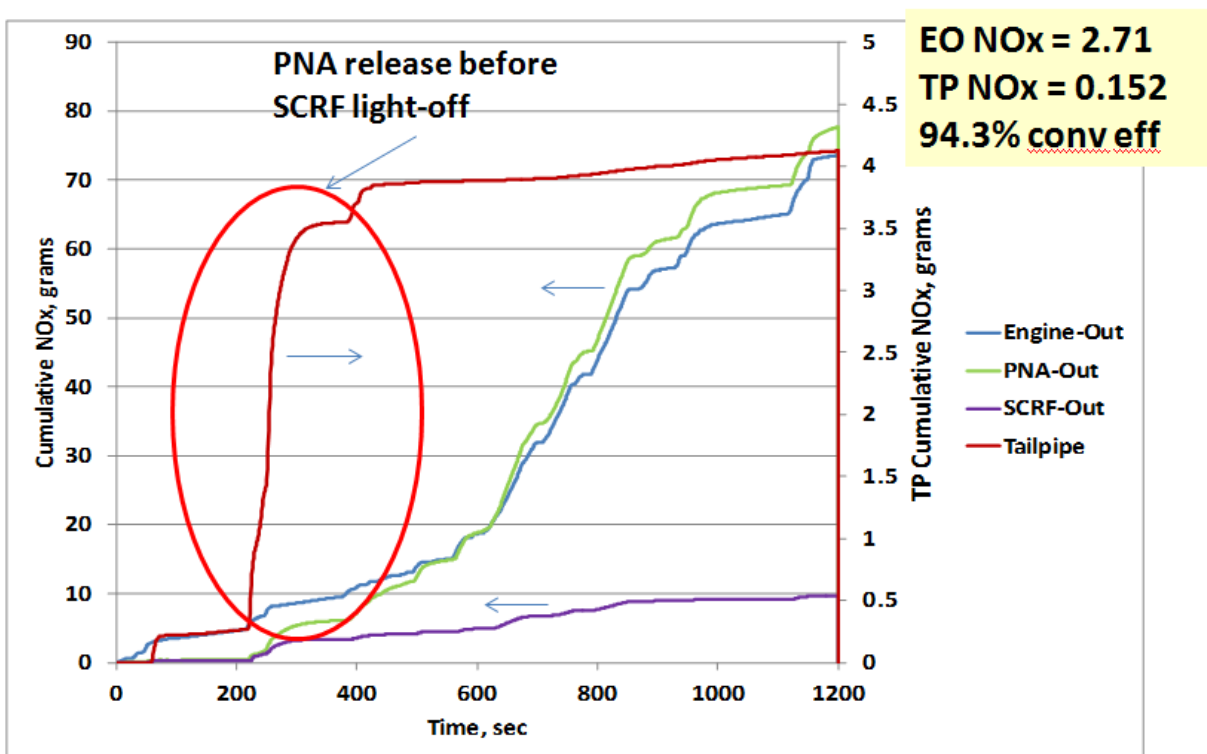


FIGURE 202. CUMULATIVE COLD-START NO_x MASS EMISSIONS AT VARIOUS POINTS IN THE SYSTEM FOR FINAL CANDIDATE CONFIGURATION 1

More detail on the cold-start performance of this configuration is given in Figure 203. NO_x in the first transient acceleration was well controlled by the PNA, with only a small release near the 60-second point. By the second acceleration, near the 225-second point, the PNA was now hot enough that it begins to release a significant amount of NO_x. By this point, it was hoped that the SCRF was hot enough to reduce the NO_x released from the PNA. However, as

seen in the figure, the SCRF inlet was just reaching 200 °C at the point of this release, while the SCRF outlet was still below 150 °C. As a result, a significant NO_x spike was seen coming out of the SCRF at 250 seconds, and this was the majority of the mass emitted during the cycle at nearly 3 grams of NO_x for this single event. From this, it was clear that the SCRF was not hot enough in Configuration 1 to reach the target.

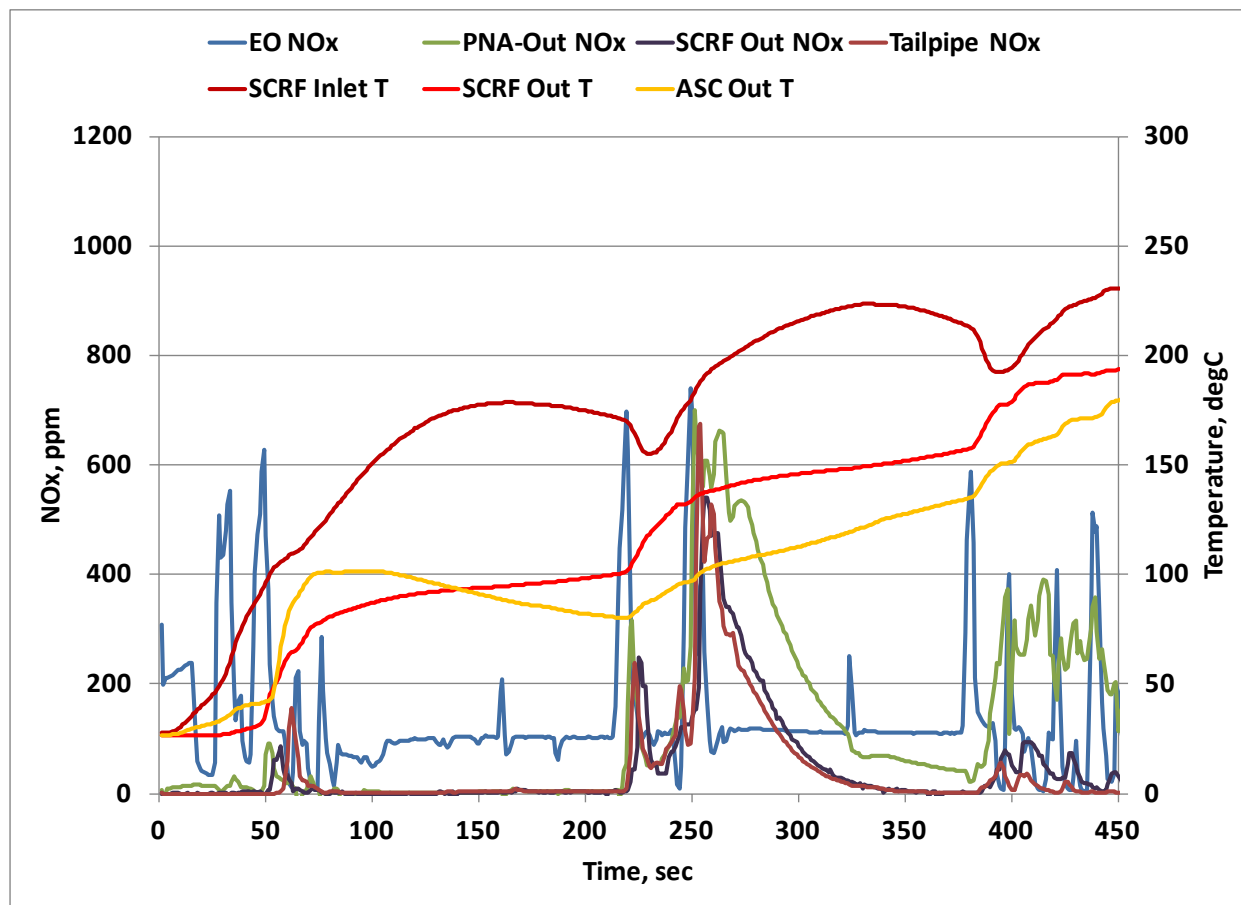


FIGURE 203. COLD-START NO_x AND TEMPERATURE AT VARIOUS POINTS IN FINAL CANDIDATE SYSTEM CONFIGURATION 1, HD1-1.8KW

It was considered that additional heat capacity at the position of the EHC system between the PNA and the SCRF could help bridge this gap. The EHC supplier for HD1 was able to supply a higher power heater, which would fit in the same package as the 2 kW unit. This updated system was capable of a heat capacity up to 6kW. Installation of this unit required some upgrades to the electrical control system for the EHC to allow for the higher current.

In addition, it was felt that at such a high power draw, it was necessary to account for the impact of the power consumption on fuel consumption directly by applying this load to the engine. Therefore, the test cell system was modified in order to account for the impact of the EHC when it was turned on. The electrical power draw of the EHC was already measured in real time at this point in order to properly account for the power draw. This electrical power was translated through an assumed generator efficiency of 55%, and then that power was then

utilized with current engine speed to calculate an equivalent torque demand. That torque demand was fed into the control system as a negative torque offset, thus requiring the engine to burn more fuel to reach the target torque commanded by the cycle. In this way, more fuel was actually burned by the engine when the EHC was active. That fuel consumption also generated a certain amount of heat, and therefore this approach provided an accurate accounting of the impact of the EHC on the system.

The impact of this increased heat input on cold-start NO_x and temperatures is illustrated in Figure 204. The temperature at the SCRF was near 200 °C prior to the second acceleration, and the SCRF outlet crosses over 150 °C halfway through that event. Compared to Figure 203, a significant amount of NO_x conversion over the SCRF can now be seen at the 250-second mark.

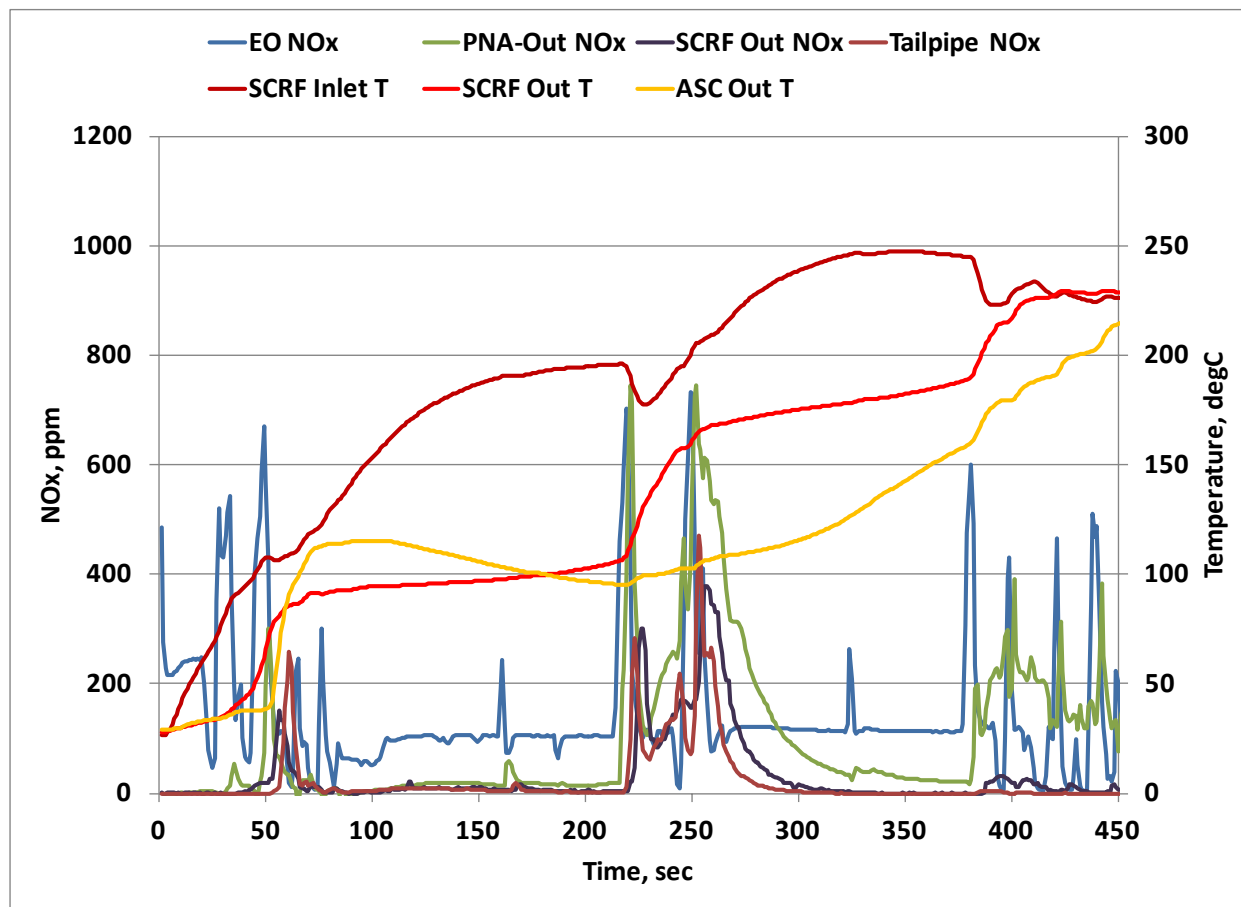


FIGURE 204. COLD-START NO_x AND TEMPERATURE AT VARIOUS POINTS IN FINAL CANDIDATE SYSTEM CONFIGURATION 1 WITH UPGRADED HEATER, HD1-6KW

Emission results for Configuration 1 with the higher power heater are summarized in Table 65. Cumulative NO_x mass for Configuration 1 with the 6kW EHC is shown in

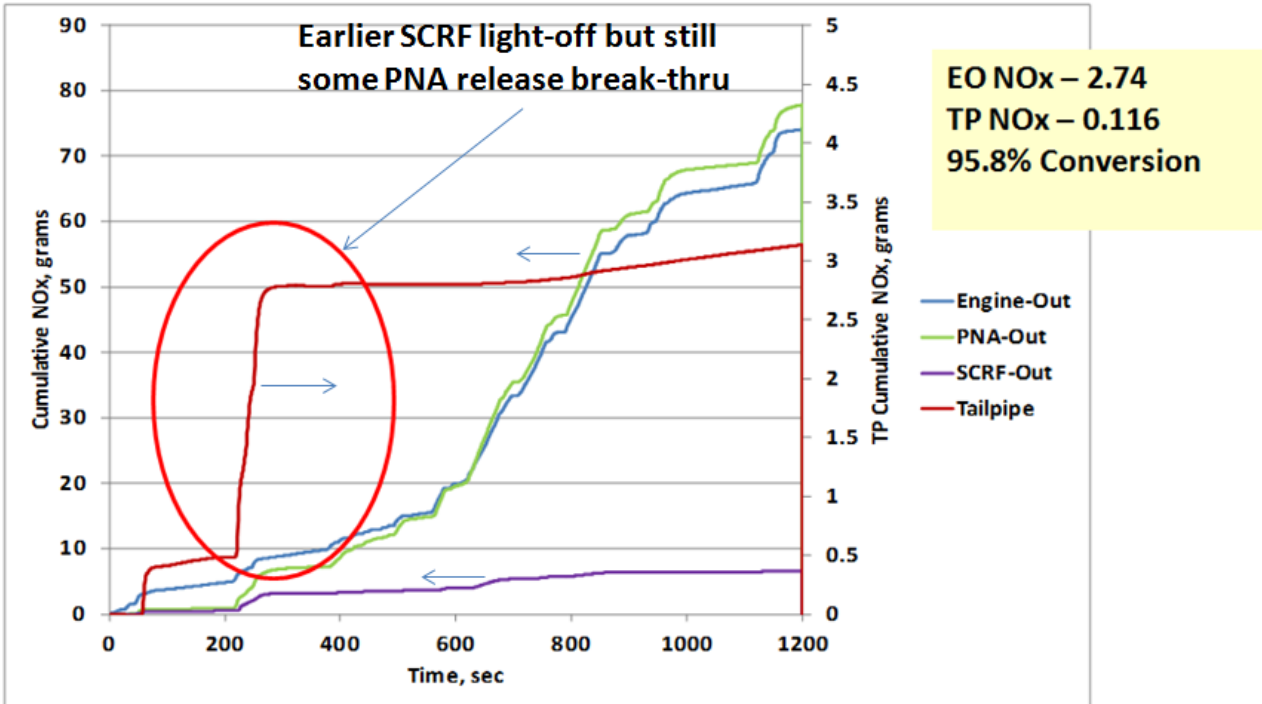


Figure 205. The large NO_x increase at the second acceleration was reduced to about half its previous size. A slightly larger release, though still small, was seen from the PNA in the first acceleration due to the additional heat from the engine that was the result of burning more fuel in order to power the EHC. These changes resulted in an improvement from 94.5% conversion to 96% conversion. However, this was still not sufficient to reach the target cold start NO_x level of 0.06 g/hp-hr, which was a 2 gram NO_x mass emitted over the cycle. This configuration results in a composite NO_x level of 0.024 g/hp-hr. It should be noted that on the hot-start FTP, the EHC was still run at the previous lower power level of 1.8kW, which was sufficient for the hot-start thermal management requirement.

**TABLE 65. FINAL CANDIDATE CONFIGURATION 1 - FTP CYCLE NO_x, G/HP-HR
HIGHER CAPACITY EHC HEATER (6KW)**

	Tailpipe	Engine-Out	AT Conversion
Cold-Start	0.116	2.7	95.8%
Hot-Start	0.009	2.9	99.7%
Composite	0.024	2.9	99.2%

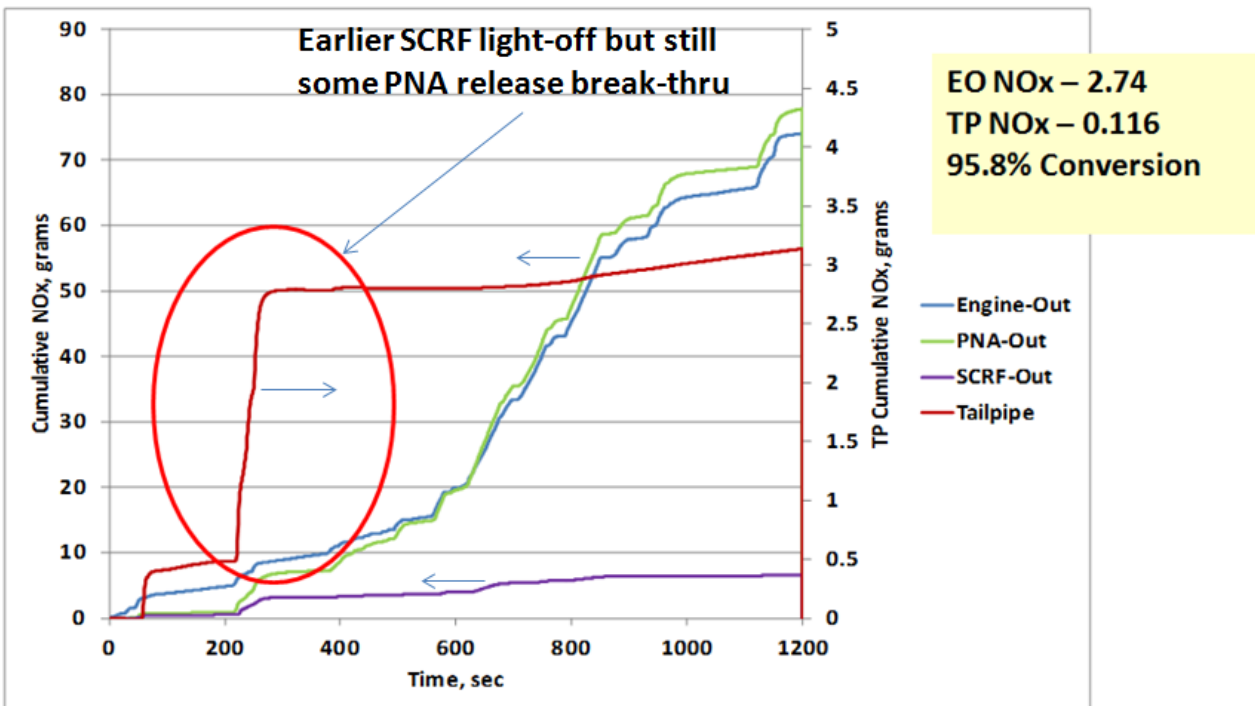


FIGURE 205. CUMULATIVE COLD-START NO_x MASS EMISSIONS AT VARIOUS POINTS IN SYSTEM FOR FINAL CANDIDATE CONFIGURATION 1 WITH 6KW EHC

However, the increased power requirement of the heater results in a nearly 3% increase in cold-start fuel consumption, which was an additional 0.4% on the composite. This would increase the composite FTP impact to 1.9%, and the system still does not quite reach under 0.02 g/hp-hr.

Additional thermal calculations were performed which indicated that a heat input of at least 10kW would be needed to get Configuration 1 reliably under 0.02 g/hp-hr. Although more heat capacity was available in the form of additional heaters, it was felt at this point that this would be problematic for several reasons. The problem with such a high heat level is that ultimately electrical heat is not very efficient in terms of fuel energy consumed for the exhaust heat generated. Generally, only about 25% of the fuel energy was actually realized as exhaust heat.

In addition, 6kW was considered the limit of what could practically be utilized given current heavy-duty truck electrical infrastructure. At a higher power level, significant upgrades would need to be made, likely including the use of a second alternator among other things. At that point, system complexity would increase considerably compared to other options.

Therefore, it was decided to stop experiments with Configuration 1 and move to the next configuration. However, it should be noted that on an engine with a more favorable exhaust temperature profile, Configuration 1 with the 6kW EHC would likely have been able to meet the 0.02 g/hp-hr target. With the cold-temperatures of the MD13TC engine and its turbo-compound waste heat recovery, this was not a viable option.

3.4.2.5 Final Candidate System Configuration 2 – HD2 + LOSCR + PNA + SCRF + SCR + ASC

The second system evaluated a concept that we initially developed during screening as a means to enable faster light-off for SCR conversion. This involved the use of a close-coupled light-off SCR (LOSCR) catalyst which was mounted upstream of the PNA (or potentially upstream of the DOC). A schematic of this approach is given below in Figure 206.

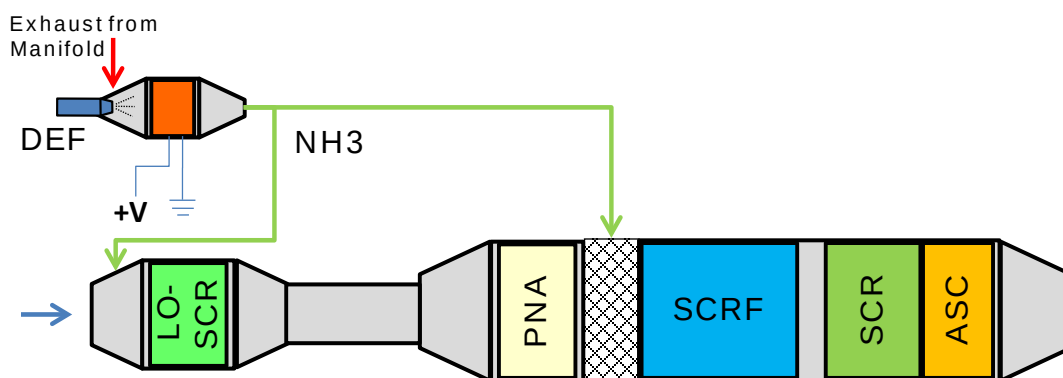


FIGURE 206. FINAL CANDIDATE SYSTEM CONFIGURATION 2 – LIGHT-OFF SCR+PNA+ SCRF+SCR+ASC WITH PARTIAL FLOW HEATED DOSING (HD2)

The concept was to move a portion of the SCR catalyst upstream of the thermal inertia of the other aftertreatment to enable rapid light-off and reduce the amount of heat input required by the system. Conversion of NO_x upstream of the PNA would also reduce the burden on the PNA for this system. In order for this concept to work however, multipoint DEF dosing was a requirement. This was because NH₃ introduced upstream of the LO-SCR would not survive through the PNA to reach the downstream SCR catalysts, and would likely be oxidized into NO_x. Therefore, it was crucial in this system approach that significant amounts of NH₃ not be allowed to slip from the LO-SCR. A second point of introduction was needed downstream of the PNA in order to effect the majority of NO_x reduction during warmed-up operation.

In a practical configuration, this multipoint dosing could be enabled by the use of the partial flow dosing system, which was designated HD2 in this program. This system would introduce a small portion of pre-turbine exhaust gases into a reactor, which contains a small EHC, which allows rapid warm-up for early DEF introduction. The reactor contains a hydrolysis catalyst, so that it generates a stream of NH₃ laden gas at the outlet. This NH₃ rich gas stream can be directed to one or more points on the exhaust using fairly simple plumbing. In addition, only gas-phase mixing was required in the primary exhaust stream, allow more compact packaging for better thermal characteristics.

However, due to hardware delays in preparing the HD2 system, the initial evaluation of this concept was carried out using a combination of a gaseous NH₃ system for the LO-SCR point, and the HD1 heated dosing system for the SCRF introduction point. The system evaluated for initial on-engine working is shown in Figure 207. This approach allowed for a final evaluation of the LO-SCR concept on engine. If the configuration proved promising, then the

modifications would be made to switch to the HD2 dosing system. Although this system was useable for evaluation of the concept, it was felt that in practice such an approach would be too complicated and expensive to be practical in application.

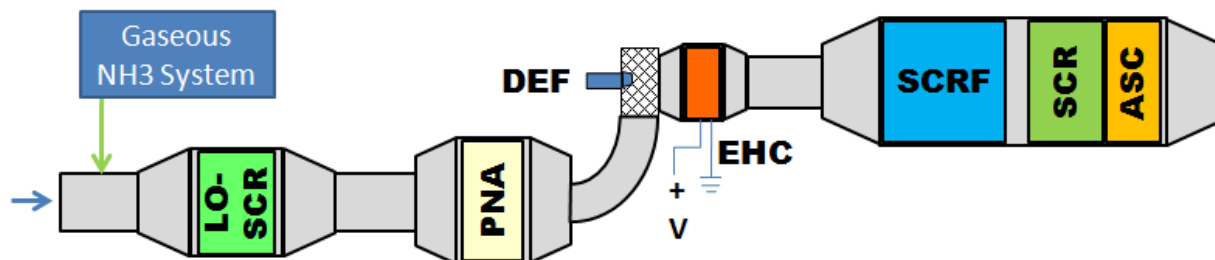


FIGURE 207. FINAL CANDIDATE SYSTEM CONFIGURATION 2 USED FOR CONCEPT EVALUATION ON ENGINE OF LOSCR APPROACH

Two different LOSCR catalysts were examined in this setup. Both were utilized in a position much closer to the engine than the rest of the aftertreatment, in a location that would approximate a firewall mounted installation roughly 3 feet from the turbo-compound outlet. The more compact size of the LOSCR allowed this sort of installation to be considered.

The initial catalyst examined was a vanadium-based catalyst, which was coated on a 10.5 X 6 inch substrate. This formulation was considered due to concerns about long-term sulfur poisoning, given that the LOSCR would be mounted upstream of the PNA which would generate the exotherm in the system for regeneration. A vanadium-based SCR catalyst would not be as sensitive to sulfur exposure in this location. Unfortunately, initial tests indicated almost no activity on the vanadium LOSCR catalyst below temperatures of 225 °C, and significant conversion did not begin until 250 °C. The LOSCR catalyst did not reach 225 °C until 230 seconds into the cycle, and did not reach 250 °C until 400 seconds into the cycle. Given this initial behavior, the vanadium catalyst was quickly switched out for a zeolite-based catalyst.

The zeolite-based LOSCR was produced by utilizing one-half of a development aged SCR catalyst from one of the MECA suppliers which was cut and re-canned for this purpose. The total volume was 6.5L. This catalyst demonstrated significantly better performance than the vanadium catalyst, and it was used for the remaining evaluation of this concept.

Figure 208 shows the performance of the LOSCR during the early portion of the cold-FTP. Although the LOSCR reaches temperatures at the inlet over 200 °C 50 seconds into the cycle, it does not begin to see measureable conversion until after the first acceleration was completed, during the subsequent idle period. By the second acceleration at 220 seconds, conversion was improving and was reaching the limits of the dosing amount by about 250 seconds. However, in this early portion of the cycle, the PNA was also still active and so this ultimately results in less storage in the PNA. That does help reduce the magnitude of the later PNA release in the second acceleration somewhat, but the majority of the early cycle NOX in the first acceleration still has to be stored in the PNA. Therefore, the improvement noted with the LOSCR was relatively small.

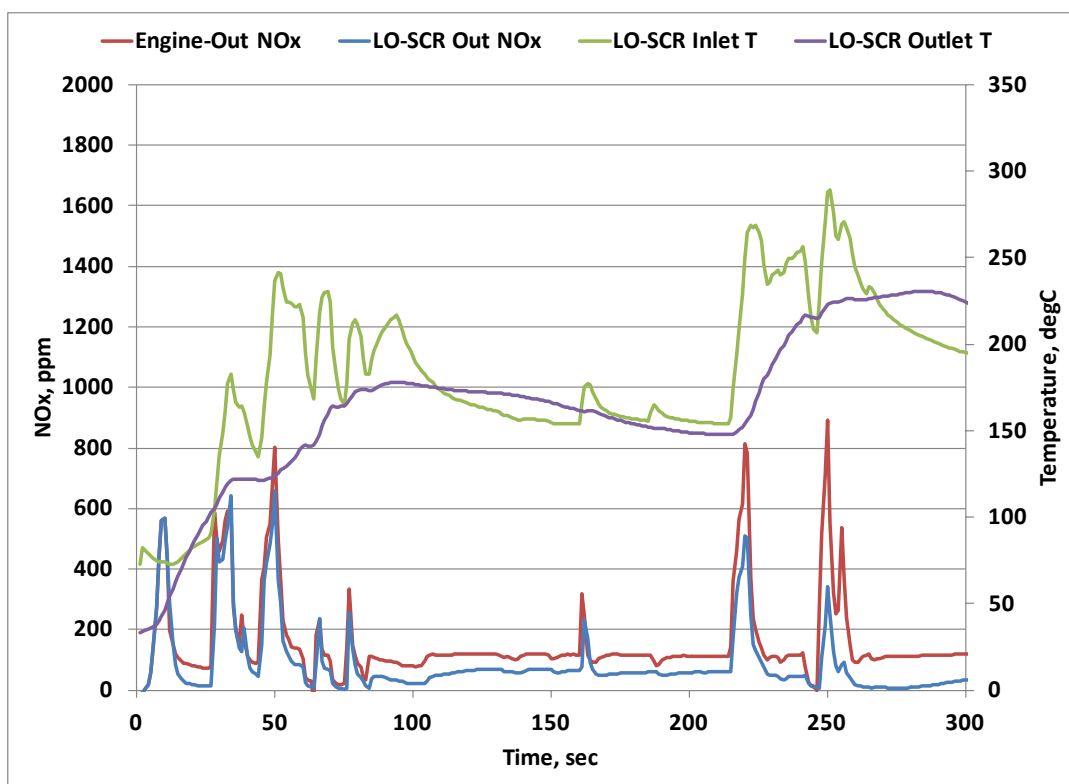


FIGURE 208. COLD-START NO_x AND TEMPERATURES BEFORE AND AFTER LO SCR, FIRST 300 SECONDS, CONFIGURATION 2

Gaseous NH₃ dosing was started as soon as exhaust reached 130 °C, at about 30 seconds into the cycle. Gaseous dosing continued until 565 seconds into the cycle for this particular test run, the point at which the SCR outlet temperature was reliably above 200 °C, at which it was deemed that further dosing upstream of the LO SCR was not needed. However, the LO SCR continued to convert NO_x until the supply of stored NH₃ was exhausted. It should be noted that the more successful strategies involved high rates of NH₃ into the LO SCR very early, in order to try to achieve reasonable NH₃ coverage before backing off. Very little NH₃ slip was seen at the LO SCR outlet, generally below 5ppm. Sufficient NH₃ was stored on the LO SCR by the point of shutdown that it continued to convert NO_x after that point. This is shown in Figure 209.

One benefit of this approach was lower tailpipe N₂O emissions. Because the LO SCR was upstream of the system DOC (or PNA), nearly all the NO_x reduction it performs involves NO only, which does not generate significant N₂O as a byproduct. This resulted in lower overall system N₂O levels, because less N₂O was generated over the SCR.

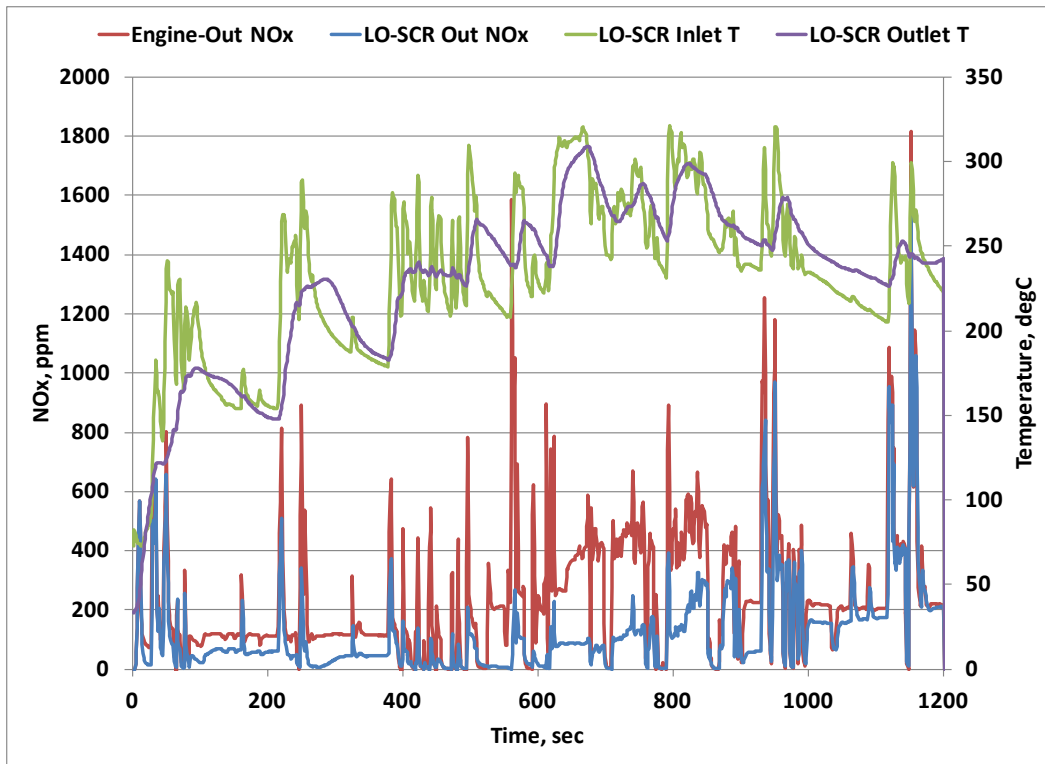


FIGURE 209. LOSCR PERFORMANCE OVER THE FULL COLD-START FTP CYCLE (NH₃ OFF AT 565 SECONDS), CONFIGURATION 2

However, one down side of the LOSCR configuration was that while there was conversion upstream in the system, the added thermal inertia slows down the light of the downstream SCRF and SCR catalysts. Figure 210 illustrates the impact of the LOSCR on downstream SCRF temperatures, shown in comparison to Configuration 1. The thermal inertia of the LOSCR also lowers the PNA inlet temperature somewhat which does delay the PNA NO_x release somewhat as well, helping to offset the slower SCRF light-off somewhat.

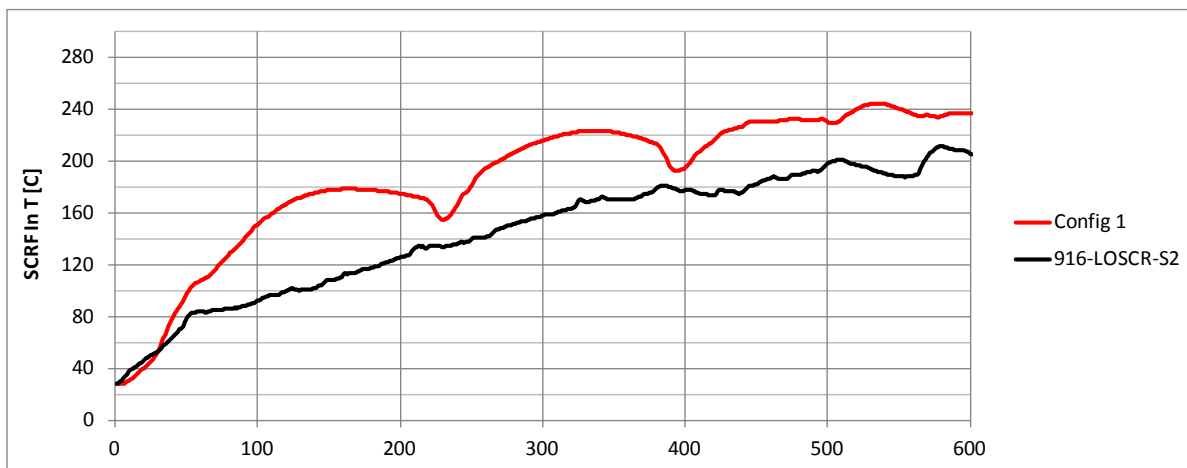


FIGURE 210. SCRF OUTLET TEMPERATURE – LOSCR (CONFIGURATION 2) VERSUS CONFIGURATION 1 WITH 6KW EHC

Continuous NO_x and temperature data for the first 450 seconds of the cold-start FTP with the LOSCR configuration are shown in Figure 211. The PNA-out NO_x release was considerable smaller than what was seen previously for Configuration 1, downstream but SCRf and SCR conversion light-off was also delayed until nearly 325 seconds until the cycle. Cumulative NO_x emissions for the final calibration that were examined on Configuration 2 are shown in Figure 212.

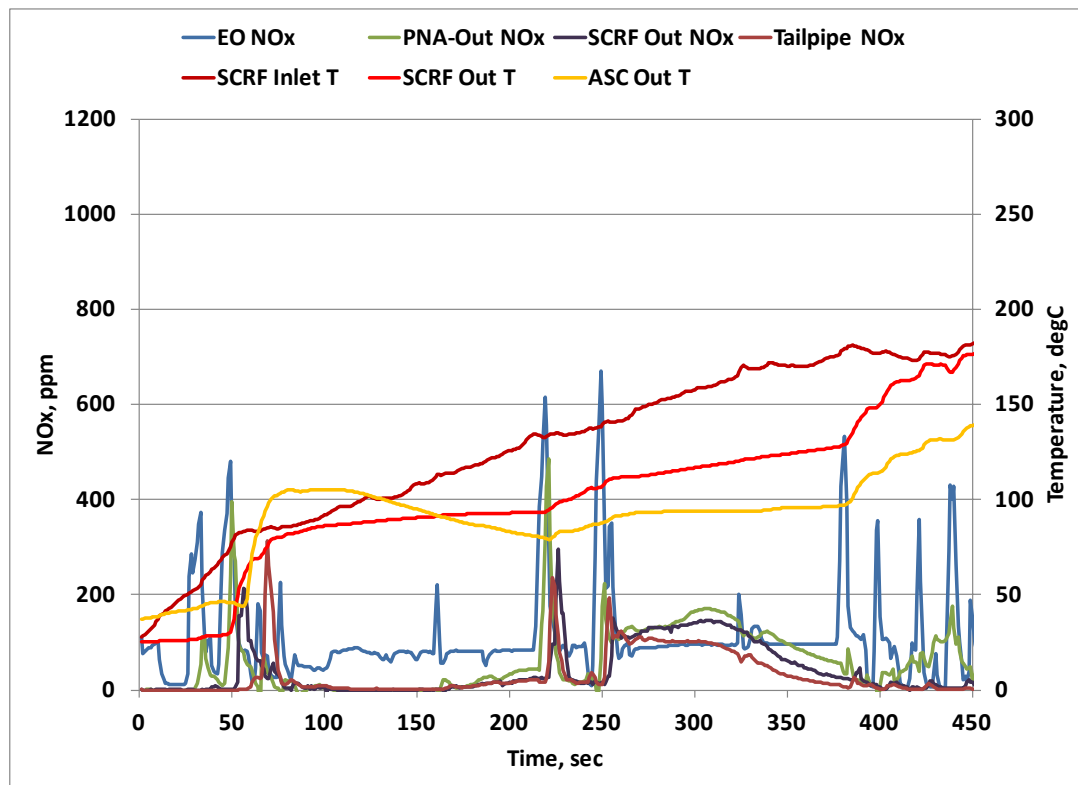


FIGURE 211. COLD-START FTP NO_x AND TEMPERATURES FOR CONFIGURATION 2, 0-450 SECONDS

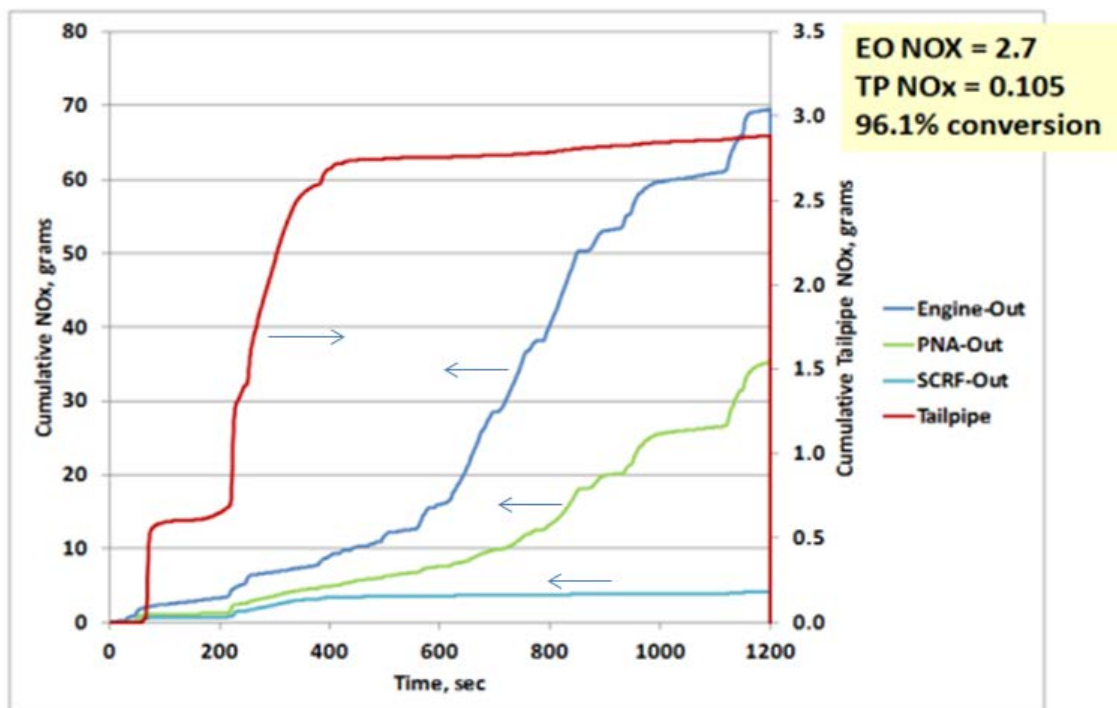


FIGURE 212. ACCUMULATED COLD-START FTP NO_x MASS FOR CONFIGURATION 2 (LO-SCR) AT VARIOUS POINTS IN THE SYSTEM

NO_x emissions for Configuration 2 are summarized below in Table 66. The system was able to achieve slightly better results than Configuration 1 with the higher heat capacity EHC. However, the GHG impact was considerably smaller, even with the demonstration system using the 1.8kW EHC to allow low temperature dosing. The net total GHG impact on the cold-FTP for this system was 3.5%, or 0.5% on the composite FTP. Therefore, the primary benefit of the use of the LOSCR was a reduced GHG impact for the same emissions level. However, Configuration 2 as tested was still not quite able to reach emission levels below 0.02 g/hp-hr with the Development Aged parts.

TABLE 66. SUMMARY NO_x EMISSIONS FOR CONFIGURATION 2 WITH LO-SCR

	Tailpipe	Engine-Out	AT Conversion
Cold-Start	0.105	2.7	96.1%
Hot-Start	0.008	2.9	99.7%
Composite	0.022	2.9	99.2%

It is likely that this system would have been able to reach levels below 0.02 g/hp-hr on a non-turbo-compound engine. However, at the low exhaust temperatures of the MD13TC engine, even the LOSCR catalyst did not quite reach high conversion quickly enough. It was also apparent that SwRI did not have the right catalyst formulation on hand to fully exploit the potential of this configuration, given that this concept was developed late in the program. Configuration 2 with the LOSCR remains a strategy of considerable interest due to the potential for high conversion at a smaller GHG impact.

Configuration 2 would likely have benefited from additional development, including a revised LO-SCR catalyst formulation, different sizing approaches, and more controls work. However, by this point in the program, time and budget constraints were beginning to restrict how much additional effort could be spent on calibration and hardware. In order to fully test Configuration 2 it was necessary to implement the partial flow heated dosing system, HD2. Given that updated catalysts were not available in a timely fashion and the fact that the concept systems had not yet reached 0.02 g/hp-hr, it was decided that a different approach was needed in order to meet the budget and time constraints of the program.

Another factor in this decision was that with the copper zeolite catalysts on hand, there was some risk associated with long-term sulfur management during final aging. There was information in the literature that sulfur can be managed on an SCR catalyst at temperatures in the area of 400°C to 450°C as long as there was NH₃ being dosed into the system at the time. However, there were not enough resources in the program to investigate this further, and therefore it was considered too much of a risk at the time.

As noted earlier, this configuration could be very promising on a non-turbo-compound engine, where inlet temperatures could easily be 30 °C to 50 °C higher. This would allow light-off during the first acceleration of the cold-FTP, and it might allow for the removal of the PNA from the system if conversion is high enough. Significantly, more development on a different engine would be required to examine this possibility further, as well as to find a strategy and formulation to deal with the long-term sulfur management question.

3.4.2.6 Final Candidate System Configuration 3 – PNA + HD1 + SCR + SCRF + SCR + ASC

This configuration was not on the original list, but it was considered as a modification to Configuration 1 that could be examined quickly in the test cell with the parts on hand. To implement this configuration, the 3" zeolite SCR that was used in Configuration 2 was installed upstream of the SCRF. The intent was to bring more SCR closer to the heat source, given that the flow through SCR catalyst had more SCR capacity in a smaller volume. Given the limited time available only one configuration was examined, and the HD1 EHC heater was used, but with a lower heat setting at 3.5kW. A schematic of this configuration is given below in Figure 213.

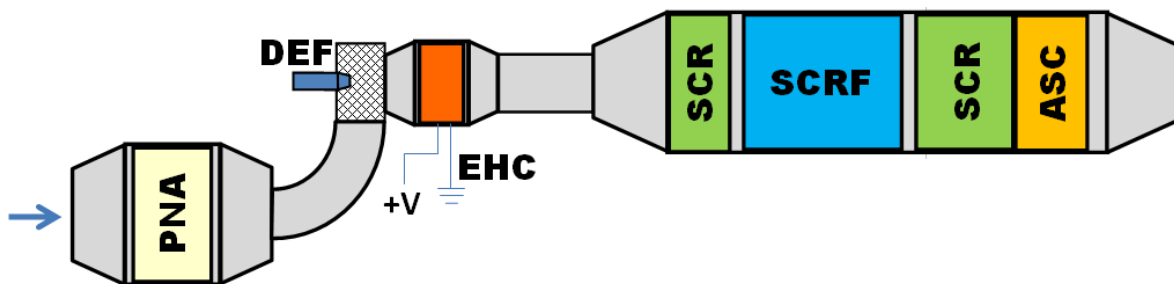


**FIGURE 213. FINAL CANDIDATE SYSTEM CONFIGURATION 3 –
PNA+HD1+SCR+SCRF+SCR+ASC**

This configuration was only examined briefly but it was able to achieve similar performance to Configuration 1 with the 6kW EHC (0.025 g/hp-hr composite), but using only 3.5kW of EHC power. This indicates that there was some improvement to be gained by moving the flow-through SCR catalyst upstream of the SCRF. However, to fully examine this approach, it would have been necessary to reconfigure both the system and the controls, and to relocate the NH₃ sensor and probe to the SCR outlet. In addition, the tailpipe performance was not yet below 0.02 g/hp-hr. Given the time and budget constraints of the program at that point, it was felt that this configuration could not be examined further.

It should be noted that a potential drawback to this approach would be a further compromise in passive regeneration on the SCRF. However, by this point, the SCRF regeneration development results were available which indicated that there was already very little such activity, so this loss would likely be a minor one with respect to GHG.

Given the higher efficiency capability of the flow-through SCR that was found during screening, it is likely that moving the SCR upstream of the SCRF would improve the likelihood of reaching 0.02 g/hp-hr. However, there were also durability concerns with this approach, such as higher temperature exposure for the SCR during active regeneration events. If more development time had been available to examine these issues, this approach could have been examined in more detail, but that was not available. Therefore, it was decided to move to another approach.

3.4.2.7 Final Candidate System Configuration 4 – EHC+DOC + SCRF + SCR + ASC

A fourth approach was considered during engine testing, but screening work on this approach had not yet been completed by the time the on-engine evaluations started. The intent was to use an upstream DOC and supplemental fuel injection (SFI) via the “7th injector,” to generate supplemental heat. Normally cold-start exhaust temperatures would prohibit the early use of this approach in the cycle, given that DOC inlet temperatures would need to be over 230°C or more to allow fuel injection. In order to allow earlier use, an EHC could be used to heat up the front of the DOC. In addition, a late post-injection could be used for a short period of time to generate CO and light HCs to help with early light-off before transitioning to SFI.

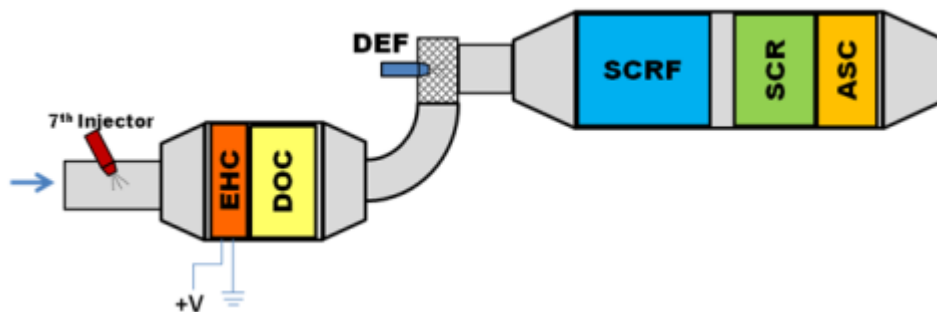


FIGURE 214. FINAL CANDIDATE SYSTEM CONFIGURATION 4 (NOT EXAMINED ON ENGINE) – EHC+DOC+SCRF+SCR+ASC

This approach was examined on the HGTR in order to look at the potential to generate heat rapidly during cold-start. It was found that the heat capacity was very good, but that sufficient heat could not be generated in the first 60 seconds of the cycle to compensate for the lack of a PNA in the system.

This approach could potentially be used downstream of a PNA in order to generate large amounts of supplemental heat. However, this was considered to be too complicated, given that it would probably require multiple SFI injectors, because injection on the PNA would also be required periodically to generate and exotherm for periodic de-sulfation. It was also felt that this combination of hardware was likely to be too complicated and expensive, and it would have required considerable development time to implement. Therefore, this approach was not examined on engine. However, good heat potential was observed on the HGTR, such that this approach might be considered for a non-turbo-compound engine.

3.4.2.8 Final Candidate System Configuration 5 – PNA + MB + SCRF + SCR + ASC

Given that the other systems did not prove capable of reaching levels 0.02 g/hp-hr in the development timeframe available for the program, it was determined that more supplemental heat capacity was needed in order to deal with the low exhaust temperatures of the MD13TC engine. Testing in Configuration 1 had indicated that electrical heat was not efficient enough at the heat input levels needed. Therefore, the mini-burner (MB) was utilized instead of the HD1 heater in order to increase the heat input downstream of the PNA. A schematic of Configuration 5 with the mini-burner is shown in Figure 215.

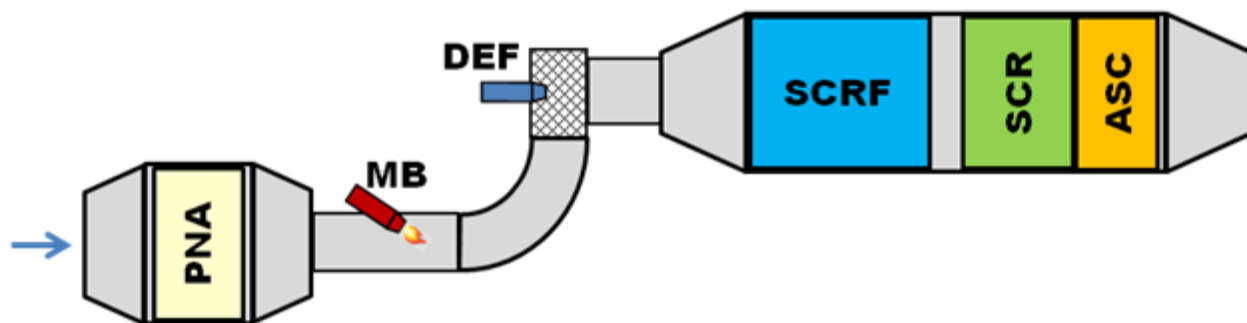


FIGURE 215. FINAL CANDIDATE SYSTEM CONFIGURATION 5 (FINAL APPROACH) – PNA+MB+SCRF+SCR+ASC

This approach is essentially similar to Configuration 1, but with the mini-burner used in place of the EHC from HD1. Given that, the mini-burner has a heat capacity well in excess of 10 kW, it was felt that this approach would likely succeed, given how close the 6 kW EHC was able to bring the system. The rapid warm-up available with the mini-burner also meant that heated dosing was not required, because the dosing section would reach sufficient temperature for DEF dosing very rapidly.

The installation of the mini-burner is shown in Figure 216 and Figure 217. For this installation, the mini-burner was installed on a 5-inch diameter pipe section (the same diameter used for the rest of the engine exhaust tubing), and it occupied a pipe section that was 15 inches

long. A more compact installation was possible, but this was the configuration that had been produced for the modular screening systems, and there was not sufficient time or budget available to re-engineer the package. A temperature sensor was mounted at the outlet end of this section in order to provide for temperature feedback and for a flame safety to ensure proper shutdown in the event of a misfire. The burner fuel supply was taken from the test cell fuel system so that it would be included in the direct measured fuel consumption for the engine. The air supply was driven by an air pump that was designed as a clutched, belt-driven pump. However, for these experiments, the air pump was driven by an electric motor. Both air and fuel rates to the burner were directly measured as well to allow for proper accounting of CO₂ impact later. In the case of air, the CO₂ impact was calculated based on the airflow measurements, and on the assumption that the air pump would be belt driven, and a clutch would be engaged and disengaged as needed.

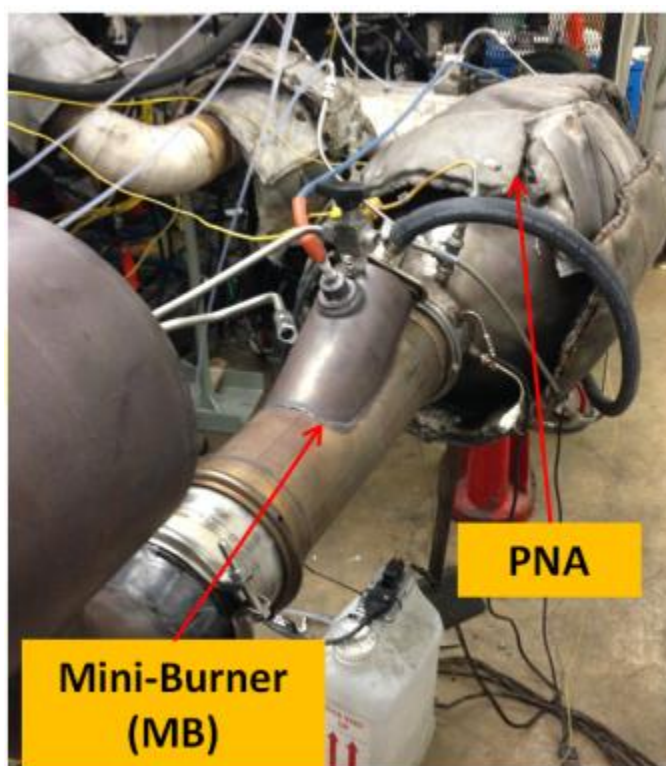


FIGURE 216. MINI-BURNER INSTALLATION, DOWNSTREAM OF PNA

The initial evaluations of this configuration on the FTP cycle were carried out using the same preliminary controls used for all other configurations. The burner was initially calibrated using a fixed schedule for these early evaluations for cold-start and hot-start control. As with all other systems, the Development Aged parts were used for the preliminary evaluations.

Figure 218 shows a comparison of the SCRF inlet temperature between the mini-burner and Configuration 1 with the 6kW EHC. The higher heat capacity of the mini-burner was evident in the more rapid warm-up and higher temperatures that can be achieved. It should be noted that the mini-burner as calibrated generated as much as 20kW of heat in short bursts, although it ran most of the time at a heat output rate of 10 – 12 kW when it was on.

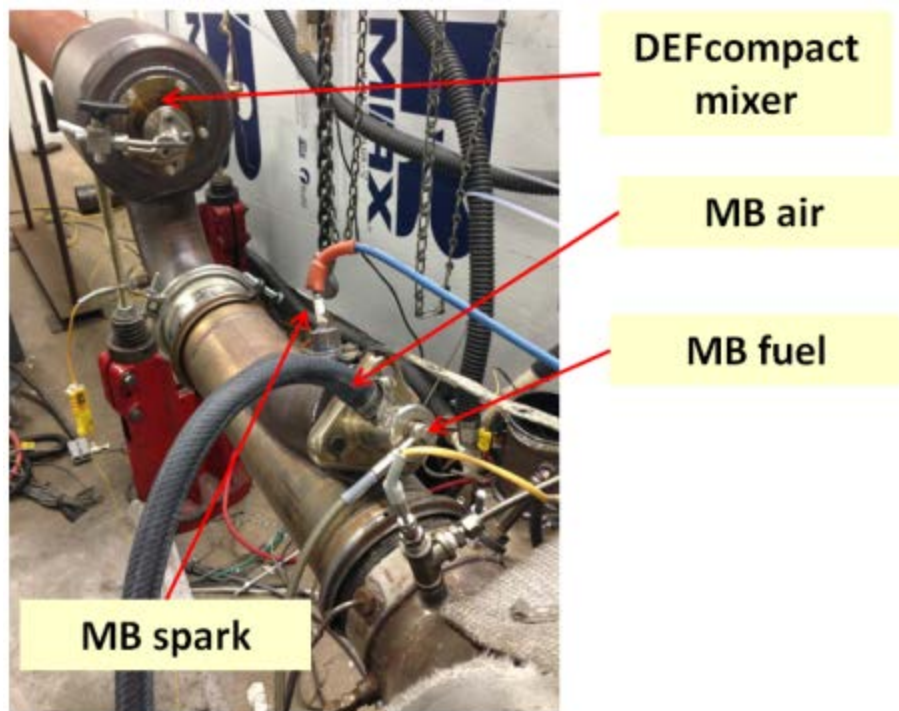


FIGURE 217. MINI-BURNER CONNECTIONS (FUEL, AIR, SPARK)

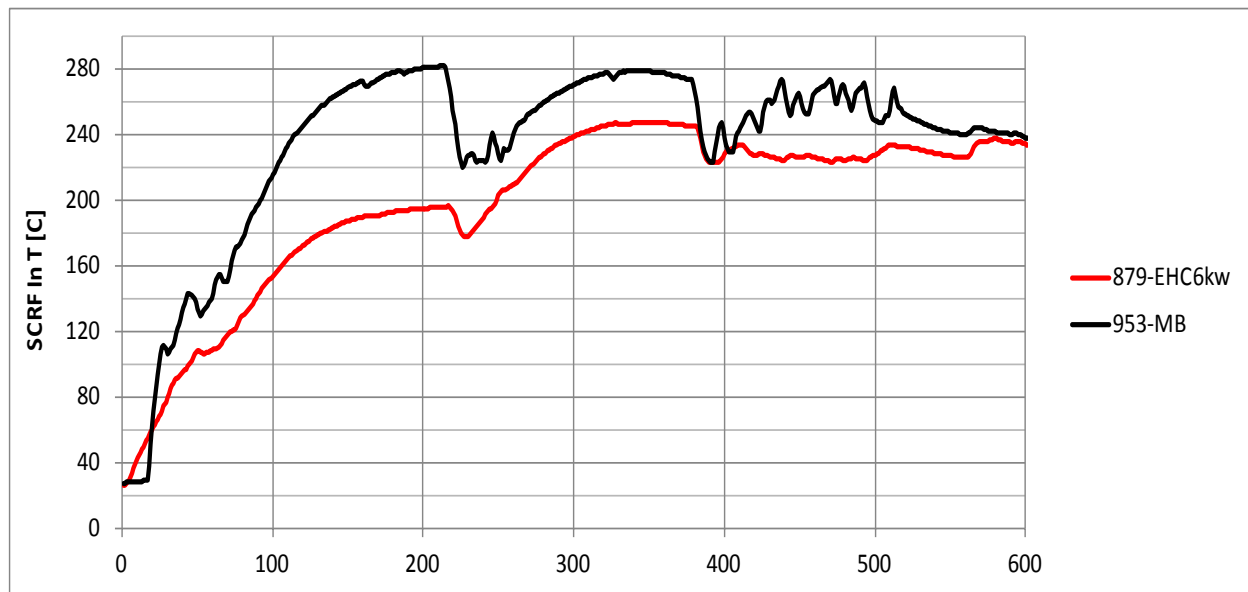


FIGURE 218. SCRf INLET TEMPERATURE COMPARISON – MINI-BURNER VERSUS 6KW EHC

Continuous NO_x and temperature for the early portion of the cold-FTP cycle are given in Figure 219. With the mini-burner, the SCRF inlet temperature reaches 200 °C 90 seconds after cold-start, and the SCRF outlet has passed 150 °C before the start of the second acceleration. As seen in the chart, this means that the SCRF can now convert the majority of the NO_x released from the PNA at that time. In addition, the downstream SCR was hot enough to begin to contribute NO_x reduction as well, which helps to trim the high space velocity spikes further. As a result, the mini-burner was able to fully bridge the gap between PNA release and SCRF light-off with some margin.

Figure 220 shows cumulative NO_x mass for Configuration 5 at various points in the system. As with other systems, there was still an initial small NO_x release of about 0.5 grams from the PNA that cannot be controlled, but the more substantial peaks near the 200-second mark have been effectively removed. There was also a small amount of late cycle NO_x due to oxidation of a portion of the ammonia that slips from the SCR into NO at higher temperatures.

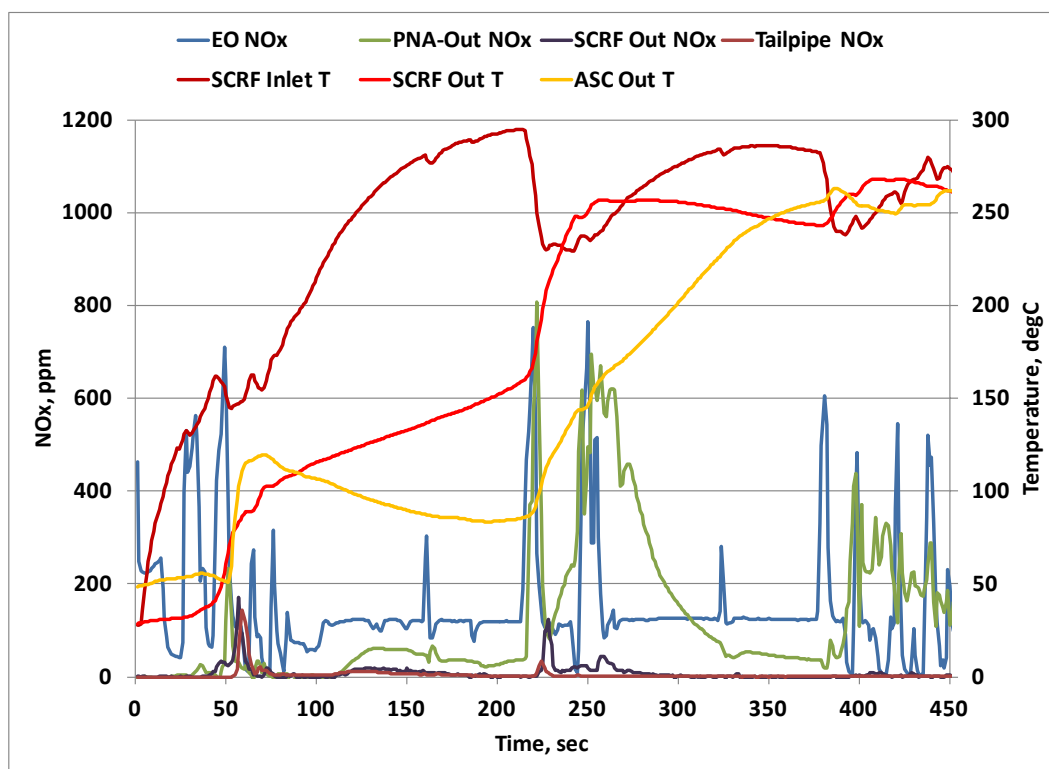


FIGURE 219. COLD-START FTP NO_x AND TEMPERATURES FOR CONFIGURATION 5 (MINI-BURNER) – 0-450 SECONDS

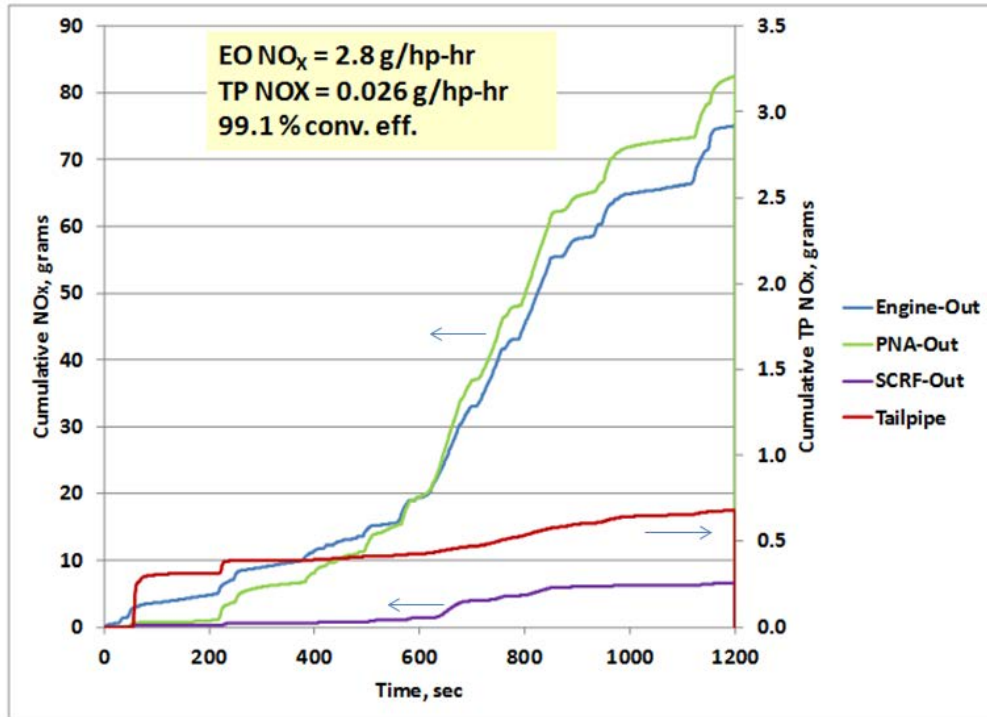


FIGURE 220. COLD-START FTP CUMULATIVE NO_x MASS AT VARIOUS POINTS – CONFIGURATION 5 WITH DEVELOPMENT AGED PARTS

This level of cold-start performance was sufficient to produce a composite FTP value well below 0.02 g/hp-hr, if it was combined with hot-start FTP levels that are at 0.01 g/hp-hr or less. As mentioned earlier, it was determined that a small amount of thermal management was needed to produce a repeatable hot-start level below 0.01 g/hp-hr, due to the low exhaust temperatures with the MD13TC engine. For the purpose of this demonstration, the most efficient means of providing this heat was to use the mini-burner during warm-start. However, a much lower heat input rate was needed, and for a significantly shorter period of time. Figure 221 shows continuous temperature and NO_x data from a hot-start FTP for the preliminary testing on the Development Aged parts. The temperature input of the mini-burner can be seen in the SCRF inlet temperature until the point at which it shuts off. As noted earlier this was also a lower heat input than was used for the cold-start, in order to minimize fuel consumption and air demand. This early thermal management was sufficient to keep both SCRF and downstream SCR temperatures above 200°C, which was the ideal point for near total conversion of NO_x. For the preliminary tests this heat rate was relatively high, it would be calibrated later to lower the heat demand somewhat during the implementation of the final controller. It should be noted that the PNA actually shows some trapping and release activity during the hot-FTP, but this was not necessary for the system to operate at very high efficiency.

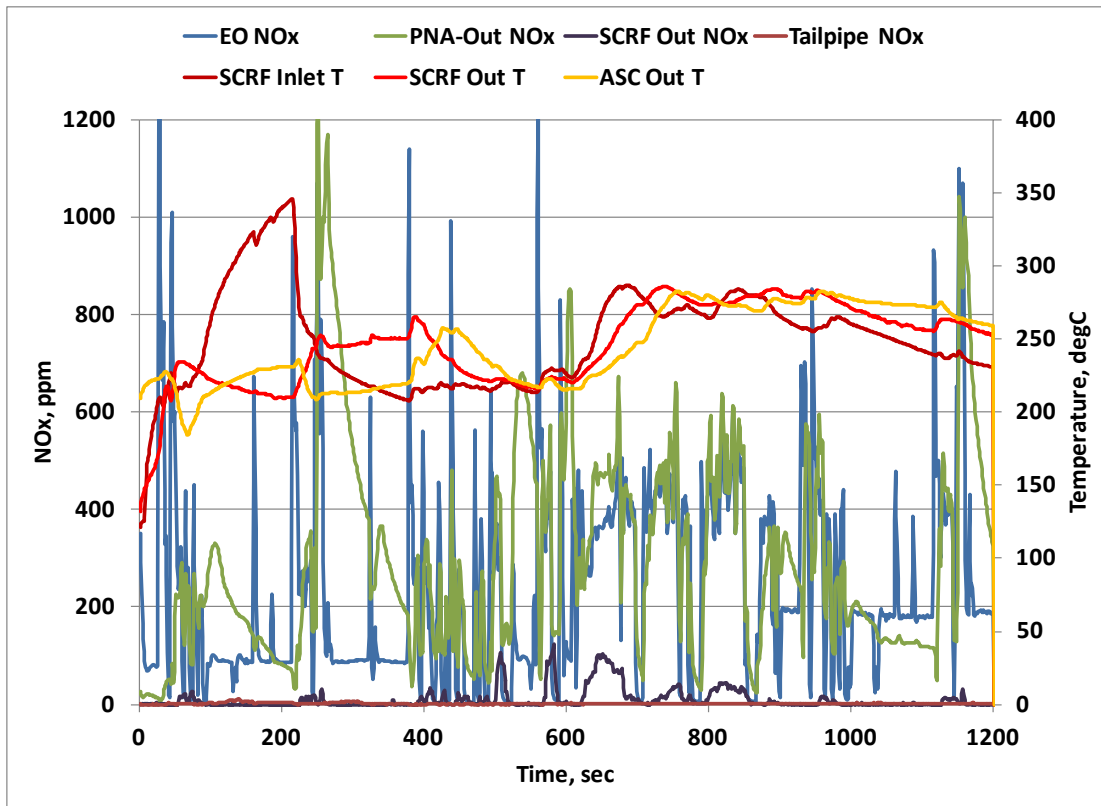


FIGURE 221. HOT-START FTP NO_x AND TEMPERATURE FOR CONFIGURATION 5 – PRELIMINARY RESULTS WITH DEVELOPMENT AGED PARTS

Figure 222 shows cumulative NO_x mass for a hot-start FTP test from the Development Aged parts. There was some breakthrough through the SCRF at high space velocity in the 600-900 second region of the cycle. However, the downstream SCR was able to deal with this as long as the ammonia coverage was properly managed. The requirement to maintain coverage does result in some late cycle ammonia oxidation into NO across the ASC. Balancing between the maintenance of mid-cycle NO_x reduction and late cycle ammonia slip was the primary controls challenge for the hot-start FTP. For the development aged parts, there was sufficient separation between these two regimes to allow for the system to be maintained at a level below 0.01 g/hp-hr. The NH₃ sensor feedback becomes a critical function for the proper maintenance of this capability.

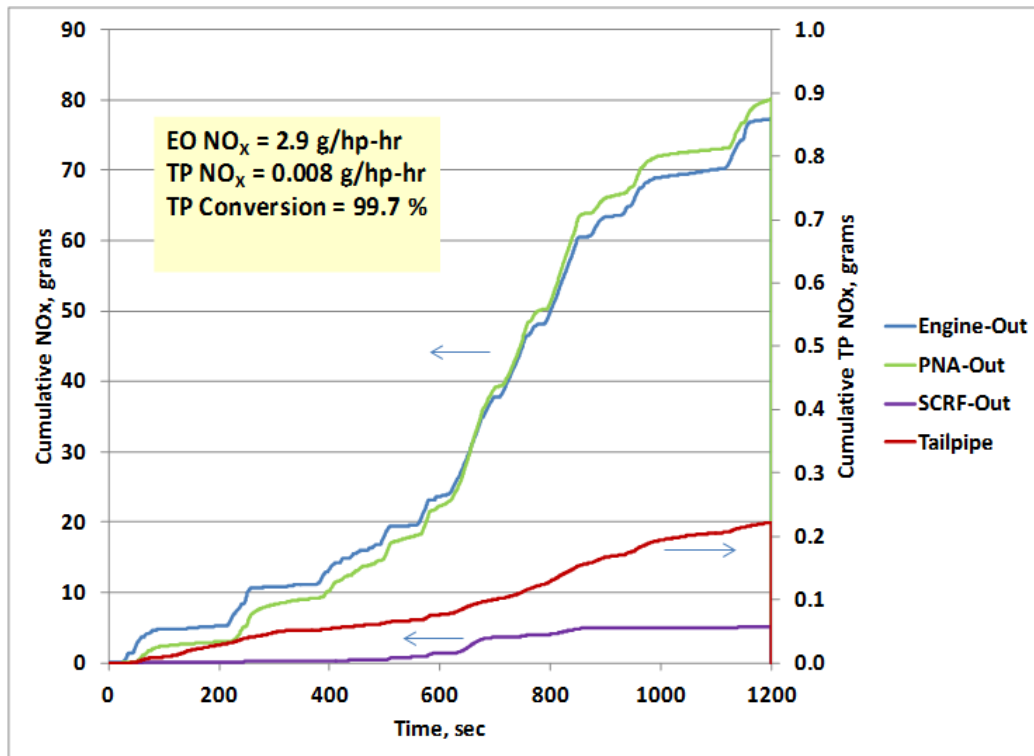


FIGURE 222. HOT-START FTP CUMULATIVE NO_x AT VARIOUS LOCATIONS – CONFIGURATION 5 PRELIMINARY DATA WITH DEVELOPMENT AGED PARTS

As a result of the performance observed with Configuration 5, as well as the time constraints of the program, and the favorable GHG efficiency as compared to Configuration 1, Configuration 5 with the PNA and mini-burner was chosen as the final configuration to proceed into the final demonstration test. Several test repeats were conducted to ensure the repeatability of the final values. A summary of the preliminary results for Configuration 5 are given below in Table 67. The table also includes a set of results for the de-greened parts that were subsequently sent into the Final Aging process. Although not given in the table, this configuration also produced RMC-SET results at a level of 0.015 g/hp-hr with preliminary controls.

TABLE 67. SUMMARY OF NO_x EMISSIONS FOR CONFIGURATION 5 WITH MINI-BURNER AND PNA

		Tailpipe FTP BSNO _x , g/hp-hr					
	Run	Cold	Hot 1	Hot 2	Hot 3	Composite	Hot Average
Development Parts (Oven Aged)	1	0.025	0.010	0.010	n/a	0.012	0.010
	2	0.027	0.009	0.009	0.010	0.012	0.009
	3	0.024	0.008	0.009	0.009	0.010	0.009
	Avg	0.025				0.011	0.009
	SD	0.0015				0.0010	0.0007
Degreened Parts before Final Aging		0.027	0.005	0.004	0.006	0.008	0.005

A preliminary summary of the impact of Configuration 5 on CO₂ emissions is given below in Table 68. These values are based on measured CO₂ emissions during baseline testing and the preliminary tests with Configuration 5. The additional impacts for increased SCRF regeneration are based on the draft values from the screening work, and the mini-burner air was based on measured air rates and a calculation based on the use of a clutched, belt-driven air pump. Based on these values, the total composite FTP impact of Configuration 5 was a 2% increase in CO₂ emissions as compared to the baseline engine. For the RMC cycle, the impact was measured at 1.2%.

In the case of the measured CO₂ emissions impact data, it should be noted that these measurements are compared to a set of engine baseline measurements that were carried out in a different test cell location nearly 2 years before the final measurements were made. It was not possible within the scope of the program to go back to repeat baseline measurements in order to allow a more precise comparison.

TABLE 68. PRELIMINARY SUMMARY OF CO₂ IMPACT OF CONFIGURATION 5 – WITH DEVELOPMENT AGED PARTS

	BSCO ₂ , g/hp-hr			
	Cold	Hot	Composite	RMC
Baseline Engine	574	543	547	458
Final ULN Config	600	547	555	462
% change	4.5%	0.7%	1.4%	0.9%
Additional GHG Impacts:				
Mini-burner air	0.5%	0.15%	0.2%	
Increased SCRF Regeneration			0.5%	0.3%
Total FTP CO2 Impact			2.1%	1.2%

The monitoring of N₂O levels was also an important part of the characterization of the system. N₂O emissions at various points in the system are shown in Figure 223 for the cold-start FTP, and in Figure 224 for the hot-start FTP respectively. Tailpipe N₂O emission levels for the Development Aged parts were at 0.075 g/hp-hr for the cold-start FTP, and 0.082 g/hp-hr for the hot-start FTP. As seen in the charts, the primary N₂O generation came about as a result of SCR reactions across the SCRF itself. Given the much of the cycle was spent in the range of 200°C to 250°C, this N₂O was likely the lower temperature pathway via the formation and subsequent decomposition of nitrates on the surface of the catalyst. It should be noted that this pathway requires NO₂ at the catalyst inlet. Measurements downstream of the PNA generally indicated NO₂ levels on the order of roughly 40% of total NO_x. It should be noted, however, that late in the cycle there was an evidence of additional N₂O being generated across the ASC. This was likely the result of oxidation of some the ammonia that slips through the downstream SCR. Most of this NH₃ was oxidized to nitrogen and water, however a small portion becomes N₂O, while an even smaller portion was oxidized into NO as discussed earlier.

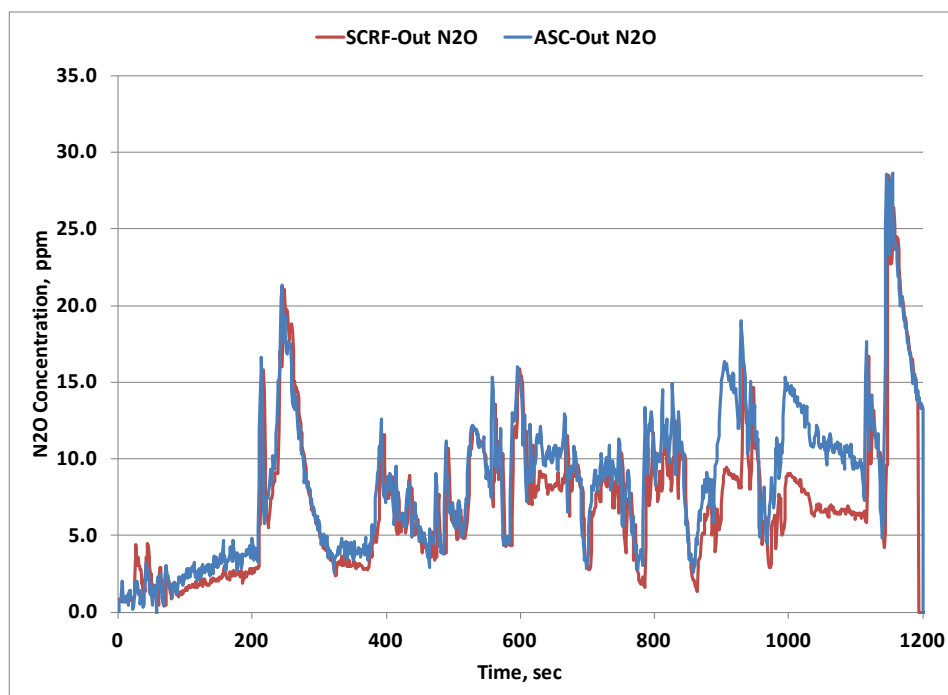


FIGURE 223. COLD-START N₂O EMISSIONS FOR CONFIGURATION 5, DEVELOPMENT AGED PARTS

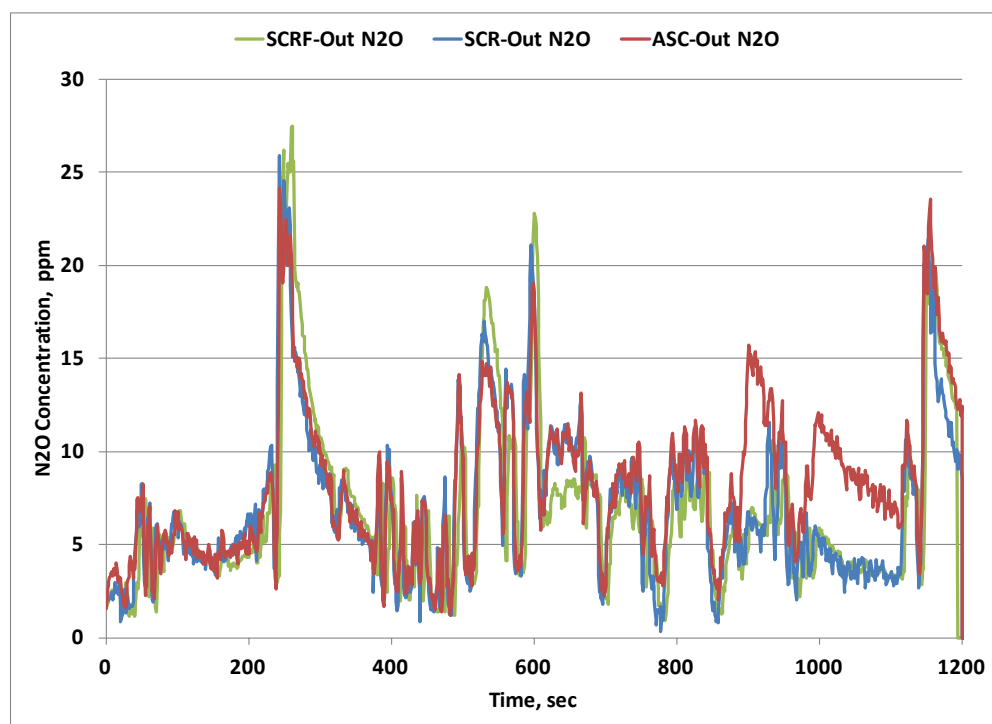


FIGURE 224. HOT-START N₂O EMISSIONS FOR CONFIGURATION 5 DEVELOPMENT AGED PARTS

3.4.2.9 Discussion of MB Configuration without PNA (DOC+MB+SCRF+SCR+ASC)

One option that was considered when the mini-burner was selected was the possibility of removing the PNA and replacing it with a DOC, in an effort to reduce system cost and complexity. Given the program time constraints by this point, a brief analysis was conducted to look at the probability of success with such a change.

The removal of the PNA would require that engine-out NO_x levels be lowered drastically during the first 90 to 100 seconds of the cold-start. In prior investigations, a modified engine calibration was attempted to generate larger engine-out NO_x reductions than the one finally utilized (which as designated Cold Cal 2). However, this approach was halted when the PNA was selected, due to the fact that its use resulted in the potential for rich excursions during accelerations in the early cold-start (thought these were no larger than the ones observed on the baseline engine). It should be noted that this calibration was only applied at low coolant temperatures (i.e., below 50 °C after cold-start only). Removal of the PNA would allow more flexibility in the engine calibration to try such modifications.

An analysis of cumulative NO_x in the early cold-start is shown in Figure 225. The plot show the engine-out NO_x from the current engine calibration, and what was observed with the modified Cold Cal 2 (marked EO_CC2). The modified Cold Cal 2 resulted in a cumulative NO_x of 2 grams by 60 seconds into the cycle and 2.5 grams by 100 seconds. Recall that the SCRF does not light-off until about 90 seconds into the cycle with the mini-burner. While this represents a reduction of nearly one third from the current engine calibration, it was still not sufficient to get under the cold-start target of 2 grams total even with some early NO_x reduction from the SCRF. In addition, no margin would be left for any other NO_x emitted anywhere else in the cycle.

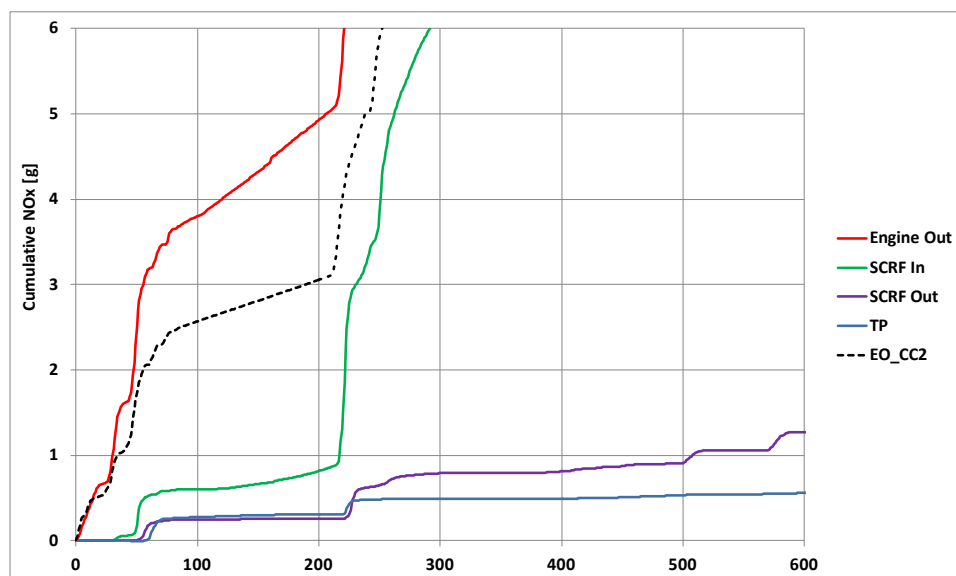


FIGURE 225. CUMULATIVE COLD-START NO_x AND ANALYSIS OF COLD CAL 2 OPTION WITHOUT PNA

As a result, this approach was considered too low a probability of success to spend engine resources on at this late stage of the program. However, with a somewhat higher initial engine exhaust temperature, perhaps from a non-turbo-compound engine, this could be a viable potential approach.

3.4.3 Final Controls Implementation and Calibration for Final Candidate System Configuration 5

Following the down-selection of Configuration 5 based on the preliminary test results, a set of parts was delivered to final aging as described earlier. While these parts were being aged, development in the transient cell continued with the implementation and calibration of the final controls. This work continued on the Development Aged parts while Final Aging was being conducted. While it would have been ideal to complete the controls development and then test the final parts again prior to aging, the time constraints of the program did not allow this to be done.

The final controls approach was described in detail earlier, and therefore will not be repeated herein. The primary differences between the Final Controller and the Preliminary Controller (used to generate the data previously discussed) were:

- Use of a model-based SCR controller with integrated NH_3 sensor feedback. This allowed a single calibration to be used for the various cycles, as well as getting rid of the need for specialized pre-conditioning beyond what was normally permitted in 40 CFR Part 1065
- The use of a state-machine based burner controller, which was driven by coolant and aftertreatment temperatures rather than a fixed schedule. This allowed for the development of a single set of calibrations that would be used on all cycles
- The use of the same state-machine controls to trigger engine changes based on temperatures rather than a time basis

This step was considered essential in order to produce a representative demonstration, as well as to enable the assessment of the system on vocational cycles, which were not meant to be individually calibrated. As mentioned earlier, a single calibration set was developed for FTP and RMC-SET cycles, and that same calibration set was generally used without modification for the vocational cycles. A slightly modified calibration was developed for the WHTC, but it was felt that this was appropriate given that a production engine would likely be calibrated for the regulatory cycles appropriate to its target market. Therefore, it is not uncommon for engines targeted at U.S. cycles to have different calibrations than those targeted at European cycles, even if the overall system architecture is similar.

During the course of the controller development, there were two incidents that occurred which affected the Development Aged parts. The first was an issue that occurred with a glitch in the communication between the engine ECU tools and the Integration Controller. This resulted in a significant post-injection event under cold-start temperatures that resulted in the exposure of the PNA to raw fuel. Although this period was brief, and there were no measured exotherms that

resulted from this event, it did appear to result in a small loss of storage on the PNA. Subsequently, an issue with the mini-burner during software development resulted in a series of burner misfire events, during which a small amount of raw fuel was pooled in the exhaust. Although this was subsequently evaporated later in the cycle, this may have also resulted in some exposure on the PNA. It should be noted that the SCRF and SCR were not affected by either of these occurrences.

A comparison of results for the Preliminary tests and the Final Controller is shown in Table 69. As noted earlier the primary reason for the difference in cold-start emissions results was the shift in PNA performance that was observed as a result of the occurrences discussed earlier. Hot-start results were noted to be more consistent with the final controller, and as noted earlier, all the results with the final controller could be achieved using only the standard preconditioning procedures that are permitted in 40 CFR Part 1065. In the case of the FTP, that meant two preconditioning hot-FTP cycles with a 20-minute soak between them. In the case of the RMC-SET, the test for record was preceded immediately by a preconditioning RMC-SET and there was no dwell time between the two cycles. With the Final Controller in place, the system was still demonstrating emission levels that were below 0.02 g/hp-hr, even with the compromise to the PNA in the development aged parts.

TABLE 69. COMPARISON OF TAILPIPE NO_x LEVELS FOR PRELIMINARY AND FINAL CONTROLS USING DEVELOPMENT AGED PARTS – FINAL CONFIGURATION

		Cold	Hot	Composite	RMC
Preliminary	g/hp-hr	0.027	0.010	0.012	0.015
	% conv	99.0%	99.7%	99.6%	99.3%
Final Controller	g/hp-hr	0.062	0.008	0.016	0.015
	% conv	97.7%	99.7%	99.5%	99.3%

Unlike the Preliminary results, the Final Controller was also tested on the WHTC cycle with the Development Aged parts, thus providing an assessment of performance on that cycle prior to Final Aging. Very limited time was available for work on the WHTC, therefore only small calibration adjustments were made. The engine calibration was essentially used as it was with a small adjustment made for transient EGR tuning. It was found that the burner settings needed to be adjusted slightly in order to achieve a stable light-off performance given that the WHTC begins to develop load less than 6 seconds after the start of the cycle. These settings were retained in the future given that they appeared to improve performance on all cycles. In addition, the burner heat rates and trigger temperatures were moved a small amount to optimize fuel consumption. Finally, some small adjustments to SCR storage targets were made in an attempt to optimize performance a little better for the WHTC. It was clear that the WHTC tailpipe levels could have benefited for a longer optimization effort, but this was not available.

WHTC emission levels for the Final Controller are given below in Table 70. As noted for the FTP results discussed earlier, these results utilize the same PNA, which had been affected by the earlier calibration occurrences. NO_x and temperature behavior over the early portion of

the cold-start WHTC are shown in Figure 226. The SCRF reaches the point of light-off about 150 seconds into the cycle, and reaches high conversion rates roughly 30 seconds later. However, there is substantial release from the PNA prior to this point, due to the nature of the WHTC. Therefore, the cold-start value is somewhat higher than what was observed with the same catalysts on the FTP cycle. It is likely that the WHTC would have benefitted from a more aggressive early burner calibration, but there was not sufficient time available to produce this calibration.

TABLE 70. WHTC NO_x LEVELS FOR THE FINAL CONTROLLER WITH DEVELOPMENT AGED PARTS

		Cold	Hot	Composite
Engine-Out	g/hp-hr	3.5	3.4	3.3
Tailpipe	g/hp-hr	0.089	0.008	0.019
NO _x Conversion	%conv	97.5%	99.8%	99.4%

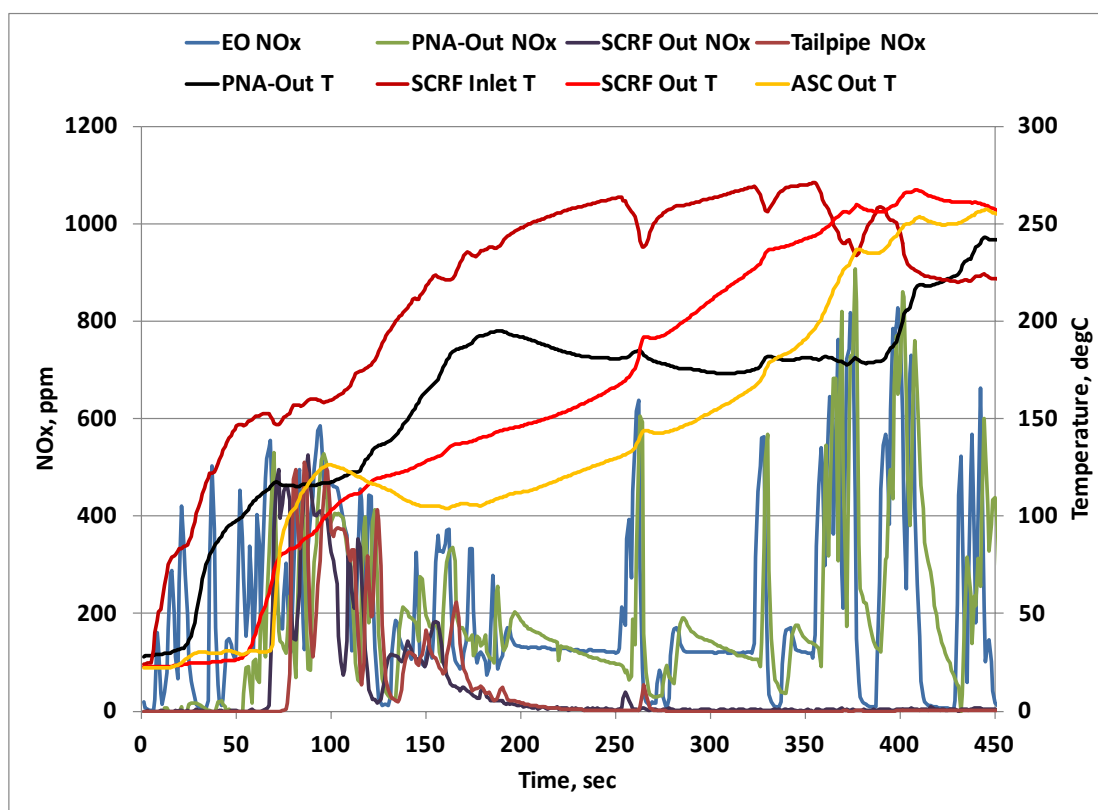


FIGURE 226. COLD-START WHTC NO_x AND TEMPERATURE – DEVELOPMENT AGED PARTS AND FINAL CONTROLLER, 0-450 SECONDS

It was noted that the WHTC cycle appears to push the capacity of the PNA slightly harder because of the manner in which it warms up and generates NO_x. Figure 227 shows a

comparison of cumulative NO_x before and after the PNA for cold-start on both cycles. Although the initial FTP engine-out rate is higher, this happens earlier when the PNA is at slightly lower temperatures. The first large increase in engine-out WHTC NO_x comes somewhat later when the PNA is at slightly higher temperatures. This leads to an earlier breakthrough of NO_x, which breakthrough happens before the SCRF reached sufficient temperatures for high efficiency NO_x conversion. At the same time, the higher exhaust flows in the early WHTC mean that more heat is needed early to achieve full SCRF light-off. While the FTP breakthrough actually comes sooner, it is smaller, and by the 90-second mark in the cycle, the release seen on the WHTC overtakes the FTP and continues. The final impact is not as large as it seems from this comparison because it should be noted that the WHTC work denominator is about 70% larger than for the FTP for this engine. Nevertheless, the final brake-specific NO_x level is still about 50% higher on this comparison, although that difference could be reduced with further calibration effort. Given the limited remaining time and resources in the program, and the fact that the tailpipe level was at 0.02 g/hp-hr on the WHTC, it was decided to stop the calibration effort at that point, in order to prepare for the testing of the Final Aged parts, which were nearly ready at that point.

FIGURE 227. COMPARISON OF EARLY COLD-START CYCLE BEHAVIOR ACROSS PNA – WHTC VERSUS FTP

Hot-start WHTC behavior is shown in Figure 228, which shows temperature and NO_x over the cycle. However, both the SCRF and tailpipe NO_x levels are essentially not visible on this scale. Therefore, Figure 229 shows both engine-out and tailpipe NO_x on separate scales with a factor of 100 difference. At this magnification, it is apparent that there are several small NO_x spikes early in the 300 to 600 second range, but the majority of the hot-start NO_x is emitted at the end of the cycle. This is again due to late cycle ammonia oxidation into NO across the ASC. Cumulative hot-start WHTC NO_x mass is depicted in Figure 230, which shows the majority of tailpipe NO_x coming at the end of the cycle due to oxidation of ammonia slip.

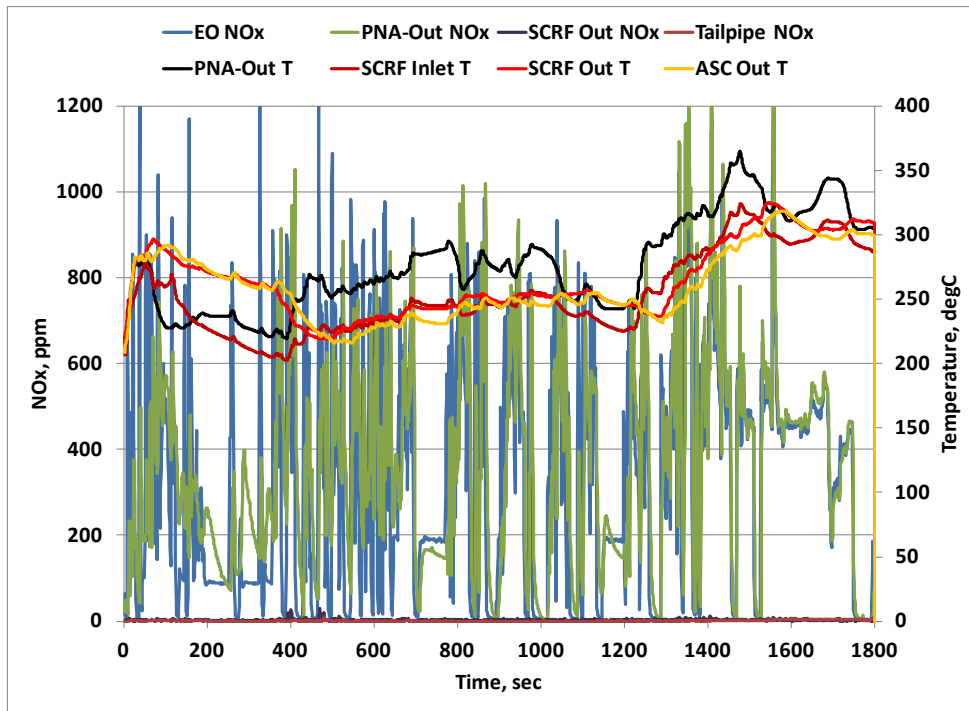


FIGURE 228. TEMPERATURE AND NO_x OVER HOT WHTC WITH DEVELOPMENT AGED PARTS – FINAL CONFIGURATION

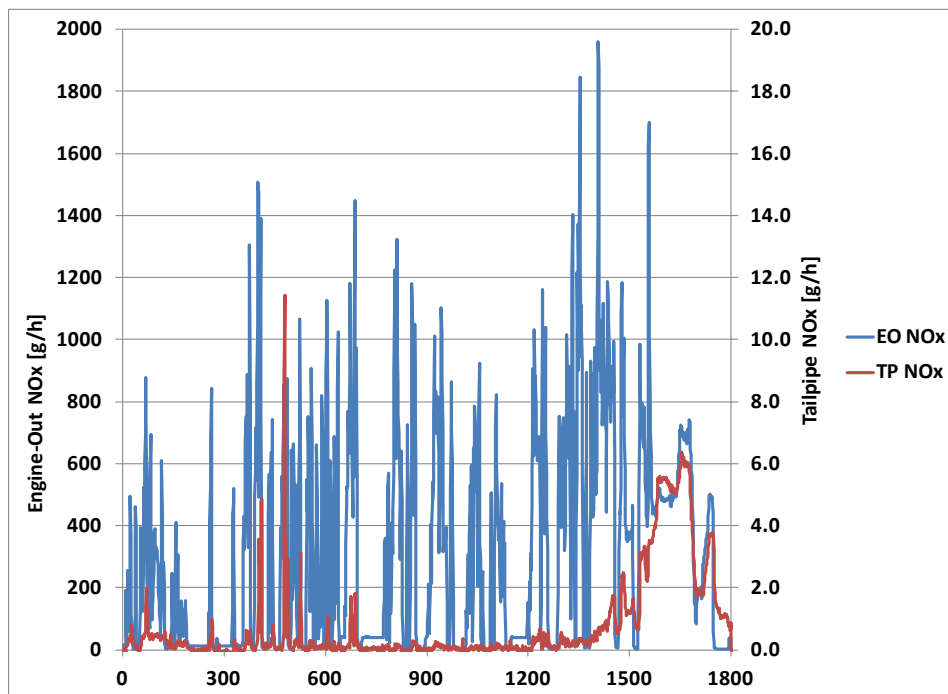


FIGURE 229. ENGINE-OUT AND TAILPIPE NO_x MASS OVER HOT WHTC WITH DEVELOPMENT AGED PARTS – FINAL CONFIGURATION

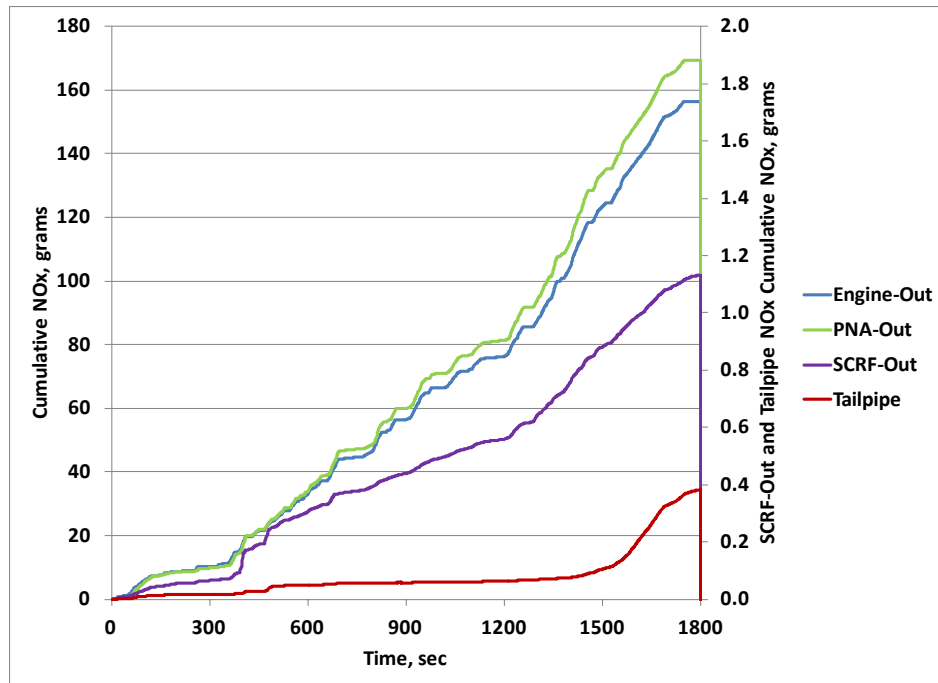


FIGURE 230. CUMULATIVE HOT WHTC NO_x MASS WITH DEVELOPMENT AGED PARTS – FINAL CONFIGURATION

One interesting contrast that was noted between the hot-start FTP and WHTC cycles was that the FTP appeared to rely slightly more on the downstream SCR to deal with high space velocity breakthroughs. Table 71 shows a comparison of the cycle conversion behavior at SCRf and Tailpipe locations for the two cycles. Although tailpipe levels are essentially the same, the WHTC relies less on the downstream SCR to manage high space velocity spikes. This could indicate an opportunity to downsize that catalyst for certain applications and duty cycles.

TABLE 71. COMPARISON OF HOT-START CONVERSION BEHAVIOR FOR WHTC AND FTP CYCLES

Location		WHTC	FTP
Engine-Out	g/hp-hr	3.34	2.91
SCRf-Out	g/hp-hr	0.024	0.029
	% conv	99.3%	99.0%
Tailpipe	g/hp-hr	0.008	0.008
	% conv	99.8%	99.7%

One difficulty that was noted with the WHTC cycle in particular was that there was a measurement related issue driven by the fact that the WHTC protocol specifies only a 10-minute soak between cold-start and hot-start tests. Given the short period of time there was not sufficient time to switch to lower analyzer ranges and recalibrate between the cold-start and the hot-start. This meant that all tests had to be run at the cold-start ranges. It was found that this appeared to result in a slightly larger amount of drift, and in particular, with issues surrounding the accuracy of the background bag read. Although these issues were small, they were still sufficient to create a discrepancy between Raw and Dilute tailpipe measurements. Similar issues

were not observed with the FTP tests, wherein the 20-minute soak period allowed for a switch to lower ranges for the hot-start tests. This was examined in more depth later when looking at the larger number of replicates available with the final aged parts.

3.4.4 Final Aging

As describe earlier, the Final Aging process was conducted on a mule engine, which was a 2009 Cummins ISX 15-liter engine that had been modified in accordance with the DAAAC protocol to produce a moderate amount of acceleration to catalyst oil exposure. The de-greened catalysts, which were tested at the end of the down-selection process, were installed on the engine, along with a set of the production NO_x, NH₃, and temperature sensors that were used by the final controller.

DEF dosing was also conducted during the aging, but given the relatively simple nature of the durability cycle, this dosing was based in a fixed ANR schedule by mode. Dosing calculations for aging were driven by the measured exhaust flow and the engine-out NO_x sensor. Given the temperatures of the aging cycle, it was not anticipated that there would be significant amounts of NO_x storage, therefore the engine-out sensor signal was deemed appropriate to drive dosing. Generally dosing was conducted at an ANR of 1.05, however that ANR was increased to 2.0 during the SCRF regeneration mode.

The initial regeneration times were based on experiments conducted with a de-greened set of parts looking at both a program DOC-DPF system and the final SCRF that was chosen. For the SCRF the experiments were conducted using a PNA to generate the exotherm for regeneration, as was the case for the final configuration. The results of these initial regeneration experiments are summarized below in Table 72. Based on these results, in initial regeneration process consisting of 25 minutes at 575°C, followed by a short 5-minute duration at 600°C was settled on. It appeared from the experiments that this would be sufficient to keep the filter clean over the long term.

TABLE 72. RESULTS OF SCRF REGENERATION EXPERIMENTS

DPF/SCR_F (w/DOC)	Part Volume (L)	Run Number	Test	Total Fuel Consumption (kg)	Soot On Part* (g)	Percent Removed*	Soot on Part* (g/L)	Cycle End Weight (g)
DPF	21.75		Cleanout					30851.3
		729-731	Loading	93	125.0		5.75	30976.3
		732	550°C-25min; 600°C-5min	19	7.2	94%	0.33	30858.5
			Cleanout					30858.5
		733,734	Loading	114	123.1		5.66	30974.4
		735	575°C-25min; 600°C-5min	18	7.0	94%	0.32	30858.3
SCR_F	26.37		Cleanout					26839.5
		713	Loading	136	125.1		4.74	26964.6
		714	550°C-25min; 600°C-5min	20	42.9	66%	1.63	26882.4
			Cleanout					26842.0
		716,717	Loading	163	148.8		5.64	26990.8
		718	550°C-25min; 600°C-5min	20	43.0	71%	1.63	26885.0
			Cleanout					26846.2
		723	Loading	142	151.6		5.75	26997.8
		721 or 724	575°C-25min; 600°C-5min	20	14.4	91%	0.55	26860.6

The initial aging cycle is depicted below in Figure 231. As discussed earlier this cycle was developed based on the initial calculated regeneration frequency of 1.7% and the regeneration process discussed above. The given regeneration frequency result in a total of 218 hours of regeneration for full useful life equivalent thermal exposure. This would be conducted over the course of 1000 hours of operating over the cycle shown in Figure 231. Based on data from Volvo and the predicted oil consumption for the DAAAC mule engine, an oil exposure acceleration of 2.5 was expected, which would result in roughly 25% full useful life oil exposure.

Following the initial installation and checkouts of the cycle, durability on this initial cycle was started. It should be noted however, that at the start of Final Aging, this configuration had not actually been run for extended periods of time due to time and budget constraints. Several issues developed over the course of the durability operation that resulted in the need to modify the original aging cycle and regeneration process. Given the developmental nature of the program, and the fact that on-engine aging of this configuration had never been attempted, some adjustments were to be expected.

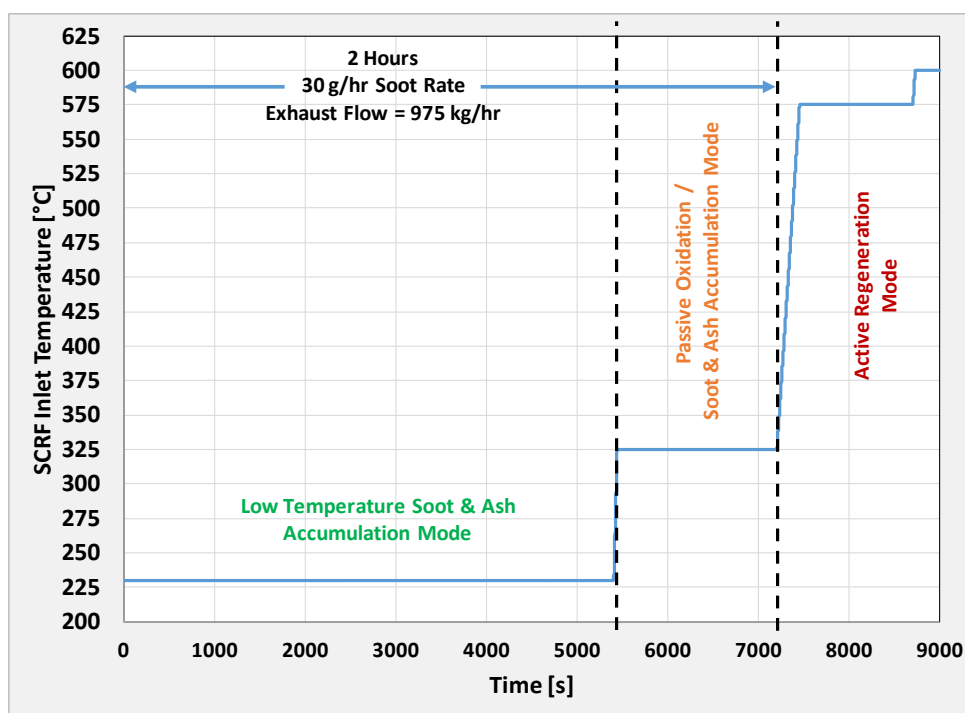


FIGURE 231. INITIAL CYCLE FOR FINAL AGING (2.5 HOUR DURATION)

A summary of the complete history of the Final Aging is given in Table 73. As noted, there were several significant events that occurred over the course of Final Aging that may have affected the parts in an abnormal fashion. These are discussed more below.

The first issue that developed during the Final Aging occurred relatively quickly after starting durability. Within about 40 hours of operation, it was noted that the delta P across the PNA was rising from cycle to cycle, and further that the exotherm was requiring an increasing amount of fuel to maintain. By the point of 70 hours, due to both this and rising SCRF delta P, durability was halted. Upon inspection, it was found that a considerable amount of coke was

building up on the front of the PNA, and this was compromising the regeneration capability of the system. It appeared that this was occurring during regeneration and the subsequent cool down back to the low temperature mode. This buildup was successfully removed by operating at 425°C for a period of about 2 hours on the engine.

After further discussion and analysis it was determined that in order to manage the buildup, a mode would be inserted into the durability cycle consisting of operation at 425°C at the PNA inlet. The duration of this mode would be set in a realistic manner to be consistent with the histogram data that was used to develop the initial cycle, although that temperature was initially not utilized. The addition of this mode helped to prevent long-term buildup of coke and therefore allow aging to continue. However, it should be noted that this initial large buildup did expose the PNA to high levels of heavy hydrocarbons through several shutdown events before it was removed. This could have resulted in some amount of abnormal degradation on the PNA, although it is not known how much this may have actually contributed to changes observed in PNA performance.

TABLE 73. FINAL AGING CHRONOLOGY AND SIGNIFICANT EVENTS

Date	Cycle Hours	Aging Cycle	Notes
8/29/2016	0	Original	
8/31/2016	40	Original	First observation of increasing PNA dP, decreasing exotherm with each cycle
9/1/2016	70	Original	SCRF weight
9/1/2016	75	Original	Large increase in SCRF dP, aging stopped
			Coking on PNA caused decreased exotherm
			Regeneration insufficient for full cleanout
			Passive regeneration and cleanout, decoke PNA at 425C, clean SCRF weight
9/1/2016	75	Modified 1	575 for 15 min, 600 for 15 min, better but still increasing SCRF dP
9/4/2016	130	Modified 2	Increase 600 to 40 min
9/8/2016	225	Modified 3	Current regen is too frequent for long term, increase non-regen 50%
9/12/2016	325	Modified 4	Further increase in non-regen, reduce 575 mode to 5 min
9/13/2016	333	Modified 4	SCRF clean weight
9/17/2016	425	Final	Final cycle times reached
9/23/2016	575	Final	SCRF dP slow increase during this period (ash), late in cycle observed more rapid increase
9/27/2016	585	Final	SCRF clean weight
9/27/2016	590	Final	Shut down on SCRF dP
			Evidence of faceplugging and ash, Insufficient exhaust distribution upstream of SCRF
			Installed diffuser inlet upstream of SCRF
9/28/2016	593	Final	Passive regeneration at 425C with no DEF (clean PNA and SCRF soot), clean weight
10/1/2016	670	Final	SCRF dP again at higher levels, passive regeneration at 425 to clean out, mat failure started ?
10/6/2016	710	Final	Shut down on very high SCRF dP and high backpressure, PNA dP data not valid due to over-range
10/7/2016			Inspection shows canning failure, heavy PNA coking and soot, SCRF plugging via mat
10/9/2016-10/21/2016			Recovery Efforts
10/21/2016	710	Final	Install re-canned part, allows for proper regeneration and clean SCRF weight
10/22/2016-10/26/2016			Removal of front ash/mat material plug
10/27/2016	712	Final	Regeneration and clean SCRF weight (to check ash load)
10/28/2016	712	Final	Restart aging (noted early coking issues, test cell heat exchanger and cycle modified)
11/4/2016	850	Final	Aging Completed

It was noted at this same time that there was also a rapid delta P increase across the SCRF. Initially it was expected that this may have been due to the PNA issue, however, on further inspection it was found to be due to incomplete regeneration and cleaning of the soot.

After several additional experiments it was determined that more time was needed at 600 °C SCRF inlet temperature to affect a thorough cleaning of the filter. The regeneration protocol was modified accordingly and durability was resumed. The overall duration of the regeneration event was also lengthened from 30 to 40 minutes. It should be noted that this change affected the final regeneration frequency, and therefore the length of the modes needed to be adjusted in order to achieve the desired thermal exposure. These adjustments were made while the aftertreatment was continuing to cycle and accumulate hours. Therefore, the final duration of the durability had to be adjusted as discussed below in order to avoid over-aging of the parts.

Prior to the re-start of durability, the excess soot was removed from the SCRF by placing the engine at a mode that would promote passive regeneration, while at the same time disabling DEF injection so that passive soot oxidation could take place. Once the filter was reduced to a reasonable delta P, an active regeneration was run.

During the course of these experiments, it was also found that the initial soot-loading target was set too low. Given the lack of precious metal on the SCRF, the only source of exotherm on the filter itself comes from the oxidation of soot. It was found that if there was not enough soot accumulated on the part prior to the start of regeneration, a thorough exotherm would not reach the edges of the part, given its large diameter at 13 inches. In addition, the soot-loading target was increased from 4 g/liter to 5 g/liter. This change, along with the change to the duration of regeneration, resulted in a re-calculation of the regeneration frequency. The final calculation indicates a slightly lower frequency of 1.7%, but this would be primarily at a higher temperature as previously discussed. Therefore, the overall thermal exposure of the parts was increased as compared to the initial aging cycle. This was necessary however, in order to for the aging to represent an accurate regeneration process.

Considering these various changes, the updated durability cycle is shown in Figure 232. The final duration of the various modes was adjusted over time in order to reach the final desired frequency. However, these adjustments were made incrementally, while the parts were still accumulating hours. The final cycle was stabilized at the 425 hours mark. Therefore, in order to prevent either over-aging or under-aging of the parts, the actually amount of time at temperature was quantified, and the duration of the durability was adjusted in order to achieve the correct thermal exposure. The final regeneration frequency of 1.7% translates to 188 hours of regeneration time over full useful life, but the majority of that was at 600 °C at the SCRF inlet.

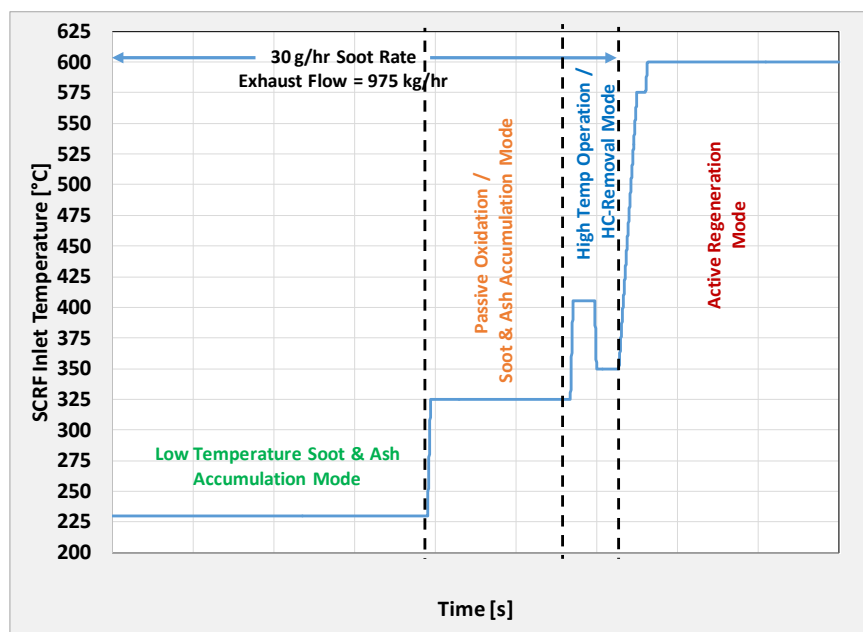


FIGURE 232. FINAL DURABILITY CYCLE USED FOR FINAL AGING (4-HOUR DURATION)

It should be noted that at this temperature, the bed temperature on the PNA where the regeneration exotherm is being generated was generally in the range of 640°C to 650°C. These bed temperatures were considered to be sufficiently high to promote regular desulfation of the PNA. However, this was primarily observed at the rear of the bed, and the front bed temperatures did not generally reach much above 400 °C. PNA inlet gas temperatures during the regeneration mode were in the range of 320 °C to 330 °C. It is therefore possible that some sulfur may have been stored over longer periods at the front face of the PNA.

The next event occurred at the 590-hour mark shortly after a clean-weight was conducted. There was evidence on the filter of face-plugging via ash around the edges of the part which was abnormal. This was determined to be the results of poor exhaust distribution at the SCR inlet face. The inlet cone was modified to include a diffuser of a design that had already been incorporated in the development cell to improve inlet distribution of NH_3 . The face ash was mechanically loosened and a passive regeneration was run to remove the excess soot that had built up. Following this, SCR delta P returned to normal behavior and durability continued. It was noted that during several of the regenerations leading up to this, SCR bed temperatures did reach levels as high as 660 °C due to high soot levels. Normally, SCR bed temperatures did not exceed 630 °C.

Durability continued at this point, until increasing delta P was again noted on the filter starting at about the 670-hour mark. However, this was still within normal levels so it was monitored over the next day. Near the 710-hour mark, a large increase was noted in both SCR delta P and overall system backpressure, and the system was shut down by test cell safeties. Subsequent inspection revealed that the source of these changes was a canning failure on the PNA. Pictures of this failure are shown in Figure 233. Figure 234 shows pictures of the SCR that was downstream of this failure.

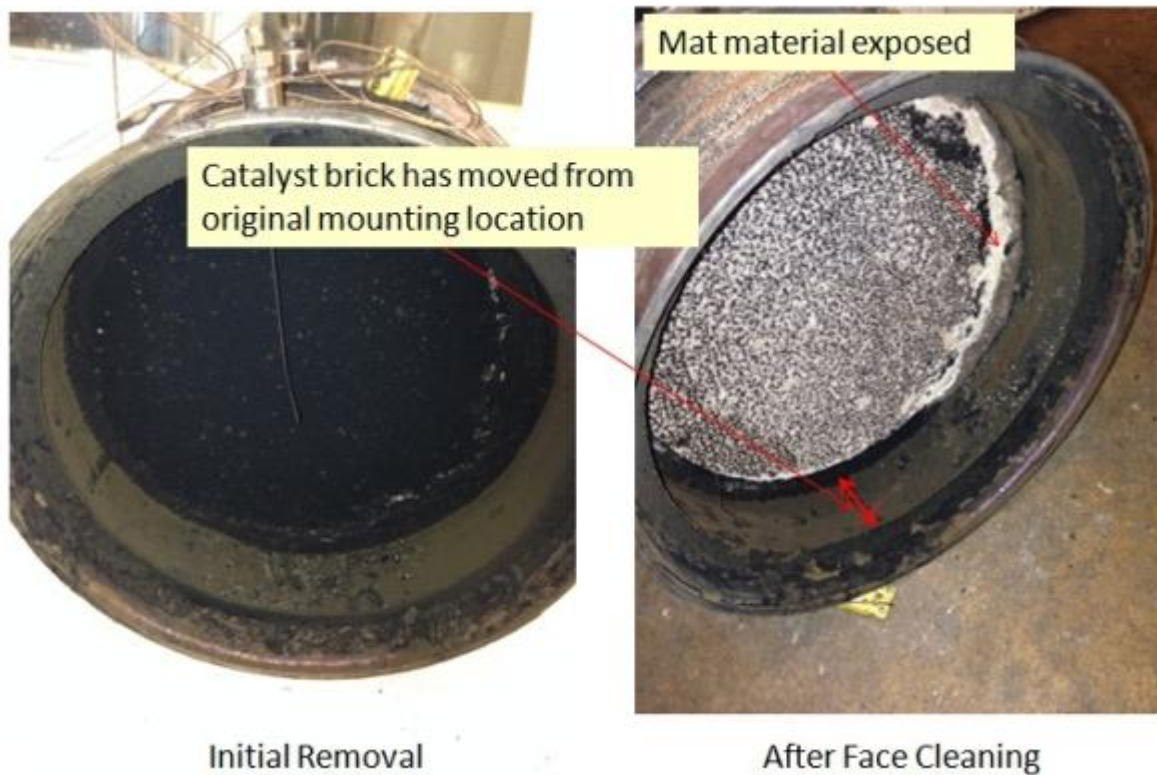


FIGURE 233. PNA IMMEDIATELY FOLLOWING CANNING FAILURE



Clear evidence of substantial mat material on front face

FIGURE 234. SCRF INLET FOLLOWING PNA CANNING FAILURE

The pictures indicate a significant buildup of coke, soot, and matting material used in canning on the front face of the PNA. This likely resulted in another exposure of the PNA to significant amounts of heavy HC, which may have affected its performance. In addition, the PNA appeared to have ingested some matting material while failure was progressing, although the majority of the material was located on the front face and easily cleaned off. Further inspection of the SCRF was carried out in order to determine if the situation was recoverable. Figure 235 shows the result of a bore scope analysis conducted from the front face, while Figure 236 shows the result of a CT-scan analysis of the filter. Both indicate evidence of unusual plugging near the front of the filter, as opposed to the normal pattern of deep ash that is also seen in this part (and is typically for aged filters). This front plug was found to be composed of a combination of mat material and ash and is not a normal occurrence in real vehicle driving.

In order to continue durability it was necessary to recover both parts if possible. The alternative would have been to start the aging process over, but this would have resulted in a 4 to 6 month program delay while new parts were obtained and re-aged, as well as the need for additional funding to support the re-aging process. Therefore, recovery approaches were launched.

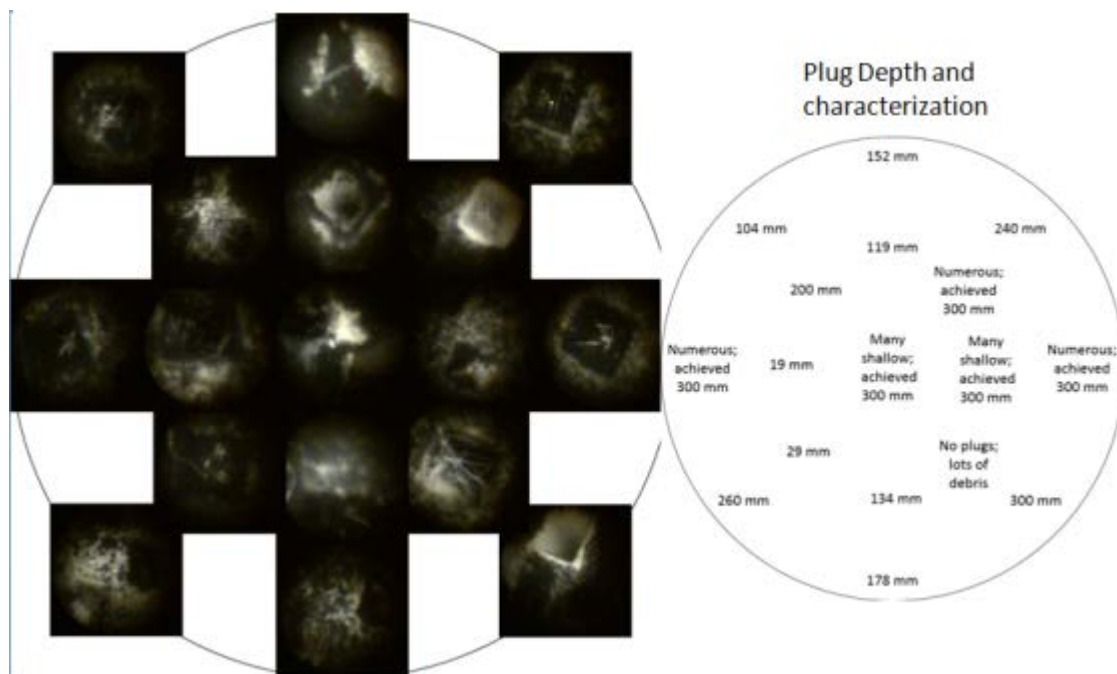


FIGURE 235. BORESCOPE INSPECTION OF SCRF FOLLOWING CANNING FAILURE

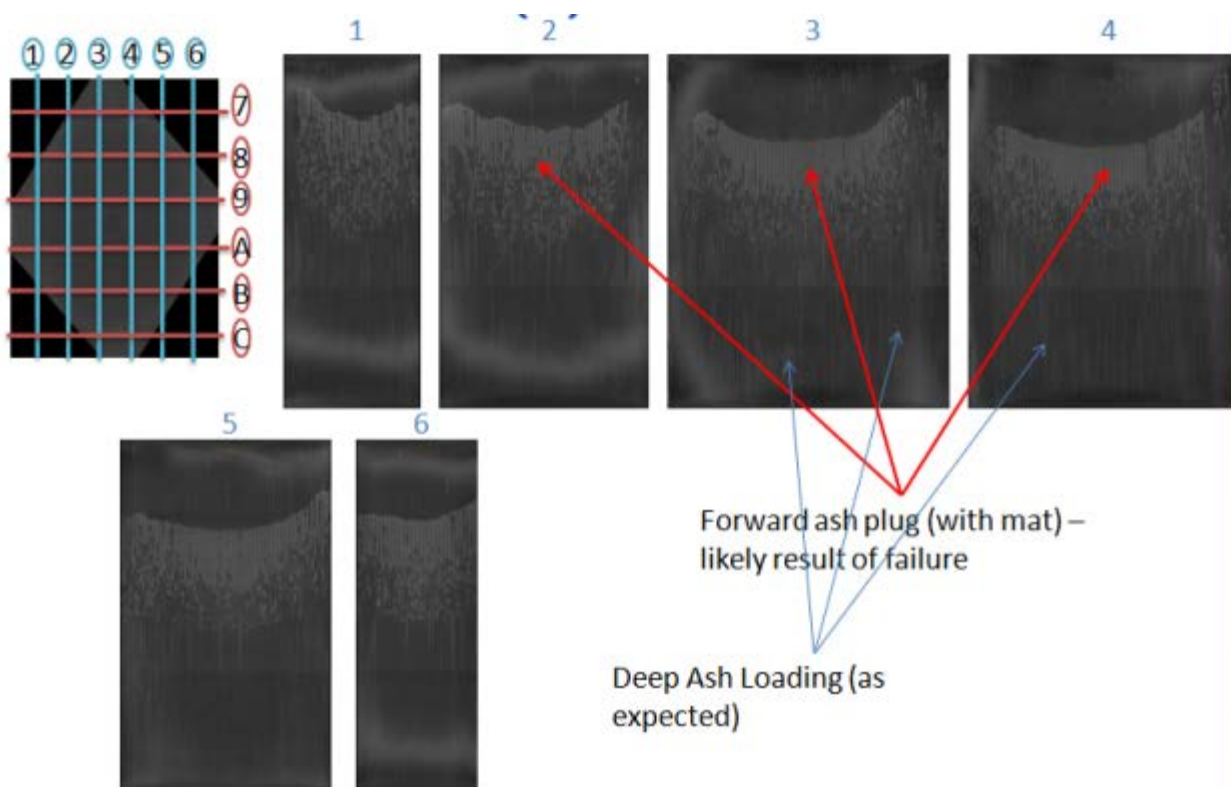


FIGURE 236. CT-SCAN ANALYSIS OF SCRF FOLLOWING PNA CANNING FAILURE

For the PNA the recovery process involved the following steps:

- The part was left in the can and initially the channels were cleaned via low pressure air from the outlet face
- The cleaned part was placed in an oven in order to remove accumulated soot and coke from the brick. It was baked at 425 °C for 30 minutes to remove HC, then at 625 °C to remove soot (it is possible that some stored sulfur was removed from the front as well during this process).
- The cleaned PNA was shipped to a canning supplier for removal and re-canning
- The re-canned part was flanged and new taps installed at SwRI

Subsequent tests indicated that the re-canned part appeared to retain the same capability to generate exotherms and oxidize NO to NO₂. NO_x sensor readings during warm-up indicated that NO_x storage behavior was present, but it was not possible to quantify this until the final tests were performed. There was no way to determine what amount of storage change if any was the result of previous aging or this failure.

For the SCRF the recovery process involved the following steps:

- Initial cleaning of debris from the face of the part
- Very light vacuum from inlet face with outlet blocked to prevent flow through the part (in order to leave deep ash intact)
- Bore scope and CT-scan analyses
- When re-canned PNA was again available, run first passive then active regeneration then perform clean weight to check ash loading trend
- Mechanically loosen the abnormal ash plug manually from front (one channel at a time)
 - It was verified with the supplier that this would not disturb the SCR washcoat
- Very light vacuum from inlet face with outlet blocked to prevent flow through the part (again in order to leave deep ash intact).
- Run a regeneration on engine and re-check clean weight to check ash loading trend

Throughout this process, the aftertreatment supplier was consulted regularly in order to ensure that the parts remained as representative as possible given the unusual nature of this failure. Nevertheless, this remained a significant incident, and the performance of both the PNA and the SCRF could have been compromised as a result, although there is no way to be certain of this.

At this point, aging resumed and was run to completion. Based on previous thermal exposure and remaining regeneration time aging was halted at 850 hours with 194 hours of actual regeneration time on the parts, mostly at 600 °C SCRF inlet temperature target. Given the small number of early hours at the lower 575 °C temperature, calculations indicated that this was equivalent to the target of 188 hours on the final aging cycle.

Given the aging did not run to the full 1000-hour duration, there was some concern about reaching the ash loading and oil exposure targets. Figure 237 shows a plot of both SCRF weight and oil consumption measurements over the course of durability.

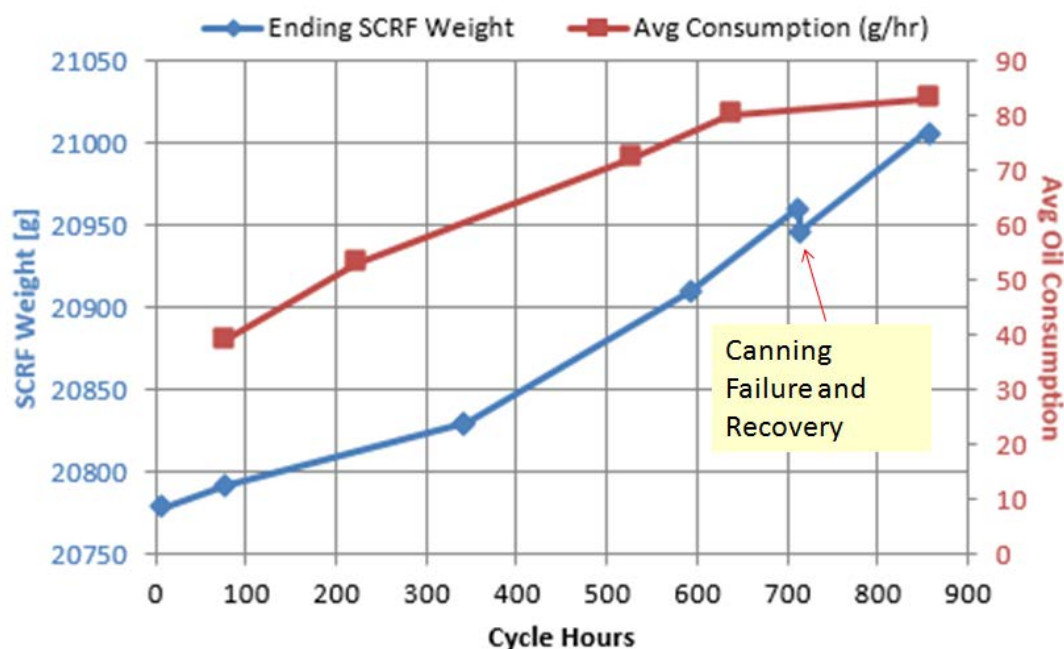


FIGURE 237. SCRF WEIGHT AND MEASURED OIL CONSUMPTION OVER THE COURSE OF FINAL AGING

It can be seen that oil consumption increased over time from the initial rate that was observed and used as the basis for exposure calculations. The oil consumption points represent oil drain and weigh events, while the points on the weight line indicate clean DPF weights to check ash loading. It should be noted that much of the increase in oil consumption was the result of the cycle modifications that were made to lengthen non-regenerating modes in order to reach the desired frequency. This resulted in larger portion of time at the higher speed, high oil consumption points. Some of the increase was also due to a change in the oil consumption rate of the modified engine, likely due to ring wear. As a result, the actual oil exposure rate over durability averaged an acceleration factor of 2.9 instead of the planned 2.5. It should be noted that largest rate observed was on the order of 4, still within an acceptable range for representative exposure (although at the higher end of the range). Based on these rates, the final oil exposure over 850 hours of durability was equivalent to 23% of full useful life, very close to the original target.

Based on the SCRF clean weights the part ended with about 220 grams of ash in it, which represents an ash finding ratio (amount of ash weight in filter over amount predicted from oil consumption) of about 50% based on oil exposure and measured ash levels. This is a reasonable finding ratio. The small step change at the 710-hour point represents the remove of about 10 grams of weight during the recovery process from the canning failure, which is a loss of less than 5%. The fact that the weight prior to that process was still on the previous trend-line indicates that there was a not a large quantity of matting material trapped in the part after the recovery. In addition, measured filter delta P has increased, but by an amount reasonable for this amount of ash loading.

Taken together these data indicated the from the standpoint of oil and ash exposure level, the Final Aged parts should be representative and reasonable close to the desired target, considering the difficulties encountered during the Final Aging process.

Although there were several unusual incidents during Final Aging, after much discussion it was determined that the program would continue into demonstration with these parts as they were. There was not sufficient time available within the program constraints to obtain and age a new set of parts, which would have delayed the result by another 4 to 6 months. Given what this set of parts has been exposed to, it is quite possible that some amount of abnormal degradation has occurred. However, given that there is no good way to separate normal and abnormal levels of degradation on these parts, the results were examined as they are. Nevertheless, it is important that these incidents be considered when assessing the final results of the program, and the implications of those results for the robustness of the final configuration.

3.4.5 Final Demonstration Testing – FTP, RMC, and CARB Idle

The Final Aged parts completed durability on November 4, 2016. A final regeneration was run in order to make sure that the parts were at minimum soot loading prior to starting the tests. It should be noted that given the time and budget constraints of the program, a regeneration controller was not developed on the Volvo MD13TC for this aftertreatment configuration. Therefore, when it was necessary to perform regeneration, the parts were regenerated offline on a different stand. Generally, this was accomplished using the HGTR to provide the exhaust gas conditions appropriate for regeneration.

The Final Aged parts were installed on the engine for preliminary testing on November 9, 2016. Because the full controller was not available over the course of the durability operation, there was no opportunity to build in a long-term adaptation function, even though this would typically be a part of an advanced controller. For a model-based controller it would typically be the case that some form of aging compensation would be built into the controller based in an empirical calibration developed by running aged catalysts. There was not sufficient time with the parts to allow for a complete recalibration of the SCR catalyst models for aged catalysts. In addition it was felt that calibration of the models to the exact catalysts from Final Aging would not be appropriate. Therefore, the SCR catalysts models were left with the calibrations used from previous work. If the scope and budget permitted the generation of an aging compensation algorithm which adapted the SCR kinetic constants and storage capacity, it is possible that aged catalyst performance could be improved somewhat.

It should be noted that the dosing controller used in this program did not incorporate a long-term adaptive algorithm (as is typical for many production SCR controllers), because the calibration of such an algorithm was beyond the scope and budget of the program. Therefore, a small global adjustment was made in the storage targets in order to manually simulate the action of such an algorithm. Otherwise, the controls were left unchanged.

Initial test results with the Final Aged parts on the FTP indicated emission levels of nominally 0.12 g/hp-hr on the cold-start FTP, and hot-start FTP levels of roughly 0.027 g/hp-hr. While the adaptation of the storage targets resulted in some improvement to the hot-start FTP

emissions, the cold-start was unaffected by these changes. It was noted that a further reduction on cold-start emissions might be achievable through a modification of the burner strategy (i.e., increased heat input), but this was not likely to be an adjustment that the controller would make for itself based on tailpipe NO_x sensor inputs. Therefore, the burner strategy was left alone for the final demonstration tests.

The final test matrix included the following tests:

- 5 replicates of an FTP-RMC sequence consisting of:
 - 2 preconditioning FTP hot-cycles
 - overnight cold-soak
 - 1 cold-start FTP test
 - 20-minute soak
 - 3 hot-start FTP tests (with a 20-minute soak between tests)
 - 1 RMC-SET test sequence (1 preconditioning RMC-SET followed immediately by 1 RMC-SET for record)
- 3 replicates of a WHTC sequence consisting of:
 - 2 preconditioning WHTC hot-cycles
 - overnight cold-soak
 - 1 cold-start WHTC test
 - 10-minute soak
 - 3 hot-start WHTC tests (with a 10-minute soak between tests)
- 3 replicates of the CARB Idle test
 - CARB idle tests were run using an FTP hot-start test as the preconditioning, followed immediately by the start of the low idle period
- 3 replicates of each of the Vocational Cycles
 - NYBCx4
 - Cruise-Creep
 - OCTA bus

The measurements included parallel measurement of tailpipe emissions using both Dilute Continuous and Raw Continuous measurement techniques. It should be noted that all of the baseline and development results given earlier were on the basis of Dilute Continuous measurements. It was planned to perform Dilute Bag measurements as well, but unfortunately, there was a malfunction with the Dilute Bag measurement system that was unable to be corrected in a timely fashion, and the program schedule did not allow the time to correct this measurement. Some Dilute Bag measurements were conducted, but a complete data set could not be generated. PM measurements were collected via the full-flow CVS double dilute sampling approach. All measurements were conducted in accordance with the procedures given in 40 CFR Part 1065.

Tailpipe measurements of N₂O and NH₃ were made via raw FTIR sampling. Additional NO_x, N₂O, and NH₃ measurements were also made periodically at different intermediate points in the system to facilitate interpretation of the data. It should be noted that on one of the

replicates the FTIR measurement was set to the SCR outlet location, rather than the tailpipe, therefore that replicate is not comparable to the other data sets. Furthermore, during post-processing an issue was found with the FTIR data from a second replicate for those data points. As a result, the data set for tailpipe N₂O and NH₃ consists of only three replicates instead of five.

A final note needs to be discussed with respect to CO₂ measurement under this program for the purposes of assessing the impact of the final configuration on GHG emissions. Due to program requirements and the length of time between the baseline and the final testing, it was not possible to test the engine in the same test cell using the same measurement equipment for both sets of tests. In the case of CO₂ measurements, this complicates the comparison between the baseline and final measurements, due to the fact that we are seeking to characterize relatively small changes in fuel consumption, on the order of 1-2%. In examining the results, it was noted that the final dilute test data set had a larger carbon balance error than the baseline by about 1%, with the final test data having a somewhat larger negative offset as compared to the measured fuel flow.

This would complicate the comparison between the two data sets. It was not possible within the budget and time constraints of the program to redo the baseline testing at the end of the program. Therefore in order to facilitate a proper comparison, the decision was made to normalize the CO₂ results to account for the average difference in carbon errors between the baseline data set and the final data set. This was done on a test cycle basis, using all of the replicates available for both data sets to determine a carbon balance offset. This offset was applied to the Final data set in order to normalize it to the same basis as the baseline. The result was a 0.8% increase in the Dilute CO₂ result, and a 2% decrease in the Raw CO₂ result, which is reflected in the data.

Without any post-processing the two measurements would have provided contradictory answers about the effect of the final configuration on CO₂ emissions. Furthermore, it is well understood that the modifications made to the system would result in some increase in fuel consumption over the baseline, therefore it was necessary to put the data in a common basis in order to allow for a meaningful assessment of that impact.

3.4.5.1 Final Results and Analysis for Criteria Pollutants on FTP and RMC-SET

The final results of the test matrix for the FTP and RMC-SET cycles are summarized below in a series of data tables, as described below. Table 74 contains a summary of the regulated pollutant data for the all the individual tests from the test matrix. It should be noted that in post-processing, an issue was found with the Raw tailpipe data from the first test day, which resulted in the need to void those results. The table summarizes both the dilute tailpipe and raw tailpipe data. PM data is only given under the dilute results, given that it was generated with the full-flow CVS tunnel.

Table 75 summarizes the individual test results for the engine-out measurements. Table 76 gives collects the individual test results into an overall summary for all five replicates. Tailpipe Dilute and Raw, and Engine-out average values, standard deviations, and coefficient of variation are summarized for each test type. In addition, the average values are used to compute aftertreatment conversion efficiency for each pollutant and test type. Table 77 shows a summary of the NO_x performance of the Final Aged parts for all five test sets, using the Dilute Tailpipe results as a basis for calculation. Table 78 shows a comparison of Tailpipe Dilute and Raw NO_x measurements based on the overall averages for all five replicates. Finally,

Table 79 provides a comparison of the FTP and RMC –SET mean NO_x values to earlier data sets, including the Development Aged parts and the De-greened performance of the system prior to Final Aging.

TABLE 74. SUMMARY OF INDIVIDUAL DILUTE AND RAW TAILPIPE TEST RESULTS FOR FINAL AGED PARTS – FTP AND RMC-SET CYCLES

Repeat	Pollutant	Units	Tailpipe Dilute							Tailpipe Raw						
			Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC
1	THC	g/hp-hr	0.045	0.022	0.020	0.019	0.020	0.025	0.000	n/a	n/a	n/a	n/a	n/a	n/a	0.002
	NMHC	g/hp-hr	0.041	0.022	0.020	0.018	0.020	0.024	0.000	n/a	n/a	n/a	n/a	n/a	n/a	0.000
	CO	g/hp-hr	0.740	0.163	0.138	0.127	0.143	0.245	0.009	n/a	n/a	n/a	n/a	n/a	n/a	0.004
	NOx	g/hp-hr	0.098	0.020	0.023	0.020	0.021	0.032	0.035	n/a	n/a	n/a	n/a	n/a	n/a	0.036
	PM	g/hp-hr	0.0014	0.0006	0.0005	0.0004	0.0005	0.0007	0.0002	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	606.3	551.5	548.5	548.5	549.5	559.3	461.9	n/a	n/a	n/a	n/a	n/a	n/a	458.5
2	THC	g/hp-hr	0.034	0.015	0.018	0.016	0.016	0.018	0.000	0.043	0.022	0.024	0.022	0.023	0.026	0.001
	NMHC	g/hp-hr	0.029	0.015	0.017	0.016	0.016	0.017	0.000	0.015	0.003	0.005	0.001	0.003	0.005	0.000
	CO	g/hp-hr	0.690	0.127	0.131	0.123	0.127	0.207	0.010	0.747	0.131	0.136	0.125	0.131	0.219	0.004
	NOx	g/hp-hr	0.105	0.020	0.022	0.019	0.020	0.032	0.037	0.105	0.021	0.023	0.020	0.021	0.033	0.037
	PM	g/hp-hr	0.0018	0.0001	0.0005	0.0006	0.0004	0.0003	0.0002	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	605.4	552.1	550.1	549.2	550.5	559.7	463.5	606.4	549.7	546.9	546.2	547.6	556.0	460.5
3	THC	g/hp-hr	0.046	0.016	0.012	0.013	0.014	0.020	0.001	0.049	0.018	0.021	0.021	0.020	0.024	0.002
	NMHC	g/hp-hr	0.040	0.016	0.012	0.011	0.013	0.019	0.000	0.015	0.000	0.000	0.008	0.003	0.005	0.000
	CO	g/hp-hr	0.723	0.109	0.118	0.097	0.108	0.197	0.010	0.797	0.113	0.121	0.096	0.110	0.208	0.004
	NOx	g/hp-hr	0.125	0.021	0.020	0.021	0.021	0.036	0.041	0.122	0.020	0.019	0.019	0.020	0.034	0.041
	PM	g/hp-hr	0.0015	0.0007	0.0007	0.0009	0.0008	0.0008	0.0002	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	608.8	554.6	552.1	551.8	552.8	562.3	465.3	610.8	552.5	550.8	549.2	550.8	559.4	465.0
4	THC	g/hp-hr	0.037	0.010	0.010	0.013	0.011	0.014	0.000	0.048	0.021	0.019	0.020	0.020	0.024	0.001
	NMHC	g/hp-hr	0.030	0.010	0.010	0.013	0.011	0.013	0.000	0.019	0.000	0.002	0.000	0.001	0.003	0.000
	CO	g/hp-hr	0.838	0.143	0.127	0.136	0.135	0.242	0.009	0.941	0.153	0.135	0.141	0.143	0.257	0.004
	NOx	g/hp-hr	0.120	0.023	0.022	0.024	0.023	0.037	0.040	0.117	0.022	0.022	0.022	0.022	0.036	0.040
	PM	g/hp-hr	0.0015	0.0010	0.0010	0.0008	0.0009	0.0011	0.0002	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	599.3	545.6	543.3	543.4	544.1	553.2	464.3	610.2	551.4	549.0	548.1	549.5	558.2	465.1
5	THC	g/hp-hr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.041	0.016	0.017	0.022	0.018	0.022	0.003
	NMHC	g/hp-hr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.002	0.000
	CO	g/hp-hr	0.748	0.122	0.128	0.135	0.128	0.211	0.006	0.832	0.131	0.138	0.143	0.137	0.237	0.004
	NOx	g/hp-hr	0.124	0.020	0.021	0.024	0.022	0.035	0.036	0.123	0.020	0.020	0.022	0.021	0.035	0.036
	PM	g/hp-hr	0.0016	0.0004	0.0007	0.0002	0.0004	0.0006	0.0002	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	602.2	548.5	546.0	546.1	546.9	556.1	463.1	615.9	555.9	553.4	553.1	554.2	563.0	467.2

TABLE 75. SUMMARY OF INDIVIDUAL ENGINE-OUT EMISSION LEVELS FOR FINAL AGED PARTS – FTP AND RMC-SET CYCLES

Repeat	Pollutant	Units	Engine-Out Raw						
			Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC
1	THC	g/hp-hr	0.22	0.14	0.15	0.15	0.15	0.16	0.06
	NMHC	g/hp-hr	0.22	0.14	0.15	0.14	0.14	0.15	0.06
	CO	g/hp-hr	2.40	1.46	1.40	1.39	1.42	1.59	0.63
	NOx	g/hp-hr	2.74	2.96	3.02	3.01	2.99	2.93	2.07
	CO2	g/hp-hr	600.4	538.9	536.1	535.9	537.0	547.7	456.0
2	THC	g/hp-hr	0.21	0.15	0.16	0.15	0.15	0.16	0.05
	NMHC	g/hp-hr	0.21	0.15	0.15	0.15	0.15	0.16	0.05
	CO	g/hp-hr	2.27	1.47	1.43	1.39	1.43	1.55	0.75
	NOx	g/hp-hr	2.72	2.99	3.00	3.00	3.00	2.96	1.98
	CO2	g/hp-hr	597.8	540.2	538.3	536.9	538.5	548.4	457.6
3	THC	g/hp-hr	0.21	0.14	0.15	0.15	0.15	0.16	0.05
	NMHC	g/hp-hr	0.21	0.14	0.14	0.15	0.14	0.15	0.05
	CO	g/hp-hr	2.35	1.53	1.48	1.45	1.49	1.61	0.86
	NOx	g/hp-hr	2.74	3.00	3.02	3.02	3.01	2.97	1.95
	CO2	g/hp-hr	603.3	544.6	541.8	540.3	542.2	553.0	461.7
4	THC	g/hp-hr	0.20	0.15	0.15	0.15	0.15	0.16	0.05
	NMHC	g/hp-hr	0.20	0.15	0.14	0.14	0.15	0.15	0.05
	CO	g/hp-hr	2.58	1.57	1.53	1.50	1.54	1.68	0.94
	NOx	g/hp-hr	2.74	3.01	3.03	3.02	3.02	2.98	1.92
	CO2	g/hp-hr	602.6	543.9	541.3	540.8	542.0	552.3	461.5
5	THC	g/hp-hr	0.19	0.14	0.14	0.17	0.15	0.16	0.08
	NMHC	g/hp-hr	0.18	0.14	0.14	0.17	0.15	0.15	0.08
	CO	g/hp-hr	2.45	1.55	1.54	1.53	1.54	1.67	0.90
	NOx	g/hp-hr	2.75	3.03	3.04	3.02	3.03	2.99	1.96
	CO2	g/hp-hr	606.7	547.9	545.5	545.2	546.2	556.3	464.4

TABLE 76. OVERALL SUMMARY OF REGULATED TAILPIPE EMISSIONS FOR BOTH RAW AND DILUTE MEASUREMENTS – FTP AND RMC-SET CYCLES

	Pollutant	Units	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC
Average	THC	g/hp-hr	0.032	0.013	0.012	0.012	0.012	0.016	0.000	0.045	0.019	0.020	0.021	0.020	0.024	0.002
	NMHC	g/hp-hr	0.028	0.012	0.012	0.012	0.012	0.015	0.000	0.016	0.001	0.002	0.002	0.002	0.004	0.000
	CO	g/hp-hr	0.748	0.133	0.128	0.124	0.128	0.221	0.009	0.829	0.132	0.133	0.126	0.130	0.230	0.004
	NOx	g/hp-hr	0.114	0.021	0.022	0.021	0.021	0.034	0.038	0.117	0.021	0.021	0.021	0.021	0.035	0.038
	PM	g/hp-hr	0.0016	0.0006	0.0007	0.0006	0.0006	0.0007	0.0002	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	604.4	550.4	548.0	547.8	548.8	558.2	463.6	610.8	552.4	550.0	549.1	550.5	559.1	463.3
Stdev	THC	g/hp-hr	0.019	0.008	0.008	0.007	0.008	0.010	0.001	0.004	0.002	0.003	0.001	0.002	0.002	0.001
	NMHC	g/hp-hr	0.017	0.008	0.008	0.007	0.008	0.009	0.000	0.002	0.001	0.002	0.004	0.001	0.001	0.000
	CO	g/hp-hr	0.055	0.021	0.007	0.016	0.013	0.022	0.001	0.082	0.016	0.008	0.022	0.015	0.022	0.000
	NOx	g/hp-hr	0.012	0.001	0.001	0.002	0.001	0.002	0.003	0.008	0.001	0.002	0.001	0.001	0.001	0.002
	PM	g/hp-hr	0.0002	0.0003	0.0002	0.0003	0.0002	0.0003	0.0000	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	3.7	3.5	3.5	3.2	3.4	3.5	1.3	3.9	2.6	2.8	2.9	2.8	2.9	3.6
COV	THC	% avg	58%	65%	66%	59%	62%	62%	224%	8%	13%	15%	6%	9%	7%	33%
	NMHC	% avg	59%	65%	66%	61%	63%	63%	#DIV/0!	12%	158%	135%	155%	88%	30%	#DIV/0!
	CO	% avg	7%	16%	6%	13%	10%	10%	16%	10%	12%	6%	17%	11%	9%	3%
	NOx	% avg	11%	7%	6%	11%	5%	6%	7%	7%	5%	8%	5%	5%	3%	6%
	PM	% avg	10%	60%	30%	49%	38%	39%	0%	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	% avg	1%	1%	1%	1%	1%	1%	0%	1%	0%	1%	1%	1%	1%	1%
Engine-Out																
	Pollutant	Units	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC							
Average	THC	g/hp-hr	0.21	0.15	0.15	0.15	0.15	0.16	0.06	Conversion Based on Dilute Tailpipe						
	NMHC	g/hp-hr	0.20	0.14	0.15	0.15	0.15	0.15	0.06	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC
	CO	g/hp-hr	2.41	1.52	1.48	1.45	1.48	1.62	0.82	THC	84%	91%	92%	92%	92%	90%
	NOx	g/hp-hr	2.74	2.99	3.02	3.01	3.01	2.96	1.97	NMHC	86%	91%	92%	92%	92%	90%
	CO2	g/hp-hr	602.2	543.1	540.6	539.8	541.2	551.5	460.2	CO	69%	91%	91%	91%	91%	86%
Stdev	THC	g/hp-hr	0.01	0.01	0.00	0.01	0.00	0.00	0.01	NOx	95.8%	99.3%	99.3%	99.3%	99.3%	98.8%
	NMHC	g/hp-hr	0.01	0.01	0.00	0.01	0.00	0.00	0.01							
	CO	g/hp-hr	0.11	0.05	0.06	0.06	0.06	0.06	0.13	Conversion Based on Raw Tailpipe						
	NOx	g/hp-hr	0.01	0.03	0.01	0.01	0.01	0.02	0.06	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	RMC
	CO2	g/hp-hr	3.3	3.6	3.6	3.7	3.6	3.5	3.4	THC	78%	87%	86%	86%	86%	85%
COV	THC	% avg	6.0%	3.9%	3.0%	6.1%	1.9%	1.8%	19.9%	NMHC	92%	99%	99%	98%	99%	98%
	NMHC	% avg	6.0%	3.9%	3.0%	6.1%	1.9%	1.8%	19.9%	CO	66%	91%	91%	91%	91%	86%
	CO	% avg	4.8%	3.3%	4.1%	4.2%	3.8%	3.4%	15.6%	NOx	95.7%	99.3%	99.3%	99.3%	99.3%	98.8%
	NOx	% avg	0.3%	0.8%	0.4%	0.3%	0.5%	0.8%	2.8%							
	CO2	% avg	0.6%	0.7%	0.7%	0.7%	0.7%	0.6%	0.7%							

TABLE 77. NO_x EMISSIONS SUMMARY FOR FTP AND RMC CYCLES, BASED ON DILUTE TAILPIPE MEASUREMENTS – FINAL CONFIGURATION, FINAL AGED PARTS

Repeat			Cold	Hot	Composite	RMC
1	engine-out	g/hp-hr	2.7	3.0	2.9	2.1
	tailpipe	g/hp-hr	0.098	0.021	0.032	0.035
		%conv	96.4%	99.3%	98.9%	98.3%
2	engine-out	g/hp-hr	2.7	3.0	3.0	2.0
	tailpipe	g/hp-hr	0.105	0.020	0.032	0.037
		%conv	96.2%	99.3%	98.9%	98.1%
3	engine-out	g/hp-hr	2.7	3.0	3.0	1.9
	tailpipe	g/hp-hr	0.125	0.021	0.036	0.041
		%conv	95.4%	99.3%	98.8%	97.9%
4	engine-out	g/hp-hr	2.7	3.0	3.0	1.9
	tailpipe	g/hp-hr	0.120	0.023	0.037	0.040
		%conv	95.6%	99.2%	98.8%	97.9%
5	engine-out	g/hp-hr	2.7	3.0	3.0	2.0
	tailpipe	g/hp-hr	0.124	0.022	0.035	0.036
		%conv	95.5%	99.3%	98.8%	98.2%
Overall TP Average			0.114	0.021	0.034	0.038
Overall TP Stdev			0.012	0.001	0.002	0.003

TABLE 78. COMPARISON OF TAILPIPE AND DILUTE NO_x MEASUREMENTS BASED ON OVERALL AVERAGES FROM FIVE REPLICATES

		Cold	Hot1	Hot2	Hot3	RMC	Composite	Hot-Avg
Engine-Out	g/hp-hr	2.74	2.99	3.02	3.01	1.97	2.96	3.01
Tailpipe Dilute	g/hp-hr	0.114	0.021	0.022	0.021	0.038	0.034	0.021
	%conv	95.8%	99.3%	99.3%	99.3%	98.1%	98.8%	99.3%
Tailpipe Raw	g/hp-hr	0.117	0.021	0.021	0.021	0.038	0.035	0.021
	%conv	95.7%	99.3%	99.3%	99.3%	98.1%	98.8%	99.3%

TABLE 79. COMPARISON OF NO_x FROM FINAL AGED PARTS TO EARLIER DATA SETS

		Cold	Hot	Composite	RMC
Engine-Out	g/hp-hr	2.7	3.0	3.0	2.1
Final Aged	g/hp-hr	0.114	0.021	0.034	0.038
	%conv	95.8%	99.3%	98.8%	98.2%
Development Targets	g/hp-hr	0.060	0.010	0.017	0.010
	%conv	97.8%	99.7%	99.4%	99.5%
Development Aged Parts	g/hp-hr	0.027	0.010	0.012	0.015
	%conv	99.0%	99.7%	99.6%	99.3%
Degreened Performance	g/hp-hr	0.027	0.005	0.008	0.010
	%conv	99.0%	99.8%	99.7%	99.5%
Final Aged Conversion Delta					
vs degreened	%conv	3.2%	0.5%	0.9%	1.3%
vs devel aged	%conv	3.2%	0.4%	0.7%	1.1%
vs target	%conv	2.0%	0.4%	0.6%	1.3%

It is apparent from the comparisons in

Table 79 that the aftertreatment system degraded somewhat as compared to its original performance. FTP composite NO_x was now at a level of 0.034 g/hp-hr, versus the de-greened performance at 0.008 g/hp-hr. In addition, the Final Aging appears to have affected the system more strongly than the Development Aging used for screening. Shifts were observed in both cold-start performance and hot-start / RMC-SET performance that contributed to the observed movement. These are discussed below individually.

Given some of the unusual events that happened over the course of the Final Aging process, it is unclear how much of this movement should be considered normal degradation, and how much should be considered abnormal as a result of the issues that occurred during Final Aging. Possibilities for abnormal effects are discussed below, but it should be noted that none of these can be stated conclusively without a more thorough post-mortem. It would likely require a repeat of the aging and testing exercise to conclusively separate the two impacts. Such analysis is outside the scope of this report, therefore we will concentrate on evaluating the performance as observed in comparison to previous data.

For the cold-start FTP data, three cases were discussed for comparison purposes. The first case was the Preliminary test results generated using the Development Aged Parts. The second case was the tests on the Final Controller using the Development Aged Parts. It was noted that the Development Aged system had been exposed to unusual levels of exhaust HC at low temperatures due to several events that happened during development. The third case was the Final Aged parts.

Continuous data showing the early cold-start behavior of the PNA for all three cases is shown in Figure 238 for the Preliminary data, Figure 239 for the Final Controller tests and Figure 240 for the Final Aged parts. Figure 241 shows a comparison of all three cases in terms of the amount of NO_x stored on the PNA as a function of time during the cold-start FTP. In this last figure, the approximate times for the light-off of the SCRF and the downstream SCR are also marked. It should be noted that these times did not shift substantially for any of these tests, including for the Final Aged parts.

It was apparent from comparing the Final Controller and Preliminary parts that some degradation of PNA capacity was observed from the unusual events that resulted in exposure to raw fuel and heavy HC at low temperatures. However, there was some margin to sustain a certain amount of loss, and the Final Controller tests still demonstrated a cold-start FTP level of 0.06 g/hp-hr, which would meet the development target. However, the Final Aged parts have experienced larger loss of NO_x storage, which is most evident in the first 100 seconds of the cycle where the PNA is relied on most. After this point, the SCRF can begin to compensate for a loss of PNA storage.

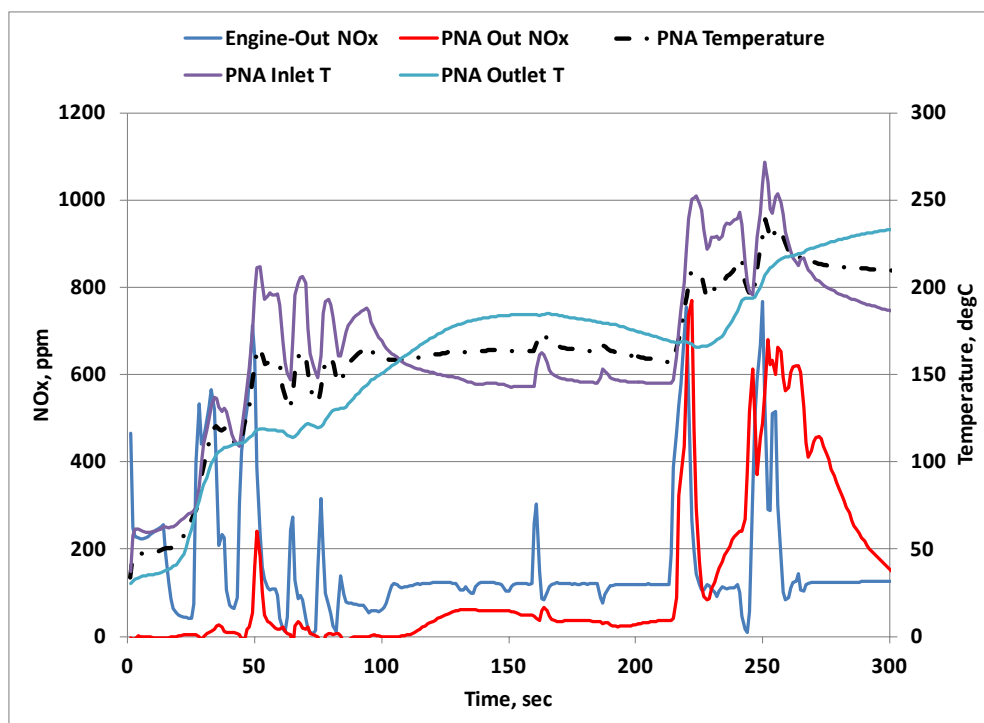


FIGURE 238. COLD-START PNA BEHAVIOR FOR PRELIMINARY RESULTS ON DEVELOPMENT AGED PARTS

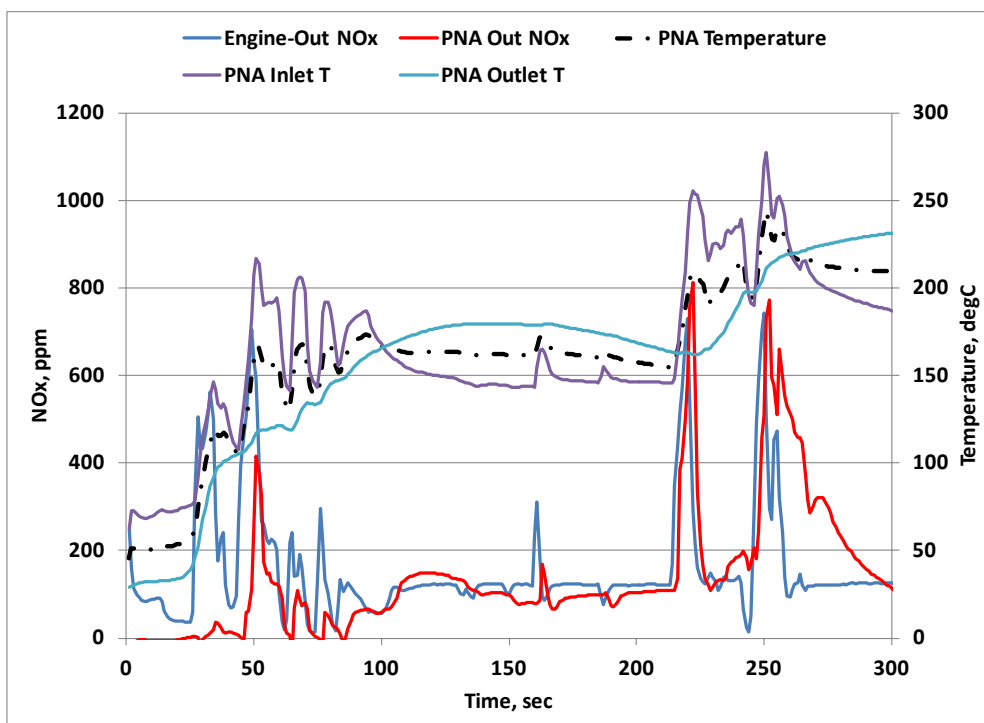


FIGURE 239. COLD-START PNA BEHAVIOR FOR FINAL CONTROLLER RESULTS ON DEVELOPMENT AGED PARTS

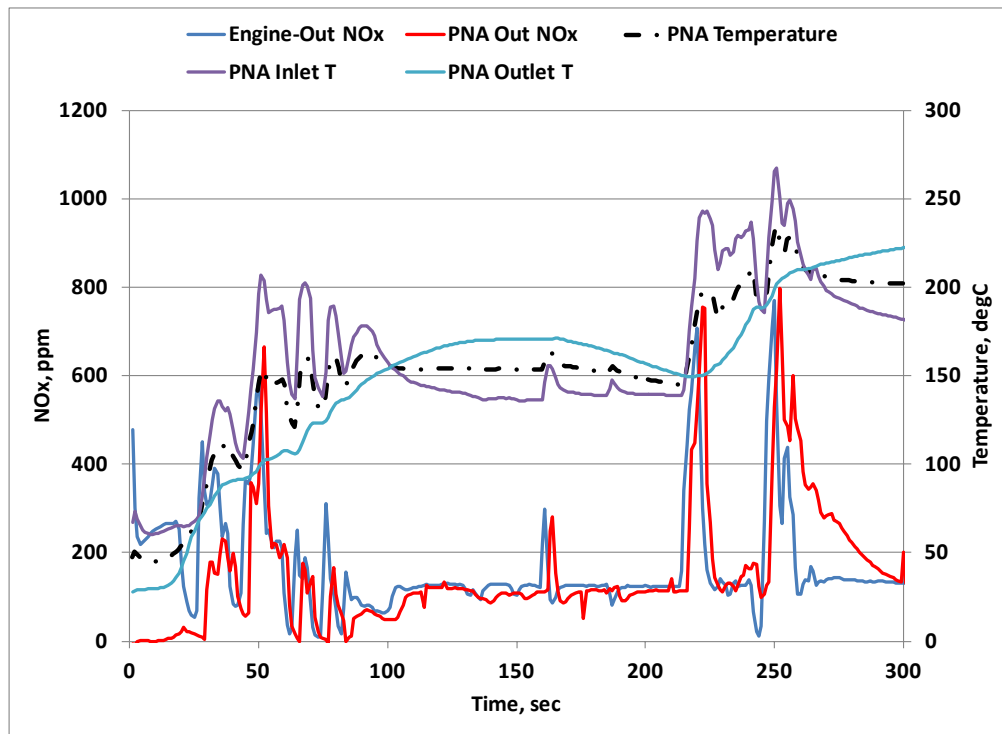


FIGURE 240. COLD-START PNA BEHAVIOR FOR FINAL AGED PARTS

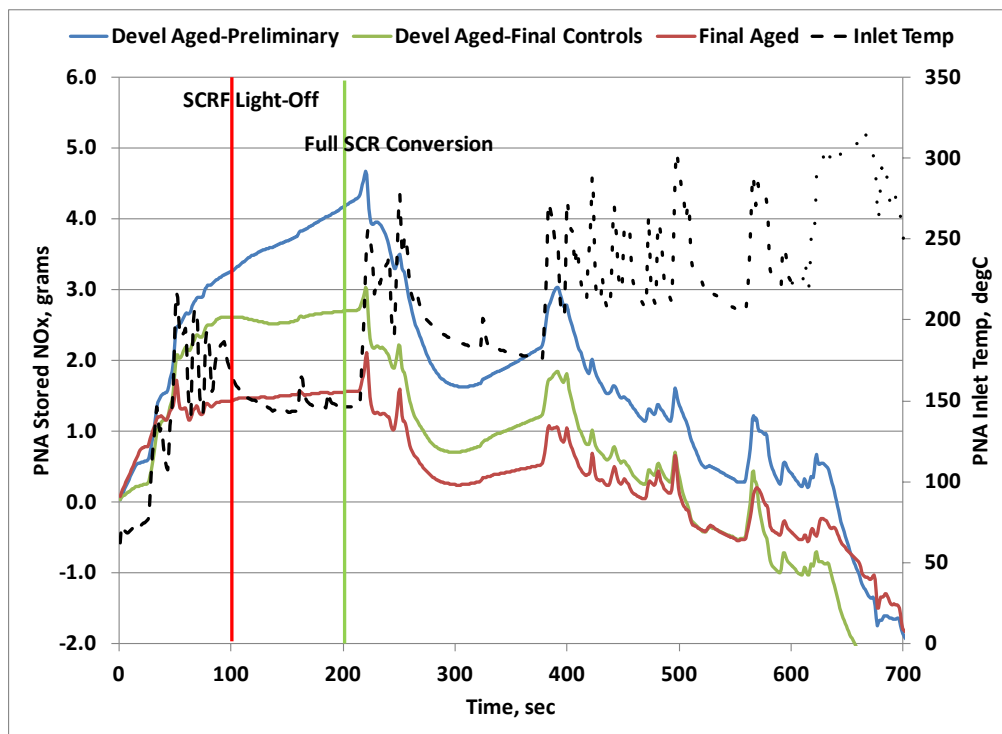


FIGURE 241. COMPARISON OF PNA-STORED NOx FOR ALL THREE CASES IN EARLY COLD-START FTP

This change results in an additional 1.8 grams of NO_x being emitted prior to the point at which the downstream system is warm enough to convert it. An additional 0.8 grams of NO_x are emitted during the time when the aftertreatment system is still in the process of reaching full conversion, resulting in about half of that being controlled by the downstream SCR system. This represents the majority of the increase in tailpipe NO_x that is observed between the Preliminary results and the Final Aged results. There is a small amount of NO_x increase, roughly 0.2 grams, which can be attributed to late cycle oxidation of ammonia due to an increase in SCR-out ammonia slip, but this is a small contribution to the overall change. Therefore, it is clear that the majority of the change in the cold-start FTP level can be attributed to the degradation of PNA storage capability at low temperatures.

It is possible that some of this change was due to the exposure of the PNA to heavy hydrocarbons during the initial coking issue. It is also possible that some of this change was due to a similar buildup that was observed following the canning failure of the PNA (this time a combination of heavy HC, soot, and matting materials). It is understood that this PNA is formulated to survive being used to generate an exotherm during regeneration, and the supplier has experience with this kind of application. Therefore, it seems unlikely that the regular dosing of HC during regeneration was the primary cause of the degradation, given that this always happened at inlet temperatures above 300°C in the presence of substantial oxygen. A review of the aging data with the supplier did not indicate exposure to temperatures high enough to cause substantial degradation.

It is also possible that some of this change is due to sulfation at the front face of the PNA where the temperatures during regeneration exotherm do not reach over 400 °C (much of the bed reaches temperatures in excess of 625 °C during regenerations, but the front inch does not). It should be noted however, that during the recovery from the canning failure, the PNA was exposed to temperatures of 625 °C in an effort to clean off all soot and materials prior to being shipped for re-canning. It is unclear whether this liberated some, all, or none of the sulfur that may have been stored at the front of the PNA. More thorough post-mortem would be needed to identify whether the PNA is currently poisoned by stored sulfur.

It should be noted that if the coking issue resulted in degradation, there is a countermeasure that can be applied in the form of a relatively small layer of precious metal catalyst upstream of the PNA itself. This would help to protect the system from HC exposure by oxidizing some of the heavier HC. Such a measure would also serve to generate more exotherm upstream of the PNA in order to ensure that the full brick is exposed to sufficient temperatures for desulfation. It is understood that the formulation of the PNA to reduce sensitivity to HC and rich exposure is an on-going area of development.

Turning to the change in hot-start FTP performance, Figure 242 shows the behavior of NO_x and temperature over the hot-start FTP for the Development Aged parts, while Figure 243 shows a similar plot for the Final Aged parts. Both plots also show the NH₃ signal downstream of the SCR. The Final Aged plot also shows SCR-out NO_x and NH₃, that data was unfortunately not available for the Development Aged parts with the final controls at the point the comparison run was made. Figure 244 shows a comparison of NO_x between the two sets of parts at the SCR outlet, while Figure 245 shows a similar comparison at the tailpipe.

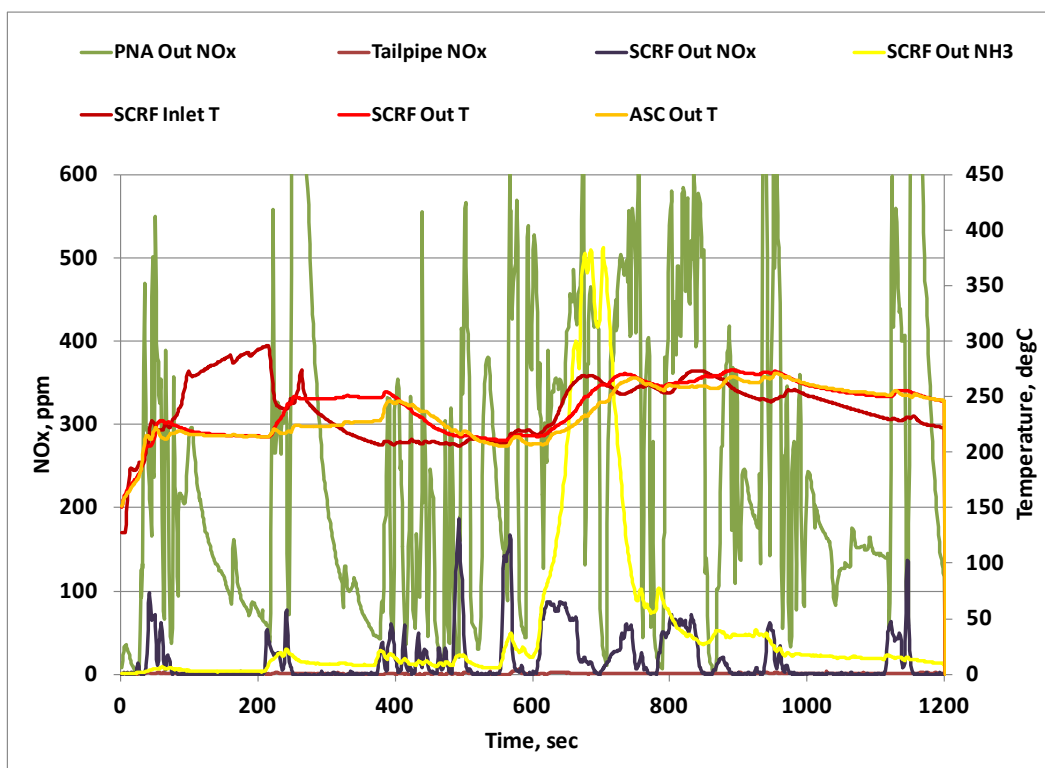


FIGURE 242. HOT-START FTP NO_x AND TEMPERATURE – DEVELOPMENT AGED PARTS

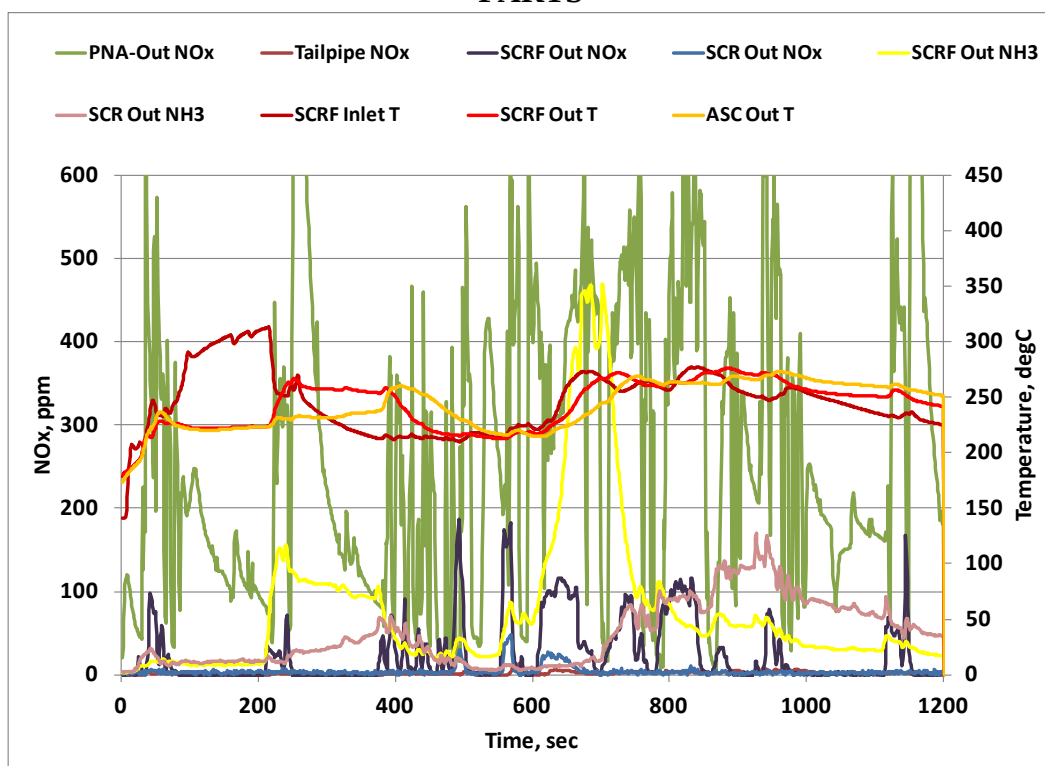


FIGURE 243. HOT-START FTP NO_x AND TEMPERATURE – FINAL AGED PARTS

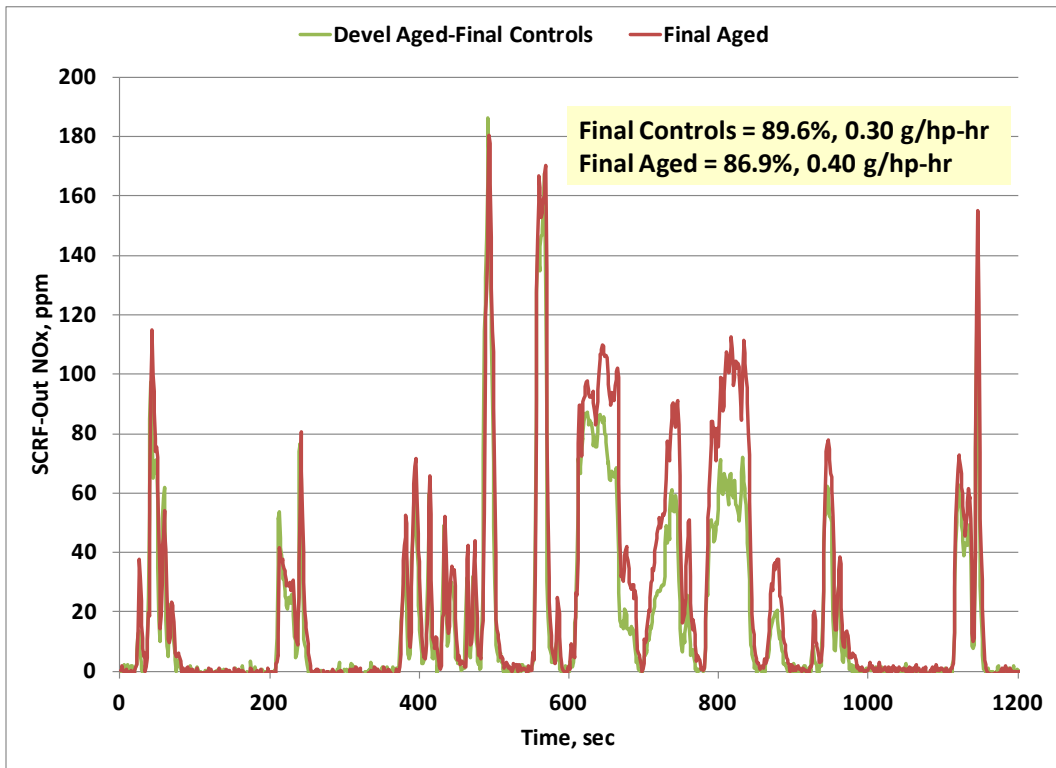


FIGURE 244. COMPARISON OF HOT-START FTP SCR-F-OUTLET NO_x – DEVELOPMENT AGED VERSUS FINAL AGED PARTS

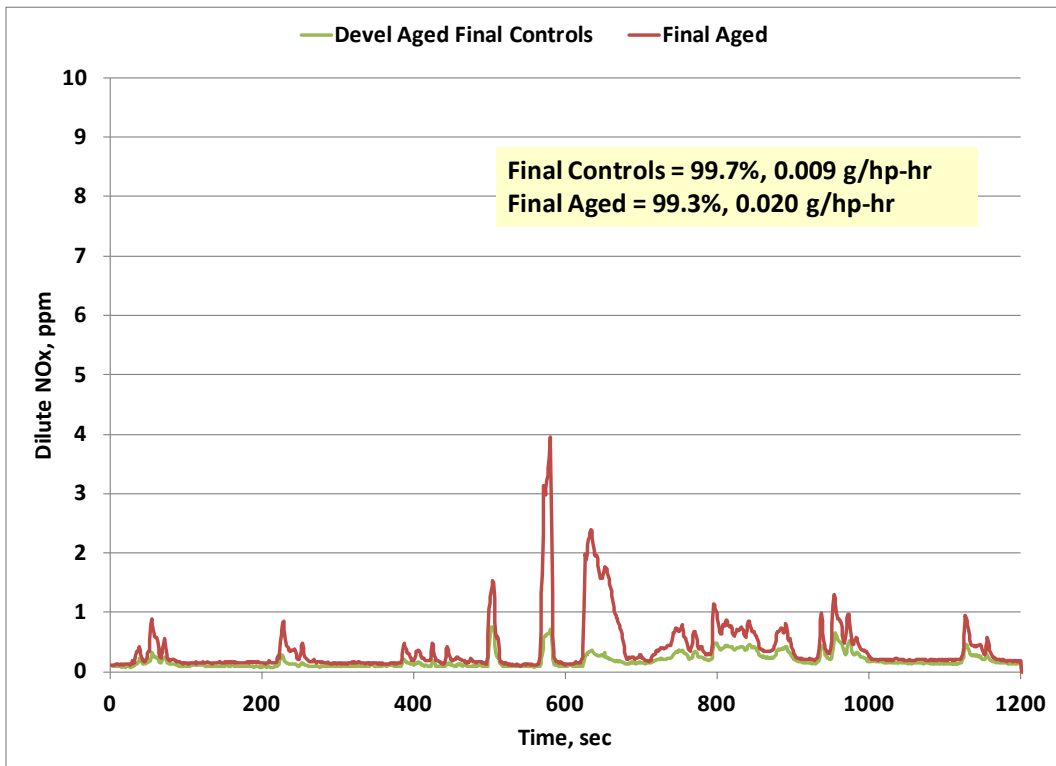


FIGURE 245. COMPARISON OF HOT-START FTP TAILPIPE NO_x – DEVELOPMENT AGED VERSUS FINAL AGED PARTS

From these data, several changes become apparent. There has been some loss in NH_3 storage capacity on both the SCRF and the SCR, as evidenced by the higher slip levels on both catalysts at relatively similar temperatures. It should be noted that some of this change is due to a small adjustment in storage targets made for the Final Aged parts, as discussed earlier. However, the SCRF catalyst is not quite as effective in its use of available NH_3 , as can be seen in Figure 244. This appears to manifest primarily at higher NO_x and space velocity regions of the cycle. However, based on comparison of Figure 244 and Figure 245, it appears there has also been a change in the downstream SCR which has reduced its capacity to deal with breakthrough events from the SCRF upstream, while these are somewhat larger. The increased storage target may have helped this somewhat, however this resulted in an increase in SCR-out NH_3 slip later in the cycle. A small amount of the increased NH_3 slip was oxidized back into NO, resulting in the increased tailpipe NO_x seen in Figure 245 in the late portions of the cycle. Further attempts to improve early cycle conversion by increasing dosing would likely result in increased late cycle NO, due to a further increase in SCR-out NH_3 slip.

It should be noted that all of these changes are small, but the net effect is to reduce the hot-start FTP NO_x conversion from 99.7% with the Development Aged parts to 99.3% with the Final Aged parts. While this seems to be a small change, it is sufficient to increase tailpipe NO_x levels from 0.01 g/hp-hr to 0.02 g/hp-hr.

Further evidence of these changes can be seen in the RMC-SET behavior of the system. Figure 246 shows NO_x , NH_3 , and temperature over the RMC-SET for the Development Aged parts, while Figure 247 and Figure 248 show similar plots for the Final Aged parts, but with a small difference in dosing strategy between the two runs. The run shown in Figure 248 featured and adjust calibration where the storage targets were increased in order to examine the deal with some of the remaining transient NO_x spikes, especially in the areas observed at 300 and 1200 seconds. It should be noted that at the higher temperatures on the RMC-SET it can be more difficult to balance NO_x reduction against the possibility of NO_x generation via ammonia oxidation.

On the Development aged parts, a workable balance is evidenced between NO_x reduction and ammonia slip. Although some SCR-out slip is observed, it is low enough that there is only small evidence of oxidation into NO at the tailpipe. For the Final Aged parts, this balance is more difficult to manage due to a combination of reduced storage capacity and an increase in the tendency of the catalysts to oxidize NH_3 . The comparison between behavior in Figure 247 and Figure 248 illustrates this point. Compared to the Development Aged parts, the Final Aged parts in Figure 247 showed increased SCRF-out and SCR-out NO_x , indicating less effective use of NH_3 . However, an attempt to increase NH_3 to compensate by increasing storage targets results in an increase in SCR-out NH_3 , part of which is oxidized back into NO. These two runs generated the same tailpipe NO_x level of 0.035 g/hp-hr, indicating that there is not much room to maneuver to try to lower final NO_x levels. Increased oxidation behavior is also evidence by higher N_2O levels at the SCRF outlet with the Final Aged parts. A plot of this is given in Figure 249. This increased oxidation behavior at higher temperatures results in less effective use of NH_3 , and it also leaves less NH_3 available for storage to absorb transient spikes.

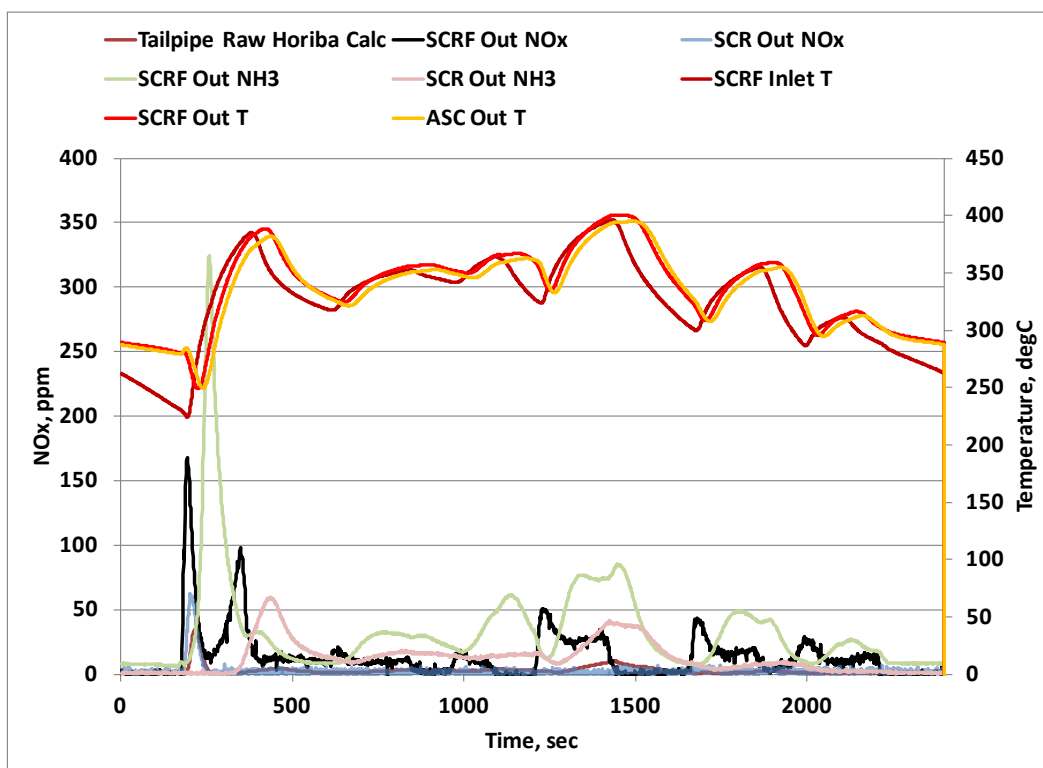


FIGURE 246. RMC-SET NO_x, NH₃, AND TEMPERATURE – DEVELOPMENT AGED PARTS

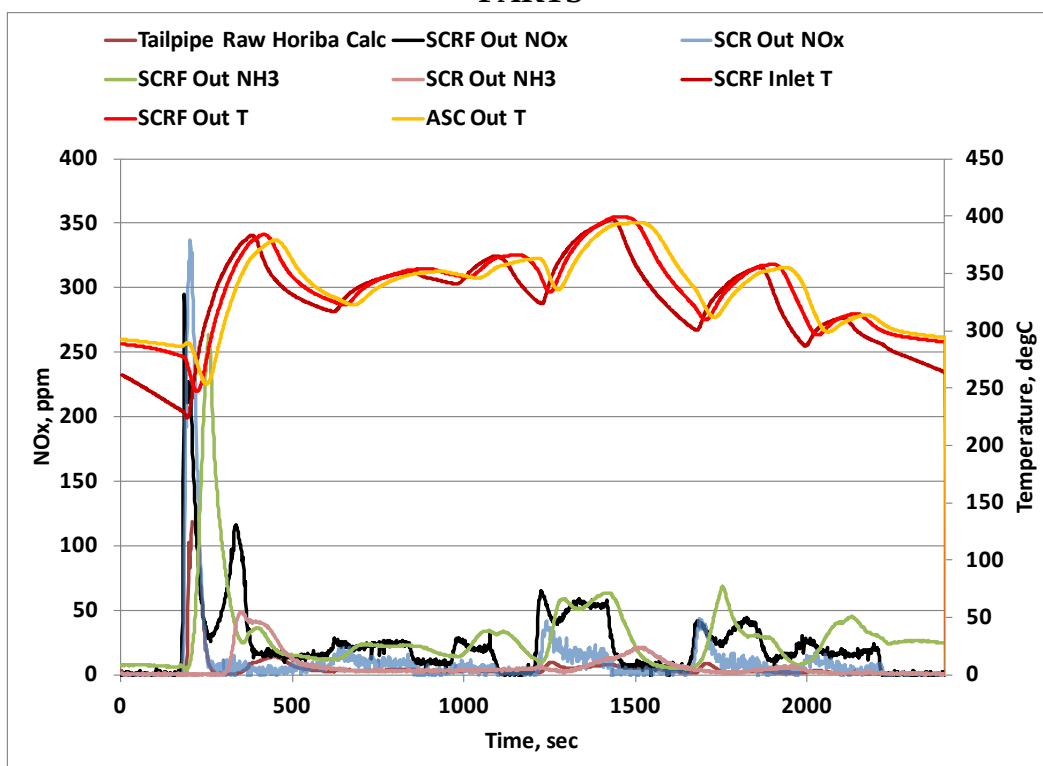


FIGURE 247. RMC-SET NO_x, NH₃, AND TEMPERATURE – FINAL AGED PARTS

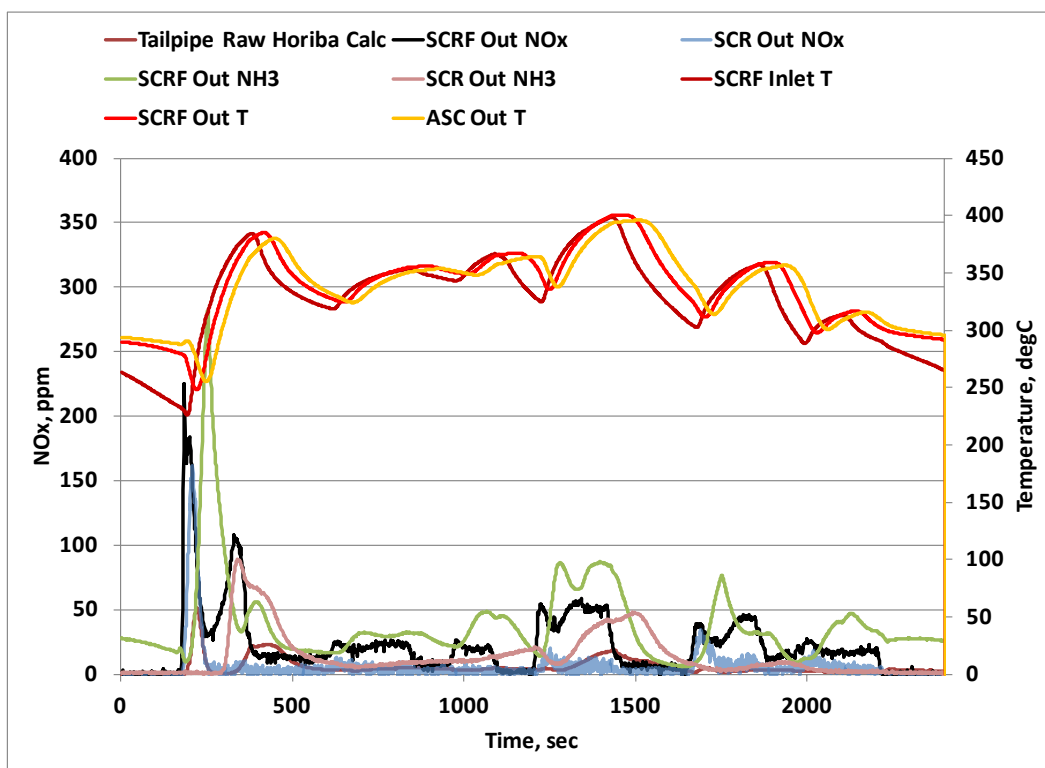


FIGURE 248. RMC-SET NO_x, NH₃, AND TEMPERATURE – FINAL AGED PARTS, INCREASED STORAGE TARGETS

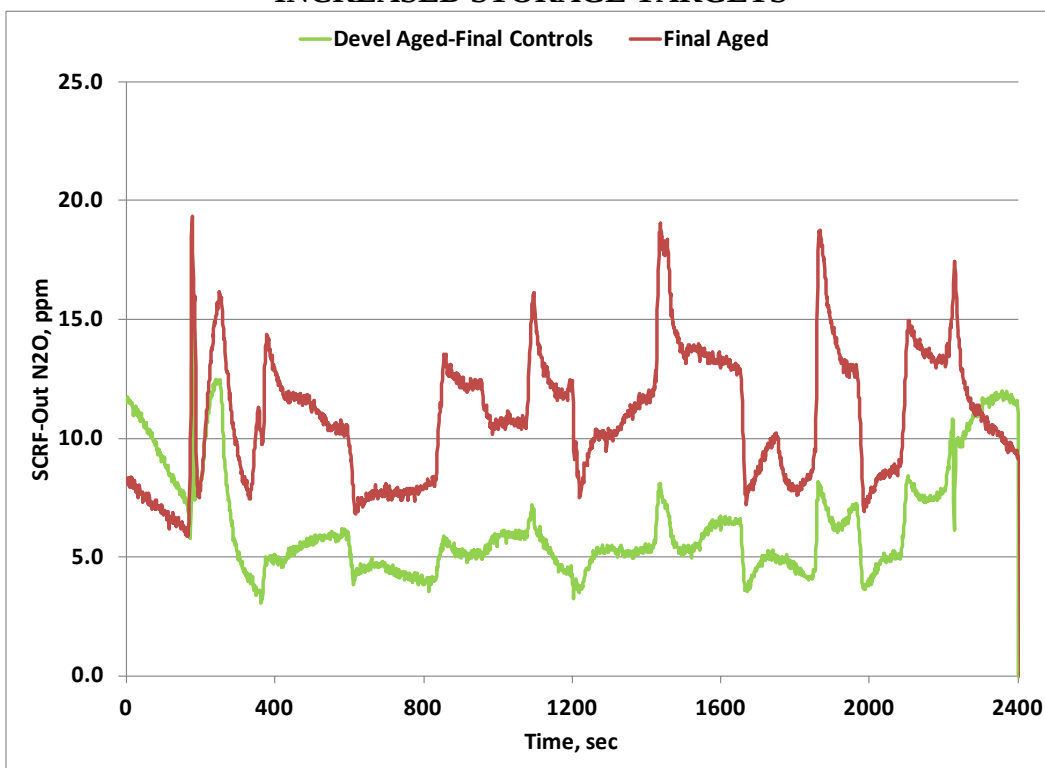


FIGURE 249. RMC-SET SCRf-OUT N₂O – FINAL AGED PARTS VERSUS DEVELOPMENT AGED PARTS

Further evidence for this change in NH_3 oxidation was evident from a brief series of experiments conducted at regeneration temperatures of 600°C in the durability cell. Earlier high temperature work with the SCRF indicated that 90% conversion of NO_x could be obtained, albeit at an increased ANR demand of 2.3. Experiments with the Final Aged parts at the end of durability indicated that an ANR of 3.4 was required to achieve the same 90% conversion of NO_x . This is further evidence of an increased tendency towards NH_3 oxidation with the Final Aged parts.

The combination of a reduction in storage capacity and increased tendency for NH_3 oxidation has shifted the balance of the SCR system just enough to make it slightly more difficult to find the balance point between NO_x reduction, with the result being an increase in both hot-start FTP and RMC-SET tailpipe NO_x levels. The shift is more pronounced on the higher temperature RMC-SET. It should be noted that with significantly more calibration time, it is likely that the controls could be adjusted to achieve a better balance, resulting in somewhat lower tailpipe NO_x levels. However, it is unlikely that those levels could be reduced back below 0.01 g/hp-hr , and in any case, this kind adjustment would likely be beyond the capability of a controller to accomplish without manual intervention.

There are several possible reasons for the change in behavior observed on the SCRF and, to a lesser extent, the downstream SCR catalyst. Some shift in storage capacity is expected as a normal part of degradation, but as long as that shift is not too large, the NH_3 sensor feedback can react to that shift in order to help maintain performance. However, this is only the case if other catalyst behaviors remain intact. Discussions with the supplier have indicated that the shift in storage was expected, but the change in NH_3 oxidation behavior was not expected at this level.

It is possible that this change in behavior is related to the ash stored on the SCRF, however, this cannot be ascertained without removing the ash. If this is the case, periodic ash cleaning could mitigate the problem. At the present stage of development, it is not clear how often SCRF requires ash cleaning, and the effect of ash on the SCRF is still being investigated.

It is also possible that the change in oxidation behavior is the result of migration of precious metal from the upstream PNA into the SCRF. The degradation of the PNA has already been established (as well as the canning failure), and if this resulted in the mobilization of precious metal onto the downstream SCRF, it would take very little precious metal to effect a significant change in oxidation behavior. There are examples in the literature of this kind of behavior from the early development of light-duty systems that featured frequent regeneration and a DOC upstream of an SCR catalyst without a filter between them. Further development of the DOC formulations to prevent precious metal loss has helped to mitigate this problem.

One possible abnormal mechanism for degradation on the SCRF could have been caused by the mal-distribution of soot and flow that would have resulted from the temporary plugging of channels with the matting material from the PNA canning failure. There was a high degree of soot loading during this incident, and although the limited bed temperature measurements did not indicate a major exotherm, it is quite possible that the mal-distribution of soot and flow could have caused local exotherms that could impact the SCRF. Such a failure is not expected under normal circumstances.

It would take a significant amount of post-mortem analysis to verify many of these potential impacts on the SCRF, and it would be difficult to separate normal and abnormal degradation mechanisms as noted earlier. Unfortunately, many of these analyses are destructive in nature, and the parts would be unavailable for further planned efforts.

3.4.5.2 Greenhouse Gas Impact on FTP and RMC-SET Cycles

In addition to an assessment of the engine-regulated pollutants, another significant characterization is the impact of the final system configuration on GHG emissions. A preliminary assessment of the impact of the final configuration was given earlier in Table 68. However, it was important to repeat this assessment based on the Final Aged parts, in order to account for any shift in the system. A summary of the final calculated impact of the system based on Final Aged data is given below in Table 80. The calculations in this table have been updated to account for the final controller durations of all systems, as well as for the revised regeneration frequency based on the actual Final Aging cycle.

TABLE 80. IMPACT OF LOW NO_x CONFIGURATION ON CO₂ EMISSIONS BASED ON FINAL AGED DATA

	BSCO2, g/hp-hr			
	Cold	Hot	Composite	RMC
Baseline Engine	574.2	542.6	547.4	457.7
Final ULN Config	604.4	548.8	558.2	463.6
% change	5.3%	1.1%	2.0%	1.3%
Mini-burner air	0.4%	0.2%	0.2%	
Increased SCRF Regeneration			0.3%	0.3%
Total FTP CO2 Impact			2.5%	1.6%

It should be noted that the final values in this table show a net increase from the preliminary value of 0.4% on average. This is primarily due to small increases in the measured CO₂ values for both FTP and RMC cycles. It is surmised that much of this is probably due to increased backpressure.

System backpressure with a clean filter in the final configuration was about 8 kpa higher than the baseline aftertreatment system. For the Final Aged part, which was ash loaded after Final Aging, this increased to a 12 kpa delta. In some cases, the soot-loaded parts as tested had as much as an 18 kpa delta above the baseline.

The reason that some of the tests were run at higher backpressure is in fact that a regeneration was not run prior to every test replicate for the final test matrix, due to the fact that the system must be regenerated offline. As a result, some of the tests were conducted at

increased backpressure levels due to soot loading. This would not normally be the case for GHG Phase 2 testing, however it is likely to have affected the results given above. However, it is likely that this is a small impact on the order of 0.1% to 0.25% depending on the duty cycle (with the RMC-SET likely affected more).

N₂O emissions were also monitored as part the Final Aged testing. As noted earlier, there was some increase in N₂O at the tailpipe following the final aging. The Final Aged parts generally showed an increase of 0.02 g/hp-hr in N₂O, as compared to the Development Aged parts. As noted earlier there was an increase on the tendency of the catalysts towards NH₃ oxidation, though some of that shift may have been to sources that can be mitigated (such as precious metal migration). The Final Aged parts are essentially at the edge of the 0.10 g/hp-hr cap standard for N₂O. It should be noted that under a normal compliance case, it is not required to determine N₂O emissions as part of deterioration factor testing, and an assumed DF factor of 0.01 g/hp-hr may be used.

TABLE 81. TAILPIPE N₂O DATA FOR FTP AND RMC-SET CYCLES

		Tailpipe N ₂ O, g/hp-hr						
		Cold	Hot1	Hot2	Hot3	RMC	Composite	Hot-Avg
Devel Aged		0.075	n/a			0.033	0.085	0.087
Final Aged	Set 1	0.103	0.105	0.111	0.101	0.056	0.105	0.106
	Set 2	0.103	0.104	0.110	0.110	0.049	0.107	0.108
	Set 3	0.096	0.102	0.113	0.117	0.060	0.109	0.111
	Average	0.101	0.104	0.111	0.109	0.055	0.107	0.108

3.4.5.3 Impact of SCRF Regeneration on NO_x and IRAF Calculations

Another factor that needs to be considered in assessing the results of the final configuration is the impact of SCRF regeneration on NO_x emissions. This is done via Infrequent Regeneration Adjustment Factor (IRAF) calculations. For the purposes of this program it was not possible to conduct emission measurements over cycles during regenerations, because the development of a transient regeneration controller for this system was well beyond the scope and budget of the program.

Instead, several experiments were conducted to examine high temperature SCR conversion with the final system, and these were used, along with the calculated regeneration frequency to predict and Upward Adjustment Factor (UAF) for this system. These calculations are summarized below in Table 82. The calculations consider the predicted regeneration frequency for both FTP and RMC cycles, as well as the measured conversion efficiency from the system catalysts at regeneration temperatures. It should be noted that a substantial increase in DEF injection is needed to maintain adequate conversion at these temperatures. These data are used to predict tailpipe NO_x levels during regeneration, which are then combined with the final regeneration frequencies to calculate an upward adjustment factor. Based on these calculations, a UAF of 0.004 g/hp-hr is estimated for both cycles. This value would be added to the cycle emission values summarize earlier to assess final compliance with a standard. For example, the average Final Aged FTP composite emission level was 0.034 g/hp-hr, but with the UAF of 0.004 added, that value would be come 0.038 g/hp-hr.

TABLE 82. SUMMARY OF CALCULATIONS TO DETERMINE UAF FOR THE FINAL LOW NO_x SYSTEM

		FTP	RMC
Regeneration Frequency			
Period Between Regenerations		41 hours	36 hours
Frequency at 575°C	5 min	0.20%	0.23%
Frequency at 600°C	35 min	1.40%	1.60%
Total	40 min	1.60%	1.83%
NO_x Conversion During Regen (from experiments)			
575°C	ANR = 2.0	94%	94%
600°C	ANR = 2.4	89%	89%
Tailpipe NO_x During Regen			
575°C	g/hp-hr	0.150	0.126
600°C	g/hp-hr	0.273	0.231
Weighted Total	g/hp-hr	0.258	0.218
Upward Adjustment Factor	g/hp-hr	0.004	0.004

It should be noted that there are several measures that could be taken to mitigate this upward adjustment. One would be to lower engine out NO_x during regeneration events, thus reducing the emissions during regeneration. Another approach would be to implement multi-point dosing, where in some of the DEF could be introduced downstream of the SCRF, which would help to enable some passive soot oxidation on a periodic basis. Finally, the formulation of the SCRF can be adjusted to enable more passive regeneration at high temperatures on the SCRF, which would shift a slightly larger amount of the burden of high temperature conversion to the downstream SCR.

3.4.5.4 WHTC Cycle Results

Three replicates of a WHTC test sequence consisting of one cold-start WHTC test and three successive hot-start WHTC tests were run on the Final Aged parts. It should be noted that the WHTC includes only a 10-minute soak between successive tests, rather than the 20-minute soak used for the FTP. This shorter soak period had significant implications for measurement at very low NO_x levels. The shorter period is insufficient to allow for a recalibration of the gaseous benches between cycles, which in turn prevents a change to a lower measurement range between cold-start and hot-start cycles. As shown later, this had an impact on the measurements, and created issues that were not observed on the FTP cycle. These issues will be discussed in more detail below.

WHTC results are summarized in a series of data tables below. Individual tailpipe cold and hot start test results are summarized in Table 83, while individual engine-out results are given in

Table 84.

Table 85 collects the data from all 3 replicates to show both tailpipe and engine-out results overall, as well as aftertreatment conversion efficiency. Table 86 shows a summary for just NO_x emissions, while Table 87 shows a comparison based on overall averages of Raw and Dilute results. Finally, Table 88 compares the final aged NO_x results to earlier results with the Development Aged parts.

TABLE 83. SUMMARY OF INDIVIDUAL DILUTE AND RAW TAILPIPE TEST RESULTS FOR FINAL AGED PARTS – WHTC CYCLES

Repeat	Pollutant	Units	Tailpipe Dilute						Tailpipe Raw					
			Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite
1	THC	g/hp-hr	0.018	0.000	0.000	0.000	0.000	0.003	0.031	0.005	0.005	0.004	0.005	0.008
	NMHC	g/hp-hr	0.018	0.000	0.000	0.000	0.000	0.003	0.030	0.005	0.004	0.004	0.004	0.008
	CO	g/hp-hr	0.337	0.025	0.024	0.025	0.025	0.068	0.332	0.007	0.007	0.006	0.007	0.052
	NOx	g/hp-hr	0.149	0.022	0.022	0.021	0.022	0.040	-	0.019	0.019	0.019	0.019	0.037
	PM	g/hp-hr	0.0037	0.0011	0.0008	0.0007	0.0009	0.0013	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	514.3	491.9	490.4	491.0	491.1	494.3	516.6	492.4	490.4	490.7	491.2	494.7
2	THC	g/hp-hr	0.009	0.000	0.000	0.000	0.000	0.001	0.016	0.003	0.004	0.004	0.004	0.005
	NMHC	g/hp-hr	0.009	0.000	0.000	0.000	0.000	0.001	0.015	0.003	0.004	0.004	0.004	0.005
	CO	g/hp-hr	0.306	0.023	0.021	0.021	0.022	0.061	0.300	0.006	0.006	0.006	0.006	0.047
	NOx	g/hp-hr	0.151	0.021	0.020	0.020	0.021	0.039	-	0.017	0.017	0.017	0.017	0.036
	PM	g/hp-hr	0.0038	0.0012	0.0011	0.0009	0.0011	0.0014	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	516.4	492.7	491.0	491.0	491.6	495.1	518.8	494.4	492.5	492.5	493.2	496.7
3	THC	g/hp-hr	0.001	0.000	0.000	0.000	0.000	0.000	0.016	0.002	0.002	0.002	0.002	0.004
	NMHC	g/hp-hr	0.001	0.000	0.000	0.000	0.000	0.000	0.016	0.002	0.002	0.002	0.002	0.004
	CO	g/hp-hr	0.294	0.064	0.069	0.062	0.065	0.097	0.281	0.006	0.006	0.006	0.006	0.044
	NOx	g/hp-hr	0.146	0.024	0.021	0.021	0.022	0.039	-	0.017	0.017	0.017	0.017	0.035
	PM	g/hp-hr	0.0041	0.0007	0.0006	0.0009	0.0007	0.0012	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	513.6	491.3	490.8	489.9	490.7	493.9	517.3	495.7	493.7	492.2	493.9	497.2

Note: Raw Cold-WHTC results not valid due to over-range, composites calculated with Dilute Cold-WHTC result

TABLE 84. SUMMARY OF INDIVIDUAL RAW ENGINE-OUT TEST RESULTS FOR FINAL AGED PARTS – WHTC CYCLES

Repeat	Pollutant	Units	Engine-Out Raw					
			Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite
1	THC	g/hp-hr	0.22	0.14	0.15	0.15	0.15	0.16
	NMHC	g/hp-hr	0.22	0.14	0.15	0.14	0.14	0.15
	CO	g/hp-hr	2.40	1.46	1.40	1.39	1.42	1.59
	NOx	g/hp-hr	2.74	2.96	3.02	3.01	2.99	2.93
	CO2	g/hp-hr	600.4	538.9	536.1	535.9	537.0	547.7
2	THC	g/hp-hr	0.21	0.15	0.16	0.15	0.15	0.16
	NMHC	g/hp-hr	0.21	0.15	0.15	0.15	0.15	0.16
	CO	g/hp-hr	2.27	1.47	1.43	1.39	1.43	1.55
	NOx	g/hp-hr	2.72	2.99	3.00	3.00	3.00	2.96
	CO2	g/hp-hr	597.8	540.2	538.3	536.9	538.5	548.4
3	THC	g/hp-hr	0.21	0.14	0.15	0.15	0.15	0.16
	NMHC	g/hp-hr	0.21	0.14	0.14	0.15	0.14	0.15
	CO	g/hp-hr	2.35	1.53	1.48	1.45	1.49	1.61
	NOx	g/hp-hr	2.74	3.00	3.02	3.02	3.01	2.97
	CO2	g/hp-hr	603.3	544.6	541.8	540.3	542.2	553.0

TABLE 85. OVERALL SUMMARY OF REGULATED TAILPIPE EMISSIONS FOR BOTH RAW AND DILUTE – WTHC CYCLES

	Pollutant	Units	Tailpipe Dilute						Tailpipe Raw					
			Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite
Average	THC	g/hp-hr	0.010	0.000	0.000	0.000	0.000	0.001	0.021	0.003	0.003	0.003	0.003	0.006
	NMHC	g/hp-hr	0.009	0.000	0.000	0.000	0.000	0.001	0.020	0.003	0.003	0.003	0.003	0.006
	CO	g/hp-hr	0.312	0.037	0.038	0.036	0.037	0.076	0.304	0.007	0.006	0.006	0.006	0.048
	NOx	g/hp-hr	0.149	0.022	0.021	0.021	0.021	0.039	-	0.018	0.018	0.018	0.018	0.036
	PM	g/hp-hr	0.0039	0.0010	0.0008	0.0008	0.0009	0.0013	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	514.8	492.0	490.8	490.6	491.1	494.4	517.6	494.2	492.2	491.8	492.7	496.2
Stdev	THC	g/hp-hr	0.009	0.000	0.000	0.000	0.000	0.001	0.008	0.001	0.001	0.001	0.001	0.002
	NMHC	g/hp-hr	0.008	0.000	0.000	0.000	0.000	0.001	0.008	0.001	0.001	0.001	0.001	0.002
	CO	g/hp-hr	0.022	0.023	0.027	0.023	0.024	0.019	0.026	0.001	0.001	0.000	0.001	0.004
	NOx	g/hp-hr	0.002	0.001	0.001	0.001	0.001	0.000	-	0.001	0.001	0.001	0.001	0.001
	PM	g/hp-hr	0.0002	0.0003	0.0003	0.0001	0.0002	0.0001	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	g/hp-hr	1.5	0.7	0.3	0.6	0.5	0.6	1.1	1.7	1.7	1.0	1.4	1.3
COV	THC	% avg	90%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	90%	41%	35%	38%	36%	35%	36%
	NMHC	% avg	90%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	90%	41%	35%	38%	36%	35%	36%
	CO	% avg	7%	63%	71%	63%	65%	25%	8%	10%	10%	6%	8%	8%
	NOx	% avg	2%	5%	5%	3%	4%	1%	-	5%	5%	6%	5%	3%
	PM	% avg	5%	26%	30%	14%	19%	10%	n/a	n/a	n/a	n/a	n/a	n/a
	CO2	% avg	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Pollutant	Units	Engine-Out											
			Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	Composite						
Average	THC	g/hp-hr	0.11	0.08	0.08	0.08	0.08	0.08	Conversion Based on Dilute Tailpipe					
	NMHC	g/hp-hr	0.11	0.07	0.08	0.08	0.08	0.08	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	
	CO	g/hp-hr	2.30	1.74	1.68	1.68	1.70	1.78	THC	91%	100%	100%	100%	100%
	NOx	g/hp-hr	3.04	3.40	3.43	3.43	3.42	3.37	NMHC	91%	100%	100%	100%	100%
									CO	86%	98%	98%	98%	98%
Stdev	THC	g/hp-hr	0.02	0.00	0.00	0.00	0.00	0.00	NOx	95.1%	99.3%	99.4%	99.4%	99.4%
	NMHC	g/hp-hr	0.02	0.00	0.00	0.00	0.00	0.00	Conversion Based on Raw Tailpipe					
	CO	g/hp-hr	0.04	0.08	0.08	0.07	0.07	0.06	Cold	Hot 1	Hot 2	Hot 3	Hot-Avg	
	NOx	g/hp-hr	0.01	0.03	0.05	0.04	0.04	0.04	THC	81%	95%	96%	96%	96%
									NMHC	81%	95%	96%	96%	96%
COV	THC	% avg	21.7%	0.9%	0.8%	1.0%	0.8%	4.8%	CO	87%	100%	100%	100%	100%
	NMHC	% avg	21.7%	0.9%	0.8%	1.0%	0.8%	4.8%	NOx	-	99.5%	99.5%	99.5%	99.5%
	CO	% avg	1.7%	4.6%	4.5%	4.0%	4.4%	3.3%						
	NOx	% avg	0.5%	0.8%	1.6%	1.2%	1.2%	1.0%						

TABLE 86. NO_x EMISSIONS SUMMARY FOR WHTC CYCLES

Repeat			Cold	Hot	Composite
1	engine-out	g/hp-hr	3.1	3.5	3.4
	tailpipe	g/hp-hr	0.149	0.019	0.037
		%conv	95.1%	99.5%	98.9%
2	engine-out	g/hp-hr	3.0	3.0	3.0
	tailpipe	g/hp-hr	0.151	0.017	0.036
		%conv	95.0%	99.4%	98.8%
3	engine-out	g/hp-hr	3.0	3.0	3.0
	tailpipe	g/hp-hr	0.146	0.017	0.035
		%conv	95.2%	99.4%	98.8%
Overall TP Average			0.149	0.018	0.036
Overall TP Stdev			0.002	0.001	0.001

TABLE 87. COMPARISON OF TAILPIPE AND DILUTE WHTC MEASUREMENTS BASED ON OVERALL AVERAGES FROM THREE REPLICATES

		Cold	Hot1	Hot2	Hot3	Composite	Hot-Avg
Engine-Out	g/hp-hr	3.04	3.40	3.43	3.43	3.37	3.42
Tailpipe Dilute	g/hp-hr	0.149	0.022	0.021	0.021	0.039	0.021
	%conv	95.1%	99.3%	99.4%	99.4%	98.8%	99.4%
Tailpipe Raw	g/hp-hr	-	0.018	0.018	0.018	0.036	0.018
	%conv	-	99.5%	99.5%	99.5%	98.9%	99.5%

TABLE 88. COMPARISON OF FINAL AGED WHTC RESULTS TO EARLIER DATA

		Cold	Hot	Composite
Engine-Out	g/hp-hr	3.1	3.5	3.4
Final Aged	g/hp-hr	0.149	0.018	0.036
	%conv	95.1%	99.5%	98.9%
Development Targets	g/hp-hr	0.060	0.010	0.017
	%conv	98.0%	99.7%	99.5%
Development Aged Parts	g/hp-hr	0.089	0.008	0.019
	%conv	97.1%	99.8%	99.4%
Final Aged Conversion Delta				
vs devel aged	%conv	2.0%	0.3%	0.5%
vs target	%conv	2.9%	0.2%	0.6%

As noted in the tables, the Raw cold-start WHTC results for these tests were not valid due to the fact that the NO_x analyzer was over-range during the initial cold-start peak. The measured concentrations were sufficiently high to saturate the analyzer at the 500-ppm range that was used chosen for cold-start, although this had not been the case for earlier results and other cycles. Given that Dilute results were already available, and the time constraints of the program, it was decided to proceed with data generation, rather than to range-find and calibrate a higher range for Raw only. This was especially important because the short WHTC soak would not allow changing of ranges between cycles, and therefore a significantly higher range would have further implications for accuracy of the hot-start WHTC measurements. Time was not available within the program to investigate and resolve the issue further, therefore measurements proceeded. Prior measurements on other cycles, and development WHTC cycles that did not show an over-range, had indicated that there was no significant difference in cold-start results between Dilute and Raw measurements. Therefore, the Raw composite values are calculated using the Dilute cold-start values, and the Raw hot-start values.

It was apparent that there was a significant discrepancy between Raw and Dilute hot-start WHTC results. This was not observed during tests on other cycles, and this measurement discrepancy will be discussed further below.

As was the case with the FTP, the WHTC results clearly indicate some catalyst degradation on both cold-start and hot-start results. As discussed under the FTP results earlier, it is not clear how much of this should be considered abnormal due to the issues observed during Final Aging. Therefore, this discussion will focus on assessment of the results based on the observed performance in comparison to earlier tests with the Development Aged parts.

Figure 251 shows NO_x at the PNA inlet and outlet, as well as PNA temperatures, both the cold-start WHTC on the Development Aged parts. As noted earlier, the temperature and NO_x profile of the WHTC is somewhat less favorable for the PNA, given that temperatures during the initial cold-start actually rise somewhat faster, and there is somewhat more demand for mass storage in the very early cold-start compared to the FTP. Nevertheless, roughly 2 grams of NO_x were stored for the Development Aged parts before the temperatures were high enough to prevent further storage. Figure 252 shows a similar chart for the Final Aged parts. Very little NO_x storage behavior is apparent on this trace. Figure 253 compares PNA stored NO_x during the cold-start FTP for the two sets of parts. For the Final Aged parts, less than 0.2 grams of NO_x are stored at a similar timeframe. All of that additional NO_x is emitted prior to the advent of SCRF light-off, and therefore this would all emerge as tailpipe NO_x.

Given that the total change in tailpipe NO_x mass between the Development Aged and Final Aged parts is on the order of 2.5 grams, this change in the PNA capability is the primary driver of the increase in tailpipe NO_x emissions. The remaining increase appears to be driven by a combination of lower ammonia storage capacity on the SCRF, which drove a small loss of performance, as well as an increase in the tendency towards ammonia oxidation. Figure 254 shows SCRF-out NO_x mass rates for both Final Aged and Development parts. A loss of conversion is apparent in the range of the cycle after SCRF light-off, roughly after 130 seconds. Much of the increased NO_x is reduced by the downstream SCR, which still demonstrated 93% conversion after light off. However, the net result was still a small increase in tailpipe NO_x, on

the order of 0.5 grams of total mass. This change can be seen in Figure 255 which compares tailpipe NO_x mass rates for both Final Aged and Development parts.

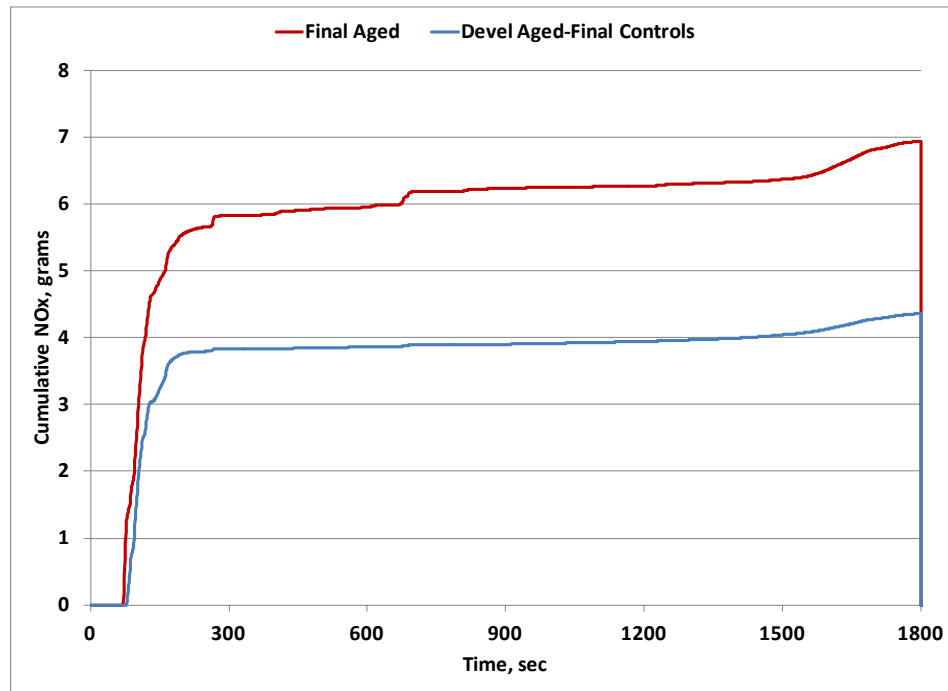


FIGURE 250. CUMULATIVE TAILPIPE NO_x COMPARISON – FINAL AGED VERSUS DEVELOPMENT AGED

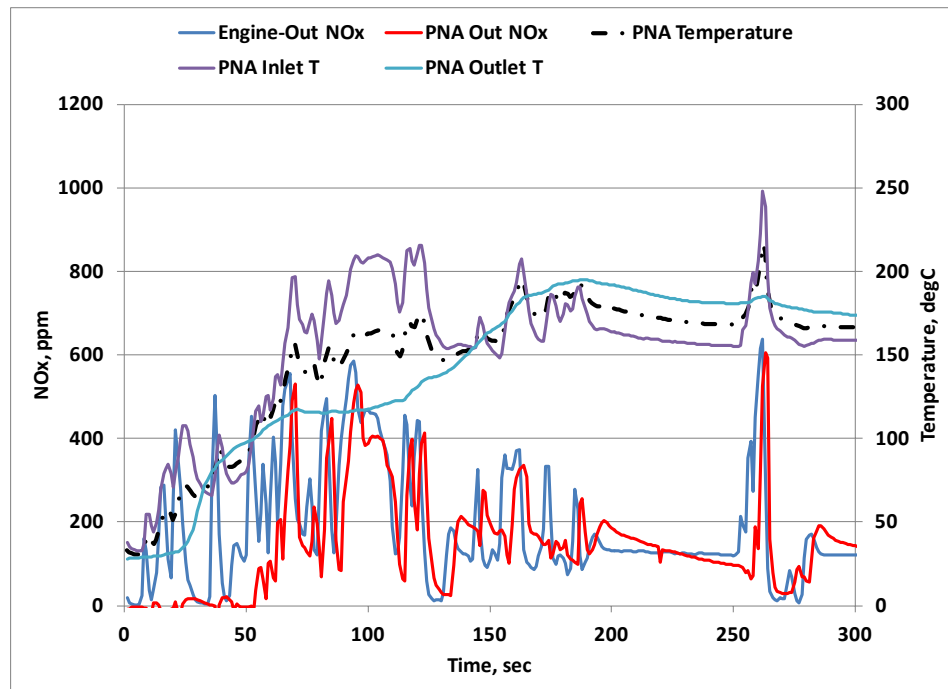


FIGURE 251. COLD-START WHTC PNA BEHAVIOR – DEVELOPMENT AGED PARTS

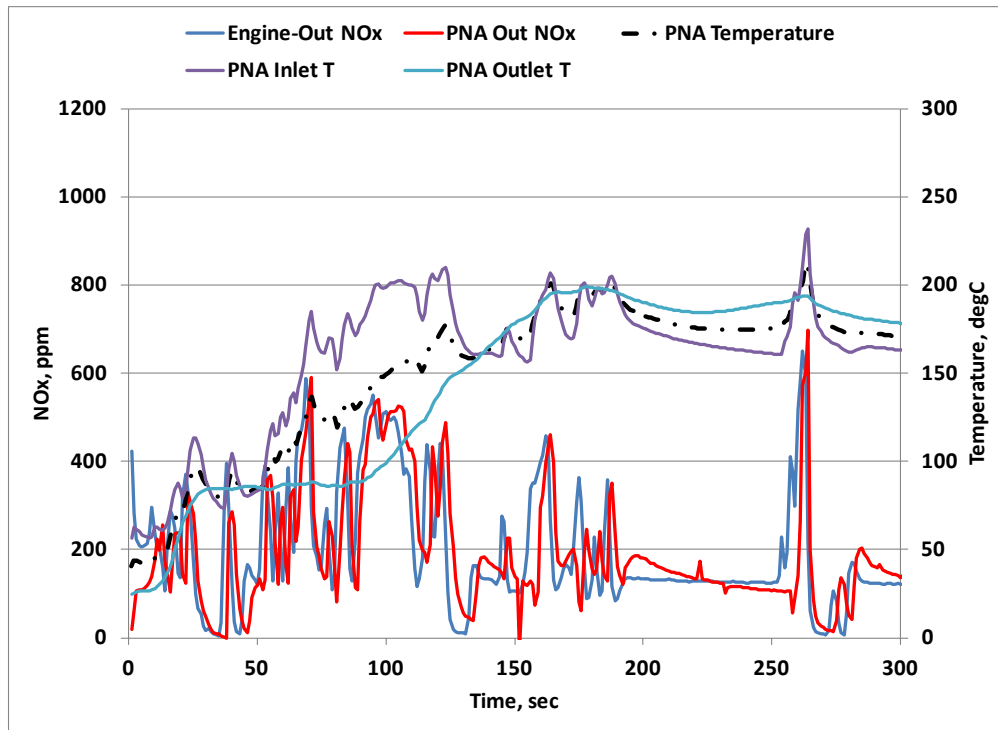


FIGURE 252. COLD-START WHTC PNA BEHAVIOR– FINAL AGED PARTS

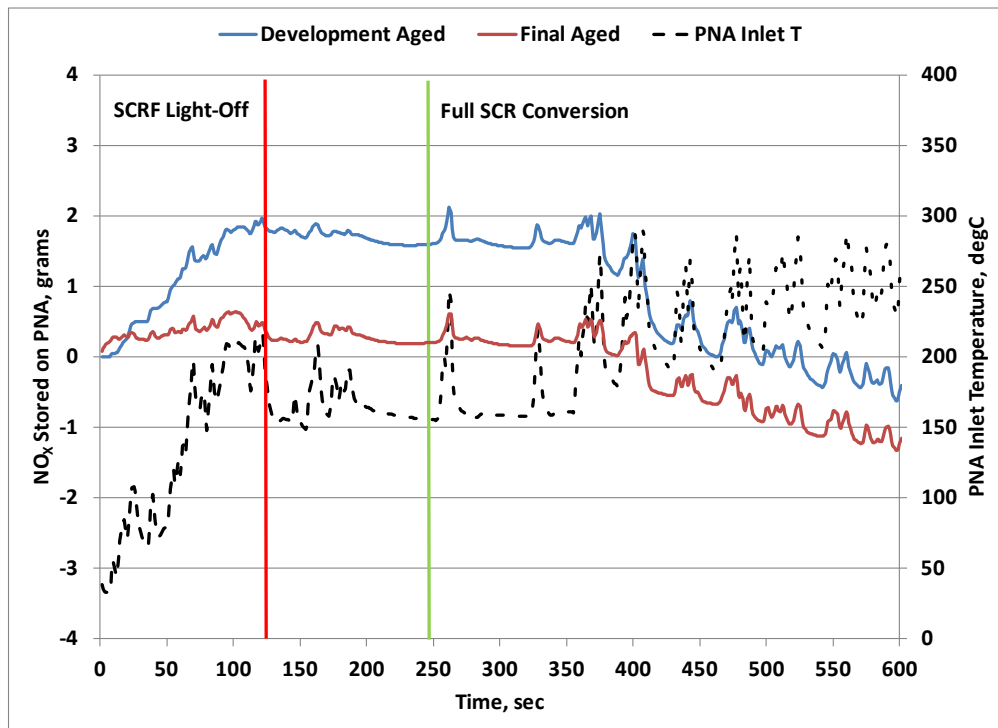


FIGURE 253. COMPARISON OF COLD-START WHTC PNA STORAGE – FINAL AGED PARTS VERSUS DEVELOPMENT PARTS

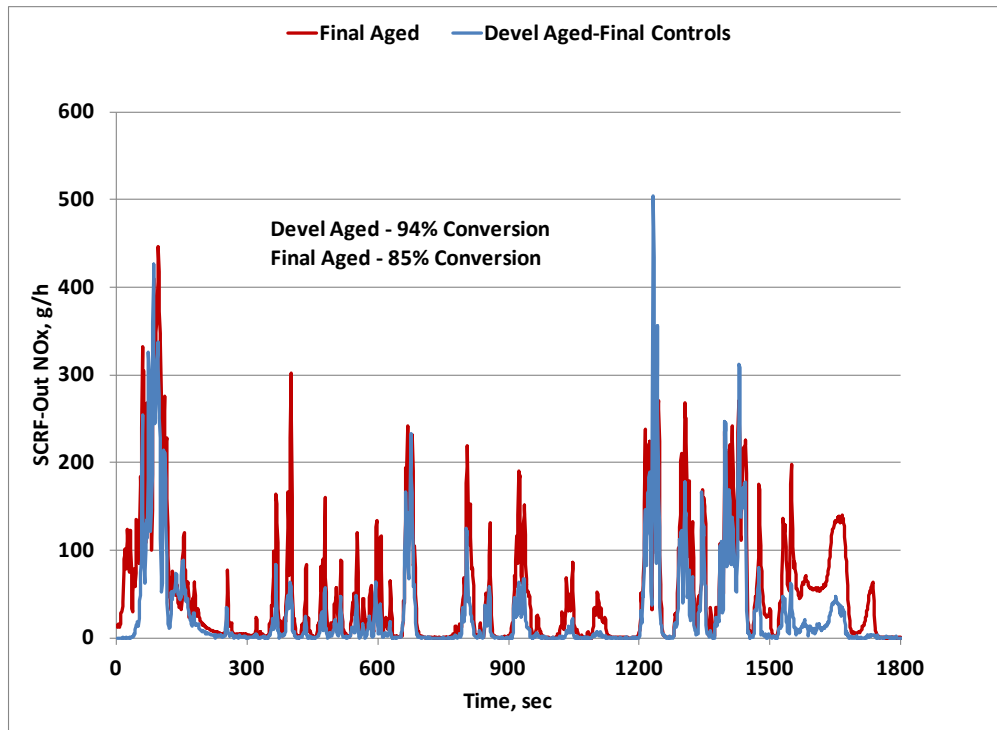


FIGURE 254. COMPARISON OF WHTC COLD-START SCR-OUT NO_x MASS RATES – FINAL AGED PARTS VERSUS DEVELOPMENT PARTS

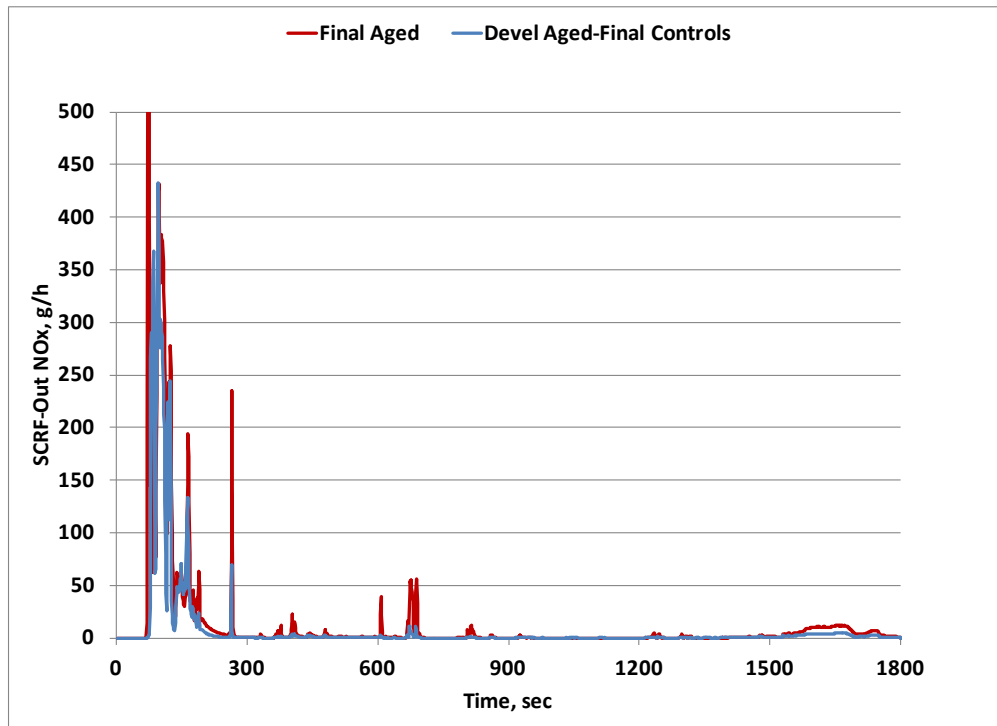


FIGURE 255. COMPARISON OF WHTC COLD-START TAILPIPE NO_x MASS RATES – FINAL AGED PARTS VERSUS DEVELOPMENT PARTS

Hot-start WHTC NO_x and temperature data are shown in Figure 256 for the Development Aged parts and Figure 257 for the Final Aged parts, respectively. The PNA capacity is not significant for the hot-start cycle, and therefore SCRF performance is more likely to be the driver of observed performance changes. In comparing the two charts, more breakthrough from the SCRF is observed with the Final Aged parts. Figure 258 shows a comparison of SCRF-out NO_x mass rates for both sets of parts. Cycle conversion at the SCRF-out location over the hot-WHTC was on the order of 96% for the Development Parts, and 86% for the Final Aged parts. The downstream SCR was able to maintain 95% conversion of whatever emissions were observed going into it, but this still resulted in a few NO_x breakthrough events reaching the tailpipe. Figure 259 shows a comparison of tailpipe NO_x mass for both sets of parts on the hot WHTC. As seen in the chart, more and larger NO_x breakthroughs are seen in the early WHTC, as well as a small increase due to late cycle oxidation of ammonia slip. The net result was a change from 99.8% to 99.3% conversion of the hot WHTC.

This behavior is consistent with the observations on the FTP and RMC-SET cycles, and results in overall performance similar to what was observed on those cycles. As with the FTP, it is possible that some of the observed changes are due the abnormal events that occurred during the canning failure, and therefore it is not possible to separate representative changes from those that are not representative.

Table 89 summarizes the impact of the final strategy with Final Aged parts on CO₂ emissions over the WHTC cycle. It should be noted that all of the cell-to-cell measurement issues discussed earlier regarding the FTP and RMC-SET cycle comparisons remain valid for the WHTC comparison. As with the previous data, carbon-balance adjusted CO₂ emissions are given in the table to enable a valid comparison. It should be noted that the impact of the strategy on the cold-start WHTC was actually smaller than what was observed on the FTP. However, this shows up as only a small improvement in the overall composite due to the cold-start weight factor. Overall, the impact of the strategy on the WHTC was similar to that observed for the FTP.

TABLE 89. COMPARISON OF CO₂ EMISSIONS ON WHTC CYCLE – FINAL LOW NO_x CONFIGURATION VERSUS ENGINE BASELINE

	BSCO2, g/hp-hr		
	Cold	Hot	Composite
Baseline Engine	496.0	485.0	485.3
Final ULN Config	514.8	491.1	494.4
% change	3.8%	1.3%	1.9%
Mini-burner air	0.4%	0.2%	0.2%
Increased SCRF Regeneration			0.3%
Total FTP CO2 Impact			2.4%

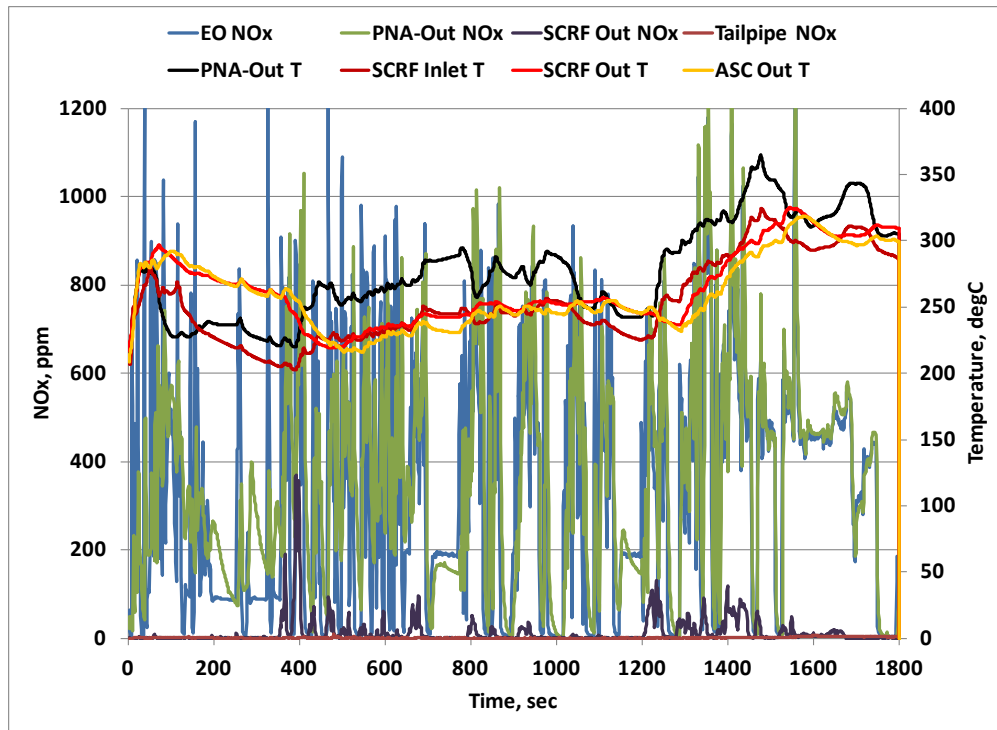


FIGURE 256. HOT-START WHTC NO_x AND TEMPERATURE FOR DEVELOPMENT AGED PARTS

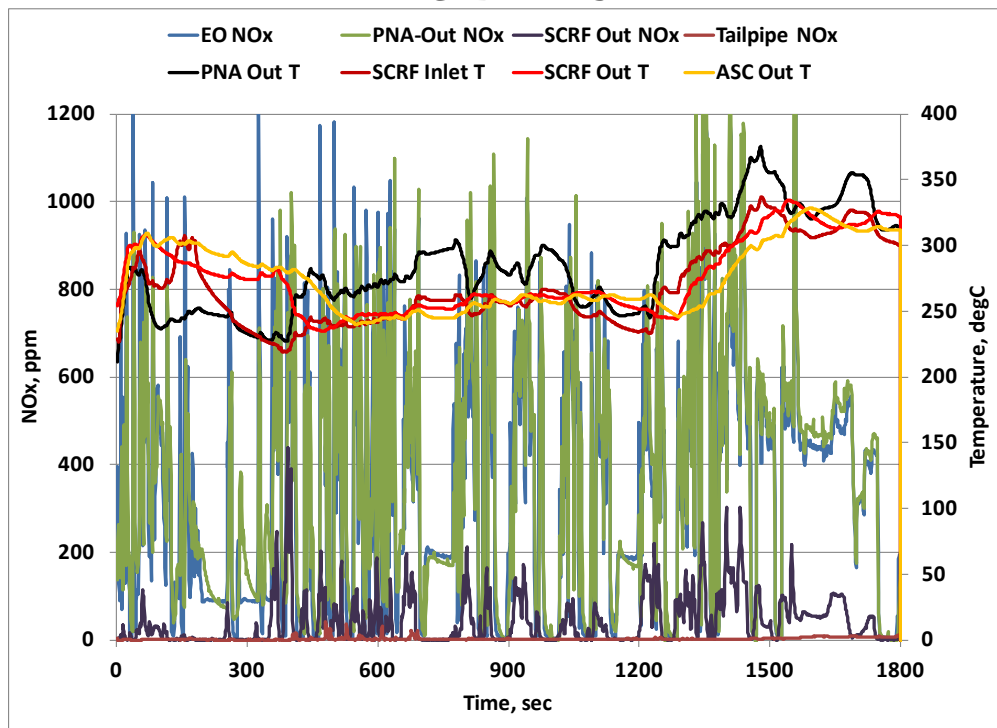


FIGURE 257. HOT-START WHTC NO_x AND TEMPERATURE FOR FINAL AGED PARTS

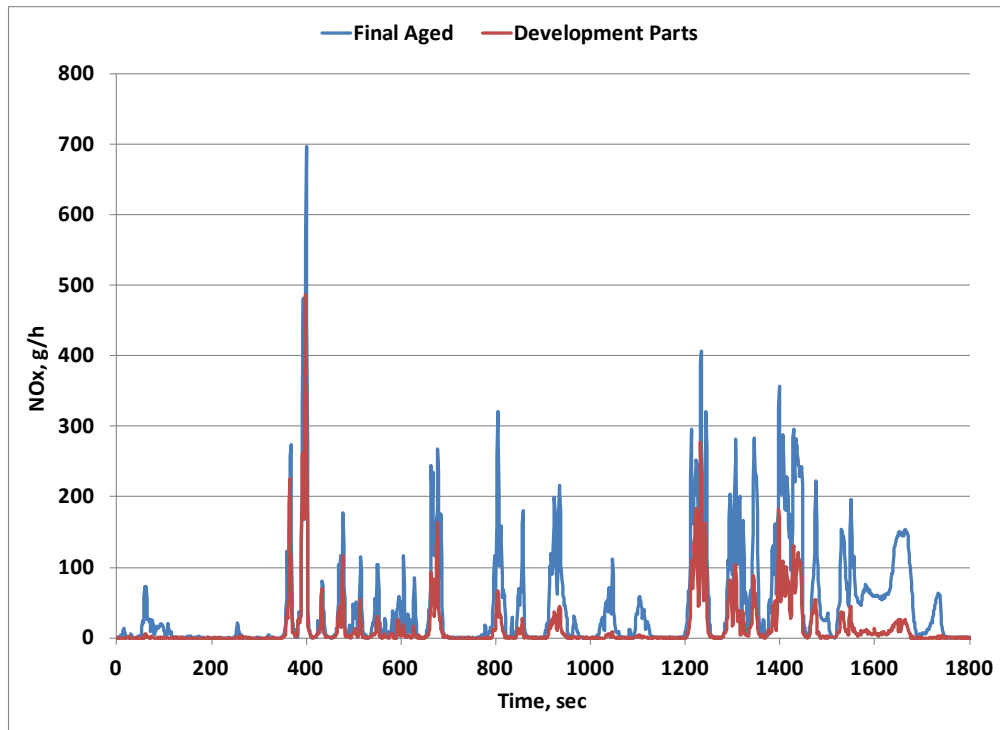


FIGURE 258. COMPARISON OF SCRf-OUT NO_x MASS – FINAL AGED PARTS VERSUS DEVELOPMENT PARTS

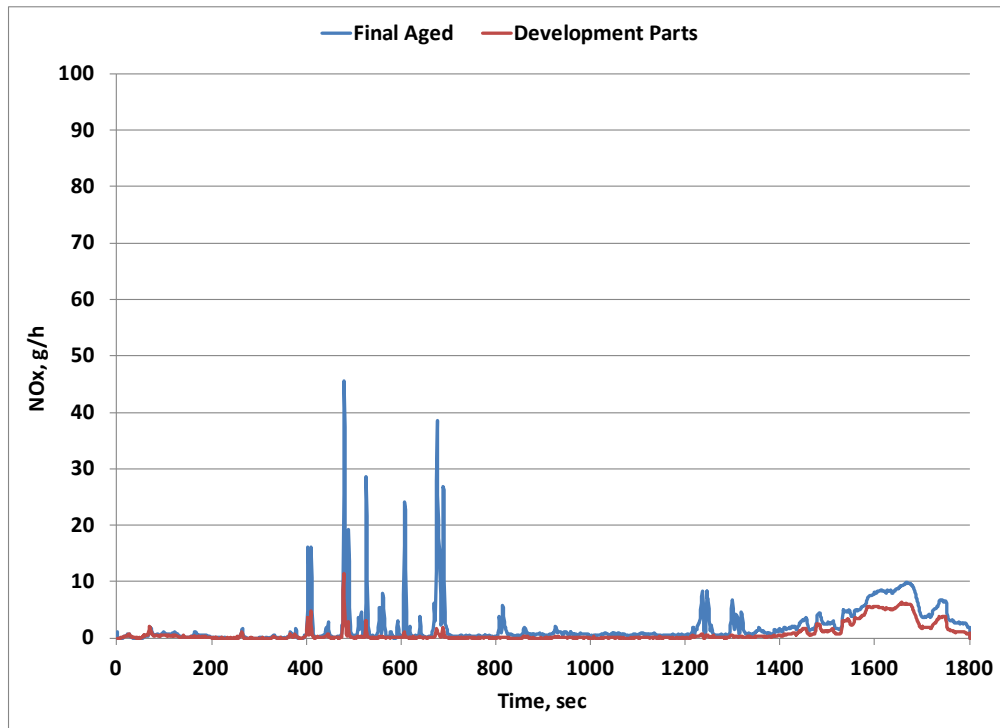


FIGURE 259. COMPARISON OF TAILPIPE NO_x MASS – FINAL AGED PARTS VERSUS DEVELOPMENT PARTS

3.4.5.5 CARB Idle Testing

Three replicates of the CARB extended idle test were also run on the Final Aged parts. It should be noted that this cycle could leverage the re-light feature that was included in the burner controls, and this value was set to allow the burner to become active during an extended cool-down period, in order to help manage NO_x emissions. However, unlike the FTP, RMC, and WHTC cycles, there was no specific target value given for this test. The current standard specifies a 30 g/hr NO_x mass rate limit during each of the 30-min idle portions. No calibration changes were made prior to this test from the calibration utilized for FTP and RMC testing. The only feature that was calibrated to become active was the burner re-light feature. The engine calibration already included a low NO_x idle that was necessary for parts of the hot-start FTP cycle when aftertreatment temperatures were lower, to help maintain system heat, and control engine-out NO_x at lower aftertreatment temperatures.

It should be noted that the choice of the temperature for the burner re-light feature, and the amount of heat and other trigger temperatures are significant with respect to how the system behaves. It should also be noted that the thresholds for this feature were set at levels below the temperatures encountered during FTP and RMC testing. The results given represent one choice in terms of where to set these thermal management thresholds, but other are possible. This becomes a case of balancing fuel consumption during thermal management against NO_x performance. In order to help examine this behavior, it was decided to run one of the three planned tests with the mini-burner disabled (i.e., without Relight). This would allow a back-to-back comparison of the effect of the thermal management on both NO_x and fuel consumption.

A summary of CARB idle test results is given below in Table 90. The table shows that NO_x data for both engine-out and tailpipe measurements. The data in this summary represent the integrated average values for each of the 30-minute long idle periods. The low idle was run at the engine's normal warmed up curb idle speed of 550 rpm, while the PTO idle was run at 1100 rpm following the test procedure. Fuel rate data is also shown as the average across the 30-minute idle segments.

TABLE 90. SUMMARY OF CARB EXTENDED IDLE TEST RESULTS – FINAL AGED VERSUS BASELINE

			Low Idle - 550rpm				PTO Idle - 1100rpm			
			EO NOx	TP NOx	NOx Conversion	Fuel Rate	EO NOx	TP NOx	NOx Conversion	Fuel Rate
			g/hr	g/hr	%	kg/hr	g/hr	g/hr	%	kg/hr
Baseline		Mass Rate	46.1	11.7	75%	1.18	66.2	52.7	20%	3.16
Final Aged	with Relight	Mass Rate	10.6	0.2	98%	1.00	42.4	14.6	66%	3.21
		% change from base	-77%	-98%	n/a	-15%	-36%	-72%	n/a	2%
	without Relight	Mass Rate	7.0	0.1	99%	0.99	30.5	33.7	-10%	2.93
		% change from base	-85%	-99%	n/a	-16%	-54%	-36%	n/a	-7%

An example of continuous data for all three test cases is given below. Figure 260 shows the baseline testing, Figure 261 shows the Final Aged configuration with the burner re-light feature, and Figure 262 shows the Final Aged configuration with the burner re-light feature disabled.

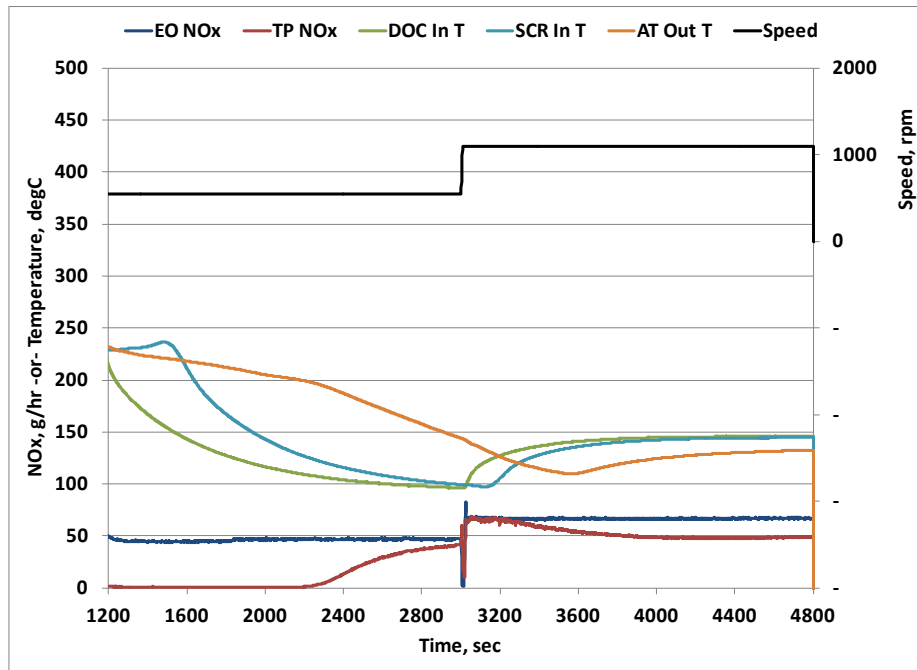


FIGURE 260. TEMPERATURE AND NO_x MASS FOR BASELINE CARB IDLE TEST

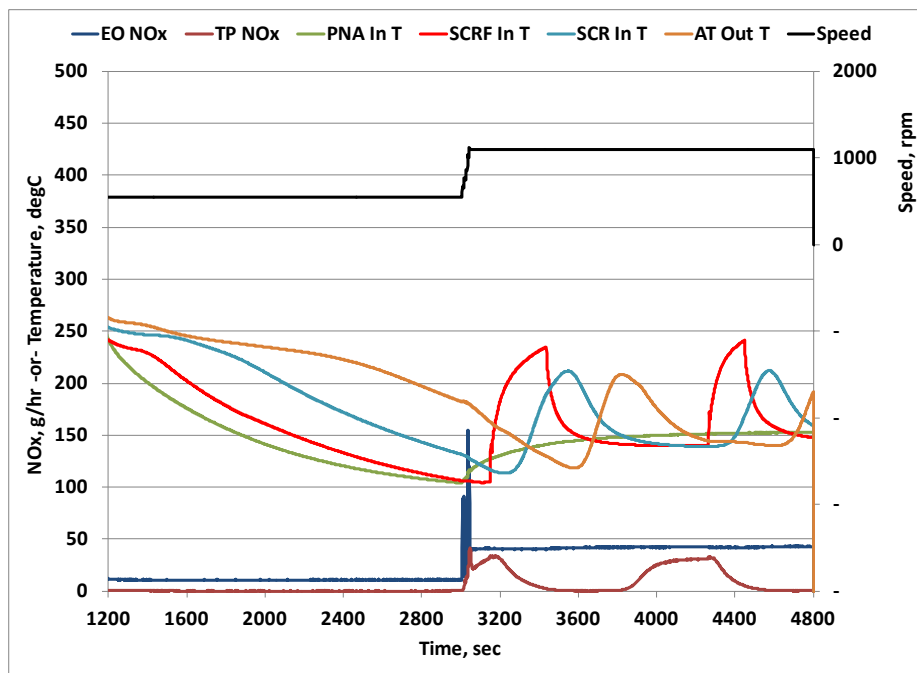


FIGURE 261. TEMPERATURE AND NO_x MASS FOR FINAL AGED CARB IDLE TEST (WITH BURNER RE-LIGHT ENABLED)

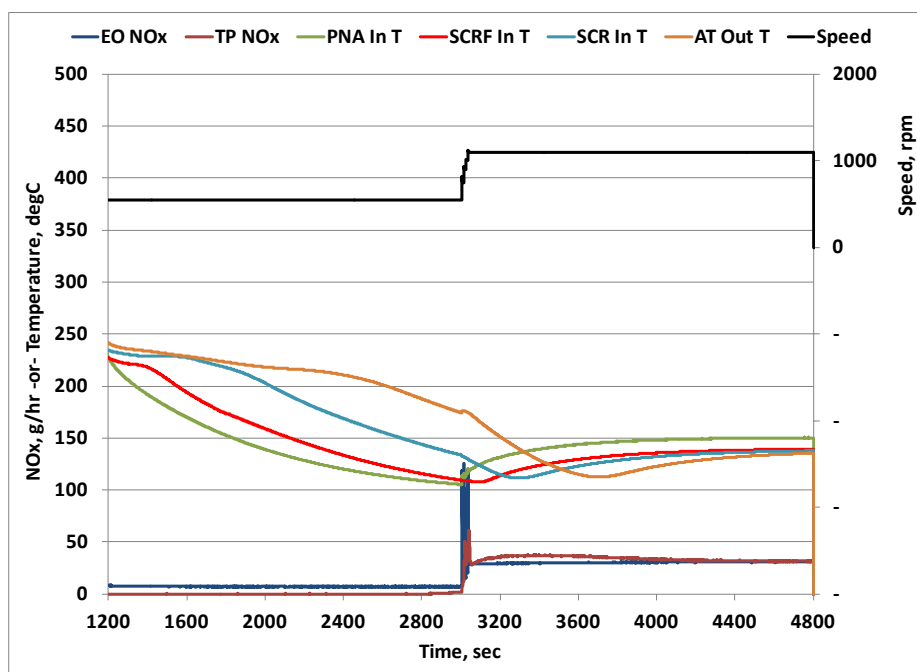


FIGURE 262. TEMPERATURE AND NO_x MASS FOR FINAL AGED CARB IDLE TEST (WITH BURNER RE-LIGHT DISABLED)

At the low idle point, the baseline engine met the 30 g/hr base requirement, but NO_x dosing had ended much earlier and by the end of the 30-minute idle period, the baseline system was nearing a zero conversion state, having begun to run out of both NH₃ and temperature about 1000 seconds into the idle period. By contrast, the Low NO_x engine was able to preserve heat longer, as well as having a greater capacity for stored ammonia. This period was further extended by having the engine running in a low NO_x idle mode, which featured higher EGR rates, resulted in less cooling flow through the system and lower NO_x. Temperatures were above the re-light threshold for the entire 30-minute period and therefore, no active thermal management was triggered. This operation did not appear to result in a significant change in fuel consumption compared to the baseline engine. In fact, the measured fuel consumption was lower than the baseline, but this difference could also be due to measurement variation given that the average fuel rate at this condition was on the order of 1 kg/hr. It should be noted that measured CO₂ rates did also confirm a small reduction as observed in the fuel rate data.

At the higher idle point (PTO idle at 1100 rpm), the baseline system did not meet the 30 g/hr standard, but given that, this was originally a European calibrated engine not normally subject to the CARB idle requirement, this is more likely a matter of calibration rather than inability of the system to perform. Given the aftertreatment temperatures, the baseline system showed very little NO_x reduction across the aftertreatment system at this condition, although some amount was detected (possibly due to incidental HC-based reduction, given the temperatures and a near 1-to-1 molar ratio of inlet NO_x and HC). The final Low NO_x engine configuration demonstrated a one-third reduction in engine out NO_x, likely due to higher EGR rates utilized in this calibration at idle. For the case without the burner, the aftertreatment system does not contribute any additional NO_x reduction, and in fact, there is a brief increase in NO_x that occurs due to a small early release from the PNA when conditions change. Without the

added thermal management, the NO_x rate at the 1100-rpm idle is just over the 30 g/hr threshold of the current standard, therefore additional measures would be required. Interestingly the measured fuel consumption is again very similar between the baseline engine calibration and the modified engine calibration. Measured CO₂ rates for both tests actually confirm a small reduction, which appears in the fuel rate data.

However, with the burner re-light enable, the added heat helps the system perform better by allowing additional dosing periodically, as well as raising catalyst temperatures. At this higher speed condition, the burner crossed the re-light threshold within the test, and in fact, two re-light episodes were observed during the 30-minute test period, as can be seen from the SCRF Inlet temperatures in Figure 261. This behavior enabled a 66% reduction of NO_x across the aftertreatment system, bringing the tailpipe mass rate down to 14 g/hr. The impact of the added thermal management was roughly a 7% increase in the measured fuel rate, compared to the original baseline.

Overall the final Low NO_x system appears to be much better at retaining heat at normal idle than the baseline system. At the higher idle, however, thermal management is required to maintain higher NO_x conversion rates, otherwise the system will cool below its operating temperature window and it will run out of stored NH₃. The emission rate for this second idle second will depend on the calibration of the thermal management. It would be possible, for instance, to calibrate thermal management to come in at higher temperatures and for shorter periods of time, thus maintaining the system heat, rather than allowing it to fall below the operating window of the SCR system and then heat back up. In addition, although the mini-burner was used as the primary means of thermal management, other approaches could also be utilized in an effort to maintain heat. From an efficiency standpoint, it would be useful to study the relative costs of maintaining heat versus adding heat to a cooled system. The relative GHG impact of such changes is a good subject for further study, and was examined on this engine as part of the Stage 2 effort.

3.4.6 Vocational Cycle Demonstration Testing

Three replicates of each of the vocational cycles were run. In all cases a pattern was followed that was similar to the CARB extended idle testing described earlier. Two of the replicates utilized the strategy that had been developed for the FTP and RMC-SET, and these included the re-light calibration that was used for the CARB extended idle test as well. The third replicate was made with the burner re-light function disabled, so that an initial examination could be made of the impact of the active thermal management via the mini-burner. The results for each cycle are summarized separately below.

3.4.6.1 NYBC Cycle

As described earlier, the NYBC vocational test consists of a preconditioning run of the NYBC cycle, followed by a 30-minute idle, followed by the test-for-record over the NYBC cycle. The NYBC cycle actually consists of four repeats of the NYBC duty cycle profile, which was derived from transit bus data. The cycle is intended to examine a profile where the system has cooled off during a long idle, after which it is tasked with operating over a highly transient,

relatively light load duty cycle. The cycle tests how well a system can preserve heat, as well as how quickly it can warm back up to operating temperatures. For reference, the average power over this cycle is roughly 17kW, or about 5% of maximum engine power.

A summary of the NYBC cycle results is given below in Table 91 below. The table shows both engine-out and tailpipe NO_x emissions over the test for record, as well as fuel flow over that same period. Baseline results are given, as well as the Final Aged cycle runs for the final Low NO_x configuration, both with and without the mini-burner re-light function active.

TABLE 91. SUMMARY OF NYBC VOCATIONAL CYCLE RESULTS

			EO NOx		TP NOx		NOx Conversion	Fuel Rate
			g/hr	g/hp-hr	g/hr	g/hp-hr	%	kg/hr
Baseline		Mass Rate	142	6.1	54	2.3	62%	5.29
Final Aged	with Relight	Mass Rate	92.1	3.9	8.8	0.38	90%	5.30
		% change from base	-35%	-36%	-84%	-84%	n/a	0%
	without Relight	Mass Rate	85	3.6	18.4	0.78	78%	5.18
		% change from base	-40%	-41%	-66%	-67%	n/a	-2%

Continuous NO_x and temperature data for the NYBC test is given in Figure 263 for the baseline case, Figure 264 for the Final Aged system with the mini-burner re-light active, and Figure 265 for the Final Aged system without the mini-burner re-light function. All three plots show both the cycle for record and the preceding 30-minute idle period. In all three cases, the beginning of the period show on the plot is at the end of the preconditioning cycle. For all tests, the engine and aftertreatment were essentially at thermal equilibrium with the test cycle before starting the 30-minute idle period. By the end of all three tests for record, the engine and aftertreatment had regained that same thermal equilibrium. For all three configurations, that value was roughly 195°C, which represents the stable temperature over many repeats of this NYBC duty cycle profile.

For the baseline engine and aftertreatment system, this was a very difficult cycle. Although it entered the cycle operating at roughly 88% conversion efficiency, the aftertreatment cooled to a temperature of near 110 °C by the end of the idle period. The DEF dosing had shut off fairly early in this period, and by the end of the idle, there was essentially no NO_x conversion over the aftertreatment. The system did start to warm up on the cycle, but DEF dosing did not resume until nearly 800 seconds into the cycle. As a result, the system exhibited very poor conversion during the early portions of this cycle, although this slowly improved as the cycle continued. NO_x conversion over the cycle was only 62%, although it had improved to 75% by the end of the final NYBC profile.

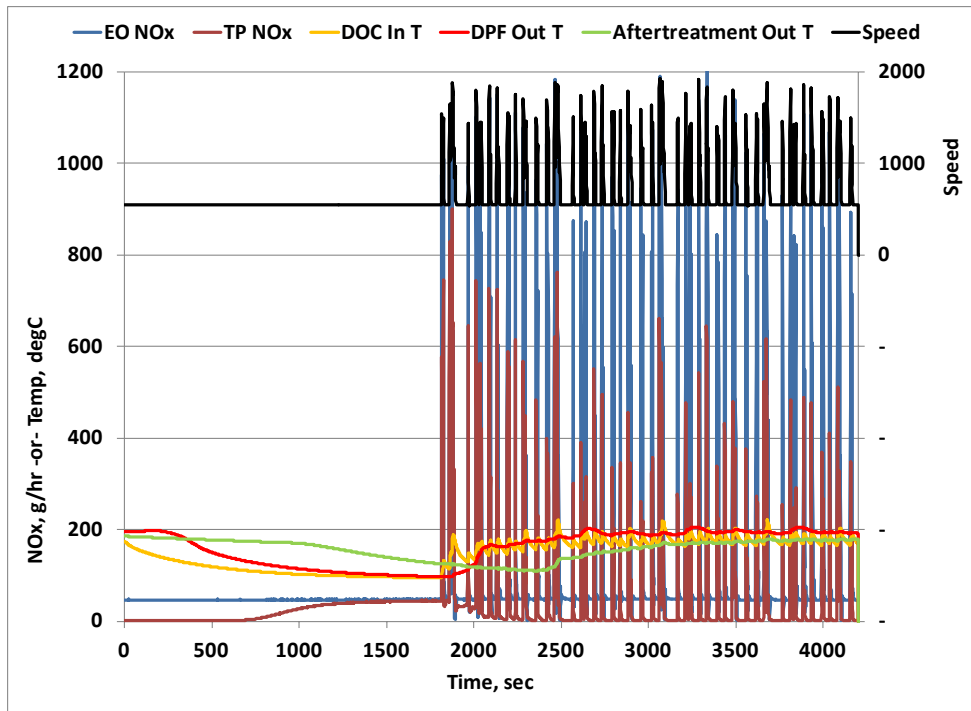


FIGURE 263. BASELINE NO_x AND TEMPERATURE DATA FOR NYBC VOCATIONAL CYCLE

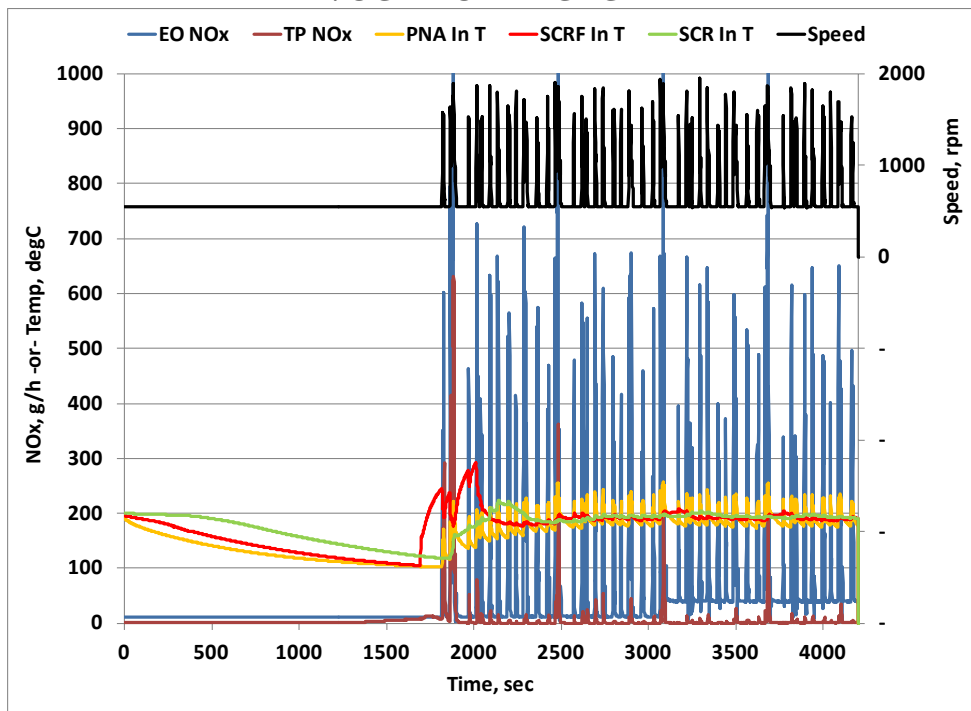


FIGURE 264. FINAL AGED NO_x AND TEMPERATURE DATA FOR NYBC VOCATIONAL CYCLE, WITH RE-LIGHT

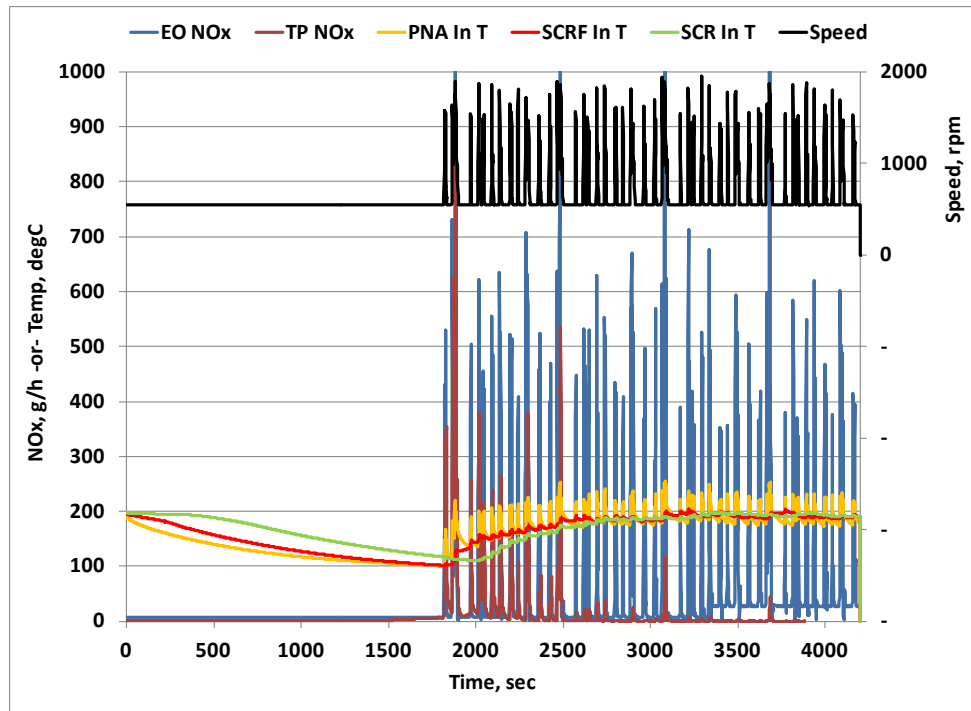


FIGURE 265. FINAL AGED NO_x AND TEMPERATURE DATA FOR NYBC VOCATIONAL CYCLE, WITHOUT RE-LIGHT

By contrast, the final Low NO_x configuration was able to maintain NO_x conversion for nearly the entire idle period, similar to the behavior observed on the extended idle test. This is in part due to the lower engine-out NO_x rate from the lower NO_x idle calibration that is active at lower aftertreatment temperatures. System temperatures do still cool off to roughly 100°C by the end of the idle period, but NO_x conversion begins to fade only near the end of the cycle. DEF dosing shuts off fairly early in this period, but there is enough stored NH₃ in the catalysts to maintain conversion for nearly the whole period. It should be noted that due to the revised engine calibration, engine-out NO_x over the NYBC is reduced by 35 to 40%. Engine-out NO_x at idle is greatly reduced due to increased EGR at that condition. However, fuel consumption was not significantly different from the baseline engine with the revised calibration, though this is likely due to the very light-load nature of the cycle.

As seen in Figure 267, with the re-light function active, the burner actually does re-light before the end of the idle period, at which point DEF dosing actually resumes and conversion is actually improving again when the cycle for record actually starts. There is a brief period of poor conversion that lasts only 70 seconds, and then NO_x conversion quickly reaches in excess of 90%. The burner stayed lit in this case for roughly five minutes, after which time the shut down threshold was reached and it turned off. Given this cycle profile, the burner did not re-light again. The overall fuel consumption on the cycle with the re-light function is actually very close to the baseline engine, and with only the single re-light event, the burner contributes only about 3% of the total fuel consumed over the test. The overall effect is an 84% reduction in tailpipe NO_x over the NYBC cycle.

Without the re-light function active, as shown in Figure 268, the period of poor conversion after the idle period lasts longer, but conversion still recovers to over 90% after about 700 seconds into the cycle. This indicates that the system has better warm-up characteristics than the baseline aftertreatment. Overall, there is still a 66% reduction in tailpipe NO_x levels as compared to the baseline. The difference between the tests with and without re-light is about a 3% change in fuel consumption over the NYBC cycle with re-light functioning.

Overall, it appeared that the ARB Low NO_x configuration resulted in a substantial improvement over the baseline over the NYBC cycle without incurring a substantial GHG penalty. Towards the end of the NYBC cycle, this configuration was realizing in excess of 96% NO_x conversion over this particular duty light-load duty cycle, with NO_x rates down to a sustained level below 4 g/hr.

3.4.6.2 Cruise-Creep Cycle

As described earlier, the Cruise-Creep cycle consists of a Cruise portion, which is intended as the preconditioning phase, followed by 10 repeats of the Creep profile that was provided by CARB. This cycle is intended to examine the behavior of a vehicle, which drives to a worksite and then begins to do repetitive light-load work. The system was at a higher temperature at the start, but would slowly cool off during the course of the cycle, unless active measures were taken to prevent cooling. The portion of the cycle that is considered to be the “test for record” was the sequence of 10 creep repeats.

A summary of the Cruise-Creep results is given below in Table 92. The table shows both average engine-out and tailpipe NO_x mass rates overall two different intervals. The first interval is the complete set of 10 creep cycles. The second interval includes only the last three creep cycles, in order to show how the system is behaving at the end of the cycle. Fuel flow rates are also shown. For reference, the average power over the creep profile for this engine is 6.5 kW, so the creep profile is very light load, less than 3% of engine maximum power.

TABLE 92. SUMMARY OF CRUISE-CREEP VOCATIONAL CYCLE RESULTS

		Creep x 10				Last 3 Creep Cycles			
		EO NO _x g/hr	TP NO _x g/hr	NO _x Conversion %	Fuel Rate kg/hr	EO NO _x g/hr	TP NO _x g/hr	NO _x Conversion %	Fuel Rate kg/hr
Baseline		71.8	13.3	81%	2.75	70.5	26.6	62%	2.8
Final Aged	with Relight	Mass Rate	41.3	7.45	82%	2.76	40.45	11.4	72%
		% change from base	-43%	-44%	n/a	0%	-43%	-57%	n/a
	without Relight	Mass Rate	41.1	12.8	69%	2.63	40.2	26.6	34%
		% change from base	-43%	-4%	n/a	-4%	-43%	0%	n/a

Continuous NO_x and temperature data for the Cruise-Creep cycle are shown in Figure 266 for the Baseline case, Figure 267 for the Final Aged data with the mini-burner re-light function active, and Figure 268 for the Final Aged data with the re-light function disabled.

On this particular cycle, the baseline aftertreatment slowly cools to an average temperature of about 150 °C, but this takes more than half of the cycle to do so. Good NO_x control is maintained by the system for about half the cycle, and then a slow increase in tailpipe

NO_x is observed. Eventually the system would likely run out of NH₃ and exhibit little control, but it is still at a level of 62% conversion over the last 3 cycles. DEF dosing shut off about 600 seconds into the cycle for the baseline case.

For the ARB Low NO_x configuration, without the mini-burner re-light function, the system appears to cool off on this cycle at a similar rate to the baseline case, and it reaches an equilibrium temperature of about 150 °C without any active intervention. Although the engine-out NO_x rate was lower, it appears that on this cycle the system began to lose conversion faster on this profile than the baseline system did. This is despite the fact that DEF dosing shut off at 900 seconds, about 300 seconds later than for the baseline. Therefore, the conversion over this cycle is only about 70%, but the conversion for the last three creep events is only 34%. This indicates that for this cycle, active thermal management was needed for this configuration. Interestingly, less fuel was burned on this cycle for the ARB Low NO_x configuration than on the baseline engine. The tailpipe NO_x in this case was about the same as the baseline engine.

With the thermal management from the mini-burner re-light active, the system fares much better. The re-light function comes active after about six creep events, and it appears to be settling into a stable pattern of lighting every three events. The temperature increase also allows DEF dosing to reactivate for short periods of time. As a result, conversion performance does not continue to decay as with the other two systems, but instead it settles into what looks like an oscillation pattern of behavior. The tailpipe NO_x for this cycle was at a level of about half the baseline engine, but the conversion on the last three creep events was at a stable level of 72%, which would be maintained as long as the system remained operating in this pattern. Eventually this resulted in a large reduction in NO_x compared to the baseline, which would eventually decay to the point of having little or no conversion over the aftertreatment system. The fuel consumption over this cycle with the re-light active was roughly the same as the baseline engine, but the NO_x result was about 45% lower.

It is clear that this cycle could benefit from additional calibration effort to adjust the thermal management strategy further. The comparison of the Cruise-Creep profile to the previous NYBC profile helped to illustrate the challenge of finding a workable balance over a wide variety of duty cycles. The ARB Low NO_x system as currently calibrated; performed very well on the NYBC cycle, but somewhat less so on the Cruise-Creep cycle. On the other hand, the combination of engine calibration and thermal management on the Cruise-Creep cycle ultimately proved to be the same in terms of fuel consumption as the baseline engine.

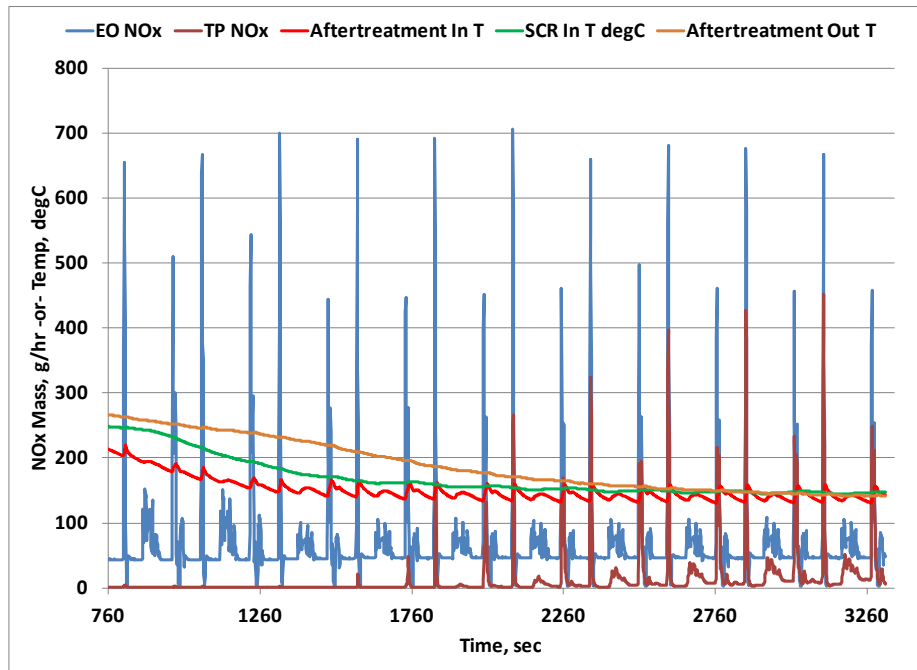


FIGURE 266. BASELINE NO_x AND TEMPERATURE DATA FOR THE CRUISE-CREEP VOCATIONAL CYCLE

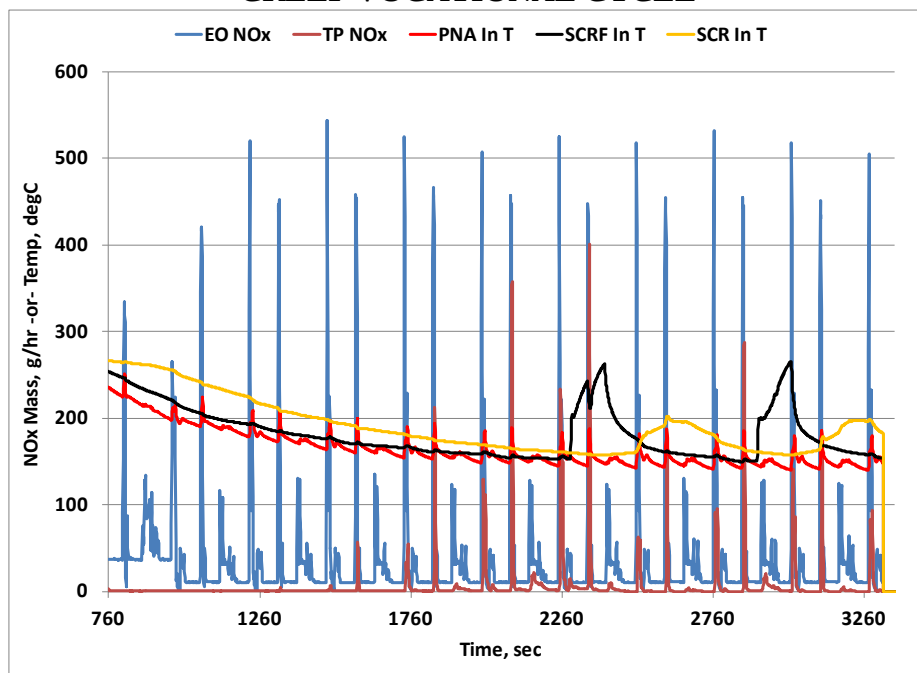


FIGURE 267. FINAL AGED NO_x AND TEMPERATURE DATA FOR THE CRUISE-CREEP VOCATIONAL CYCLE, WITH RE-LIGHT

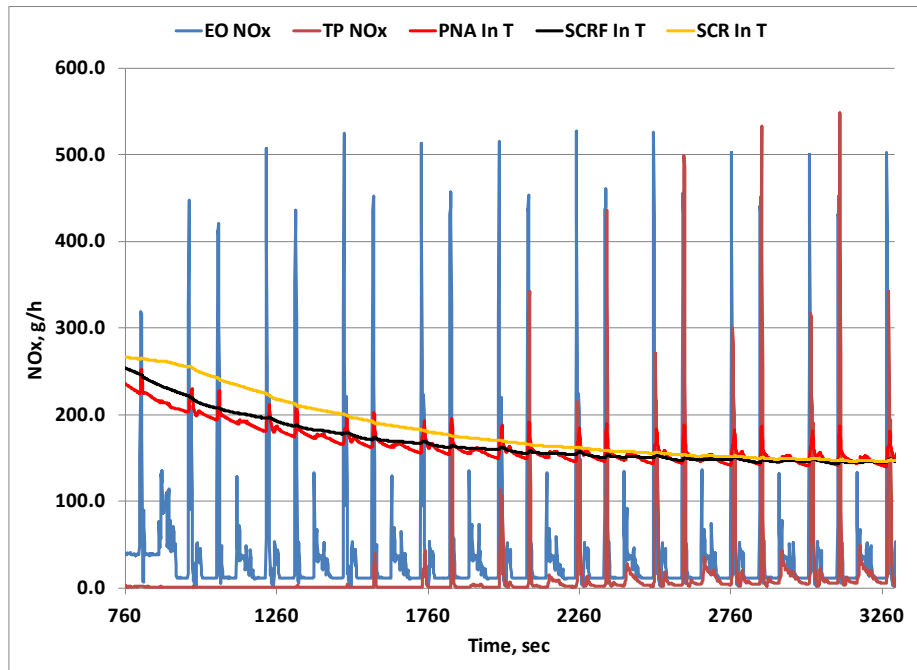


FIGURE 268. FINAL AGED NO_x AND TEMPERATURE DATA FOR THE CRUISE-CREEP VOCATIONAL CYCLE, WITHOUT RE-LIGHT

3.4.6.3 OCTA Bus Cycle

As described earlier, the OCTA bus cycle consists of a profile derived from a transit bus operating in the Orange County area. The profile was run twice, once was a preconditioning, and then again as the test for record. There was no dwell between the profiles. The intent of the cycle was to capture highly transient operation, but it was not intended to test the low temperature capabilities of the system by design. The OCTA bus cycle had a higher load factor than the other two vocational cycles, and essentially represented hot running operation. For reference the average power over this duty cycle was 53 kW or about 15% of maximum engine power. It was therefore, still a lower duty factor than the FTP, however, not nearly as light load as the other two cycles.

A summary of OCTA bus cycle results is given below in

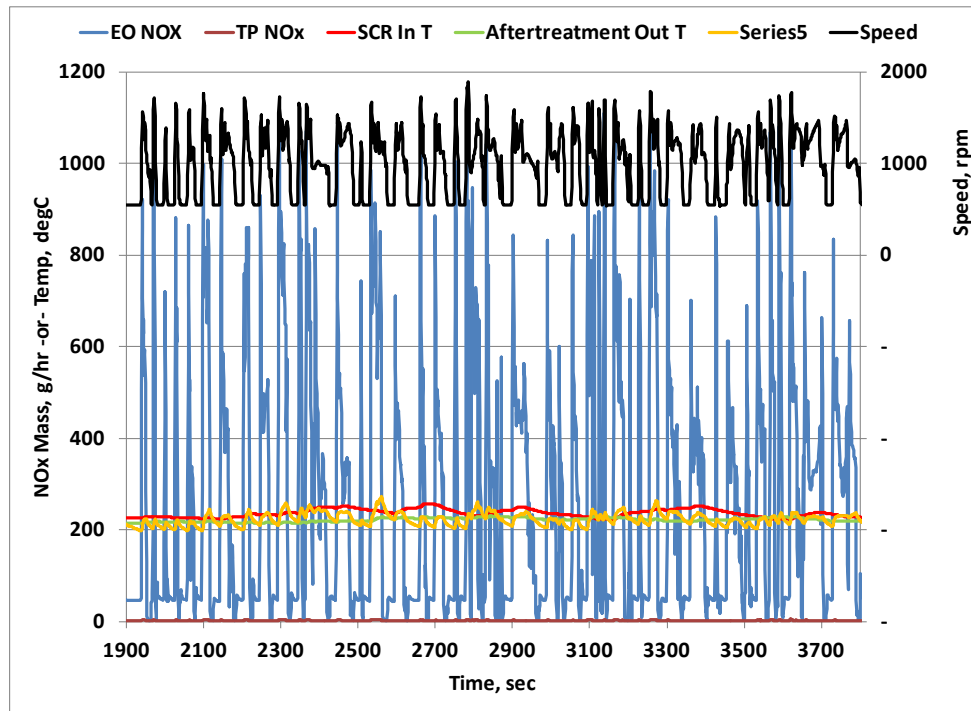
Table 93. Because the load factor of this cycle was high enough, the use of brake-specific emission results became meaningful, and therefore the results are reported in that fashion, similar to other regulatory cycles. Engine-out and Tailpipe NO_x results are given, as well as BSCO₂ over the cycle.

TABLE 93. SUMMARY OF OCTA BUS VOCATIONAL CYCLE RESULTS

			EO NOx	TP NOx	NOx Conversion	CO2
			g/hp-hr	g/hp-hr	%	g/hp-hr
Baseline		Emissions	3.8	0.023	99.4%	529
Final Aged	with Relight	Emissions	2.7	0.006	99.8%	534
		% change from base	-28%	-74%	n/a	0.9%
	without Relight	Emissions	2.7	0.011	99.6%	543
		% change from base	-28%	-52%	n/a	2.6%
Note: without Relight conducted just prior to SCRF regeneration at high backpressures						

Continuous temperature and NO_x data are given below for the Baseline case in Figure 269, and for the Final Aged case in Figure 270. In both cases, the sustained temperature on this cycle was between 225 °C and 250 °C, and therefore, despite the highly transient nature of the duty cycle, both systems were able to handle the OCTA bus cycle with relative ease. There was no difference between the Final Aged system with and without the mini-burner because that function did not come into play at all on the OCTA bus cycle. Therefore, no example is given for that case.

There did appear to be an increase in CO₂ emissions as a result of the hot-start calibration of the CARB Low NO_x engine for this particular duty cycle. One note on these results is that the repeat conducted with the relight function was run when the SCRf was almost fully loaded with soot, and the increased backpressure did appear to shift those results upward.

**FIGURE 269. BASELINE NO_x AND TEMPERATURE DATA FOR THE OCTA BUS VOCATIONAL CYCLE**

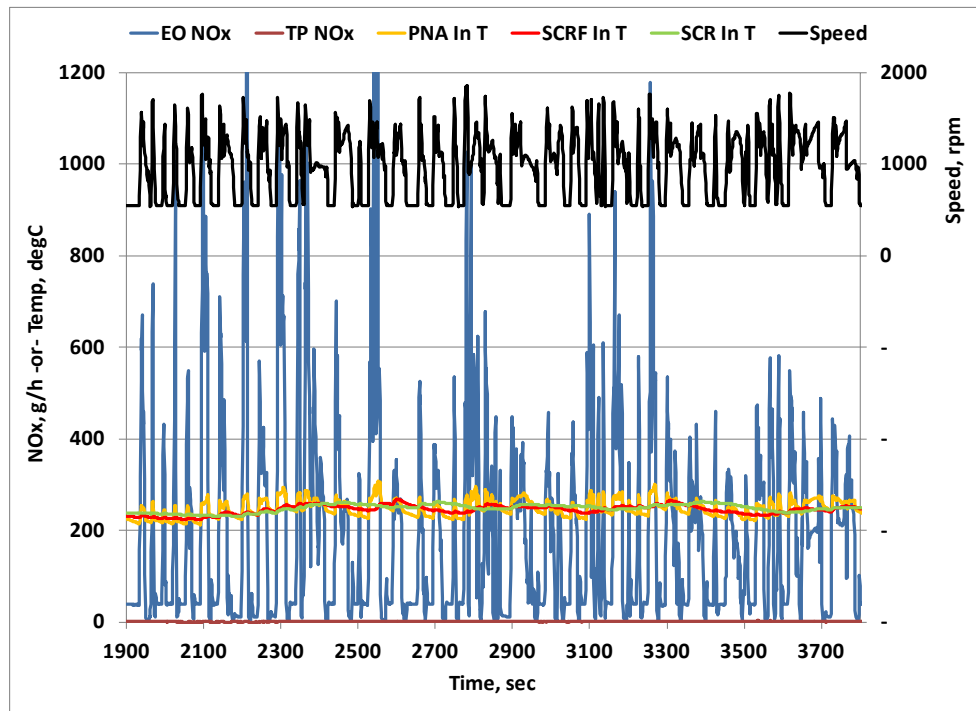


FIGURE 270. FINAL AGED NO_x AND TEMPERATURE DATA FOR THE OCTA BUS VOCATIONAL CYCLE

4.0 SUMMARY AND CONCLUDING REMARKS

This section of the report presents the program results in a summary format, and includes additional comments with regard to the implications of the data and recommendations for next steps and further efforts. Each of the two engine platforms is summarized and discussed in a separate section below.

4.1 CNG Engine – Cummins ISX12-G



The development of the CNG engine platform to meet ultra-low NO_x (ULN) levels was generally more straightforward than the diesel platform. Although a considerable amount of development effort was still required, the fact that the engine was a stoichiometric spark ignition (SI) unit allowed the use of the more mature TWC technology that is capable of very high NO_x reduction, as long as the engine's air-fuel ratio (AFR) can be appropriately controlled.

The baseline engine was a throttle body injected SI engine, and there was some discussion in the earlier phase of the program of the possible need to move to port-fuel injection (PFI). Taking that step was ultimately proven to be unnecessary, and sufficient control was achieved with an advanced form of throttle body injection. However, advanced injection hardware and controls were not available from the OEM during the program, thus an advanced third-party system produced by EControls was installed on the engine that used a model-based control approach and employed proprietary injection and mixing hardware. As the ISX 12-G engine employed a high-pressure loop EGR system that complicated air-fuel ratio control, the proprietary mixing hardware was essential to achieve very good mixing between the main air-fuel and EGR flows.

The final catalyst system chosen was a combination of close-coupled three way catalyst (ccTWC) and conventional under-floor TWC (ufTWC), which is similar to configurations used on Tier 2 gasoline light-duty passenger vehicles. A schematic of the system is shown in the figure below.

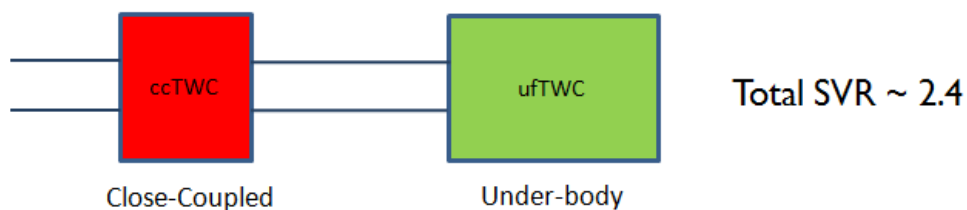


FIGURE 271. SCHEMATIC OF FINAL LOW NO_x CNG ENGINE AFTERTREATMENT SYSTEM

The tables below show the results of the final tests on the Low NO_x demonstration engine using the Final Aged parts, as compared to the Baseline Engine. Table 94 shows a comparison of tailpipe NO_x emissions between the Low NO_x and Baseline engines over regulatory test cycles. In general the results show roughly an order of magnitude reduction in tailpipe NO_x emissions for the Low NO_x engine, as compared to the Baseline. For all regulatory test cycles, tailpipe NO_x emissions were below the 0.02 g/hp-hr target.

TABLE 94. CNG ENGINE NO_x EMISSIONS COMPARISON – LOW NO_x ENGINE (FINAL AGED PARTS) VERSUS BASELINE, G/HP-HR

Engine	FTP			RMC-SET	WHTC		
	Cold	Hot	Composite		Cold	Hot	Composite
Baseline	0.247	0.093	0.115	0.012	0.310	0.308	0.308
Low NO_x Engine	0.065	0.001	0.010	0.001	0.043	0.006	0.011
% Reduction	74%	99%	91%	92%	86%	98%	96%

Table 95 shows a summary of GHG and NH₃ emissions for both the Low NO_x and Baseline engines. The Low NO_x engine generally showed significantly lower NH₃ and methane emissions, as compared to the Baseline engine, which can be attributed to the improved air-fuel ratio control. The CO₂ emissions impact varied by the cycle, but in general there was an increase of about 1% on duty cycles which featured a cold-start, due to the impact of the rapid cold-start warm-up strategy. However, this was generally offset by lower methane emissions in terms of overall GHG impact.

TABLE 95. CNG ENGINE COMPARISON OF GHG AND NH₃ EMISSIONS – LOW NO_x ENGINE (FINAL AGED PARTS) VERSUS BASELINE

Engine	Pollutant	FTP	RMC-SET	WHTC
Baseline	CH ₄ , g/hp-hr	0.96	1.20	1.54
	NH ₃ , avg ppm	76	162	100
	CO ₂ , g/hp-hr	542	454	510
Low NO _x Engine	CH ₄ , g/hp-hr	0.15	0.93	0.10
	NH ₃ , avg ppm	52	37	44
	CO ₂ , g/hp-hr	547	445	513
% Change from Baseline	CH ₄	-84%	-23%	-94%
	NH ₃	-32%	-77%	-56%
	CO ₂	0.9%	-2.0%	0.6%

It should be noted that the cycle average NH_3 concentration did exceed the program target of 10 ppm, even on the Low NO_x engine. However, this was due to a shortcoming of the AFR controller, which did not include an oxygen storage model for the catalysts at the time of development. However, such controls technology is in production on Tier 2 gasoline engines, and could be added to a heavy-duty CNG engine given sufficient development time and resources. The resulting improved AFR control would likely result in lower NH_3 emissions.

Table 96 shows a summary of the test results of both the Low NO_x and Baseline engines over vocational cycles, namely the NYBC, Cruise Creep and OCTA cycles. The Low NO_x CNG engine is able to achieve NO_x levels below 0.02 g/hp-hr over all the cycles, as well as generally lower methane and NH₃ levels compared to the baseline. This result implies that the CNG engine will be able to provide sustained low NO_x levels even during lower load field duty cycles. In addition, while the highly transient nature of some of these cycles proved problematic for the controls on the Baseline engine, the improved air-fuel ratio control on the Low NO_x engine was more robust to this kind of operation. That said, there is still room for improvement as evidenced by the NH₃ emission levels observed on some of these cycles. It should be noted that the same improvements discussed earlier, such as the inclusion of a robust oxygen storage model, would benefit these cycles as well.

**TABLE 96. CNG ENGINE VOCATIONAL CYCLE EMISSIONS – LOW NO_x ENGINE
(FINAL AGED PARTS) VERSUS BASELINE**

Cycle	Baseline			Low NO _x Engine		
	NO _x , g/hp-hr	NH ₃ , ppm	CH ₄ , g/hp-hr	NO _x , g/hp-hr	NH ₃ , ppm	CH ₄ , g/hp-hr
NYBC	0.91	12	1.9	0.002	25	0.5
Cruise Creep	0.07	124	1.6	0.002	85	1.0
OCTA	0.11	92	1.1	0.0003	47	0.04

Overall, the results indicate the feasibility of reaching NO_x levels below 0.02 g/hp-hr on a CNG engine. While the catalysts are somewhat larger than those used on current 2010 CNG engines, this can be improved over time. The required improvements in air-fuel ratio control are achievable using available control technologies, and controls can be further improved via the incorporation of more control approaches already in use for light-duty gasoline engines. In addition, further improvements in performance are likely available via the adoption of port fuel injection approaches, although this did not prove necessary to reach 0.02 g/hp-hr on ISX12-G engine. Based on the data shown above and what is available in the public domain, it appears that some form of limit on NH₃ emissions may be important in ensuring robust air-fuel ratio controls.

It should be noted that the advent of heavy-duty OBD requirements for CNG engines in the 2018 timeframe will introduce additional work effort on the introduction of a low NO_x CNG engine. However, the oxygen-storage based approaches used for TWC catalyst monitoring on smaller gasoline catalysts should be applicable, although they will need to be calibrated and tested. Misfire monitoring should also be noted as a challenge on engines of this size that will be installed in a variety of different larger applications.

4.1.1 CNG Engine Recommendations and Next Steps

The CNG engine demonstration effort was generally successful in showing the feasibility of meeting a 0.02 g/hp-hr level with a stoichiometric CNG engine. The demonstration was accomplished with technologies available in the marketplace, and with systems feasible for production. Given that there is a production CNG engine now available that is certified to a level of 0.02 g/hp-hr under the CARB Voluntary Low NO_x standard, it is unlikely that further development efforts are needed regarding demonstration.

It is understood that there are some similarities between the current program engine and the now certified Cummins 9L CNG engine. Both engines are stoichiometric CNG engines equipped with EGR, and both engine approaches did not require the use of port fuel injection. The engine for this program was a larger engine at a 12L displacement, with a relatively low power rating. The catalyst strategy was different, in that the program 12L engine utilized a close-coupled light-off catalyst in addition to an under-floor main catalyst, whereas the 9L engine utilizes a single catalyst bed. The information from both engines indicate that there are multiple ways to approach ULN NO_x levels with a CNG engine, with regard to aftertreatment architecture and controls. Manufacturers will determine which options are most efficient for each given engine.

The results of the program, as well as information available about the certified 9L engine, do imply some areas that should be monitored in the event of a widespread deployment of CNG engines to meet a 0.02 g/hp-hr level, even under the voluntary program.

- Tailpipe NH₃ emissions – Tailpipe ammonia levels, while lower than the baseline engine, were still quite high in certain situations. This was the case for both regulatory cycles and some of the vocational cycles. It is understood that this is the case for production offerings as well at the moment. This can generally be mitigated by improved air-fuel ratio controls, but the question remains whether such controls will be deployed in the absence of a regulatory driver. Given that NH₃ is itself an irritant, and can also be a precursor for secondary PM formation, it may be important to ensure that tailpipe NH₃ remains well controlled in the event of a large-scale adoption of CNG engines.
- Methane emissions – While CH₄ emissions were generally lower on the Low NO_x engine than for the Baseline, methane was still above the 0.1 g/hp-hr cap for Phase 1 and Phase 2 GHG standards, in some cases by a significant amount, including on some Vocational cycles. While the total GHG emissions were below the 2017 Phase 1 targets, the methane emissions nevertheless offset some of the GHG benefit of the CNG fuel. Given that the increased methane can also be mitigated at least in part by improved AFR controls, it may be important to ensure that such controls are deployed in the event of a large-scale adoption of CNG engines.
- It is apparent from the results that even a small loss of air-fuel ratio control can result in large increases in NO_x and other emissions (such as ammonia and methane). Given the importance of air-fuel ratio control in maintaining low NO_x levels, it will be important to that this control is maintained over time. It is understood that HD-OBD requirements will apply to CNG engines starting in 2018, and robust AFR monitoring will be important to insuring that the low NO_x potential of stoichiometric CNG engines is realized in the field. The level of effort associated with such robust OBD monitoring should not be underestimated, and this may be an area where future development or demonstration could be warranted. It is assumed that the same methodology associated with light-duty gasoline will be applicable, but it may be important to validate this assumption.

4.2 Diesel Engine – Volvo MD13TC



The diesel engine platform presented a much greater challenge to achieving ULN emissions levels. As with all diesel engines, the combination of lean exhaust and lower exhaust temperatures makes NO_x control particularly difficult. However, the Volvo MD13TC engine utilized for this program was a particularly challenging platform due to its use of high temperature waste heat recovery via a mechanical turbocompound system. This resulted in very low exhaust temperatures which made reaching ULN levels particularly challenging. The architecture of the system prevented any method of bypassing the system for cold-start and low temperature operation from being implemented within the scope and budget of the program. This likely resulted in a more complicated aftertreatment system.

Although this engine is representative of one OEM's approach to upcoming GHG standards for certain applications in 2017 and beyond, at this point it appears that this engine architecture represents something of a corner case with respect to the broader industry. As such, the resulting technology approach to achieving ULN levels should likely be viewed as closer to a "worst-case" example of what is required to reach 0.02 g/hp-hr, rather than a typical application. Nevertheless, an example of this type of engine is currently in production in the U.S., and therefore this case remains a useful one in illustrating the challenge that can be presented by adopting different approaches to meeting engine system efficiency targets.

4.2.1 Implications of Aftertreatment Screening Results

The large number of diesel aftertreatment system options that were screened in the program provided a useful body of information for examining the potential of reaching ULN levels, both on this engine platform and on other platforms. Figure 272, which is repeated from earlier in the report, provides a good summary of the potential of various approaches for reaching composite FTP NO_x levels near or below 0.02 g/hp-hr. The final configuration demonstrated on the engine required SCRF, a PNA for cold-temperature NO_x storage, and a large amount of supplemental heat addition in the form of a mini-burner to reach levels below the 0.02 g/hp-hr target. This system raised concerns with regard to both complication and robustness. However, a significant number of less complicated options were able to reach levels of 0.03 g/hp-hr,

without large amounts of supplemental heat addition. Those results indicate that with a more favorable exhaust temperature profile, some of these options may be viable for reaching levels below 0.02 g/hp-hr.

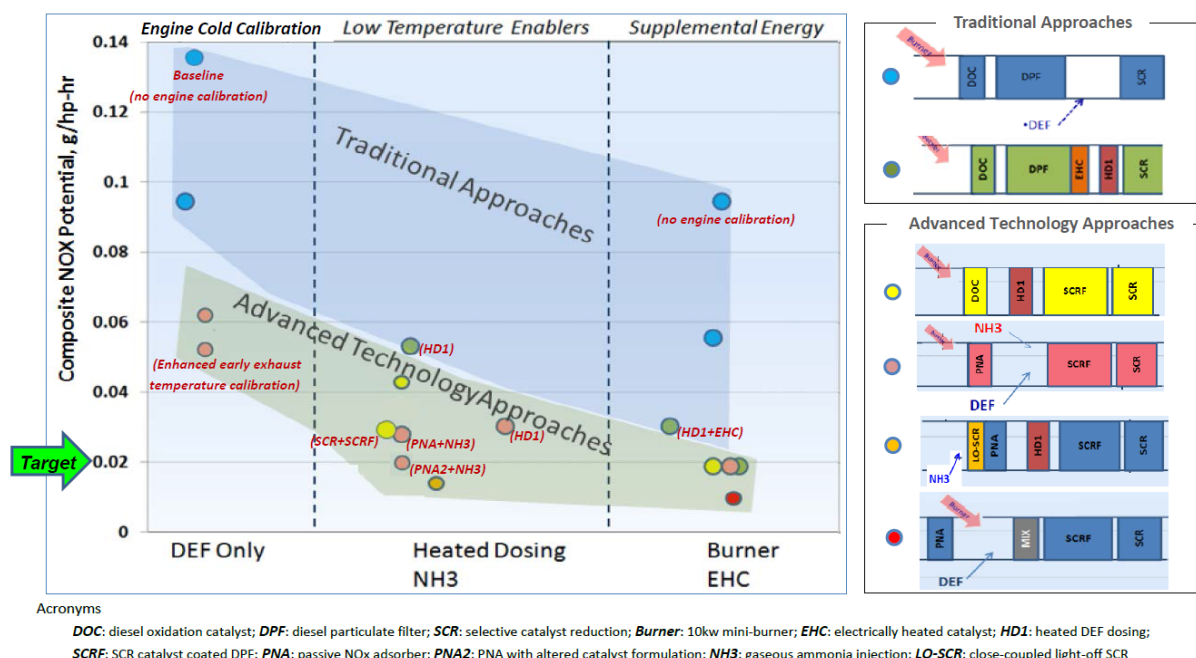


FIGURE 272. COMPOSITE ULTRA-LOW NO_x POTENTIAL OF VARIOUS TECHNOLOGY CONFIGURATIONS

A limited set of screening tests were conducted to simulate such an environment, and these indicated a reduced need for supplemental heat, possibly permitting a simpler system configuration. However, given that such a change was not possible for the MD13TC engine, this possibility was not pursued further, due to time and budget constraints. Nevertheless, it would be valuable to examine these options in the context of a different engine platform that could be modified to present a more favorable exhaust temperature profile.

4.2.2 Diesel Engine NO_x Emission Results and Discussion

The final results for the diesel Low NO_x engine are summarized in the tables below, along with the Baseline engine results for comparison. Results are given for the final demonstration parts in both the Fresh and Final Aged states. Results for the Development Aged parts are also shown for comparison. Table 97 presents a comparison of tailpipe NO_x results, while Table 98 shows the aftertreatment performance in terms of NO_x reduction from the engine-out emission levels.

As can be seen in the tables, the Development Aged parts were able to demonstrate emission levels below the 0.02 g/hp-hr target. However, although the Final parts demonstrated levels at half the target when fresh, the Final Aged parts were not below the target, and generally demonstrated a tailpipe level on the order of 0.034 to 0.038 g/hp-hr, depending on the cycle. This represented a loss of roughly 0.9% conversion over the FTP cycle in NO_x conversion. The

change observed on the WHTC was very similar, while the RMC-SET showed a 1.3% loss of conversion. Nevertheless, the Final Aged system still produced a tailpipe NO_x reduction of 70 to 75% from the Baseline on transient cycles, and 55% on the RMC, despite the difficulties encountered in the final aging process.

TABLE 97. DIESEL ENGINE NO_x EMISSIONS COMPARISON –LOW NO_x ENGINE VERSUS BASELINE, G/HP-HR

Engine		FTP			RMC-SET	WHTC		
		Cold	Hot	Composite		Cold	Hot	Composite
Baseline		0.710	0.047	0.140	0.084	0.492	0.049	0.115
Low NO _x Engine	Devel Aged	0.062 ¹	0.008	0.016¹	0.015	0.089 ¹	0.008	0.019
	Final Parts Fresh	0.027	0.005	0.008	0.010	n/a	n/a	n/a
	Final Parts Aged	0.114	0.021	0.034	0.038	0.149	0.018	0.036
% Reduction from Baseline	Devel Aged	91%	83%	89%	82%	82%	84%	83%
	Final Aged	84%	55%	76%	55%	70%	63%	69%

¹ Note: Development PNA was slightly compromised by raw fuel exposure due to a cold-start engine malfunction that occurred during development.

TABLE 98. DIESEL ENGINE NO_x AFTERTREATMENT PERFORMANCE – LOW NO_x ENGINE VERSUS BASELINE

Engine		FTP			RMC-SET	WHTC		
		Cold	Hot	Composite		Cold	Hot	Composite
Baseline	Engine-Out, g/hp-hr	2.8	3.0	3.0	2.6	3.1	3.5	3.4
	% Conversion	75%	98.4%	95.2%	96.7%	84%	98.6%	96.7%
Low NO _x Engine	Engine-Out, g/hp-hr	2.8	3.0	3.0	2.0	3.0	3.4	3.4
	Devel Aged, % Conversion	97.7%	99.7%	99.5%	99.3%	97.5%	99.8	99.4%
	Final Parts Fresh, % Conversion	99.0%	99.8%	99.7%	99.5%	n/a	n/a	n/a
	Final Parts Aged, % Conversion	95.8%	99.3%	98.8%	98.2%	95.1%	99.5%	98.8%

% Conversion calculated as [Engine-Out – Tailpipe] / Engine-Out, based on TP results from table above

About half of the change in the composite FTP can be attributed to a 3% loss of cold-start FTP conversion efficiency, which was due primarily to a loss of storage capacity on the PNA. It is not known how much of this change was the result of normal aging, and how much could be the result of the large soot and HC exposure that occurred during the canning failure. The results for the Development parts in comparison to the Fresh results indicate that it is possible to lose some storage capacity on the PNA and still produce results under 0.02 g/hp-hr, if hot-start performance remains stable.

The other half of the change can be attributed to a 0.5% loss of hot-start FTP conversion performance, primarily due a combination of degradation on the SCRF, and a small increase in the tendency of the system to oxidize ammonia into NO. It is not clear how much of this degradation was the result of normal aging, and how much could have resulted from high soot loadings and localized exotherm due to the matting material from the canning failure. The change in hot performance could also be related to migration of precious metal from the PNA to the SCRF, however this cannot be verified without a destructive post-mortem analysis of the parts. The RMC-SET results indicate similar mechanisms of degradation to the hot-start FTP, but to a slightly larger degree due to the higher cycle temperatures.

Overall, the Low NO_x Engine was able to achieve substantial reductions in tailpipe NO_x levels, on the order of 60 to 75% from the Baseline engine, generally demonstrating a level of 0.035 g/hp-hr with aged parts. This level was demonstrated on a test article with unusually low exhaust temperatures (due to the mechanical turbocompound system), and with parts that may have been compromised in part by an unusual canning failure during the aging process. The results with the Development Aged parts indicate that more performance is potentially available if the robustness of some of the aftertreatment components can be improved somewhat.

It should be further noted that the robustness of these aftertreatment components remains an area for further development. The improvement of the PNA formulation to make the technology more robust during exposure to rich conditions is an active development area. Furthermore, the incorporation of a small precious metal layer upstream of the PNA could be an effective countermeasure to prevent degradation due to localized exposure to higher molecular weight hydrocarbons, which occurred during the early aging process due to coke and soot buildup. In a similar fashion, the durability of SCRF is another very active current area of development, given the interest in that technology for a number of applications beyond the Low NO_x application explored in this program. Therefore it is reasonable to assume that these systems can be made more durable in the future. Whether such developments will be sufficient to ensure durable performance at tailpipe levels below 0.02 g/hp-hr is a valid question, but the performance of the Final Aged parts even in the face of an abnormal failure is a source of some encouragement.

Given the results shown for the Final Aged parts, it is clear that the development of a robust system for this low temperature engine platform at a tailpipe NO_x level below 0.02 g/hp-hr is a significant challenge. The margin for loss of performance due to degradation on this engine is small, only about 0.3% composite conversion. Even with more flexibility on a different engine platform that margin is unlikely to be greater than 0.5%. However, due to the unusual failure that occurred during the Final Aging process, it is not clear exactly what the level

of conversion performance loss would have been if Final Aging had proceeded without incident. Discussions with the catalyst supplier have indicated that the change in hot-start and RMC-SET performance appeared unusual based on the aging conditions that were seen outside of the failure itself. If time and budget were available for a repeat of the Final Aging experiment and demonstration tests, it would be possible to resolve some of the questions related to the final performance level.

The final aftertreatment configuration was highly influenced by the low engine-out exhaust temperatures due to the presence of the mechanical turbocompound WHR system on the MD13TC engine. With regard to the key system components described earlier, it is likely that the SCRF would remain a key component for reaching ULN levels, even on a different engine platform. However, it is likely that the requirement for both low temperature NO_x storage (in the form of a PNA) and a large amount of supplemental heat addition (in the form of the mini-burner) would not be as great on a different engine platform. A higher engine-out exhaust temperature, or greater flexibility to increase exhaust temperature could reduce the need for supplemental heat addition, and thus allow the use of a less complicated heat system than the mini-burner. Alternatively, more flexibility on the engine platform in terms of both temperature and NO_x could permit the removal of the PNA, or at least could allow for reduced reliance on the NO_x storage function. Lessons learned, and information gained from this program could be leveraged to allow the examination of ULN solutions for other engine platforms, if time and funding are available to do so. The results of the extensive screening effort conducted on this program indicate a number of potential directions for future development of ULN technologies.

4.2.3 Diesel Engine GHG Results and Discussion

A comparison of GHG emissions between the Low NO_x engine and the Baseline engine is given below in

Table 99. These results summarize CO₂ and N₂O emissions over the various regulatory cycles.

The N₂O emissions show an increased tendency towards N₂O generation with the final Low NO_x configuration, and the Final Aged parts indicated N₂O levels just at the 0.1 g/hp-hr cap standard specified for GHG Phases 1 and 2. However, this increase for the Final Aged parts may be due in part to precious metal migration, and it is not clear how much of that may have resulted from the canning failure incident during Final Aging. It is clear, however, that the Low NO_x Engine would have been well over the 0.05 g/hp-hr limit that was originally proposed for the GHG Phase 2 program, even without this possible noise factor.

TABLE 99. DIESEL ENGINE COMPARISON OF GHG EMISSIONS – LOW NO_x ENGINE VERSUS BASELINE

Engine		Pollutant	FTP			RMC-SET	WHTC Composite
			Cold	Hot	Composite		
Baseline		CO ₂ , g/hp-hr	574	543	547	458	485
		N ₂ O, g/hp-hr	0.024	0.047	0.044	0.05	0.06
Low NO _x Engine	Devel Aged	CO ₂ , g/hp-hr	600	547	555	462	491
		N ₂ O, g/hp-hr	0.075	0.087	0.085	0.033	0.085
	Final Aged	CO ₂ , g/hp-hr	604	549	558	464	494
		N ₂ O, g/hp-hr	0.101	0.108	0.107	0.055	0.086

For the FTP cycle, which is used to assess Vocational applications, the Final Aged values indicate an increase in GHG emissions over the baseline of 5.3% on the cold-start FTP and 1.1% on the hot-start FTP, resulting in a composite increase of 2%. The cold-start increase is due to a combination of 2.5% from engine calibration changes and 2 to 2.5 % from fuel consumption by the mini-burner. A small amount is also likely due to increased backpressure, likely due to ash loading on the SCRF. The hot-start increase is due to a combination of about 0.5% to 0.7% fuel consumed by the mini-burner for thermal management, with the remainder attributed to increased backpressure. However, these values should be adjusted upwards by a further 0.6% to account for the impact of increased SCRF regeneration and the fuel consumption required to drive the air for the mini-burner. Therefore the final composite FTP impact on GHG is on the order of a 2.5% increase on the FTP. The WHTC is very similar at 2.4%.

The RMC-SET, which is the cycle relevant for Tractor application, showed an increase of 1.3% for the Final Aged parts, likely due primarily to the increased backpressure of the final system. This should again be adjusted to account for increased SCRF regeneration, which would result in a final GHG impact of 1.6% on the RMC-SET cycle. It should be noted that the mini-burner did not activate on the RMC-SET due to the elevated temperature of that cycle.

These values represent a substantial increase in GHG emissions and fuel consumption compared to the baseline engine, especially in light of the upcoming Phase 2 GHG limits. It is likely that a portion of this could be mitigated by improved thermal packaging of the aftertreatment system to reduce the need for supplemental heat, and from an improved mixing design that helps to lower overall system backpressure.

However, it should be noted that a significant portion of the GHG increase observed was due to the need to add substantial amounts of heat to the exhaust in order to counteract the loss of exhaust heat due to the presence of the mechanical turbocompound system on the MD13TC engine. Given that the system could not be bypassed or modified, the presence of the turbocompound likely increased the GHG impact of the final Low NO_x approach for this engine. In the case of the FTP cycle, the need for supplemental heat addition essentially eliminated the likely benefit of the turbocompound system. For the RMC-SET there is still likely a net gain from the turbocompound, but its presence still results in a more complicated aftertreatment system. Given that this engine architecture does not appear to represent the mainstream

approaches to meeting upcoming GHG limits, it is likely that the GHG impact observed on this engine is at the high end of the spectrum as compared to other engines.

Nevertheless, it does appear that some level of impact in GHG emissions should be anticipated as a consequence of adopting a Low NO_x standard on the order of 0.02 g/hp-hr. This would result in the likely need to expend more effort to meet GHG Phase 2 standards than would otherwise be the case. However, the magnitude of this impact is also likely to be smaller than what was observed during this program, on this particular engine.

Further development efforts to apply ULN technologies to other platforms would be beneficial in determining the impact of a given Low NO_x standard on the overall industry effort required to meet Phase 2 GHG targets. Such information will be important in determining where an eventual regulatory standard should be set.

4.2.4 Diesel Engine Vocational Cycle Results and Discussion

The results for the three Vocational cycles are shown in Table 100 below. Different behaviors were observed for each of the three cycles, as can be seen from the results in the table, but certain consistent trends were still apparent in all three cycles. First, the Low NO_x engine had consistently lower tailpipe emissions than the Baseline engine for all three cycles, though the amount of reduction varied. Second, on two of the three cycles, the NYBC and the Cruise Creep, while performance on the Low NO_x engine was better, aftertreatment conversion was still not as high as the levels observed on the FTP and RMC cycles. NO_x conversion on these two cycles for the Low NO_x engine was 90% and 82% respectively. While better than the baseline, this is not nearly as good as the 98 to 99% conversion observed on the regulatory cycles, indicating room for further improvement. It should be noted that the performance of both engines on these two cycles could likely be improved with further calibration effort, although it appears that the Low NO_x engine likely has more flexibility to reach lower levels. Interestingly, on these cycles, little impact on fuel consumption and CO₂ was observed when comparing the Low NO_x engine to the Baseline.

TABLE 100. DIESEL ENGINE VOCATIONAL CYCLE EMISSIONS – LOW NO_x ENGINE (FINAL AGED PARTS) VERSUS BASELINE

Cycle	Baseline				Low NO _x Engine				% TP NO _x Reduction
	EO NO _x , g/hp-hr	TP NO _x , g/hp-hr	Fuel Rate, kg/hr	CO ₂ , g/hp-hr	EO NO _x , g/hp-hr	TP NO _x , g/hp-hr	Fuel Rate, kg/hr	CO ₂ , g/hp-hr	
NYBC	6.1	2.3	5.3		3.9	0.4	5.3		83%
OCTA	3.8	0.023		529	2.7	0.006		534	74%
		NO _x , g/hr	Fuel Rate, kg/hr			NO _x , g/hr	Fuel Rate, kg/hr		
Cruise Creep - 10 cycles	72	13.3	2.8		41	7.5	2.8		44%

Cruise Creep - last 3 cycles	71	27			40	11.3			58%

On the NYBC cycle, the Low NO_x engine performed very well, and demonstrated an 83% reduction in tailpipe emission from the Baseline, relatively similar to what was observed for the reduction observed on the regulatory cycles, albeit starting from a much higher baseline emission rate. It appeared that the updated engine calibration was slightly more efficient under these operating conditions, which likely offset the relatively minor use of the thermal management system on the NYBC cycle. In the case of both engines, the fact that average engine power is only 5% of maximum on this cycle makes the brake-specific NO_x values seem quite large.

The Cruise Creep cycle was less favorable for the Low NO_x engine with its current calibration, and the engine was much more reliant on the thermal management system calibration to maintain improved NO_x performance. Still, the Low NO_x engine was able to achieve roughly a 50% reduction in tailpipe NO_x, without a measureable penalty on fuel consumption. It should be noted that the Cruise Creep NO_x is reported as mass rate because the work is so low that the brake-specific NO_x becomes arbitrarily large.

The OCTA bus cycle, while being highly transient in nature had a significantly higher load factor than the other two vocational cycles. Both the Baseline and Low NO_x engines were well within their operating range for these cycles, and both had tailpipe emissions well below the levels observed on the Regulatory cycles. The Low NO_x engine was well below 0.02 g/hp-hr, but there was a 1% increase in CO₂ emissions on this cycle, likely the result of a combination of engine calibration and backpressure. Thermal management was not active on this cycle, as temperatures were well above the range where it was needed.

Overall these results indicate that there is much work that can be done to reduce the emission performance gap between regulatory cycle operation and low load field cycle operation. The Stage 2 program effort will examine the effect of further optimization of the Low NO_x engine for low load cycles. However, these results do provide some very encouraging indications with respect to the potential for further emission reductions on low load cycles.

4.2.5 Diesel Engine Recommendation and Next Steps

Overall, the diesel program results indicate that there is technology available to achieve ULN NO_x levels substantially lower than current tailpipe NO_x levels, with a 0.035 g/hp-hr demonstrated using aged parts, despite a challenging low temperature platform and unusual failure during aging. The results indicate that there is available technology to reach levels at or near 0.02 g/hp-hr, but there are some significant challenges with respect to system robustness and complexity. The Final Aged system was not below the target level of 0.02 g/hp-hr, however it did still demonstrate significant NO_x reduction, especially over some of the low temperature Vocational cycles.

More effort could also be directed at reducing the GHG impact observed in the program, which was on the order of 1.5% to 2.5% depending on the regulatory cycle, although it should be noted that the Vocational cycles indicated either no impact on GHG or a much smaller impact than the regulatory cycles. Several important questions are left open at the conclusion of the program, and these suggest direction for further efforts.

- Final Aging issues and the NO_x potential of the final configuration for the MD13TC engine – as detailed earlier, the abnormal issues that were encountered during Final Aging, and especially the canning failure, leave some question as to whether at least some of the observed degradation in the aftertreatment system was not representative. In order to answer these questions, if time and budget were available it would be desirable to repeat the Final Aging and testing experiment on another set of parts. This would answer questions regarding abnormal versus normal degradation and provide a more definitive answer regarding the robustness of the system.
- Performance potential of ULN technology – The low temperature presented by the MD13TC platform, and the limited options for addressing that on engine, likely resulted in a more complicated aftertreatment system technology package being needed to reach ULN levels. As discussed earlier, this package is likely to represent more of a worst case of the level of effort required to reach ULN levels. In order to make a more broadly applicable assessment, it would be useful to look at a second engine platform that is more representative of the broader industry approach to GHG Phase 2 targets. Such an effort could leverage the information and lessons learned from the current program in order to generate another valuable data point for determining the technical feasibility for ULN levels.
- GHG Impact of ULN technology – the MD13TC platform represents a particular challenging case due to the use of the turbocompound technology. This drove the development of a system with a significant GHG impact due to the need for large amounts of supplemental heat addition. While this is useful for looking at a worst case example, it would be preferable to look at another more representative platform in order to make a more broadly applicable determination of the impact of a given Low NO_x standard on the overall industry effort required to meet Phase 2 GHG targets. The knowledge gained and lessons learned from the current effort could be leveraged to apply ULN technology on a more flexible and representative engine platform.
- Low load and vocational field cycles – The current program was focused primarily on regulatory cycles, given that these are the primary current targets for any emissions development. The Vocational cycle tests give some insight into the potential for low load cycle emission controls, and there are some promising initial signs, but much more work can be done in this area. A significant amount of information is needed with regard to the potential for low load cycle emissions controls, and the associated GHG impact of those controls. The Stage 2 effort which is just getting under way will provide some of this information, but more effort in this area is recommended. Any other efforts on a different engine platform should incorporate low load cycle NO_x control as a target, rather as a relatively small demonstration test. A robust regulatory scheme to insure real

world NO_x reductions on low load duty cycles will hopefully be an important feature of any upcoming NO_x regulation.

- Measurement and testing variation – The current program has produced a test article that can generate emissions at ULN levels, with hot-start emissions in the area of 0.01 g/hp-hr in some cases. The program provided an initial data set regarding the repeatability the test and measurement process at these levels, but this remains a limited data set that leaves several questions open with regard to the test process. These include questions regarding the influence of different preconditioning approaches, test cell environment, and other factors. In addition, other portions of the regulatory process, such as in-use measurement and PEMS, will need to be examined at these much lower levels. A robust effort to examine these issues would be recommended, and this is an area where a cooperative program could prove valuable. The current test article could be used to examine such issues, and the data set from the current program could be analyzed in detail to look at measurement related questions. It should be noted that these issues apply not only to NO_x measurement, but also to the accurate determination of small changes in CO₂ that are critical for assessing the GHG impact, wherein even changes less than 0.5% are considered very important.

While this program has provided much valuable information regarding the potential for ultra-low NO_x levels, additional investigation in the recommended areas would be valuable to help fully inform future low NO_x regulatory efforts.

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APPENDIX A
SECOND-BY-SECOND VOCATIONAL CYCLE SCHEDULES

TABLE A-1. NYBCX4 CYCLE

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1	0	0	51	0	0	101	0	0	151	0	0
2	0	0	52	0	0	102	0	0	152	0	0
3	0	0	53	0	0	103	0	0	153	0	0
4	0	0	54	0	0	104	0	0	154	0	0
5	0	0	55	0	0	105	0	0	155	0	0
6	0	0	56	0	0	106	0	0	156	0	0
7	0	0	57	0	0	107	0	0	157	0	0
8	0	0	58	0	0	108	0	0	158	0	0
9	0	0	59	0.758929	27.89713	109	0	0	159	0	0
10	0	0	60	29.44643	75.07435	110	0	0	160	0	0
11	0	0	61	67.60714	50.77779	111	0	0	161	0	0
12	0	0	62	78.41071	71.45981	112	0	0	162	0	0
13	0	0	63	66.99107	46.06938	113	0	0	163	0	0
14	0	0	64	73.83036	62.58143	114	0	0	164	0	0
15	8.428571	73.96348	65	29.20536	-1	115	0	0	165	1.357143	44.63394
16	49.66964	49.90602	66	29.20536	9.52581	116	0	0	166	29.92857	40.36464
17	77.85714	75.56562	67	33.30357	28.09184	117	0	0	167	56.69643	55.01315
18	56.54464	-1	68	38.55357	36.13183	118	0	0	168	76.88393	60.86539
19	13.46429	22.34273	69	40.54464	17.24001	119	0	0	169	29.49107	-1
20	2.651786	5.967185	70	39.60714	5.164195	120	0	0	170	3.330357	20.42918
21	8.8125	12.24594	71	36.58036	-1	121	0	0	171	5.017857	6.094688
22	18.16964	2.275748	72	33.73214	14.25033	122	0	0	172	7.910714	8.695512
23	44.5625	21.53246	73	38.375	28.35443	123	0	0	173	0	0
24	64.40179	42.07195	74	40.57143	16.18787	124	0	0	174	0	0
25	69.59821	53.42187	75	52.92857	80.68386	125	0	0	175	0	0
26	18.13393	0	76	67.89286	99.66096	126	0	0	176	0	0
27	6.125	19.16606	77	84.70536	98.27023	127	0	0	177	0	0
28	3.357143	7.496072	78	96.4375	96.8401	128	0	0	178	0	0
29	8.276786	14.03339	79	69.19643	98.44166	129	0	0	179	0	0
30	0	0	80	80.39286	98.84011	130	0	0	180	0	0
31	0	0	81	84.58036	-1	131	0	0	181	0	0
32	0	0	82	75.1875	8.727714	132	0	0	182	0	0
33	0	0	83	58.28571	19.40349	133	0	0	183	0	0
34	0	0	84	37.69643	40.39512	134	0	0	184	0	0
35	0	0	85	40.4375	30.46129	135	0	0	185	0	0
36	0	0	86	40.84821	33.72064	136	0	0	186	0	0
37	0	0	87	37.63393	-1	137	0	0	187	0	0
38	0	0	88	31.11607	-1	138	0	0	188	0	0
39	0	0	89	23.49107	-1	139	0	0	189	0	0
40	0	0	90	20.5	-1	140	0	0	190	0	0
41	0	0	91	14.25893	-1	141	0	0	191	0	0
42	0	0	92	33.59821	-1	142	0	0	192	0	0
43	0	0	93	22.80357	-1	143	0	0	193	0	0
44	0	0	94	9.169643	10.00105	144	0	0	194	0	0
45	0	0	95	2.705357	7.576401	145	0	0	195	0	0
46	0	0	96	5.553571	6.960098	146	0	0	196	0	0
47	0	0	97	0	0	147	0	0	197	0	0
48	0	0	98	0	0	148	0	0	198	0	0
49	0	0	99	0	0	149	0	0	199	0	0
50	0	0	100	0	0	150	0	0	200	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
201	0	0	251	0	0	301	0	0	351	0	0
202	0	0	252	0	0	302	0	0	352	0	0
203	0	0	253	0	0	303	0	0	353	0	0
204	0	0	254	0	0	304	0	0	354	0	0
205	0	0	255	0	0	305	0	0	355	0	0
206	0	0	256	0	0	306	0	0	356	0	0
207	0	0	257	0	0	307	0	0	357	0	0
208	0	0	258	0	0	308	0	0	358	0	0
209	0	0	259	0	0	309	0	0	359	0	0
210	12.55357	71.51749	260	0	0	310	0	0	360	0	0
211	54.8125	49.91657	261	0	0	311	0	0	361	0	0
212	86.63393	84.39607	262	0	0	312	0	0	362	0	0
213	92.33036	60.38129	263	0	0	313	0	0	363	0	0
214	63.83929	38.44917	264	0	0	314	0	0	364	0	0
215	42.91071	21.51204	265	0	0	315	0	0	365	0	0
216	31.10714	1.28921	266	0	0	316	0	0	366	0	0
217	31.65179	9.204982	267	0	0	317	0	0	367	0	0
218	34.11607	26.71505	268	0	0	318	0	0	368	0	0
219	37.40179	28.55656	269	0	0	319	0	0	369	0	0
220	37.76786	8.597729	270	0	0	320	0	0	370	0	0
221	33	-1	271	0	0	321	0	0	371	0	0
222	29	-1	272	0	0	322	0	0	372	0	0
223	14.92857	-1	273	0	0	323	0	0	373	0	0
224	5.705357	10.24958	274	0	0	324	0	0	374	0	0
225	0	0	275	0	0	325	0	0	375	0	0
226	0	0	276	0	0	326	0	0	376	0	0
227	0	0	277	0	0	327	0	0	377	0	0
228	0	0	278	0	0	328	0	0	378	0	0
229	0	0	279	0	0	329	0	0	379	0	0
230	0	0	280	0	0	330	0	0	380	0	0
231	0	0	281	0	0	331	46.10714	68.05551	381	0	0
232	0	0	282	0	0	332	81.74107	90.26944	382	0	0
233	13.26786	51.39829	283	0	0	333	90.78571	62.83144	383	0	0
234	42.78571	40.59021	284	0	0	334	75.83929	66.3202	384	0	0
235	60.79464	48.50009	285	0	0	335	32.21429	-1	385	0	0
236	67.42857	-1	286	44.0625	64.95887	336	32.53571	-1	386	0	0
237	31.32143	-1	287	79.85714	93.37173	337	33.83036	23.4417	387	0	0
238	11.51786	10.19789	288	97.39286	64.20672	338	37.72321	32.78956	388	0	0
239	12.97321	2.957214	289	69.9375	41.90339	339	41.63393	37.11298	389	0	0
240	2.258929	4.244089	290	45.44643	24.87013	340	43.00893	14.91014	390	7.517857	47.40657
241	4.303571	35.26	291	31.5	5.79369	341	40.42857	4.043395	391	38.38393	41.06525
242	35.35714	36.91512	292	29.89286	3.573217	342	36.95536	-1	392	65.5	60.1887
243	62.82143	54.84601	293	34.875	32.05164	343	33.04464	-1	393	82.97321	63.77762
244	69.875	-1	294	39.4375	33.91503	344	18.15179	-1	394	28.25893	0
245	18.23214	-1	295	33.29464	-1	345	6.196429	9.805506	395	13.13393	2.657795
246	10.40179	8.996902	296	22.67857	-1	346	1.107143	11.42281	396	10.98214	8.270442
247	4.383929	1.499816	297	6.696429	8.306632	347	0	0	397	2.714286	10.85727
248	0	4.59275	298	3.375	12.40402	348	0	0	398	6.035714	7.222359
249	0	0	299	6.383929	3.632256	349	0	0	399	45.875	22.99262
250	0	0	300	0	0	350	0	0	400	67.57143	45.08743

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
401	73.10714	52.51843	451	0	0	501	31.14286	-1	551	0	0
402	16.17857	0	452	0	0	502	28.88393	-1	552	0	0
403	1.491071	13.09488	453	0	0	503	26.16071	-1	553	0	0
404	3.428571	18.83206	454	0	0	504	12.34821	8.574993	554	0	0
405	5.75	6.976592	455	0	0	505	19.25	-1	555	6.526786	62.09521
406	0	0	456	0	0	506	0	4.348675	556	50.96429	50.53358
407	0	0	457	0	0	507	0	0	557	68.40179	62.28794
408	0	0	458	0	0	508	0	0	558	60.83929	29.97316
409	0	0	459	0	0	509	0	0	559	47.55357	-1
410	0	0	460	0	0	510	0	0	560	6.910714	18.46374
411	0	0	461	0	0	511	0	0	561	8.026786	8.01328
412	0	0	462	0	0	512	0	0	562	11.09821	20.49628
413	0	0	463	0	0	513	0	0	563	24.79464	32.60014
414	0	0	464	0	0	514	0	0	564	45.13393	38.1572
415	0	0	465	0	0	515	0	0	565	49.07143	27.07767
416	0	0	466	0	0	516	0	0	566	11.26786	0
417	0	0	467	0	0	517	0	0	567	17.07143	11.53371
418	0	0	468	0	0	518	0	0	568	0	9.848402
419	0	0	469	0	0	519	0	0	569	0	0
420	0	0	470	0	0	520	0	0	570	0	0
421	0	0	471	0	0	521	0	0	571	0	0
422	0	0	472	0	0	522	0	0	572	0	0
423	0	0	473	0	0	523	0	0	573	0	0
424	0	0	474	0	0	524	0	0	574	0	0
425	0	0	475	0	0	525	0	0	575	0	0
426	0	0	476	0	0	526	0	0	576	0	0
427	0	0	477	0	0	527	0	0	577	0	0
428	0	0	478	0	0	528	0	0	578	0	0
429	0	0	479	0.142857	29.72761	529	0	0	579	0	0
430	0	0	480	0.660714	41.7899	530	0	0	580	0	0
431	0	0	481	41.625	80.45899	531	0	0	581	0	0
432	0	0	482	75.10714	82.16039	532	0	0	582	0	0
433	0	0	483	83.35714	56.17033	533	0	0	583	0	0
434	0	0	484	67.27679	58.82357	534	0	0	584	0	0
435	0	0	485	23.25	-1	535	0	0	585	0	0
436	32.88393	44.18858	486	10.83929	11.94045	536	0	0	586	0	0
437	57.19643	55.07564	487	25.875	34.00432	537	0	0	587	0	0
438	80.78571	74.1373	488	30.60714	40.49481	538	0	0	588	0	0
439	90.76786	-1	489	35.99107	30.68264	539	0	0	589	0	0
440	17.85714	27.09979	490	36.21429	4.338795	540	0	0	590	0	0
441	0	4.345105	491	33.83036	9.927051	541	0	0	591	0	0
442	7.464286	20.15004	492	38.5625	37.14431	542	0	0	592	0	0
443	0	0	493	47.69643	52.84161	543	0	0	593	0	0
444	0	0	494	56.25893	55.74333	544	0	0	594	0	0
445	0	0	495	59.09821	17.09889	545	0	0	595	0	0
446	0	0	496	56.16964	-0.13126	546	0	0	596	0	0
447	0	0	497	55.47321	12.47459	547	0	0	597	0	0
448	0	0	498	60.51786	36.95595	548	0	0	598	0	0
449	0	0	499	63.16964	47.8089	549	0	0	599	0	0
450	0	0	500	33.14286	-1	550	0	0	600	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
601	0	0	651	0	0	701	0	0	751	0	0
602	0	0	652	0	0	702	0	0	752	0	0
603	0	0	653	0	0	703	0	0	753	0	0
604	0	0	654	0	0	704	0	0	754	0	0
605	0	0	655	0	0	705	0	0	755	0	0
606	0	0	656	0	0	706	0	0	756	0	0
607	0	0	657	0	0	707	0	0	757	0	0
608	0	0	658	0	0	708	0	0	758	0	0
609	0	0	659	0	0	709	0	0	759	0	0
610	0	0	660	0.723214	68.32194	710	0	0	760	0	0
611	0	0	661	45.08036	50.57481	711	0	0	761	0	0
612	0	0	662	80.83929	93.81209	712	0	0	762	0	0
613	0	0	663	99.25893	72.95122	713	0	0	763	0	0
614	0	0	664	72.99107	48.74006	714	0	0	764	0.392857	27.7661
615	0	0	665	28.46429	-1	715	0	0	765	0	46.02924
616	26.47321	51.41794	666	22.17857	0	716	0	0	766	42.32143	67.92143
617	54.11607	41.49141	667	29.84821	34.79725	717	0	0	767	66.70536	50.92311
618	78.85714	63.72672	668	37.0625	44.92511	718	0	0	768	70.55357	42.02064
619	83.71429	-1	669	45.00893	48.00707	719	0	0	769	50.33929	-1
620	16.89286	23.51446	670	41.30357	-1	720	0	0	770	9.714286	16.02236
621	6.008929	4.024013	671	38.03571	-1	721	0	0	771	3.776786	7.96541
622	4.357143	9.364796	672	33.8125	-1	722	0	0	772	7.910714	13.91494
623	31.41071	31.40225	673	31.1875	25.73414	723	0	0	773	0	0
624	65.95536	37.4745	674	46.69643	78.33681	724	0	0	774	0	0
625	64.03571	56.70517	675	62.4375	98.31289	725	0	0	775	0	0
626	13.82143	-1	676	79.09821	98.86766	726	0	0	776	0	0
627	0	13.54386	677	95.77679	98.41694	727	0	0	777	0	0
628	0	0	678	68.61607	95.74533	728	0	0	778	0	0
629	0	0	679	77.64286	98.52749	729	0	0	779	0	0
630	0	0	680	87.13393	99.63082	730	0	0	780	0	0
631	0	0	681	89.70536	-1	731	0	0	781	0	0
632	0	0	682	79.75	-1	732	0	0	782	0	0
633	0	0	683	76.01786	11.2657	733	0	0	783	0	0
634	0	0	684	78.32143	31.94492	734	0	0	784	0	0
635	0	0	685	56.14286	45.7674	735	0	0	785	0	0
636	0	0	686	39.5	-1	736	0	0	786	0	0
637	0	0	687	38.92857	-1	737	0	0	787	0	0
638	0	0	688	36.8125	-1	738	0	0	788	0	0
639	0	0	689	23.375	-1	739	0	0	789	0	0
640	0	0	690	17.91964	-1	740	0	0	790	0	0
641	0	0	691	31.1875	-1	741	0	0	791	0	0
642	0	0	692	37.08929	-1	742	0	0	792	0	0
643	0	0	693	19.96429	-1	743	0	0	793	0	0
644	0	0	694	8.285714	7.85392	744	0	0	794	0	0
645	0	0	695	1.491071	11.32235	745	0	0	795	0	0
646	0	0	696	3.839286	7.322971	746	0	0	796	0	0
647	0	0	697	0	0	747	0	0	797	0	0
648	0	0	698	0	0	748	0	0	798	0	0
649	0	0	699	0	0	749	0	0	799	0	0
650	0	0	700	0	0	750	0	0	800	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
801	0	0	851	0	0	901	0	0	951	0	0
802	0	0	852	0	0	902	0	0	952	0	0
803	0	0	853	0	0	903	0	0	953	0	0
804	0	0	854	0	0	904	0	0	954	0	0
805	0	0	855	0	0	905	0	0	955	0	0
806	0	0	856	0	0	906	0	0	956	0	0
807	0	0	857	0	0	907	0	0	957	0	0
808	0	0	858	0	0	908	0	0	958	0	0
809	0	0	859	0	0	909	0	0	959	0	0
810	0	0	860	0	0	910	0	0	960	0	0
811	49.41071	64.26155	861	0	0	911	0	0	961	0	0
812	84.26786	85.96649	862	0	0	912	0	0	962	0	0
813	88.47321	52.76315	863	0	0	913	0	0	963	0	0
814	57.91964	33.25397	864	0	0	914	0	0	964	0	0
815	32.17857	20.44849	865	0	0	915	0	0	965	0	0
816	26.77679	9.838795	866	0	0	916	0	0	966	0	0
817	29.63393	29.09699	867	0	0	917	0	0	967	0	0
818	34.82143	37.60643	868	0	0	918	0	0	968	0	0
819	38.91071	26.12552	869	0	0	919	0	0	969	0	0
820	40.61607	13.93323	870	0	0	920	0	0	970	0	0
821	36.02679	-1	871	0	0	921	0	0	971	0	0
822	30.73214	-1	872	0	0	922	0	0	972	0	0
823	11.75893	10.14018	873	0	0	923	0	0	973	0	0
824	3.107143	4.966126	874	0	0	924	0	0	974	0	0
825	2.875	7.537771	875	0	0	925	0	0	975	0	0
826	0	0	876	0	0	926	0	0	976	0	0
827	0	0	877	0	0	927	0	0	977	0	0
828	0	0	878	0	0	928	0	0	978	0	0
829	0	0	879	0	0	929	0	0	979	0	0
830	0	0	880	0	0	930	0	0	980	0	0
831	0	0	881	0	0	931	44.74107	66.93528	981	0	0
832	0	0	882	0	0	932	80.88393	86.67591	982	0	0
833	2.660714	51.88372	883	0	0	933	88.59821	65.91627	983	0	0
834	35.64286	40.47402	884	0	0	934	84	81.92274	984	0	0
835	60.63393	53.31521	885	0	0	935	87.26786	62.37512	985	0	0
836	71.45536	-1	886	42.08036	62.20518	936	42.80357	-1	986	0	0
837	25.48214	-1	887	75	87.1732	937	39.83929	-1	987	0	0
838	8.428571	10.98085	888	92.11607	90.88087	938	41.84821	29.28379	988	0	0
839	12.02679	4.341372	889	70.04464	54.19471	939	46.02679	34.83414	989	0	0
840	1.419643	16.44308	890	54.5	30.78292	940	39.33036	-1	990	1.991071	76.83954
841	25.03571	35.69006	891	34.5	14.39845	941	35.47321	-1	991	53.09821	51.08036
842	48.23214	42.6313	892	32.34821	4.490809	942	31.30357	-1	992	75.82143	74.60623
843	63.35714	48.71458	893	36.88393	29.55773	943	27.38393	-1	993	63.0625	26.57645
844	25.41071	-1	894	40.42857	30.59292	944	7.580357	13.34234	994	29.97321	-1
845	11.15179	-1	895	35.84821	-1	945	0	0	995	8.133929	19.6905
846	14.78571	7.3122	896	21.58929	-1	946	0	0	996	6.3125	8.393946
847	0	0	897	9.107143	11.4225	947	0	0	997	6.366071	6.753592
848	0	0	898	1.473214	4.903504	948	0	0	998	18.57143	-1
849	0	0	899	2.214286	9.408853	949	0	0	999	53.09821	43.65882
850	0	0	900	0	0	950	0	0	1000	80.13393	63.96407

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1001	63.34821	-1	1051	0	0	1101	30.9375	-1	1151	0	0
1002	8.946429	-1	1052	0	0	1102	28.48214	-1	1152	0	0
1003	16.05357	15.36013	1053	0	0	1103	25.26786	-1	1153	0	0
1004	3.205357	4.848713	1054	0	0	1104	13.03571	-1	1154	0	0
1005	8.419643	9.091319	1055	0	0	1105	19.50893	7.405141	1155	3.794643	68.40281
1006	0	0	1056	0	0	1106	2.678571	6.157287	1156	55.26786	51.13847
1007	0	0	1057	0	0	1107	4.794643	9.480974	1157	88.02679	87.71945
1008	0	0	1058	0	0	1108	0	0	1158	48.32143	-1
1009	0	0	1059	0	0	1109	0	0	1159	11.89286	18.67051
1010	0	0	1060	0	0	1110	0	0	1160	7.25	4.397709
1011	0	0	1061	0	0	1111	0	0	1161	7.232143	6.626455
1012	0	0	1062	0	0	1112	0	0	1162	5.741071	5.160807
1013	0	0	1063	0	0	1113	0	0	1163	13.26786	29.44979
1014	0	0	1064	0	0	1114	0	0	1164	37.05357	39.42559
1015	0	0	1065	0	0	1115	0	0	1165	56.84821	49.02293
1016	0	0	1066	0	0	1116	0	0	1166	15.75	-1
1017	0	0	1067	0	0	1117	0	0	1167	14.40179	11.92348
1018	0	0	1068	0	0	1118	0	0	1168	2.696429	4.614777
1019	0	0	1069	0	0	1119	0	0	1169	5.660714	10.87554
1020	0	0	1070	0	0	1120	0	0	1170	0	0
1021	0	0	1071	0	0	1121	0	0	1171	0	0
1022	0	0	1072	0	0	1122	0	0	1172	0	0
1023	0	0	1073	0	0	1123	0	0	1173	0	0
1024	0	0	1074	0	0	1124	0	0	1174	0	0
1025	0	0	1075	0	0	1125	0	0	1175	0	0
1026	0	0	1076	0	0	1126	0	0	1176	0	0
1027	0	0	1077	0	0	1127	0	0	1177	0	0
1028	0	0	1078	0	0	1128	0	0	1178	0	0
1029	0	0	1079	0	0	1129	0	0	1179	0	0
1030	0	0	1080	1.5	77.63581	1130	0	0	1180	0	0
1031	0	0	1081	49.01786	51.34575	1131	0	0	1181	0	0
1032	0	0	1082	83.59821	91.0819	1132	0	0	1182	0	0
1033	0	0	1083	93.32143	50.82922	1133	0	0	1183	0	0
1034	0	0	1084	60.00893	34.57959	1134	0	0	1184	0	0
1035	0	0	1085	31.28571	-1	1135	0	0	1185	0	0
1036	51.90179	65.76352	1086	19.73214	12.13045	1136	0	0	1186	0	0
1037	78.0625	77.39016	1087	26.28571	44.56935	1137	0	0	1187	0	0
1038	64.8125	26.68724	1088	34.05357	52.33126	1138	0	0	1188	0	0
1039	20.55357	0	1089	37.28571	16.33087	1139	0	0	1189	0	0
1040	8.017857	16.30588	1090	32.07143	-1	1140	0	0	1190	0	0
1041	4.553571	6.254236	1091	33.67857	24.62684	1141	0	0	1191	0	0
1042	7.883929	11.77985	1092	38.16071	38.26598	1142	0	0	1192	0	0
1043	0	0	1093	47.52679	57.28766	1143	0	0	1193	0	0
1044	0	0	1094	58.74107	60.61614	1144	0	0	1194	0	0
1045	0	0	1095	63.0625	-1	1145	0	0	1195	0	0
1046	0	0	1096	30.45536	-1	1146	0	0	1196	0	0
1047	0	0	1097	32.75	18.28491	1147	0	0	1197	0	0
1048	0	0	1098	33.32143	31.40992	1148	0	0	1198	0	0
1049	0	0	1099	35.85714	35.1179	1149	0	0	1199	0	0
1050	0	0	1100	31.8125	-1	1150	0	0	1200	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1201	0	0	1251	0	0	1301	0	0	1351	0	0
1202	0	0	1252	0	0	1302	0	0	1352	0	0
1203	0	0	1253	0	0	1303	0	0	1353	0	0
1204	0	0	1254	0	0	1304	0	0	1354	0	0
1205	0	0	1255	0	0	1305	0	0	1355	0	0
1206	0	0	1256	0	0	1306	0	0	1356	0	0
1207	0	0	1257	0	0	1307	0	0	1357	0	0
1208	0	0	1258	0	0	1308	0	0	1358	0	0
1209	0	0	1259	0	0	1309	0	0	1359	0	0
1210	0	0	1260	11.57143	72.74	1310	0	0	1360	0	0
1211	0	0	1261	56.875	68.83651	1311	0	0	1361	0	0
1212	0	0	1262	88.90179	96.53806	1312	0	0	1362	0	0
1213	0	0	1263	100	82.30012	1313	0	0	1363	0	0
1214	0	0	1264	77.875	51.21042	1314	0	0	1364	0	0
1215	0	0	1265	28.86607	-1	1315	0	0	1365	0	0
1216	35.98214	72.839	1266	33.91071	-1	1316	0	0	1366	30.52679	69.72746
1217	71.83929	83.20851	1267	26.61607	12.29811	1317	0	0	1367	64.29464	51.57929
1218	88.29464	-1	1268	31.08036	34.38368	1318	0	0	1368	70.375	35.35375
1219	18.64286	23.20295	1269	38.11607	46.17486	1319	0	0	1369	51.36607	-1
1220	4.053571	6.114949	1270	41.40179	-1	1320	0	0	1370	6.339286	22.66572
1221	6.160714	15.93983	1271	34.86607	-1	1321	0	0	1371	2.991071	8.909513
1222	8.964286	9.52081	1272	30.70536	-1	1322	0	0	1372	8.401786	18.56506
1223	49.19643	25.37106	1273	30.51786	20.81551	1323	0	0	1373	0	0
1224	63.27679	45.47725	1274	72.33036	78.4503	1324	0	0	1374	0	0
1225	71.23214	63.1878	1275	93.22321	99.67111	1325	0	0	1375	0	0
1226	13.0625	0	1276	73.13393	99.24124	1326	0	0	1376	0	0
1227	0	19.02924	1277	89.32143	99.84054	1327	0	0	1377	0	0
1228	3.901786	12.29613	1278	94.39286	95.93896	1328	0	0	1378	0	0
1229	6.1875	13.36595	1279	67.61607	99.91193	1329	0	0	1379	0	0
1230	0	0	1280	82.57143	95.92338	1330	0	0	1380	0	0
1231	0	0	1281	86.02679	-1	1331	0	0	1381	0	0
1232	0	0	1282	76.52679	7.394806	1332	0	0	1382	0	0
1233	0	0	1283	58.01786	7.845392	1333	0	0	1383	0	0
1234	0	0	1284	38.11607	32.72696	1334	0	0	1384	0	0
1235	0	0	1285	41.17857	55.70852	1335	0	0	1385	0	0
1236	0	0	1286	43.83036	56.76874	1336	0	0	1386	0	0
1237	0	0	1287	40.61607	-1	1337	0	0	1387	0	0
1238	0	0	1288	40.16071	-1	1338	0	0	1388	0	0
1239	0	0	1289	27.97321	-1	1339	0	0	1389	0	0
1240	0	0	1290	16.58929	-1	1340	0	0	1390	0	0
1241	0	0	1291	32.59821	-1	1341	0	0	1391	0	0
1242	0	0	1292	34.0625	-1	1342	0	0	1392	0	0
1243	0	0	1293	25.40179	-1	1343	0	0	1393	0	0
1244	0	0	1294	8.410714	10.98563	1344	0	0	1394	0	0
1245	0	0	1295	2.196429	6.420486	1345	0	0	1395	0	0
1246	0	0	1296	5.383929	11.08758	1346	0	0	1396	0	0
1247	0	0	1297	0	0	1347	0	0	1397	0	0
1248	0	0	1298	0	0	1348	0	0	1398	0	0
1249	0	0	1299	0	0	1349	0	0	1399	0	0
1250	0	0	1300	0	0	1350	0	0	1400	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1401	0	0	1451	0	0	1501	0	0	1551	0	0
1402	0	0	1452	0	0	1502	0	0	1552	0	0
1403	0	0	1453	0	0	1503	0	0	1553	0	0
1404	0	0	1454	0	0	1504	0	0	1554	0	0
1405	0	0	1455	0	0	1505	0	0	1555	0	0
1406	0	0	1456	0	0	1506	0	0	1556	0	0
1407	0	0	1457	0	0	1507	0	0	1557	0	0
1408	0	0	1458	0	0	1508	0	0	1558	0	0
1409	0	0	1459	0	0	1509	0	0	1559	0	0
1410	13.29464	64.53132	1460	0	0	1510	0	0	1560	0	0
1411	58.24107	50.76175	1461	0	0	1511	0	0	1561	0	0
1412	91.83036	91.91419	1462	0	0	1512	0	0	1562	0	0
1413	78.96429	61.84945	1463	0	0	1513	0	0	1563	0	0
1414	68.25	45.22799	1464	0	0	1514	0	0	1564	0	0
1415	32.50893	-1	1465	0	0	1515	0	0	1565	0	0
1416	29.74107	-1	1466	0	0	1516	0	0	1566	0	0
1417	31.24107	22.03279	1467	0	0	1517	0	0	1567	0	0
1418	33.25	29.1886	1468	0	0	1518	0	0	1568	0	0
1419	37.57143	27.29773	1469	0	0	1519	0	0	1569	0	0
1420	37.34821	-1	1470	0	0	1520	0	0	1570	0	0
1421	32.41964	-1	1471	0	0	1521	0	0	1571	0	0
1422	25.23214	-1	1472	0	0	1522	0	0	1572	0	0
1423	6.9375	9.821295	1473	0	0	1523	0	0	1573	0	0
1424	3.116071	6.597274	1474	0	0	1524	0	0	1574	0	0
1425	4.464286	9.512467	1475	0	0	1525	0	0	1575	0	0
1426	0	0	1476	0	0	1526	0	0	1576	0	0
1427	0	0	1477	0	0	1527	0	0	1577	0	0
1428	0	0	1478	0	0	1528	0	0	1578	0	0
1429	0	0	1479	0	0	1529	0	0	1579	0	0
1430	0	0	1480	0	0	1530	1.375	80.04261	1580	0	0
1431	0	0	1481	0	0	1531	49.22321	50.82491	1581	0	0
1432	0	0	1482	0	0	1532	79.38393	90.56137	1582	0	0
1433	16.46429	51.53612	1483	0	0	1533	91.79464	99.39374	1583	0	0
1434	44.92857	40.91166	1484	0	0	1534	77.35714	96.02209	1584	0	0
1435	69.73214	57.90537	1485	0	0	1535	30.51786	-1	1585	0	0
1436	44.88393	-1	1486	44.95536	77.09519	1536	28.55357	-1	1586	0	0
1437	24.88393	-1	1487	80.10714	93.48338	1537	27.91964	16.46415	1587	0	0
1438	10.14286	11.32193	1488	100	99.96936	1538	31.22321	27.49736	1588	0	0
1439	14.53571	1.355486	1489	79.40179	50.26767	1539	37.64286	44.89388	1589	0	0
1440	1.267857	4.408767	1490	26.52679	-1	1540	44.19643	46.96855	1590	1.116071	58.94269
1441	0	43.24842	1491	23.99107	-1	1541	39.27679	-1	1591	45.375	74.65141
1442	36.46429	32.97404	1492	27.4375	20.48296	1542	34.67857	-1	1592	62.53571	37.0402
1443	63.47321	54.95534	1493	30.125	26.6537	1543	24.91964	-1	1593	53.58036	26.19319
1444	69.34821	-1	1494	34.35714	33.32182	1544	14.44643	-1	1594	61.9375	24.17271
1445	13.50893	-1	1495	39.25	33.03888	1545	3.428571	12.34138	1595	14.73214	-1
1446	1.223214	13.03713	1496	32.58036	-1	1546	0	0	1596	4.875	20.98802
1447	5.973214	0	1497	17.72321	-1	1547	0	0	1597	6.4375	8.10626
1448	0	0	1498	3.035714	14.04469	1548	0	0	1598	7.821429	20.40657
1449	0	0	1499	0	0	1549	0	0	1599	30.91071	35.58283
1450	0	0	1500	0	0	1550	0	0	1600	53.94643	47.8497

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1601	59.70536	-1	1651	0	0	1701	31.5	-1	1751	0	0
1602	12.69643	12.75559	1652	0	0	1702	29.26786	-1	1752	0	0
1603	4.348214	-1	1653	0	0	1703	25.10714	-1	1753	0	0
1604	0	7.798852	1654	0	0	1704	12.875	7.050251	1754	0	0
1605	0	0	1655	0	0	1705	19.45536	-1	1755	0.375	27.77797
1606	0	0	1656	0	0	1706	0	5.640433	1756	29.83036	72.07997
1607	0	0	1657	0	0	1707	0	0	1757	59.57143	46.35377
1608	0	0	1658	0	0	1708	0	0	1758	67.85714	57.16961
1609	0	0	1659	0	0	1709	0	0	1759	68.58929	26.49933
1610	0	0	1660	0	0	1710	0	0	1760	6.946429	-1
1611	0	0	1661	0	0	1711	0	0	1761	12.86607	18.77466
1612	0	0	1662	0	0	1712	0	0	1762	7.803571	6.320429
1613	0	0	1663	0	0	1713	0	0	1763	20.97321	29.84974
1614	0	0	1664	0	0	1714	0	0	1764	41.48214	37.08594
1615	0	0	1665	0	0	1715	0	0	1765	50.54464	40.62182
1616	0	0	1666	0	0	1716	0	0	1766	8.1875	-1
1617	0	0	1667	0	0	1717	0	0	1767	17.44643	13.90859
1618	0	0	1668	0	0	1718	0	0	1768	1.732143	2.938514
1619	0	0	1669	0	0	1719	0	0	1769	5.892857	11.21772
1620	0	0	1670	0	0	1720	0	0	1770	0	0
1621	0	0	1671	0	0	1721	0	0	1771	0	0
1622	0	0	1672	0	0	1722	0	0	1772	0	0
1623	0	0	1673	0	0	1723	0	0	1773	0	0
1624	0	0	1674	0	0	1724	0	0	1774	0	0
1625	0	0	1675	0	0	1725	0	0	1775	0	0
1626	0	0	1676	0	0	1726	0	0	1776	0	0
1627	0	0	1677	0	0	1727	0	0	1777	0	0
1628	0	0	1678	0	0	1728	0	0	1778	0	0
1629	0	0	1679	0	0	1729	0	0	1779	0	0
1630	0	0	1680	0.875	76.92959	1730	0	0	1780	0	0
1631	0	0	1681	49.3125	50.13353	1731	0	0	1781	0	0
1632	0	0	1682	85.20536	90.45539	1732	0	0	1782	0	0
1633	0	0	1683	91.91964	58.8283	1733	0	0	1783	0	0
1634	0	0	1684	62.77679	37.16589	1734	0	0	1784	0	0
1635	1.919643	44.07816	1685	20.08929	0	1735	0	0	1785	0	0
1636	32.45536	40.98214	1686	26.54464	10.13538	1736	0	0	1786	0	0
1637	60.29464	56.75943	1687	28.03571	41.31702	1737	0	0	1787	0	0
1638	82.63393	64.91779	1688	35.22321	48.21994	1738	0	0	1788	0	0
1639	84.89286	-1	1689	37.24107	-1	1739	0	0	1789	0	0
1640	19.60714	22.16283	1690	31.70536	-1	1740	0	0	1790	0	0
1641	3.348214	2.830346	1691	29.50893	15.93708	1741	0	0	1791	0	0
1642	8.258929	15.03946	1692	35.73214	42.79652	1742	0	0	1792	0	0
1643	0	0	1693	45.5625	54.82486	1743	0	0	1793	0	0
1644	0	0	1694	55.5	57.1601	1744	0	0	1794	0	0
1645	0	0	1695	60.69643	-1	1745	0	0	1795	0	0
1646	0	0	1696	53.00893	11.4117	1746	0	0	1796	0	0
1647	0	0	1697	58.05357	30.95332	1747	0	0	1797	0	0
1648	0	0	1698	62.45536	35.95922	1748	0	0	1798	0	0
1649	0	0	1699	37.39286	39.34046	1749	0	0	1799	0	0
1650	0	0	1700	33.82143	-1	1750	0	0	1800	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1801	0	0	1851	0	0	1901	0	0	1951	0	0
1802	0	0	1852	0	0	1902	0	0	1952	0	0
1803	0	0	1853	0	0	1903	0	0	1953	0	0
1804	0	0	1854	0	0	1904	0	0	1954	0	0
1805	0	0	1855	0	0	1905	0	0	1955	0	0
1806	0	0	1856	0	0	1906	0	0	1956	0	0
1807	0	0	1857	0	0	1907	0	0	1957	0	0
1808	0	0	1858	0	0	1908	0	0	1958	0	0
1809	0	0	1859	0.758929	27.89713	1909	0	0	1959	0	0
1810	0	0	1860	29.44643	75.07435	1910	0	0	1960	0	0
1811	0	0	1861	67.60714	50.77779	1911	0	0	1961	0	0
1812	0	0	1862	78.41071	71.45981	1912	0	0	1962	0	0
1813	0	0	1863	66.99107	46.06938	1913	0	0	1963	0	0
1814	0	0	1864	73.83036	62.58143	1914	0	0	1964	0	0
1815	8.428571	73.96348	1865	29.20536	-1	1915	0	0	1965	1.357143	44.63394
1816	49.66964	49.90602	1866	29.20536	9.52581	1916	0	0	1966	29.92857	40.36464
1817	77.85714	75.56562	1867	33.30357	28.09184	1917	0	0	1967	56.69643	55.01315
1818	56.54464	-1	1868	38.55357	36.13183	1918	0	0	1968	76.88393	60.86539
1819	13.46429	22.34273	1869	40.54464	17.24001	1919	0	0	1969	29.49107	-1
1820	2.651786	5.967185	1870	39.60714	5.164195	1920	0	0	1970	3.330357	20.42918
1821	8.8125	12.24594	1871	36.58036	-1	1921	0	0	1971	5.017857	6.094688
1822	18.16964	2.275748	1872	33.73214	14.25033	1922	0	0	1972	7.910714	8.695512
1823	44.5625	21.53246	1873	38.375	28.35443	1923	0	0	1973	0	0
1824	64.40179	42.07195	1874	40.57143	16.18787	1924	0	0	1974	0	0
1825	69.59821	53.42187	1875	52.92857	80.68386	1925	0	0	1975	0	0
1826	18.13393	0	1876	67.89286	99.66096	1926	0	0	1976	0	0
1827	6.125	19.16606	1877	84.70536	98.27023	1927	0	0	1977	0	0
1828	3.357143	7.496072	1878	96.4375	96.8401	1928	0	0	1978	0	0
1829	8.276786	14.03339	1879	69.19643	98.44166	1929	0	0	1979	0	0
1830	0	0	1880	80.39286	98.84011	1930	0	0	1980	0	0
1831	0	0	1881	84.58036	-1	1931	0	0	1981	0	0
1832	0	0	1882	75.1875	8.727714	1932	0	0	1982	0	0
1833	0	0	1883	58.28571	19.40349	1933	0	0	1983	0	0
1834	0	0	1884	37.69643	40.39512	1934	0	0	1984	0	0
1835	0	0	1885	40.4375	30.46129	1935	0	0	1985	0	0
1836	0	0	1886	40.84821	33.72064	1936	0	0	1986	0	0
1837	0	0	1887	37.63393	-1	1937	0	0	1987	0	0
1838	0	0	1888	31.11607	-1	1938	0	0	1988	0	0
1839	0	0	1889	23.49107	-1	1939	0	0	1989	0	0
1840	0	0	1890	20.5	-1	1940	0	0	1990	0	0
1841	0	0	1891	14.25893	-1	1941	0	0	1991	0	0
1842	0	0	1892	33.59821	-1	1942	0	0	1992	0	0
1843	0	0	1893	22.80357	-1	1943	0	0	1993	0	0
1844	0	0	1894	9.169643	10.00105	1944	0	0	1994	0	0
1845	0	0	1895	2.705357	7.576401	1945	0	0	1995	0	0
1846	0	0	1896	5.553571	6.960098	1946	0	0	1996	0	0
1847	0	0	1897	0	0	1947	0	0	1997	0	0
1848	0	0	1898	0	0	1948	0	0	1998	0	0
1849	0	0	1899	0	0	1949	0	0	1999	0	0
1850	0	0	1900	0	0	1950	0	0	2000	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
2001	0	0	2051	0	0	2101	0	0	2151	0	0
2002	0	0	2052	0	0	2102	0	0	2152	0	0
2003	0	0	2053	0	0	2103	0	0	2153	0	0
2004	0	0	2054	0	0	2104	0	0	2154	0	0
2005	0	0	2055	0	0	2105	0	0	2155	0	0
2006	0	0	2056	0	0	2106	0	0	2156	0	0
2007	0	0	2057	0	0	2107	0	0	2157	0	0
2008	0	0	2058	0	0	2108	0	0	2158	0	0
2009	0	0	2059	0	0	2109	0	0	2159	0	0
2010	12.55357	71.51749	2060	0	0	2110	0	0	2160	0	0
2011	54.8125	49.91657	2061	0	0	2111	0	0	2161	0	0
2012	86.63393	84.39607	2062	0	0	2112	0	0	2162	0	0
2013	92.33036	60.38129	2063	0	0	2113	0	0	2163	0	0
2014	63.83929	38.44917	2064	0	0	2114	0	0	2164	0	0
2015	42.91071	21.51204	2065	0	0	2115	0	0	2165	0	0
2016	31.10714	1.28921	2066	0	0	2116	0	0	2166	0	0
2017	31.65179	9.204982	2067	0	0	2117	0	0	2167	0	0
2018	34.11607	26.71505	2068	0	0	2118	0	0	2168	0	0
2019	37.40179	28.55656	2069	0	0	2119	0	0	2169	0	0
2020	37.76786	8.597729	2070	0	0	2120	0	0	2170	0	0
2021	33	-1	2071	0	0	2121	0	0	2171	0	0
2022	29	-1	2072	0	0	2122	0	0	2172	0	0
2023	14.92857	-1	2073	0	0	2123	0	0	2173	0	0
2024	5.705357	10.24958	2074	0	0	2124	0	0	2174	0	0
2025	0	0	2075	0	0	2125	0	0	2175	0	0
2026	0	0	2076	0	0	2126	0	0	2176	0	0
2027	0	0	2077	0	0	2127	0	0	2177	0	0
2028	0	0	2078	0	0	2128	0	0	2178	0	0
2029	0	0	2079	0	0	2129	0	0	2179	0	0
2030	0	0	2080	0	0	2130	0	0	2180	0	0
2031	0	0	2081	0	0	2131	46.10714	68.05551	2181	0	0
2032	0	0	2082	0	0	2132	81.74107	90.26944	2182	0	0
2033	13.26786	51.39829	2083	0	0	2133	90.78571	62.83144	2183	0	0
2034	42.78571	40.59021	2084	0	0	2134	75.83929	66.3202	2184	0	0
2035	60.79464	48.50009	2085	0	0	2135	32.21429	-1	2185	0	0
2036	67.42857	-1	2086	44.0625	64.95887	2136	32.53571	-1	2186	0	0
2037	31.32143	-1	2087	79.85714	93.37173	2137	33.83036	23.4417	2187	0	0
2038	11.51786	10.19789	2088	97.39286	64.20672	2138	37.72321	32.78956	2188	0	0
2039	12.97321	2.957214	2089	69.9375	41.90339	2139	41.63393	37.11298	2189	0	0
2040	2.258929	4.244089	2090	45.44643	24.87013	2140	43.00893	14.91014	2190	7.517857	47.40657
2041	4.303571	35.26	2091	31.5	5.79369	2141	40.42857	4.043395	2191	38.38393	41.06525
2042	35.35714	36.91512	2092	29.89286	3.573217	2142	36.95536	-1	2192	65.5	60.1887
2043	62.82143	54.84601	2093	34.875	32.05164	2143	33.04464	-1	2193	82.97321	63.77762
2044	69.875	-1	2094	39.4375	33.91503	2144	18.15179	-1	2194	28.25893	0
2045	18.23214	-1	2095	33.29464	-1	2145	6.196429	9.805506	2195	13.13393	2.657795
2046	10.40179	8.996902	2096	22.67857	-1	2146	1.107143	11.42281	2196	10.98214	8.270442
2047	4.383929	1.499816	2097	6.696429	8.306632	2147	0	0	2197	2.714286	10.85727
2048	0	4.59275	2098	3.375	12.40402	2148	0	0	2198	6.035714	7.222359
2049	0	0	2099	6.383929	3.632256	2149	0	0	2199	45.875	22.99262
2050	0	0	2100	0	0	2150	0	0	2200	67.57143	45.08743

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
2201	73.10714	52.51843	2251	0	0	2301	31.14286	-1	2351	0	0
2202	16.17857	0	2252	0	0	2302	28.88393	-1	2352	0	0
2203	1.491071	13.09488	2253	0	0	2303	26.16071	-1	2353	0	0
2204	3.428571	18.83206	2254	0	0	2304	12.34821	8.574993	2354	0	0
2205	5.75	6.976592	2255	0	0	2305	19.25	-1	2355	6.526786	62.09521
2206	0	0	2256	0	0	2306	0	4.348675	2356	50.96429	50.53358
2207	0	0	2257	0	0	2307	0	0	2357	68.40179	62.28794
2208	0	0	2258	0	0	2308	0	0	2358	60.83929	29.97316
2209	0	0	2259	0	0	2309	0	0	2359	47.55357	-1
2210	0	0	2260	0	0	2310	0	0	2360	6.910714	18.46374
2211	0	0	2261	0	0	2311	0	0	2361	8.026786	8.01328
2212	0	0	2262	0	0	2312	0	0	2362	11.09821	20.49628
2213	0	0	2263	0	0	2313	0	0	2363	24.79464	32.60014
2214	0	0	2264	0	0	2314	0	0	2364	45.13393	38.1572
2215	0	0	2265	0	0	2315	0	0	2365	49.07143	27.07767
2216	0	0	2266	0	0	2316	0	0	2366	11.26786	0
2217	0	0	2267	0	0	2317	0	0	2367	17.07143	11.53371
2218	0	0	2268	0	0	2318	0	0	2368	0	9.848402
2219	0	0	2269	0	0	2319	0	0	2369	0	0
2220	0	0	2270	0	0	2320	0	0	2370	0	0
2221	0	0	2271	0	0	2321	0	0	2371	0	0
2222	0	0	2272	0	0	2322	0	0	2372	0	0
2223	0	0	2273	0	0	2323	0	0	2373	0	0
2224	0	0	2274	0	0	2324	0	0	2374	0	0
2225	0	0	2275	0	0	2325	0	0	2375	0	0
2226	0	0	2276	0	0	2326	0	0	2376	0	0
2227	0	0	2277	0	0	2327	0	0	2377	0	0
2228	0	0	2278	0	0	2328	0	0	2378	0	0
2229	0	0	2279	0.142857	29.72761	2329	0	0	2379	0	0
2230	0	0	2280	0.660714	41.7899	2330	0	0	2380	0	0
2231	0	0	2281	41.625	80.45899	2331	0	0	2381	0	0
2232	0	0	2282	75.10714	82.16039	2332	0	0	2382	0	0
2233	0	0	2283	83.35714	56.17033	2333	0	0	2383	0	0
2234	0	0	2284	67.27679	58.82357	2334	0	0	2384	0	0
2235	0	0	2285	23.25	-1	2335	0	0	2385	0	0
2236	32.88393	44.18858	2286	10.83929	11.94045	2336	0	0	2386	0	0
2237	57.19643	55.07564	2287	25.875	34.00432	2337	0	0	2387	0	0
2238	80.78571	74.1373	2288	30.60714	40.49481	2338	0	0	2388	0	0
2239	90.76786	-1	2289	35.99107	30.68264	2339	0	0	2389	0	0
2240	17.85714	27.09979	2290	36.21429	4.338795	2340	0	0	2390	0	0
2241	0	4.345105	2291	33.83036	9.927051	2341	0	0	2391	0	0
2242	7.464286	20.15004	2292	38.5625	37.14431	2342	0	0	2392	0	0
2243	0	0	2293	47.69643	52.84161	2343	0	0	2393	0	0
2244	0	0	2294	56.25893	55.74333	2344	0	0	2394	0	0
2245	0	0	2295	59.09821	17.09889	2345	0	0	2395	0	0
2246	0	0	2296	56.16964	-0.13126	2346	0	0	2396	0	0
2247	0	0	2297	55.47321	12.47459	2347	0	0	2397	0	0
2248	0	0	2298	60.51786	36.95595	2348	0	0	2398	0	0
2249	0	0	2299	63.16964	47.8089	2349	0	0	2399	0	0
2250	0	0	2300	33.14286	-1	2350	0	0	2400	0	0

TABLE A-2. CRUISE-CREEPX10 CYCLE

Cycle Time	Speed	Torque	Mode
1	0	0	Cruise
2	0	0	Cruise
3	0	0	Cruise
4	0	0	Cruise
5	0	0	Cruise
6	0	0	Cruise
7	0	0	Cruise
8	0	0	Cruise
9	0	0	Cruise
10	0	0	Cruise
11	0	0	Cruise
12	0	0	Cruise
13	0	0	Cruise
14	0	0	Cruise
15	0	0	Cruise
16	0	0	Cruise
17	0	0	Cruise
18	0	0	Cruise
19	0	0	Cruise
20	0	0	Cruise
21	0	0	Cruise
22	0	0	Cruise
23	0	0	Cruise
24	0	0	Cruise
25	0	0	Cruise
26	0	0	Cruise
27	0	0	Cruise
28	0	0	Cruise
29	2	9	Cruise
30	10	19	Cruise
31	7	29	Cruise
32	17	35	Cruise
33	9	-5	Cruise
34	26	22	Cruise
35	33	22	Cruise
36	43	19	Cruise
37	58	13	Cruise
38	61	9	Cruise
39	62	17	Cruise
40	81	33	Cruise
41	87	11	Cruise
42	88	-3	Cruise
43	86	9	Cruise
44	87	9	Cruise
45	87	2	Cruise
46	87	3	Cruise
47	86	5	Cruise
48	87	2	Cruise
49	87	0	Cruise
50	87	1	Cruise
51	86	-4	Cruise
52	75	-5	Cruise
53	62	-5	Cruise
54	49	-5	Cruise
55	25	-5	Cruise
56	5	-5	Cruise
57	0	-5	Cruise
58	0	0	Cruise
59	0	0	Cruise
60	0	0	Cruise
61	30	19	Cruise
62	32	21	Cruise
63	17	-5	Cruise
64	24	33	Cruise
65	48	25	Cruise
66	68	24	Cruise
67	81	4	Cruise
68	56	-5	Cruise
69	29	-5	Cruise
70	55	22	Cruise
71	66	36	Cruise
72	78	48	Cruise
73	85	32	Cruise
74	75	-5	Cruise
75	42	-5	Cruise

Cycle Time	Speed	Torque	Mode
76	52	30	Cruise
77	67	48	Cruise
78	80	46	Cruise
79	86	10	Cruise
80	62	-5	Cruise
81	48	-5	Cruise
82	57	47	Cruise
83	60	63	Cruise
84	71	74	Cruise
85	79	65	Cruise
86	85	37	Cruise
87	81	-5	Cruise
88	46	-5	Cruise
89	53	61	Cruise
90	60	82	Cruise
91	67	91	Cruise
92	73	92	Cruise
93	79	80	Cruise
94	83	32	Cruise
95	60	-5	Cruise
96	60	41	Cruise
97	52	-5	Cruise
98	55	92	Cruise
99	59	93	Cruise
100	63	95	Cruise
101	66	97	Cruise
102	70	97	Cruise
103	71	38	Cruise
104	71	-5	Cruise
105	69	-5	Cruise
106	68	0	Cruise
107	67	8	Cruise
108	66	25	Cruise
109	65	16	Cruise
110	65	-5	Cruise
111	64	-5	Cruise
112	61	-5	Cruise
113	57	-5	Cruise
114	51	-5	Cruise
115	46	-5	Cruise
116	41	-5	Cruise
117	37	-5	Cruise
118	37	-5	Cruise
119	34	-5	Cruise
120	29	-5	Cruise
121	45	-5	Cruise
122	52	-5	Cruise
123	46	-5	Cruise
124	37	-5	Cruise
125	32	-5	Cruise
126	32	30	Cruise
127	35	42	Cruise
128	33	15	Cruise
129	36	-5	Cruise
130	27	-5	Cruise
131	24	-5	Cruise
132	20	-5	Cruise
133	20	9	Cruise
134	19	0	Cruise
135	17	-5	Cruise
136	17	-5	Cruise
137	18	15	Cruise
138	17	47	Cruise
139	19	60	Cruise
140	22	69	Cruise
141	26	81	Cruise
142	31	86	Cruise
143	37	90	Cruise
144	44	90	Cruise
145	51	90	Cruise
146	58	90	Cruise
147	65	43	Cruise
148	39	-5	Cruise
149	43	25	Cruise
150	37	-5	Cruise

Cycle Time	Speed	Torque	Mode
151	41	87	Cruise
152	45	93	Cruise
153	48	93	Cruise
154	52	93	Cruise
155	56	93	Cruise
156	60	93	Cruise
157	64	96	Cruise
158	67	98	Cruise
159	71	37	Cruise
160	41	-5	Cruise
161	37	-5	Cruise
162	40	93	Cruise
163	42	93	Cruise
164	44	93	Cruise
165	46	93	Cruise
166	48	93	Cruise
167	49	93	Cruise
168	51	93	Cruise
169	53	93	Cruise
170	55	93	Cruise
171	56	93	Cruise
172	58	93	Cruise
173	60	93	Cruise
174	61	94	Cruise
175	63	95	Cruise
176	65	96	Cruise
177	66	98	Cruise
178	67	98	Cruise
179	69	99	Cruise
180	71	99	Cruise
181	72	99	Cruise
182	73	99	Cruise
183	75	99	Cruise
184	76	98	Cruise
185	83	38	Cruise
186	44	-5	Cruise
187	49	80	Cruise
188	46	93	Cruise
189	47	93	Cruise
190	48	93	Cruise
191	49	93	Cruise
192	49	93	Cruise
193	50	93	Cruise
194	50	93	Cruise
195	51	93	Cruise
196	52	93	Cruise
197	52	93	Cruise
198	53	93	Cruise
199	54	93	Cruise
200	54	93	Cruise
201	55	93	Cruise
202	56	93	Cruise
203	56	93	Cruise
204	57	93	Cruise
205	57	93	Cruise
206	58	93	Cruise
207	59	93	Cruise
208	59	65	Cruise
209	59	48	Cruise
210	59	75	Cruise
211	60	88	Cruise
212	60	60	Cruise
213	60	42	Cruise
214	59	56	Cruise
215	60	69	Cruise
216	60	71	Cruise
217	60	64	Cruise
218	60	33	Cruise
219	60	11	Cruise
220	60	38	Cruise
221	59	64	Cruise
222	59	82	Cruise
223	60	91	Cruise
224	60	69	Cruise
225	60	40	Cruise

Cycle Time	Speed	Torque	Mode
226	60	23	Cruise
227	59	24	Cruise
228	59	34	Cruise
229	59	64	Cruise
230	59	73	Cruise
231	59	74	Cruise
232	59	58	Cruise
233	59	31	Cruise
234	59	37	Cruise
235	59	40	Cruise
236	59	51	Cruise
237	59	71	Cruise
238	59	76	Cruise
239	59	63	Cruise
240	59	37	Cruise
241	59	17	Cruise
242	59	12	Cruise
243	58	15	Cruise
244	57	17	Cruise
245	57	34	Cruise
246	57	46	Cruise
247	56	37	Cruise
248	57	23	Cruise
249	56	34	Cruise
250	56	42	Cruise
251	56	48	Cruise
252	56	50	Cruise
253	56	61	Cruise
254	56	74	Cruise
255	56	93	Cruise
256	56	87	Cruise
257	57	100	Cruise
258	57	100	Cruise
259	57	99	Cruise
260	58	100	Cruise
261	58	100	Cruise
262	58	100	Cruise
263	58	100	Cruise
264	59	100	Cruise
265	59	87	Cruise
266	59	82	Cruise
267	59	84	Cruise
268	59	85	Cruise
269	60	78	Cruise
270	60	79	Cruise
271	60	83	Cruise
272	59	80	Cruise
273	60	70	Cruise
274	60	54	Cruise
275	59	23	Cruise
276	59	63	Cruise
277	59	58	Cruise
278	59	55	Cruise
279	59	58	Cruise
280	58	68	Cruise
281	59	52	Cruise
282	58	67	Cruise
283	58	73	Cruise
284	58	85	Cruise
285	59	85	Cruise
286	59	83	Cruise
287	59	83	Cruise
288	59	78	Cruise
289	59	54	Cruise
290	59	63	Cruise
291	59	55	Cruise
292	59	56	Cruise
293	58	77	Cruise
294	59	77	Cruise
295	59	77	Cruise
296	59	75	Cruise
297	59	72	Cruise
298	59	58	Cruise
299	59	58	Cruise
300	59	60	Cruise

Cycle Time	Speed	Torque	Mode
301	58	65	Cruise
302	58	63	Cruise
303	58	64	Cruise
304	58	71	Cruise
305	58	82	Cruise
306	58	82	Cruise
307	58	83	Cruise
308	58	82	Cruise
309	58	82	Cruise
310	58	80	Cruise
311	58	82	Cruise
312	58	82	Cruise
313	59	80	Cruise
314	59	82	Cruise
315	59	81	Cruise
316	59	71	Cruise
317	59	73	Cruise
318	59	70	Cruise
319	59	70	Cruise
320	59	71	Cruise
321	59	80	Cruise
322	59	86	Cruise
323	59	80	Cruise
324	59	80	Cruise
325	59	80	Cruise
326	59	83	Cruise
327	59	85	Cruise
328	59	75	Cruise
329	59	77	Cruise
330	59	78	Cruise
331	59	75	Cruise
332	59	77	Cruise
333	59	78	Cruise
334	59	77	Cruise
335	59	77	Cruise
336	59	77	Cruise
337	59	77	Cruise
338	59	80	Cruise
339	59	82	Cruise
340	59	82	Cruise
341	59	82	Cruise
342	59	81	Cruise
343	59	75	Cruise
344	59	75	Cruise
345	59	75	Cruise
346	59	77	Cruise
347	59	77	Cruise
348	59	77	Cruise
349	59	78	Cruise
350	59	75	Cruise
351	59	77	Cruise
352	60	78	Cruise
353	59	78	Cruise
354	60	77	Cruise
355	60	70	Cruise
356	60	72	Cruise
357	60	73	Cruise
358	60	73	Cruise
359	60	72	Cruise
360	60	72	Cruise
361	60	72	Cruise
362	60	71	Cruise
363	60	75	Cruise
364	60	82	Cruise
365	60	72	Cruise
366	60	72	Cruise
367	60	74	Cruise
368	60	79	Cruise
369	60	84	Cruise
370	60	87	Cruise
371	60	88	Cruise
372	60	82	Cruise
373	61	60	Cruise
374	60	71	Cruise
375	60	76	Cruise

Cycle Time	Speed	Torque	Mode
376	60	81	Cruise
377	60	82	Cruise
378	61	77	Cruise
379	61	80	Cruise
380	61	80	Cruise
381	61	72	Cruise
382	61	75	Cruise
383	61	81	Cruise
384	61	75	Cruise
385	61	75	Cruise
386	61	76	Cruise
387	61	80	Cruise
388	61	76	Cruise
389	61	71	Cruise
390	61	74	Cruise
391	61	62	Cruise
392	61	65	Cruise
393	61	65	Cruise
394	61	65	Cruise
395	61	65	Cruise
396	61	65	Cruise
397	60	65	Cruise
398	60	65	Cruise
399	60	68	Cruise
400	60	72	Cruise
401	60	73	Cruise
402	60	73	Cruise
403	60	81	Cruise
404	60	83	Cruise
405	60	78	Cruise
406	60	79	Cruise
407	60	80	Cruise
408	60	73	Cruise
409	60	78	Cruise
410	60	84	Cruise
411	60	85	Cruise
412	60	85	Cruise
413	60	85	Cruise
414	61	82	Cruise
415	61	81	Cruise
416	60	78	Cruise
417	61	74	Cruise
418	61	75	Cruise
419	60	77	Cruise
420	60	78	Cruise
421	61	78	Cruise
422	60	79	Cruise
423	61	80	Cruise
424	61	80	Cruise
425	60	78	Cruise
426	60	78	Cruise
427	61	78	Cruise
428	61	78	Cruise
429	61	78	Cruise
430	61	78	Cruise
431	61	78	Cruise
432	60	77	Cruise
433	61	69	Cruise
434	61	70	Cruise
435	61	68	Cruise
436	61	66	Cruise
437	61	68	Cruise
438	61	68	Cruise
439	60	68	Cruise
440	60	68	Cruise
441	60	69	Cruise
442	61	71	Cruise
443	62	70	Cruise
444	62	68	Cruise
445	63	66	Cruise
446	63	63	Cruise
447	64	61	Cruise
448	64	59	Cruise
449	65	57	Cruise
450	65	58	Cruise

Cycle Time	Speed	Torque	Mode
451	66	69	Cruise
452	66	57	Cruise
453	67	52	Cruise
454	67	46	Cruise
455	68	37	Cruise
456	68	41	Cruise
457	69	39	Cruise
458	69	38	Cruise
459	70	36	Cruise
460	71	34	Cruise
461	71	28	Cruise
462	72	25	Cruise
463	71	25	Cruise
464	71	25	Cruise
465	71	25	Cruise
466	71	25	Cruise
467	71	25	Cruise
468	71	25	Cruise
469	71	25	Cruise
470	71	25	Cruise
471	71	25	Cruise
472	71	25	Cruise
473	71	25	Cruise
474	71	25	Cruise
475	70	25	Cruise
476	71	25	Cruise
477	71	25	Cruise
478	70	25	Cruise
479	70	25	Cruise
480	70	25	Cruise
481	70	25	Cruise
482	68	10	Cruise
483	69	26	Cruise
484	69	31	Cruise
485	69	56	Cruise
486	69	51	Cruise
487	70	38	Cruise
488	70	37	Cruise
489	70	37	Cruise
490	70	37	Cruise
491	70	24	Cruise
492	70	24	Cruise
493	70	24	Cruise
494	69	24	Cruise
495	69	19	Cruise
496	69	17	Cruise
497	69	32	Cruise
498	69	32	Cruise
499	69	26	Cruise
500	69	25	Cruise
501	69	26	Cruise
502	69	26	Cruise
503	69	33	Cruise
504	69	35	Cruise
505	69	35	Cruise
506	69	35	Cruise
507	70	35	Cruise
508	70	35	Cruise
509	70	35	Cruise
510	70	34	Cruise
511	70	34	Cruise
512	70	34	Cruise
513	70	34	Cruise
514	71	34	Cruise
515	71	34	Cruise
516	71	34	Cruise
517	71	34	Cruise
518	71	34	Cruise
519	71	34	Cruise
520	71	37	Cruise
521	72	41	Cruise
522	72	41	Cruise
523	72	40	Cruise
524	72	40	Cruise
525	73	39	Cruise

Cycle Time	Speed	Torque	Mode
526	72	35	Cruise
527	72	31	Cruise
528	72	28	Cruise
529	72	26	Cruise
530	72	25	Cruise
531	72	26	Cruise
532	72	27	Cruise
533	72	27	Cruise
534	72	28	Cruise
535	72	28	Cruise
536	72	28	Cruise
537	72	25	Cruise
538	72	15	Cruise
539	72	15	Cruise
540	71	15	Cruise
541	71	15	Cruise
542	71	22	Cruise
543	71	29	Cruise
544	71	29	Cruise
545	71	29	Cruise
546	71	29	Cruise
547	71	32	Cruise
548	71	34	Cruise
549	71	36	Cruise
550	71	37	Cruise
551	71	35	Cruise
552	71	35	Cruise
553	71	35	Cruise
554	71	35	Cruise
555	71	35	Cruise
556	71	33	Cruise
557	71	24	Cruise
558	71	24	Cruise
559	71	24	Cruise
560	71	31	Cruise
561	71	32	Cruise
562	71	32	Cruise
563	71	32	Cruise
564	71	32	Cruise
565	71	33	Cruise
566	71	31	Cruise
567	71	31	Cruise
568	71	31	Cruise
569	71	31	Cruise
570	71	30	Cruise
571	71	23	Cruise
572	71	23	Cruise
573	71	23	Cruise
574	71	23	Cruise
575	71	23	Cruise
576	71	23	Cruise
577	71	23	Cruise
578	71	23	Cruise
579	71	25	Cruise
580	71	27	Cruise
581	70	27	Cruise
582	70	27	Cruise
583	70	27	Cruise
584	70	27	Cruise
585	70	27	Cruise
586	71	27	Cruise
587	70	27	Cruise
588	70	27	Cruise
589	70	27	Cruise
590	70	27	Cruise
591	70	28	Cruise
592	70	29	Cruise
593	70	29	Cruise
594	70	29	Cruise
595	70	31	Cruise
596	70	31	Cruise
597	70	31	Cruise
598	70	31	Cruise
599	71	31	Cruise
600	71	31	Cruise

Cycle Time	Speed	Torque	Mode
601	70	31	Cruise
602	70	31	Cruise
603	71	31	Cruise
604	71	31	Cruise
605	71	31	Cruise
606	71	31	Cruise
607	70	31	Cruise
608	71	31	Cruise
609	71	32	Cruise
610	71	32	Cruise
611	71	32	Cruise
612	71	32	Cruise
613	71	33	Cruise
614	71	35	Cruise
615	71	39	Cruise
616	71	40	Cruise
617	71	39	Cruise
618	72	39	Cruise
619	72	39	Cruise
620	72	33	Cruise
621	72	33	Cruise
622	72	33	Cruise
623	72	33	Cruise
624	72	34	Cruise
625	72	34	Cruise
626	72	34	Cruise
627	72	34	Cruise
628	72	34	Cruise
629	72	34	Cruise
630	72	32	Cruise
631	72	31	Cruise
632	72	30	Cruise
633	72	29	Cruise
634	72	29	Cruise
635	73	28	Cruise
636	72	29	Cruise
637	72	29	Cruise
638	72	28	Cruise
639	72	28	Cruise
640	72	30	Cruise
641	72	31	Cruise
642	72	30	Cruise
643	73	30	Cruise
644	73	32	Cruise
645	73	33	Cruise
646	73	32	Cruise
647	73	36	Cruise
648	74	38	Cruise
649	74	36	Cruise
650	74	37	Cruise
651	73	40	Cruise
652	73	29	Cruise
653	75	30	Cruise
654	73	48	Cruise
655	73	44	Cruise
656	73	39	Cruise
657	74	32	Cruise
658	73	52	Cruise
659	74	55	Cruise
660	74	56	Cruise
661	74	50	Cruise
662	75	35	Cruise
663	74	46	Cruise
664	74	61	Cruise
665	75	68	Cruise
666	76	55	Cruise
667	75	-9	Cruise
668	75	18	Cruise
669	73	75	Cruise
670	74	54	Cruise
671	72	9	Cruise
672	72	2	Cruise
673	70	-5	Cruise
674	68	-5	Cruise
675	67	-5	Cruise

Cycle Time	Speed	Torque	Mode
676	64	-5	Cruise
677	61	-5	Cruise
678	59	-5	Cruise
679	57	-5	Cruise
680	56	-5	Cruise
681	54	-5	Cruise
682	53	-5	Cruise
683	53	13	Cruise
684	52	60	Cruise
685	53	65	Cruise
686	51	26	Cruise
687	53	-5	Cruise
688	52	-5	Cruise
689	53	5	Cruise
690	50	30	Cruise
691	51	29	Cruise
692	50	24	Cruise
693	51	23	Cruise
694	50	10	Cruise
695	49	5	Cruise
696	49	6	Cruise
697	48	4	Cruise
698	47	-5	Cruise
699	46	5	Cruise
700	45	1	Cruise
701	44	19	Cruise
702	44	15	Cruise
703	43	-5	Cruise
704	43	1	Cruise
705	42	16	Cruise
706	41	12	Cruise
707	41	-5	Cruise
708	41	14	Cruise
709	39	45	Cruise
710	36	28	Cruise
711	64	-5	Cruise
712	70	33	Cruise
713	70	51	Cruise
714	70	4	Cruise
715	68	-5	Cruise
716	67	-5	Cruise
717	63	-5	Cruise
718	93	-5	Cruise
719	100	-5	Cruise
720	95	-5	Cruise
721	90	-5	Cruise
722	82	-5	Cruise
723	73	-5	Cruise
724	63	-5	Cruise
725	51	-5	Cruise
726	85	-5	Cruise
727	84	-5	Cruise
728	68	-5	Cruise
729	53	-5	Cruise
730	39	-5	Cruise
731	21	-5	Cruise
732	1	-5	Cruise
733	0	0	Cruise
734	0	0	Cruise
735	0	0	Cruise
736	0	0	Cruise
737	0	0	Cruise
738	0	0	Cruise
739	0	0	Cruise
740	0	0	Cruise
741	0	0	Cruise
742	0	0	Cruise
743	0	0	Cruise
744	0	0	Cruise
745	0	0	Cruise
746	0	0	Cruise
747	0	0	Cruise
748	0	0	Cruise
749	0	0	Cruise
750	0	0	Cruise

Cycle Time	Speed	Torque	Mode
751	0	0	Cruise
752	0	0	Cruise
753	0	0	Cruise
754	0	0	Cruise
755	0	0	Cruise
756	0	0	Cruise
757	0	0	Cruise
758	0	0	Cruise
759	0	0	Cruise
760	0	0	Cruise
761	0	0	Creep
762	0	0	Creep
763	0	0	Creep
764	0	0	Creep
765	0	0	Creep
766	0	0	Creep
767	0	0	Creep
768	0	0	Creep
769	0	0	Creep
770	0	0	Creep
771	0	0	Creep
772	0	0	Creep
773	0	0	Creep
774	0	0	Creep
775	0	0	Creep
776	0	0	Creep
777	0	0	Creep
778	0	0	Creep
779	0	0	Creep
780	0	0	Creep
781	0	0	Creep
782	0	0	Creep
783	0	0	Creep
784	0	0	Creep
785	0	0	Creep
786	0	0	Creep
787	0	0	Creep
788	0	0	Creep
789	0	0	Creep
790	0	0	Creep
791	0	0	Creep
792	0	0	Creep
793	0	0	Creep
794	0	0	Creep
795	0	0	Creep
796	0	0	Creep
797	0	0	Creep
798	0	0	Creep
799	0	0	Creep
800	0	0	Creep
801	0	0	Creep
802	0	0	Creep
803	0	0	Creep
804	0	0	Creep
805	0	0	Creep
806	0	0	Creep
807	10	28	Creep
808	12	32	Creep
809	12	48	Creep
810	23	37	Creep
811	39	24	Creep
812	59	29	Creep
813	72	26	Creep
814	81	23	Creep
815	83	7	Creep
816	67	0	Creep
817	51	0	Creep
818	30	0	Creep
819	23	0	Creep
820	0	0	Creep
821	0	0	Creep
822	0	0	Creep
823	0	0	Creep
824	0	0	Creep
825	0	0	Creep

Cycle Time	Speed	Torque	Mode
826	0	0	Creep
827	0	0	Creep
828	0	0	Creep
829	0	0	Creep
830	0	0	Creep
831	0	0	Creep
832	0	0	Creep
833	0	0	Creep
834	0	0	Creep
835	0	0	Creep
836	0	0	Creep
837	0	0	Creep
838	0	0	Creep
839	0	0	Creep
840	0	0	Creep
841	0	0	Creep
842	0	0	Creep
843	0	0	Creep
844	0	0	Creep
845	0	0	Creep
846	0	0	Creep
847	0	0	Creep
848	0	0	Creep
849	0	0	Creep
850	0	0	Creep
851	0	0	Creep
852	0	0	Creep
853	0	0	Creep
854	0	0	Creep
855	0	0	Creep
856	0	0	Creep
857	0	0	Creep
858	0	0	Creep
859	0	0	Creep
860	0	0	Creep
861	0	0	Creep
862	0	0	Creep
863	0	0	Creep
864	0	0	Creep
865	0	0	Creep
866	0	0	Creep
867	0	0	Creep
868	0	0	Creep
869	0	0	Creep
870	0	0	Creep
871	12	23	Creep
872	9	8	Creep
873	12	6	Creep
874	18	10	Creep
875	15	6	Creep
876	14	6	Creep
877	14	8	Creep
878	13	13	Creep
879	19	13	Creep
880	20	8	Creep
881	20	12	Creep
882	22	7	Creep
883	22	5	Creep
884	20	4	Creep
885	20	5	Creep
886	18	6	Creep
887	19	6	Creep
888	19	6	Creep
889	20	6	Creep
890	19	6	Creep
891	21	6	Creep
892	21	6	Creep
893	21	6	Creep
894	21	6	Creep
895	22	6	Creep
896	23	6	Creep
897	22	6	Creep
898	22	3	Creep
899	19	1	Creep
900	17	2	Creep

Cycle Time	Speed	Torque	Mode
901	16	3	Creep
902	15	7	Creep
903	18	10	Creep
904	19	5	Creep
905	15	0	Creep
906	13	3	Creep
907	14	7	Creep
908	10	0	Creep
909	13	7	Creep
910	14	2	Creep
911	8	0	Creep
912	10	2	Creep
913	10	4	Creep
914	6	0	Creep
915	8	6	Creep
916	6	7	Creep
917	9	7	Creep
918	9	7	Creep
919	9	6	Creep
920	9	5	Creep
921	8	5	Creep
922	5	4	Creep
923	4	3	Creep
924	0	0	Creep
925	0	0	Creep
926	0	0	Creep
927	0	0	Creep
928	0	0	Creep
929	0	0	Creep
930	0	0	Creep
931	0	0	Creep
932	0	0	Creep
933	0	0	Creep
934	0	0	Creep
935	0	0	Creep
936	0	0	Creep
937	0	0	Creep
938	0	0	Creep
939	0	0	Creep
940	0	0	Creep
941	0	0	Creep
942	0	0	Creep
943	0	0	Creep
944	0	0	Creep
945	0	0	Creep
946	0	0	Creep
947	0	0	Creep
948	0	0	Creep
949	0	0	Creep
950	0	0	Creep
951	0	0	Creep
952	0	0	Creep
953	0	0	Creep
954	0	0	Creep
955	0	0	Creep
956	0	0	Creep
957	0	0	Creep
958	0	0	Creep
959	0	0	Creep
960	0	0	Creep
961	0	0	Creep
962	0	0	Creep
963	0	0	Creep
964	0	0	Creep
965	0	0	Creep
966	0	0	Creep
967	0	0	Creep
968	8	20	Creep
969	14	33	Creep
970	13	48	Creep
971	27	23	Creep
972	30	8	Creep
973	43	9	Creep
974	40	9	Creep
975	49	8	Creep

Cycle Time	Speed	Torque	Mode
976	47	9	Creep
977	55	15	Creep
978	62	19	Creep
979	70	16	Creep
980	69	8	Creep
981	69	4	Creep
982	68	6	Creep
983	64	0	Creep
984	66	6	Creep
985	64	4	Creep
986	64	4	Creep
987	62	2	Creep
988	57	0	Creep
989	55	0	Creep
990	50	0	Creep
991	48	0	Creep
992	44	0	Creep
993	42	0	Creep
994	38	0	Creep
995	36	2	Creep
996	34	4	Creep
997	35	3	Creep
998	32	2	Creep
999	33	4	Creep
1000	31	4	Creep
1001	32	4	Creep
1002	32	4	Creep
1003	32	4	Creep
1004	32	4	Creep
1005	31	3	Creep
1006	24	0	Creep
1007	2	0	Creep
1008	0	0	Creep
1009	0	0	Creep
1010	0	0	Creep
1011	0	0	Creep
1012	0	0	Creep
1013	0	0	Creep
1014	0	0	Creep
1015	0	0	Creep
1016	0	0	Creep
1017	0	0	Creep
1018	0	0	Creep
1019	0	0	Creep
1020	0	0	Creep
1021	0	0	Creep
1022	0	0	Creep
1023	0	0	Creep
1024	0	0	Creep
1025	0	0	Creep
1026	0	0	Creep
1027	0	0	Creep
1028	0	0	Creep
1029	0	0	Creep
1030	0	0	Creep
1031	0	0	Creep
1032	0	0	Creep
1033	0	0	Creep
1034	0	0	Creep
1035	0	0	Creep
1036	0	0	Creep
1037	0	0	Creep
1038	0	0	Creep
1039	0	0	Creep
1040	0	0	Creep
1041	0	0	Creep
1042	0	0	Creep
1043	0	0	Creep
1044	0	0	Creep
1045	0	0	Creep
1046	0	0	Creep
1047	0	0	Creep
1048	0	0	Creep
1049	0	0	Creep
1050	0	0	Creep

Cycle Time	Speed	Torque	Mode
1051	0	0	Creep
1052	0	0	Creep
1053	0	0	Creep
1054	0	0	Creep
1055	0	0	Creep
1056	0	0	Creep
1057	0	0	Creep
1058	0	0	Creep
1059	0	0	Creep
1060	0	0	Creep
1061	0	0	Creep
1062	0	0	Creep
1063	10	28	Creep
1064	12	32	Creep
1065	12	48	Creep
1066	23	37	Creep
1067	39	24	Creep
1068	59	29	Creep
1069	72	26	Creep
1070	81	23	Creep
1071	83	7	Creep
1072	67	0	Creep
1073	51	0	Creep
1074	30	0	Creep
1075	23	0	Creep
1076	0	0	Creep
1077	0	0	Creep
1078	0	0	Creep
1079	0	0	Creep
1080	0	0	Creep
1081	0	0	Creep
1082	0	0	Creep
1083	0	0	Creep
1084	0	0	Creep
1085	0	0	Creep
1086	0	0	Creep
1087	0	0	Creep
1088	0	0	Creep
1089	0	0	Creep
1090	0	0	Creep
1091	0	0	Creep
1092	0	0	Creep
1093	0	0	Creep
1094	0	0	Creep
1095	0	0	Creep
1096	0	0	Creep
1097	0	0	Creep
1098	0	0	Creep
1099	0	0	Creep
1100	0	0	Creep
1101	0	0	Creep
1102	0	0	Creep
1103	0	0	Creep
1104	0	0	Creep
1105	0	0	Creep
1106	0	0	Creep
1107	0	0	Creep
1108	0	0	Creep
1109	0	0	Creep
1110	0	0	Creep
1111	0	0	Creep
1112	0	0	Creep
1113	0	0	Creep
1114	0	0	Creep
1115	0	0	Creep
1116	0	0	Creep
1117	0	0	Creep
1118	0	0	Creep
1119	0	0	Creep
1120	0	0	Creep
1121	0	0	Creep
1122	0	0	Creep
1123	0	0	Creep
1124	0	0	Creep
1125	0	0	Creep

Cycle Time	Speed	Torque	Mode
1126	0	0	Creep
1127	12	23	Creep
1128	9	8	Creep
1129	12	6	Creep
1130	18	10	Creep
1131	15	6	Creep
1132	14	6	Creep
1133	14	8	Creep
1134	13	13	Creep
1135	19	13	Creep
1136	20	8	Creep
1137	20	12	Creep
1138	22	7	Creep
1139	22	5	Creep
1140	20	4	Creep
1141	20	5	Creep
1142	18	6	Creep
1143	19	6	Creep
1144	19	6	Creep
1145	20	6	Creep
1146	19	6	Creep
1147	21	6	Creep
1148	21	6	Creep
1149	21	6	Creep
1150	21	6	Creep
1151	22	6	Creep
1152	23	6	Creep
1153	22	6	Creep
1154	22	3	Creep
1155	19	1	Creep
1156	17	2	Creep
1157	16	3	Creep
1158	15	7	Creep
1159	18	10	Creep
1160	19	5	Creep
1161	15	0	Creep
1162	13	3	Creep
1163	14	7	Creep
1164	10	0	Creep
1165	13	7	Creep
1166	14	2	Creep
1167	8	0	Creep
1168	10	2	Creep
1169	10	4	Creep
1170	6	0	Creep
1171	8	6	Creep
1172	6	7	Creep
1173	9	7	Creep
1174	9	7	Creep
1175	9	6	Creep
1176	9	5	Creep
1177	8	5	Creep
1178	5	4	Creep
1179	4	3	Creep
1180	0	0	Creep
1181	0	0	Creep
1182	0	0	Creep
1183	0	0	Creep
1184	0	0	Creep
1185	0	0	Creep
1186	0	0	Creep
1187	0	0	Creep
1188	0	0	Creep
1189	0	0	Creep
1190	0	0	Creep
1191	0	0	Creep
1192	0	0	Creep
1193	0	0	Creep
1194	0	0	Creep
1195	0	0	Creep
1196	0	0	Creep
1197	0	0	Creep
1198	0	0	Creep
1199	0	0	Creep
1200	0	0	Creep

Cycle Time	Speed	Torque	Mode
1201	0	0	Creep
1202	0	0	Creep
1203	0	0	Creep
1204	0	0	Creep
1205	0	0	Creep
1206	0	0	Creep
1207	0	0	Creep
1208	0	0	Creep
1209	0	0	Creep
1210	0	0	Creep
1211	0	0	Creep
1212	0	0	Creep
1213	0	0	Creep
1214	0	0	Creep
1215	0	0	Creep
1216	0	0	Creep
1217	0	0	Creep
1218	0	0	Creep
1219	0	0	Creep
1220	0	0	Creep
1221	0	0	Creep
1222	0	0	Creep
1223	0	0	Creep
1224	8	20	Creep
1225	14	33	Creep
1226	13	48	Creep
1227	27	23	Creep
1228	30	8	Creep
1229	43	9	Creep
1230	40	9	Creep
1231	49	8	Creep
1232	47	9	Creep
1233	55	15	Creep
1234	62	19	Creep
1235	70	16	Creep
1236	69	8	Creep
1237	69	4	Creep
1238	68	6	Creep
1239	64	0	Creep
1240	66	6	Creep
1241	64	4	Creep
1242	64	4	Creep
1243	62	2	Creep
1244	57	0	Creep
1245	55	0	Creep
1246	50	0	Creep
1247	48	0	Creep
1248	44	0	Creep
1249	42	0	Creep
1250	38	0	Creep
1251	36	2	Creep
1252	34	4	Creep
1253	35	3	Creep
1254	32	2	Creep
1255	33	4	Creep
1256	31	4	Creep
1257	32	4	Creep
1258	32	4	Creep
1259	32	4	Creep
1260	32	4	Creep
1261	31	3	Creep
1262	24	0	Creep
1263	2	0	Creep
1264	0	0	Creep
1265	0	0	Creep
1266	0	0	Creep
1267	0	0	Creep
1268	0	0	Creep
1269	0	0	Creep
1270	0	0	Creep
1271	0	0	Creep
1272	0	0	Creep
1273	0	0	Creep
1274	0	0	Creep
1275	0	0	Creep

Cycle Time	Speed	Torque	Mode
1276	0	0	Creep
1277	0	0	Creep
1278	0	0	Creep
1279	0	0	Creep
1280	0	0	Creep
1281	0	0	Creep
1282	0	0	Creep
1283	0	0	Creep
1284	0	0	Creep
1285	0	0	Creep
1286	0	0	Creep
1287	0	0	Creep
1288	0	0	Creep
1289	0	0	Creep
1290	0	0	Creep
1291	0	0	Creep
1292	0	0	Creep
1293	0	0	Creep
1294	0	0	Creep
1295	0	0	Creep
1296	0	0	Creep
1297	0	0	Creep
1298	0	0	Creep
1299	0	0	Creep
1300	0	0	Creep
1301	0	0	Creep
1302	0	0	Creep
1303	0	0	Creep
1304	0	0	Creep
1305	0	0	Creep
1306	0	0	Creep
1307	0	0	Creep
1308	0	0	Creep
1309	0	0	Creep
1310	0	0	Creep
1311	0	0	Creep
1312	0	0	Creep
1313	0	0	Creep
1314	0	0	Creep
1315	0	0	Creep
1316	0	0	Creep
1317	0	0	Creep
1318	0	0	Creep
1319	10	28	Creep
1320	12	32	Creep
1321	12	48	Creep
1322	23	37	Creep
1323	39	24	Creep
1324	59	29	Creep
1325	72	26	Creep
1326	81	23	Creep
1327	83	7	Creep
1328	67	0	Creep
1329	51	0	Creep
1330	30	0	Creep
1331	23	0	Creep
1332	0	0	Creep
1333	0	0	Creep
1334	0	0	Creep
1335	0	0	Creep
1336	0	0	Creep
1337	0	0	Creep
1338	0	0	Creep
1339	0	0	Creep
1340	0	0	Creep
1341	0	0	Creep
1342	0	0	Creep
1343	0	0	Creep
1344	0	0	Creep
1345	0	0	Creep
1346	0	0	Creep
1347	0	0	Creep
1348	0	0	Creep
1349	0	0	Creep
1350	0	0	Creep

Cycle Time	Speed	Torque	Mode
1351	0	0	Creep
1352	0	0	Creep
1353	0	0	Creep
1354	0	0	Creep
1355	0	0	Creep
1356	0	0	Creep
1357	0	0	Creep
1358	0	0	Creep
1359	0	0	Creep
1360	0	0	Creep
1361	0	0	Creep
1362	0	0	Creep
1363	0	0	Creep
1364	0	0	Creep
1365	0	0	Creep
1366	0	0	Creep
1367	0	0	Creep
1368	0	0	Creep
1369	0	0	Creep
1370	0	0	Creep
1371	0	0	Creep
1372	0	0	Creep
1373	0	0	Creep
1374	0	0	Creep
1375	0	0	Creep
1376	0	0	Creep
1377	0	0	Creep
1378	0	0	Creep
1379	0	0	Creep
1380	0	0	Creep
1381	0	0	Creep
1382	0	0	Creep
1383	12	23	Creep
1384	9	8	Creep
1385	12	6	Creep
1386	18	10	Creep
1387	15	6	Creep
1388	14	6	Creep
1389	14	8	Creep
1390	13	13	Creep
1391	19	13	Creep
1392	20	8	Creep
1393	20	12	Creep
1394	22	7	Creep
1395	22	5	Creep
1396	20	4	Creep
1397	20	5	Creep
1398	18	6	Creep
1399	19	6	Creep
1400	19	6	Creep
1401	20	6	Creep
1402	19	6	Creep
1403	21	6	Creep
1404	21	6	Creep
1405	21	6	Creep
1406	21	6	Creep
1407	22	6	Creep
1408	23	6	Creep
1409	22	6	Creep
1410	22	3	Creep
1411	19	1	Creep
1412	17	2	Creep
1413	16	3	Creep
1414	15	7	Creep
1415	18	10	Creep
1416	19	5	Creep
1417	15	0	Creep
1418	13	3	Creep
1419	14	7	Creep
1420	10	0	Creep
1421	13	7	Creep
1422	14	2	Creep
1423	8	0	Creep
1424	10	2	Creep
1425	10	4	Creep

Cycle Time	Speed	Torque	Mode
1426	6	0	Creep
1427	8	6	Creep
1428	6	7	Creep
1429	9	7	Creep
1430	9	7	Creep
1431	9	6	Creep
1432	9	5	Creep
1433	8	5	Creep
1434	5	4	Creep
1435	4	3	Creep
1436	0	0	Creep
1437	0	0	Creep
1438	0	0	Creep
1439	0	0	Creep
1440	0	0	Creep
1441	0	0	Creep
1442	0	0	Creep
1443	0	0	Creep
1444	0	0	Creep
1445	0	0	Creep
1446	0	0	Creep
1447	0	0	Creep
1448	0	0	Creep
1449	0	0	Creep
1450	0	0	Creep
1451	0	0	Creep
1452	0	0	Creep
1453	0	0	Creep
1454	0	0	Creep
1455	0	0	Creep
1456	0	0	Creep
1457	0	0	Creep
1458	0	0	Creep
1459	0	0	Creep
1460	0	0	Creep
1461	0	0	Creep
1462	0	0	Creep
1463	0	0	Creep
1464	0	0	Creep
1465	0	0	Creep
1466	0	0	Creep
1467	0	0	Creep
1468	0	0	Creep
1469	0	0	Creep
1470	0	0	Creep
1471	0	0	Creep
1472	0	0	Creep
1473	0	0	Creep
1474	0	0	Creep
1475	0	0	Creep
1476	0	0	Creep
1477	0	0	Creep
1478	0	0	Creep
1479	0	0	Creep
1480	8	20	Creep
1481	14	33	Creep
1482	13	48	Creep
1483	27	23	Creep
1484	30	8	Creep
1485	43	9	Creep
1486	40	9	Creep
1487	49	8	Creep
1488	47	9	Creep
1489	55	15	Creep
1490	62	19	Creep
1491	70	16	Creep
1492	69	8	Creep
1493	69	4	Creep
1494	68	6	Creep
1495	64	0	Creep
1496	66	6	Creep
1497	64	4	Creep
1498	64	4	Creep
1499	62	2	Creep
1500	57	0	Creep

Cycle Time	Speed	Torque	Mode
1501	55	0	Creep
1502	50	0	Creep
1503	48	0	Creep
1504	44	0	Creep
1505	42	0	Creep
1506	38	0	Creep
1507	36	2	Creep
1508	34	4	Creep
1509	35	3	Creep
1510	32	2	Creep
1511	33	4	Creep
1512	31	4	Creep
1513	32	4	Creep
1514	32	4	Creep
1515	32	4	Creep
1516	32	4	Creep
1517	31	3	Creep
1518	24	0	Creep
1519	2	0	Creep
1520	0	0	Creep
1521	0	0	Creep
1522	0	0	Creep
1523	0	0	Creep
1524	0	0	Creep
1525	0	0	Creep
1526	0	0	Creep
1527	0	0	Creep
1528	0	0	Creep
1529	0	0	Creep
1530	0	0	Creep
1531	0	0	Creep
1532	0	0	Creep
1533	0	0	Creep
1534	0	0	Creep
1535	0	0	Creep
1536	0	0	Creep
1537	0	0	Creep
1538	0	0	Creep
1539	0	0	Creep
1540	0	0	Creep
1541	0	0	Creep
1542	0	0	Creep
1543	0	0	Creep
1544	0	0	Creep
1545	0	0	Creep
1546	0	0	Creep
1547	0	0	Creep
1548	0	0	Creep
1549	0	0	Creep
1550	0	0	Creep
1551	0	0	Creep
1552	0	0	Creep
1553	0	0	Creep
1554	0	0	Creep
1555	0	0	Creep
1556	0	0	Creep
1557	0	0	Creep
1558	0	0	Creep
1559	0	0	Creep
1560	0	0	Creep
1561	0	0	Creep
1562	0	0	Creep
1563	0	0	Creep
1564	0	0	Creep
1565	0	0	Creep
1566	0	0	Creep
1567	0	0	Creep
1568	0	0	Creep
1569	0	0	Creep
1570	0	0	Creep
1571	0	0	Creep
1572	0	0	Creep
1573	0	0	Creep
1574	0	0	Creep
1575	10	28	Creep

Cycle Time	Speed	Torque	Mode
1576	12	32	Creep
1577	12	48	Creep
1578	23	37	Creep
1579	39	24	Creep
1580	59	29	Creep
1581	72	26	Creep
1582	81	23	Creep
1583	83	7	Creep
1584	67	0	Creep
1585	51	0	Creep
1586	30	0	Creep
1587	23	0	Creep
1588	0	0	Creep
1589	0	0	Creep
1590	0	0	Creep
1591	0	0	Creep
1592	0	0	Creep
1593	0	0	Creep
1594	0	0	Creep
1595	0	0	Creep
1596	0	0	Creep
1597	0	0	Creep
1598	0	0	Creep
1599	0	0	Creep
1600	0	0	Creep
1601	0	0	Creep
1602	0	0	Creep
1603	0	0	Creep
1604	0	0	Creep
1605	0	0	Creep
1606	0	0	Creep
1607	0	0	Creep
1608	0	0	Creep
1609	0	0	Creep
1610	0	0	Creep
1611	0	0	Creep
1612	0	0	Creep
1613	0	0	Creep
1614	0	0	Creep
1615	0	0	Creep
1616	0	0	Creep
1617	0	0	Creep
1618	0	0	Creep
1619	0	0	Creep
1620	0	0	Creep
1621	0	0	Creep
1622	0	0	Creep
1623	0	0	Creep
1624	0	0	Creep
1625	0	0	Creep
1626	0	0	Creep
1627	0	0	Creep
1628	0	0	Creep
1629	0	0	Creep
1630	0	0	Creep
1631	0	0	Creep
1632	0	0	Creep
1633	0	0	Creep
1634	0	0	Creep
1635	0	0	Creep
1636	0	0	Creep
1637	0	0	Creep
1638	0	0	Creep
1639	12	23	Creep
1640	9	8	Creep
1641	12	6	Creep
1642	18	10	Creep
1643	15	6	Creep
1644	14	6	Creep
1645	14	8	Creep
1646	13	13	Creep
1647	19	13	Creep
1648	20	8	Creep
1649	20	12	Creep
1650	22	7	Creep

Cycle Time	Speed	Torque	Mode
1651	22	5	Creep
1652	20	4	Creep
1653	20	5	Creep
1654	18	6	Creep
1655	19	6	Creep
1656	19	6	Creep
1657	20	6	Creep
1658	19	6	Creep
1659	21	6	Creep
1660	21	6	Creep
1661	21	6	Creep
1662	21	6	Creep
1663	22	6	Creep
1664	23	6	Creep
1665	22	6	Creep
1666	22	3	Creep
1667	19	1	Creep
1668	17	2	Creep
1669	16	3	Creep
1670	15	7	Creep
1671	18	10	Creep
1672	19	5	Creep
1673	15	0	Creep
1674	13	3	Creep
1675	14	7	Creep
1676	10	0	Creep
1677	13	7	Creep
1678	14	2	Creep
1679	8	0	Creep
1680	10	2	Creep
1681	10	4	Creep
1682	6	0	Creep
1683	8	6	Creep
1684	6	7	Creep
1685	9	7	Creep
1686	9	7	Creep
1687	9	6	Creep
1688	9	5	Creep
1689	8	5	Creep
1690	5	4	Creep
1691	4	3	Creep
1692	0	0	Creep
1693	0	0	Creep
1694	0	0	Creep
1695	0	0	Creep
1696	0	0	Creep
1697	0	0	Creep
1698	0	0	Creep
1699	0	0	Creep
1700	0	0	Creep
1701	0	0	Creep
1702	0	0	Creep
1703	0	0	Creep
1704	0	0	Creep
1705	0	0	Creep
1706	0	0	Creep
1707	0	0	Creep
1708	0	0	Creep
1709	0	0	Creep
1710	0	0	Creep
1711	0	0	Creep
1712	0	0	Creep
1713	0	0	Creep
1714	0	0	Creep
1715	0	0	Creep
1716	0	0	Creep
1717	0	0	Creep
1718	0	0	Creep
1719	0	0	Creep
1720	0	0	Creep
1721	0	0	Creep
1722	0	0	Creep
1723	0	0	Creep
1724	0	0	Creep
1725	0	0	Creep

Cycle Time	Speed	Torque	Mode
1726	0	0	Creep
1727	0	0	Creep
1728	0	0	Creep
1729	0	0	Creep
1730	0	0	Creep
1731	0	0	Creep
1732	0	0	Creep
1733	0	0	Creep
1734	0	0	Creep
1735	0	0	Creep
1736	8	20	Creep
1737	14	33	Creep
1738	13	48	Creep
1739	27	23	Creep
1740	30	8	Creep
1741	43	9	Creep
1742	40	9	Creep
1743	49	8	Creep
1744	47	9	Creep
1745	55	15	Creep
1746	62	19	Creep
1747	70	16	Creep
1748	69	8	Creep
1749	69	4	Creep
1750	68	6	Creep
1751	64	0	Creep
1752	66	6	Creep
1753	64	4	Creep
1754	64	4	Creep
1755	62	2	Creep
1756	57	0	Creep
1757	55	0	Creep
1758	50	0	Creep
1759	48	0	Creep
1760	44	0	Creep
1761	42	0	Creep
1762	38	0	Creep
1763	36	2	Creep
1764	34	4	Creep
1765	35	3	Creep
1766	32	2	Creep
1767	33	4	Creep
1768	31	4	Creep
1769	32	4	Creep
1770	32	4	Creep
1771	32	4	Creep
1772	32	4	Creep
1773	31	3	Creep
1774	24	0	Creep
1775	2	0	Creep
1776	0	0	Creep
1777	0	0	Creep
1778	0	0	Creep
1779	0	0	Creep
1780	0	0	Creep
1781	0	0	Creep
1782	0	0	Creep
1783	0	0	Creep
1784	0	0	Creep
1785	0	0	Creep
1786	0	0	Creep
1787	0	0	Creep
1788	0	0	Creep
1789	0	0	Creep
1790	0	0	Creep
1791	0	0	Creep
1792	0	0	Creep
1793	0	0	Creep
1794	0	0	Creep
1795	0	0	Creep
1796	0	0	Creep
1797	0	0	Creep
1798	0	0	Creep
1799	0	0	Creep
1800	0	0	Creep

Cycle Time	Speed	Torque	Mode
1801	0	0	Creep
1802	0	0	Creep
1803	0	0	Creep
1804	0	0	Creep
1805	0	0	Creep
1806	0	0	Creep
1807	0	0	Creep
1808	0	0	Creep
1809	0	0	Creep
1810	0	0	Creep
1811	0	0	Creep
1812	0	0	Creep
1813	0	0	Creep
1814	0	0	Creep
1815	0	0	Creep
1816	0	0	Creep
1817	0	0	Creep
1818	0	0	Creep
1819	0	0	Creep
1820	0	0	Creep
1821	0	0	Creep
1822	0	0	Creep
1823	0	0	Creep
1824	0	0	Creep
1825	0	0	Creep
1826	0	0	Creep
1827	0	0	Creep
1828	0	0	Creep
1829	0	0	Creep
1830	0	0	Creep
1831	10	28	Creep
1832	12	32	Creep
1833	12	48	Creep
1834	23	37	Creep
1835	39	24	Creep
1836	59	29	Creep
1837	72	26	Creep
1838	81	23	Creep
1839	83	7	Creep
1840	67	0	Creep
1841	51	0	Creep
1842	30	0	Creep
1843	23	0	Creep
1844	0	0	Creep
1845	0	0	Creep
1846	0	0	Creep
1847	0	0	Creep
1848	0	0	Creep
1849	0	0	Creep
1850	0	0	Creep
1851	0	0	Creep
1852	0	0	Creep
1853	0	0	Creep
1854	0	0	Creep
1855	0	0	Creep
1856	0	0	Creep
1857	0	0	Creep
1858	0	0	Creep
1859	0	0	Creep
1860	0	0	Creep
1861	0	0	Creep
1862	0	0	Creep
1863	0	0	Creep
1864	0	0	Creep
1865	0	0	Creep
1866	0	0	Creep
1867	0	0	Creep
1868	0	0	Creep
1869	0	0	Creep
1870	0	0	Creep
1871	0	0	Creep
1872	0	0	Creep
1873	0	0	Creep
1874	0	0	Creep
1875	0	0	Creep

Cycle Time	Speed	Torque	Mode
1876	0	0	Creep
1877	0	0	Creep
1878	0	0	Creep
1879	0	0	Creep
1880	0	0	Creep
1881	0	0	Creep
1882	0	0	Creep
1883	0	0	Creep
1884	0	0	Creep
1885	0	0	Creep
1886	0	0	Creep
1887	0	0	Creep
1888	0	0	Creep
1889	0	0	Creep
1890	0	0	Creep
1891	0	0	Creep
1892	0	0	Creep
1893	0	0	Creep
1894	0	0	Creep
1895	12	23	Creep
1896	9	8	Creep
1897	12	6	Creep
1898	18	10	Creep
1899	15	6	Creep
1900	14	6	Creep
1901	14	8	Creep
1902	13	13	Creep
1903	19	13	Creep
1904	20	8	Creep
1905	20	12	Creep
1906	22	7	Creep
1907	22	5	Creep
1908	20	4	Creep
1909	20	5	Creep
1910	18	6	Creep
1911	19	6	Creep
1912	19	6	Creep
1913	20	6	Creep
1914	19	6	Creep
1915	21	6	Creep
1916	21	6	Creep
1917	21	6	Creep
1918	21	6	Creep
1919	22	6	Creep
1920	23	6	Creep
1921	22	6	Creep
1922	22	3	Creep
1923	19	1	Creep
1924	17	2	Creep
1925	16	3	Creep
1926	15	7	Creep
1927	18	10	Creep
1928	19	5	Creep
1929	15	0	Creep
1930	13	3	Creep
1931	14	7	Creep
1932	10	0	Creep
1933	13	7	Creep
1934	14	2	Creep
1935	8	0	Creep
1936	10	2	Creep
1937	10	4	Creep
1938	6	0	Creep
1939	8	6	Creep
1940	6	7	Creep
1941	9	7	Creep
1942	9	7	Creep
1943	9	6	Creep
1944	9	5	Creep
1945	8	5	Creep
1946	5	4	Creep
1947	4	3	Creep
1948	0	0	Creep
1949	0	0	Creep
1950	0	0	Creep

Cycle Time	Speed	Torque	Mode
1951	0	0	Creep
1952	0	0	Creep
1953	0	0	Creep
1954	0	0	Creep
1955	0	0	Creep
1956	0	0	Creep
1957	0	0	Creep
1958	0	0	Creep
1959	0	0	Creep
1960	0	0	Creep
1961	0	0	Creep
1962	0	0	Creep
1963	0	0	Creep
1964	0	0	Creep
1965	0	0	Creep
1966	0	0	Creep
1967	0	0	Creep
1968	0	0	Creep
1969	0	0	Creep
1970	0	0	Creep
1971	0	0	Creep
1972	0	0	Creep
1973	0	0	Creep
1974	0	0	Creep
1975	0	0	Creep
1976	0	0	Creep
1977	0	0	Creep
1978	0	0	Creep
1979	0	0	Creep
1980	0	0	Creep
1981	0	0	Creep
1982	0	0	Creep
1983	0	0	Creep
1984	0	0	Creep
1985	0	0	Creep
1986	0	0	Creep
1987	0	0	Creep
1988	0	0	Creep
1989	0	0	Creep
1990	0	0	Creep
1991	0	0	Creep
1992	8	20	Creep
1993	14	33	Creep
1994	13	48	Creep
1995	27	23	Creep
1996	30	8	Creep
1997	43	9	Creep
1998	40	9	Creep
1999	49	8	Creep
2000	47	9	Creep
2001	55	15	Creep
2002	62	19	Creep
2003	70	16	Creep
2004	69	8	Creep
2005	69	4	Creep
2006	68	6	Creep
2007	64	0	Creep
2008	66	6	Creep
2009	64	4	Creep
2010	64	4	Creep
2011	62	2	Creep
2012	57	0	Creep
2013	55	0	Creep
2014	50	0	Creep
2015	48	0	Creep
2016	44	0	Creep
2017	42	0	Creep
2018	38	0	Creep
2019	36	2	Creep
2020	34	4	Creep
2021	35	3	Creep
2022	32	2	Creep
2023	33	4	Creep
2024	31	4	Creep
2025	32	4	Creep

Cycle Time	Speed	Torque	Mode
2026	32	4	Creep
2027	32	4	Creep
2028	32	4	Creep
2029	31	3	Creep
2030	24	0	Creep
2031	2	0	Creep
2032	0	0	Creep
2033	0	0	Creep
2034	0	0	Creep
2035	0	0	Creep
2036	0	0	Creep
2037	0	0	Creep
2038	0	0	Creep
2039	0	0	Creep
2040	0	0	Creep
2041	0	0	Creep
2042	0	0	Creep
2043	0	0	Creep
2044	0	0	Creep
2045	0	0	Creep
2046	0	0	Creep
2047	0	0	Creep
2048	0	0	Creep
2049	0	0	Creep
2050	0	0	Creep
2051	0	0	Creep
2052	0	0	Creep
2053	0	0	Creep
2054	0	0	Creep
2055	0	0	Creep
2056	0	0	Creep
2057	0	0	Creep
2058	0	0	Creep
2059	0	0	Creep
2060	0	0	Creep
2061	0	0	Creep
2062	0	0	Creep
2063	0	0	Creep
2064	0	0	Creep
2065	0	0	Creep
2066	0	0	Creep
2067	0	0	Creep
2068	0	0	Creep
2069	0	0	Creep
2070	0	0	Creep
2071	0	0	Creep
2072	0	0	Creep
2073	0	0	Creep
2074	0	0	Creep
2075	0	0	Creep
2076	0	0	Creep
2077	0	0	Creep
2078	0	0	Creep
2079	0	0	Creep
2080	0	0	Creep
2081	0	0	Creep
2082	0	0	Creep
2083	0	0	Creep
2084	0	0	Creep
2085	0	0	Creep
2086	0	0	Creep
2087	10	28	Creep
2088	12	32	Creep
2089	12	48	Creep
2090	23	37	Creep
2091	39	24	Creep
2092	59	29	Creep
2093	72	26	Creep
2094	81	23	Creep
2095	83	7	Creep
2096	67	0	Creep
2097	51	0	Creep
2098	30	0	Creep
2099	23	0	Creep
2100	0	0	Creep

Cycle Time	Speed	Torque	Mode
2101	0	0	Creep
2102	0	0	Creep
2103	0	0	Creep
2104	0	0	Creep
2105	0	0	Creep
2106	0	0	Creep
2107	0	0	Creep
2108	0	0	Creep
2109	0	0	Creep
2110	0	0	Creep
2111	0	0	Creep
2112	0	0	Creep
2113	0	0	Creep
2114	0	0	Creep
2115	0	0	Creep
2116	0	0	Creep
2117	0	0	Creep
2118	0	0	Creep
2119	0	0	Creep
2120	0	0	Creep
2121	0	0	Creep
2122	0	0	Creep
2123	0	0	Creep
2124	0	0	Creep
2125	0	0	Creep
2126	0	0	Creep
2127	0	0	Creep
2128	0	0	Creep
2129	0	0	Creep
2130	0	0	Creep
2131	0	0	Creep
2132	0	0	Creep
2133	0	0	Creep
2134	0	0	Creep
2135	0	0	Creep
2136	0	0	Creep
2137	0	0	Creep
2138	0	0	Creep
2139	0	0	Creep
2140	0	0	Creep
2141	0	0	Creep
2142	0	0	Creep
2143	0	0	Creep
2144	0	0	Creep
2145	0	0	Creep
2146	0	0	Creep
2147	0	0	Creep
2148	0	0	Creep
2149	0	0	Creep
2150	0	0	Creep
2151	12	23	Creep
2152	9	8	Creep
2153	12	6	Creep
2154	18	10	Creep
2155	15	6	Creep
2156	14	6	Creep
2157	14	8	Creep
2158	13	13	Creep
2159	19	13	Creep
2160	20	8	Creep
2161	20	12	Creep
2162	22	7	Creep
2163	22	5	Creep
2164	20	4	Creep
2165	20	5	Creep
2166	18	6	Creep
2167	19	6	Creep
2168	19	6	Creep
2169	20	6	Creep
2170	19	6	Creep
2171	21	6	Creep
2172	21	6	Creep
2173	21	6	Creep
2174	21	6	Creep
2175	22	6	Creep

Cycle Time	Speed	Torque	Mode
2176	23	6	Creep
2177	22	6	Creep
2178	22	3	Creep
2179	19	1	Creep
2180	17	2	Creep
2181	16	3	Creep
2182	15	7	Creep
2183	18	10	Creep
2184	19	5	Creep
2185	15	0	Creep
2186	13	3	Creep
2187	14	7	Creep
2188	10	0	Creep
2189	13	7	Creep
2190	14	2	Creep
2191	8	0	Creep
2192	10	2	Creep
2193	10	4	Creep
2194	6	0	Creep
2195	8	6	Creep
2196	6	7	Creep
2197	9	7	Creep
2198	9	7	Creep
2199	9	6	Creep
2200	9	5	Creep
2201	8	5	Creep
2202	5	4	Creep
2203	4	3	Creep
2204	0	0	Creep
2205	0	0	Creep
2206	0	0	Creep
2207	0	0	Creep
2208	0	0	Creep
2209	0	0	Creep
2210	0	0	Creep
2211	0	0	Creep
2212	0	0	Creep
2213	0	0	Creep
2214	0	0	Creep
2215	0	0	Creep
2216	0	0	Creep
2217	0	0	Creep
2218	0	0	Creep
2219	0	0	Creep
2220	0	0	Creep
2221	0	0	Creep
2222	0	0	Creep
2223	0	0	Creep
2224	0	0	Creep
2225	0	0	Creep
2226	0	0	Creep
2227	0	0	Creep
2228	0	0	Creep
2229	0	0	Creep
2230	0	0	Creep
2231	0	0	Creep
2232	0	0	Creep
2233	0	0	Creep
2234	0	0	Creep
2235	0	0	Creep
2236	0	0	Creep
2237	0	0	Creep
2238	0	0	Creep
2239	0	0	Creep
2240	0	0	Creep
2241	0	0	Creep
2242	0	0	Creep
2243	0	0	Creep
2244	0	0	Creep
2245	0	0	Creep
2246	0	0	Creep
2247	0	0	Creep
2248	8	20	Creep
2249	14	33	Creep
2250	13	48	Creep

Cycle Time	Speed	Torque	Mode
2251	27	23	Creep
2252	30	8	Creep
2253	43	9	Creep
2254	40	9	Creep
2255	49	8	Creep
2256	47	9	Creep
2257	55	15	Creep
2258	62	19	Creep
2259	70	16	Creep
2260	69	8	Creep
2261	69	4	Creep
2262	68	6	Creep
2263	64	0	Creep
2264	66	6	Creep
2265	64	4	Creep
2266	64	4	Creep
2267	62	2	Creep
2268	57	0	Creep
2269	55	0	Creep
2270	50	0	Creep
2271	48	0	Creep
2272	44	0	Creep
2273	42	0	Creep
2274	38	0	Creep
2275	36	2	Creep
2276	34	4	Creep
2277	35	3	Creep
2278	32	2	Creep
2279	33	4	Creep
2280	31	4	Creep
2281	32	4	Creep
2282	32	4	Creep
2283	32	4	Creep
2284	32	4	Creep
2285	31	3	Creep
2286	24	0	Creep
2287	2	0	Creep
2288	0	0	Creep
2289	0	0	Creep
2290	0	0	Creep
2291	0	0	Creep
2292	0	0	Creep
2293	0	0	Creep
2294	0	0	Creep
2295	0	0	Creep
2296	0	0	Creep
2297	0	0	Creep
2298	0	0	Creep
2299	0	0	Creep
2300	0	0	Creep
2301	0	0	Creep
2302	0	0	Creep
2303	0	0	Creep
2304	0	0	Creep
2305	0	0	Creep
2306	0	0	Creep
2307	0	0	Creep
2308	0	0	Creep
2309	0	0	Creep
2310	0	0	Creep
2311	0	0	Creep
2312	0	0	Creep
2313	0	0	Creep
2314	0	0	Creep
2315	0	0	Creep
2316	0	0	Creep
2317	0	0	Creep
2318	0	0	Creep
2319	0	0	Creep
2320	0	0	Creep
2321	0	0	Creep
2322	0	0	Creep
2323	0	0	Creep
2324	0	0	Creep
2325	0	0	Creep

Cycle Time	Speed	Torque	Mode
2326	0	0	Creep
2327	0	0	Creep
2328	0	0	Creep
2329	0	0	Creep
2330	0	0	Creep
2331	0	0	Creep
2332	0	0	Creep
2333	0	0	Creep
2334	0	0	Creep
2335	0	0	Creep
2336	0	0	Creep
2337	0	0	Creep
2338	0	0	Creep
2339	0	0	Creep
2340	0	0	Creep
2341	0	0	Creep
2342	0	0	Creep
2343	10	28	Creep
2344	12	32	Creep
2345	12	48	Creep
2346	23	37	Creep
2347	39	24	Creep
2348	59	29	Creep
2349	72	26	Creep
2350	81	23	Creep
2351	83	7	Creep
2352	67	0	Creep
2353	51	0	Creep
2354	30	0	Creep
2355	23	0	Creep
2356	0	0	Creep
2357	0	0	Creep
2358	0	0	Creep
2359	0	0	Creep
2360	0	0	Creep
2361	0	0	Creep
2362	0	0	Creep
2363	0	0	Creep
2364	0	0	Creep
2365	0	0	Creep
2366	0	0	Creep
2367	0	0	Creep
2368	0	0	Creep
2369	0	0	Creep
2370	0	0	Creep
2371	0	0	Creep
2372	0	0	Creep
2373	0	0	Creep
2374	0	0	Creep
2375	0	0	Creep
2376	0	0	Creep
2377	0	0	Creep
2378	0	0	Creep
2379	0	0	Creep
2380	0	0	Creep
2381	0	0	Creep
2382	0	0	Creep
2383	0	0	Creep
2384	0	0	Creep
2385	0	0	Creep
2386	0	0	Creep
2387	0	0	Creep
2388	0	0	Creep
2389	0	0	Creep
2390	0	0	Creep
2391	0	0	Creep
2392	0	0	Creep
2393	0	0	Creep
2394	0	0	Creep
2395	0	0	Creep
2396	0	0	Creep
2397	0	0	Creep
2398	0	0	Creep
2399	0	0	Creep
2400	0	0	Creep

Cycle Time	Speed	Torque	Mode
2401	0	0	Creep
2402	0	0	Creep
2403	0	0	Creep
2404	0	0	Creep
2405	0	0	Creep
2406	0	0	Creep
2407	12	23	Creep
2408	9	8	Creep
2409	12	6	Creep
2410	18	10	Creep
2411	15	6	Creep
2412	14	6	Creep
2413	14	8	Creep
2414	13	13	Creep
2415	19	13	Creep
2416	20	8	Creep
2417	20	12	Creep
2418	22	7	Creep
2419	22	5	Creep
2420	20	4	Creep
2421	20	5	Creep
2422	18	6	Creep
2423	19	6	Creep
2424	19	6	Creep
2425	20	6	Creep
2426	19	6	Creep
2427	21	6	Creep
2428	21	6	Creep
2429	21	6	Creep
2430	21	6	Creep
2431	22	6	Creep
2432	23	6	Creep
2433	22	6	Creep
2434	22	3	Creep
2435	19	1	Creep
2436	17	2	Creep
2437	16	3	Creep
2438	15	7	Creep
2439	18	10	Creep
2440	19	5	Creep
2441	15	0	Creep
2442	13	3	Creep
2443	14	7	Creep
2444	10	0	Creep
2445	13	7	Creep
2446	14	2	Creep
2447	8	0	Creep
2448	10	2	Creep
2449	10	4	Creep
2450	6	0	Creep
2451	8	6	Creep
2452	6	7	Creep
2453	9	7	Creep
2454	9	7	Creep
2455	9	6	Creep
2456	9	5	Creep
2457	8	5	Creep
2458	5	4	Creep
2459	4	3	Creep
2460	0	0	Creep
2461	0	0	Creep
2462	0	0	Creep
2463	0	0	Creep
2464	0	0	Creep
2465	0	0	Creep
2466	0	0	Creep
2467	0	0	Creep
2468	0	0	Creep
2469	0	0	Creep
2470	0	0	Creep
2471	0	0	Creep
2472	0	0	Creep
2473	0	0	Creep
2474	0	0	Creep
2475	0	0	Creep

Cycle Time	Speed	Torque	Mode
2476	0	0	Creep
2477	0	0	Creep
2478	0	0	Creep
2479	0	0	Creep
2480	0	0	Creep
2481	0	0	Creep
2482	0	0	Creep
2483	0	0	Creep
2484	0	0	Creep
2485	0	0	Creep
2486	0	0	Creep
2487	0	0	Creep
2488	0	0	Creep
2489	0	0	Creep
2490	0	0	Creep
2491	0	0	Creep
2492	0	0	Creep
2493	0	0	Creep
2494	0	0	Creep
2495	0	0	Creep
2496	0	0	Creep
2497	0	0	Creep
2498	0	0	Creep
2499	0	0	Creep
2500	0	0	Creep
2501	0	0	Creep
2502	0	0	Creep
2503	0	0	Creep
2504	8	20	Creep
2505	14	33	Creep
2506	13	48	Creep
2507	27	23	Creep
2508	30	8	Creep
2509	43	9	Creep
2510	40	9	Creep
2511	49	8	Creep
2512	47	9	Creep
2513	55	15	Creep
2514	62	19	Creep
2515	70	16	Creep
2516	69	8	Creep
2517	69	4	Creep
2518	68	6	Creep
2519	64	0	Creep
2520	66	6	Creep
2521	64	4	Creep
2522	64	4	Creep
2523	62	2	Creep
2524	57	0	Creep
2525	55	0	Creep
2526	50	0	Creep
2527	48	0	Creep
2528	44	0	Creep
2529	42	0	Creep
2530	38	0	Creep
2531	36	2	Creep
2532	34	4	Creep
2533	35	3	Creep
2534	32	2	Creep
2535	33	4	Creep
2536	31	4	Creep
2537	32	4	Creep
2538	32	4	Creep
2539	32	4	Creep
2540	32	4	Creep
2541	31	3	Creep
2542	24	0	Creep
2543	2	0	Creep
2544	0	0	Creep
2545	0	0	Creep
2546	0	0	Creep
2547	0	0	Creep
2548	0	0	Creep
2549	0	0	Creep
2550	0	0	Creep

Cycle Time	Speed	Torque	Mode
2551	0	0	Creep
2552	0	0	Creep
2553	0	0	Creep
2554	0	0	Creep
2555	0	0	Creep
2556	0	0	Creep
2557	0	0	Creep
2558	0	0	Creep
2559	0	0	Creep
2560	0	0	Creep
2561	0	0	Creep
2562	0	0	Creep
2563	0	0	Creep
2564	0	0	Creep
2565	0	0	Creep
2566	0	0	Creep
2567	0	0	Creep
2568	0	0	Creep
2569	0	0	Creep
2570	0	0	Creep
2571	0	0	Creep
2572	0	0	Creep
2573	0	0	Creep
2574	0	0	Creep
2575	0	0	Creep
2576	0	0	Creep
2577	0	0	Creep
2578	0	0	Creep
2579	0	0	Creep
2580	0	0	Creep
2581	0	0	Creep
2582	0	0	Creep
2583	0	0	Creep
2584	0	0	Creep
2585	0	0	Creep
2586	0	0	Creep
2587	0	0	Creep
2588	0	0	Creep
2589	0	0	Creep
2590	0	0	Creep
2591	0	0	Creep
2592	0	0	Creep
2593	0	0	Creep
2594	0	0	Creep
2595	0	0	Creep
2596	0	0	Creep
2597	0	0	Creep
2598	0	0	Creep
2599	10	28	Creep
2600	12	32	Creep
2601	12	48	Creep
2602	23	37	Creep
2603	39	24	Creep
2604	59	29	Creep
2605	72	26	Creep
2606	81	23	Creep
2607	83	7	Creep
2608	67	0	Creep
2609	51	0	Creep
2610	30	0	Creep
2611	23	0	Creep
2612	0	0	Creep
2613	0	0	Creep
2614	0	0	Creep
2615	0	0	Creep
2616	0	0	Creep
2617	0	0	Creep
2618	0	0	Creep
2619	0	0	Creep
2620	0	0	Creep
2621	0	0	Creep
2622	0	0	Creep
2623	0	0	Creep
2624	0	0	Creep
2625	0	0	Creep

Cycle Time	Speed	Torque	Mode
2626	0	0	Creep
2627	0	0	Creep
2628	0	0	Creep
2629	0	0	Creep
2630	0	0	Creep
2631	0	0	Creep
2632	0	0	Creep
2633	0	0	Creep
2634	0	0	Creep
2635	0	0	Creep
2636	0	0	Creep
2637	0	0	Creep
2638	0	0	Creep
2639	0	0	Creep
2640	0	0	Creep
2641	0	0	Creep
2642	0	0	Creep
2643	0	0	Creep
2644	0	0	Creep
2645	0	0	Creep
2646	0	0	Creep
2647	0	0	Creep
2648	0	0	Creep
2649	0	0	Creep
2650	0	0	Creep
2651	0	0	Creep
2652	0	0	Creep
2653	0	0	Creep
2654	0	0	Creep
2655	0	0	Creep
2656	0	0	Creep
2657	0	0	Creep
2658	0	0	Creep
2659	0	0	Creep
2660	0	0	Creep
2661	0	0	Creep
2662	0	0	Creep
2663	12	23	Creep
2664	9	8	Creep
2665	12	6	Creep
2666	18	10	Creep
2667	15	6	Creep
2668	14	6	Creep
2669	14	8	Creep
2670	13	13	Creep
2671	19	13	Creep
2672	20	8	Creep
2673	20	12	Creep
2674	22	7	Creep
2675	22	5	Creep
2676	20	4	Creep
2677	20	5	Creep
2678	18	6	Creep
2679	19	6	Creep
2680	19	6	Creep
2681	20	6	Creep
2682	19	6	Creep
2683	21	6	Creep
2684	21	6	Creep
2685	21	6	Creep
2686	21	6	Creep
2687	22	6	Creep
2688	23	6	Creep
2689	22	6	Creep
2690	22	3	Creep
2691	19	1	Creep
2692	17	2	Creep
2693	16	3	Creep
2694	15	7	Creep
2695	18	10	Creep
2696	19	5	Creep
2697	15	0	Creep
2698	13	3	Creep
2699	14	7	Creep
2700	10	0	Creep

Cycle Time	Speed	Torque	Mode
2701	13	7	Creep
2702	14	2	Creep
2703	8	0	Creep
2704	10	2	Creep
2705	10	4	Creep
2706	6	0	Creep
2707	8	6	Creep
2708	6	7	Creep
2709	9	7	Creep
2710	9	7	Creep
2711	9	6	Creep
2712	9	5	Creep
2713	8	5	Creep
2714	5	4	Creep
2715	4	3	Creep
2716	0	0	Creep
2717	0	0	Creep
2718	0	0	Creep
2719	0	0	Creep
2720	0	0	Creep
2721	0	0	Creep
2722	0	0	Creep
2723	0	0	Creep
2724	0	0	Creep
2725	0	0	Creep
2726	0	0	Creep
2727	0	0	Creep
2728	0	0	Creep
2729	0	0	Creep
2730	0	0	Creep
2731	0	0	Creep
2732	0	0	Creep
2733	0	0	Creep
2734	0	0	Creep
2735	0	0	Creep
2736	0	0	Creep
2737	0	0	Creep
2738	0	0	Creep
2739	0	0	Creep
2740	0	0	Creep
2741	0	0	Creep
2742	0	0	Creep
2743	0	0	Creep
2744	0	0	Creep
2745	0	0	Creep
2746	0	0	Creep
2747	0	0	Creep
2748	0	0	Creep
2749	0	0	Creep
2750	0	0	Creep
2751	0	0	Creep
2752	0	0	Creep
2753	0	0	Creep
2754	0	0	Creep
2755	0	0	Creep
2756	0	0	Creep
2757	0	0	Creep
2758	0	0	Creep
2759	0	0	Creep
2760	8	20	Creep
2761	14	33	Creep
2762	13	48	Creep
2763	27	23	Creep
2764	30	8	Creep
2765	43	9	Creep
2766	40	9	Creep
2767	49	8	Creep
2768	47	9	Creep
2769	55	15	Creep
2770	62	19	Creep
2771	70	16	Creep
2772	69	8	Creep
2773	69	4	Creep
2774	68	6	Creep
2775	64	0	Creep

Cycle Time	Speed	Torque	Mode
2776	66	6	Creep
2777	64	4	Creep
2778	64	4	Creep
2779	62	2	Creep
2780	57	0	Creep
2781	55	0	Creep
2782	50	0	Creep
2783	48	0	Creep
2784	44	0	Creep
2785	42	0	Creep
2786	38	0	Creep
2787	36	2	Creep
2788	34	4	Creep
2789	35	3	Creep
2790	32	2	Creep
2791	33	4	Creep
2792	31	4	Creep
2793	32	4	Creep
2794	32	4	Creep
2795	32	4	Creep
2796	32	4	Creep
2797	31	3	Creep
2798	24	0	Creep
2799	2	0	Creep
2800	0	0	Creep
2801	0	0	Creep
2802	0	0	Creep
2803	0	0	Creep
2804	0	0	Creep
2805	0	0	Creep
2806	0	0	Creep
2807	0	0	Creep
2808	0	0	Creep
2809	0	0	Creep
2810	0	0	Creep
2811	0	0	Creep
2812	0	0	Creep
2813	0	0	Creep
2814	0	0	Creep
2815	0	0	Creep
2816	0	0	Creep
2817	0	0	Creep
2818	0	0	Creep
2819	0	0	Creep
2820	0	0	Creep
2821	0	0	Creep
2822	0	0	Creep
2823	0	0	Creep
2824	0	0	Creep
2825	0	0	Creep
2826	0	0	Creep
2827	0	0	Creep
2828	0	0	Creep
2829	0	0	Creep
2830	0	0	Creep
2831	0	0	Creep
2832	0	0	Creep
2833	0	0	Creep
2834	0	0	Creep
2835	0	0	Creep
2836	0	0	Creep
2837	0	0	Creep
2838	0	0	Creep
2839	0	0	Creep
2840	0	0	Creep
2841	0	0	Creep
2842	0	0	Creep
2843	0	0	Creep
2844	0	0	Creep
2845	0	0	Creep
2846	0	0	Creep
2847	0	0	Creep
2848	0	0	Creep
2849	0	0	Creep
2850	0	0	Creep

Cycle Time	Speed	Torque	Mode
2851	0	0	Creep
2852	0	0	Creep
2853	0	0	Creep
2854	0	0	Creep
2855	10	28	Creep
2856	12	32	Creep
2857	12	48	Creep
2858	23	37	Creep
2859	39	24	Creep
2860	59	29	Creep
2861	72	26	Creep
2862	81	23	Creep
2863	83	7	Creep
2864	67	0	Creep
2865	51	0	Creep
2866	30	0	Creep
2867	23	0	Creep
2868	0	0	Creep
2869	0	0	Creep
2870	0	0	Creep
2871	0	0	Creep
2872	0	0	Creep
2873	0	0	Creep
2874	0	0	Creep
2875	0	0	Creep
2876	0	0	Creep
2877	0	0	Creep
2878	0	0	Creep
2879	0	0	Creep
2880	0	0	Creep
2881	0	0	Creep
2882	0	0	Creep
2883	0	0	Creep
2884	0	0	Creep
2885	0	0	Creep
2886	0	0	Creep
2887	0	0	Creep
2888	0	0	Creep
2889	0	0	Creep
2890	0	0	Creep
2891	0	0	Creep
2892	0	0	Creep
2893	0	0	Creep
2894	0	0	Creep
2895	0	0	Creep
2896	0	0	Creep
2897	0	0	Creep
2898	0	0	Creep
2899	0	0	Creep
2900	0	0	Creep
2901	0	0	Creep
2902	0	0	Creep
2903	0	0	Creep
2904	0	0	Creep
2905	0	0	Creep
2906	0	0	Creep
2907	0	0	Creep
2908	0	0	Creep
2909	0	0	Creep
2910	0	0	Creep
2911	0	0	Creep
2912	0	0	Creep
2913	0	0	Creep
2914	0	0	Creep
2915	0	0	Creep
2916	0	0	Creep
2917	0	0	Creep
2918	0	0	Creep
2919	12	23	Creep
2920	9	8	Creep
2921	12	6	Creep
2922	18	10	Creep
2923	15	6	Creep
2924	14	6	Creep
2925	14	8	Creep

Cycle Time	Speed	Torque	Mode
2926	13	13	Creep
2927	19	13	Creep
2928	20	8	Creep
2929	20	12	Creep
2930	22	7	Creep
2931	22	5	Creep
2932	20	4	Creep
2933	20	5	Creep
2934	18	6	Creep
2935	19	6	Creep
2936	19	6	Creep
2937	20	6	Creep
2938	19	6	Creep
2939	21	6	Creep
2940	21	6	Creep
2941	21	6	Creep
2942	21	6	Creep
2943	22	6	Creep
2944	23	6	Creep
2945	22	6	Creep
2946	22	3	Creep
2947	19	1	Creep
2948	17	2	Creep
2949	16	3	Creep
2950	15	7	Creep
2951	18	10	Creep
2952	19	5	Creep
2953	15	0	Creep
2954	13	3	Creep
2955	14	7	Creep
2956	10	0	Creep
2957	13	7	Creep
2958	14	2	Creep
2959	8	0	Creep
2960	10	2	Creep
2961	10	4	Creep
2962	6	0	Creep
2963	8	6	Creep
2964	6	7	Creep
2965	9	7	Creep
2966	9	7	Creep
2967	9	6	Creep
2968	9	5	Creep
2969	8	5	Creep
2970	5	4	Creep
2971	4	3	Creep
2972	0	0	Creep
2973	0	0	Creep
2974	0	0	Creep
2975	0	0	Creep
2976	0	0	Creep
2977	0	0	Creep
2978	0	0	Creep
2979	0	0	Creep
2980	0	0	Creep
2981	0	0	Creep
2982	0	0	Creep
2983	0	0	Creep
2984	0	0	Creep
2985	0	0	Creep
2986	0	0	Creep
2987	0	0	Creep
2988	0	0	Creep
2989	0	0	Creep
2990	0	0	Creep
2991	0	0	Creep
2992	0	0	Creep
2993	0	0	Creep
2994	0	0	Creep
2995	0	0	Creep
2996	0	0	Creep
2997	0	0	Creep
2998	0	0	Creep
2999	0	0	Creep
3000	0	0	Creep

Cycle Time	Speed	Torque	Mode	Cycle Time	Speed	Torque	Mode	Cycle Time	Speed	Torque	Mode	Cycle Time	Speed	Torque	Mode	Cycle Time	Speed	Torque	Mode
3001	0	0	Creep	3076	0	0	Creep	3151	0	0	Creep	3226	5	4	Creep	3301	35	3	Creep
3002	0	0	Creep	3077	0	0	Creep	3152	0	0	Creep	3227	4	3	Creep	3302	32	2	Creep
3003	0	0	Creep	3078	0	0	Creep	3153	0	0	Creep	3228	0	0	Creep	3303	33	4	Creep
3004	0	0	Creep	3079	0	0	Creep	3154	0	0	Creep	3229	0	0	Creep	3304	31	4	Creep
3005	0	0	Creep	3080	0	0	Creep	3155	0	0	Creep	3230	0	0	Creep	3305	32	4	Creep
3006	0	0	Creep	3081	0	0	Creep	3156	0	0	Creep	3231	0	0	Creep	3306	32	4	Creep
3007	0	0	Creep	3082	0	0	Creep	3157	0	0	Creep	3232	0	0	Creep	3307	32	4	Creep
3008	0	0	Creep	3083	0	0	Creep	3158	0	0	Creep	3233	0	0	Creep	3308	32	4	Creep
3009	0	0	Creep	3084	0	0	Creep	3159	0	0	Creep	3234	0	0	Creep	3309	31	3	Creep
3010	0	0	Creep	3085	0	0	Creep	3160	0	0	Creep	3235	0	0	Creep	3310	24	0	Creep
3011	0	0	Creep	3086	0	0	Creep	3161	0	0	Creep	3236	0	0	Creep	3311	2	0	Creep
3012	0	0	Creep	3087	0	0	Creep	3162	0	0	Creep	3237	0	0	Creep	3312	0	0	Creep
3013	0	0	Creep	3088	0	0	Creep	3163	0	0	Creep	3238	0	0	Creep	3313	0	0	Creep
3014	0	0	Creep	3089	0	0	Creep	3164	0	0	Creep	3239	0	0	Creep	3314	0	0	Creep
3015	0	0	Creep	3090	0	0	Creep	3165	0	0	Creep	3240	0	0	Creep	3315	0	0	Creep
3016	8	20	Creep	3091	0	0	Creep	3166	0	0	Creep	3241	0	0	Creep	3316	0	0	Creep
3017	14	33	Creep	3092	0	0	Creep	3167	0	0	Creep	3242	0	0	Creep	3317	0	0	Creep
3018	13	48	Creep	3093	0	0	Creep	3168	0	0	Creep	3243	0	0	Creep	3318	0	0	Creep
3019	27	23	Creep	3094	0	0	Creep	3169	0	0	Creep	3244	0	0	Creep	3319	0	0	Creep
3020	30	8	Creep	3095	0	0	Creep	3170	0	0	Creep	3245	0	0	Creep	3320	0	0	Creep
3021	43	9	Creep	3096	0	0	Creep	3171	0	0	Creep	3246	0	0	Creep				
3022	40	9	Creep	3097	0	0	Creep	3172	0	0	Creep	3247	0	0	Creep				
3023	49	8	Creep	3098	0	0	Creep	3173	0	0	Creep	3248	0	0	Creep				
3024	47	9	Creep	3099	0	0	Creep	3174	0	0	Creep	3249	0	0	Creep				
3025	55	15	Creep	3100	0	0	Creep	3175	12	23	Creep	3250	0	0	Creep				
3026	62	19	Creep	3101	0	0	Creep	3176	9	8	Creep	3251	0	0	Creep				
3027	70	16	Creep	3102	0	0	Creep	3177	12	6	Creep	3252	0	0	Creep				
3028	69	8	Creep	3103	0	0	Creep	3178	18	10	Creep	3253	0	0	Creep				
3029	69	4	Creep	3104	0	0	Creep	3179	15	6	Creep	3254	0	0	Creep				
3030	68	6	Creep	3105	0	0	Creep	3180	14	6	Creep	3255	0	0	Creep				
3031	64	0	Creep	3106	0	0	Creep	3181	14	8	Creep	3256	0	0	Creep				
3032	66	6	Creep	3107	0	0	Creep	3182	13	13	Creep	3257	0	0	Creep				
3033	64	4	Creep	3108	0	0	Creep	3183	19	13	Creep	3258	0	0	Creep				
3034	64	4	Creep	3109	0	0	Creep	3184	20	8	Creep	3259	0	0	Creep				
3035	62	2	Creep	3110	0	0	Creep	3185	20	12	Creep	3260	0	0	Creep				
3036	57	0	Creep	3111	10	28	Creep	3186	22	7	Creep	3261	0	0	Creep				
3037	55	0	Creep	3112	12	32	Creep	3187	22	5	Creep	3262	0	0	Creep				
3038	50	0	Creep	3113	12	48	Creep	3188	20	4	Creep	3263	0	0	Creep				
3039	48	0	Creep	3114	23	37	Creep	3189	20	5	Creep	3264	0	0	Creep				
3040	44	0	Creep	3115	39	24	Creep	3190	18	6	Creep	3265	0	0	Creep				
3041	42	0	Creep	3116	59	29	Creep	3191	19	6	Creep	3266	0	0	Creep				
3042	38	0	Creep	3117	72	26	Creep	3192	19	6	Creep	3267	0	0	Creep				
3043	36	2	Creep	3118	81	23	Creep	3193	20	6	Creep	3268	0	0	Creep				
3044	34	4	Creep	3119	83	7	Creep	3194	19	6	Creep	3269	0	0	Creep				
3045	35	3	Creep	3120	67	0	Creep	3195	21	6	Creep	3270	0	0	Creep				
3046	32	2	Creep	3121	51	0	Creep	3196	21	6	Creep	3271	0	0	Creep				
3047	33	4	Creep	3122	30	0	Creep	3197	21	6	Creep	3272	8	20	Creep				
3048	31	4	Creep	3123	23	0	Creep	3198	21	6	Creep	3273	14	33	Creep				
3049	32	4	Creep	3124	0	0	Creep	3199	22	6	Creep	3274	13	48	Creep				
3050	32	4	Creep	3125	0	0	Creep	3200	23	6	Creep	3275	27	23	Creep				
3051	32	4	Creep	3126	0	0	Creep	3201	22	6	Creep	3276	30	8	Creep				
3052	32	4	Creep	3127	0	0	Creep	3202	22	3	Creep	3277	43	9	Creep				
3053	31	3	Creep	3128	0	0	Creep	3203	19	1	Creep	3278	40	9	Creep				
3054	24	0	Creep	3129	0	0	Creep	3204	17	2	Creep	3279	49	8	Creep				
3055	2	0	Creep	3130	0	0	Creep	3205	16	3	Creep	3280	47	9	Creep				
3056	0	0	Creep	3131	0	0	Creep	3206	15	7	Creep	3281	55	15	Creep				
3057	0	0	Creep	3132	0	0	Creep	3207	18	10	Creep	3282	62	19	Creep				
3058	0	0	Creep	3133	0	0	Creep	3208	19	5	Creep	3283	70	16	Creep				
3059	0	0	Creep	3134	0	0	Creep	3209	15	0	Creep	3284	69	8	Creep				
3060	0	0	Creep	3135	0	0	Creep	3210	13	3	Creep	3285	69	4	Creep				
3061	0	0	Creep	3136	0	0	Creep	3211	14	7	Creep	3286	68	6	Creep				
3062	0	0	Creep	3137	0	0	Creep	3212	10	0	Creep	3287	64	0	Creep				
3063	0	0	Creep	3138	0	0	Creep	3213	13	7	Creep	3288	66	6	Creep				
3064	0	0	Creep	3139	0	0	Creep	3214	14	2	Creep	3289	64	4	Creep				
3065	0	0	Creep	3140	0	0	Creep	3215	8	0	Creep	3290	64	4	Creep				
3066	0	0	Creep	3141	0	0	Creep	3216	10	2	Creep	3291	62	2	Creep				
3067	0	0	Creep	3142	0	0	Creep	3217	10	4	Creep	3292	57	0	Creep				
3068	0	0	Creep	3143	0	0	Creep	3218	6	0	Creep	3293	55	0	Creep				
3069	0	0	Creep	3144	0	0	Creep	3219	8	6	Creep	3294	50	0	Creep				
3070	0	0	Creep	3145	0	0	Creep	3220	6	7	Creep	3295	48	0	Creep				
3071	0	0	Creep	3146	0	0	Creep	3221	9	7	Creep	3296	44	0	Creep				
3072	0	0	Creep	3147	0	0	Creep	3222	9	7	Creep	3297	42	0	Creep				
3073	0	0	Creep	3148	0	0	Creep	3223	9	6	Creep	3298	38	0	Creep				
3074	0	0	Creep	3149	0	0	Creep	3224	9	5	Creep	3299	36	2	Creep				
3075	0	0	Creep	3150	0	0	Creep	3225	8	5	Creep	3300	34	4	Creep				

TABLE A-3. OCTA BUS CYCLE

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1	0	0	50	0	0	101	0	0	151	32.35714	14.71755
2	0	0	51	0	0	102	0	0	152	34.375	17.82685
3	0	0	52	12.9375	44.83105	103	0	0	153	36.3125	18.7667
4	0	0	53	43.67857	36.357	104	0	0	154	38.33036	19.65006
5	0	0	54	68.98214	60.01164	105	0	0	155	40.17857	19.45694
6	0	0	55	81.5	64.81707	106	0	0	156	42.00893	18.26826
7	0	0	56	74.8125	68.88076	107	0	0	157	42.89286	7.230355
8	0	0	57	77.5	48.58839	108	0.946429	30.93163	158	37.61607	-1
9	0	0	58	36.80357	-1	109	27.38393	46.92834	159	33.45536	-1
10	0	0	59	34.77679	-1	110	54.25893	40.90372	160	29.47321	-1
11	0	0	60	20.38393	-1	111	69.85714	51.69378	161	13.34821	-1
12	0	0	61	6.580357	6.753592	112	76.55357	59.06927	162	3.223214	10.63345
13	0	0	62	5.089286	14.39828	113	72.44643	62.51268	163	2.330357	11.48201
14	0	0	63	0	0	114	47.94643	62.2336	164	0	0
15	0	0	64	0	0	115	49.35714	33.94065	165	0	0
16	0	0	65	0	0	116	44	-1	166	0	0
17	0	0	66	0	0	117	39.40179	-1	167	0	0
18	0	0	67	0	0	118	22.98214	-1	168	0	0
19	0	0	68	0	0	119	10.1875	-1	169	0	0
20	0	0	69	0	0	120	2.4375	12.3983	170	0	0
21	0	0	70	0	0	121	6.035714	5.266661	171	0	0
22	10.96429	50.37443	71	0	0	122	0	5.234652	172	0	0
23	37.14286	38.82918	72	0	0	123	0	0	173	0	0
24	59.5	50.81015	73	0	0	124	0	0	174	0	0
25	70.51786	44.42186	74	0	0	125	0	0	175	0	0
26	66.99107	50.99183	75	0	0	126	0	0	176	0	0
27	68.16071	53.64888	76	0	0	127	0	0	177	0	0
28	47.04464	56.11299	77	0	0	128	0	0	178	0	0
29	44.00893	30.51037	78	0	0	129	0	0	179	0	0
30	52.86607	42.06924	79	0	0	130	0	0	180	22.08036	47.97727
31	60.29464	45.02205	80	0	0	131	0	0	181	48.39286	40.99476
32	62.61607	47.68288	81	8.473214	48.34515	132	0	0	182	75.57143	63.32286
33	38.90179	23.86613	82	32.28571	35.11691	133	0	0	183	83.75	68.81641
34	39.89286	10.65404	83	38.125	27.31214	134	0	0	184	80.16964	72.50389
35	36.73214	-1	84	44.84821	30.50815	135	0	0	185	47.23214	73.10508
36	34.11607	-1	85	54.07143	31.76559	136	0	0	186	58.41071	54.11999
37	31.36607	-1	86	64.91071	30.10199	137	0	0	187	63.66071	58.93658
38	29.20536	-1	87	11.875	-1	138	0	0	188	41.01786	61.21143
39	26.47321	-1	88	5.6875	20.21093	139	0	0	189	50.21429	59.87732
40	24.00893	-1	89	6.428571	9.951207	140	0	0	190	55.54464	59.45616
41	21.5625	-1	90	6.785714	9.882532	141	1.071429	27.32739	191	61.92857	60.56726
42	15.96429	-1	91	0	0	142	19.00893	43.99111	192	65.21429	58.72597
43	28.39286	-1	92	0	0	143	34.63393	34.34389	193	33.20536	65.10192
44	23.47321	-1	93	0	0	144	48.40179	42.84622	194	37	59.22847
45	19.63393	-1	94	0	0	145	68.11607	49.78861	195	39.97321	64.61828
46	10.78571	7.446933	95	0	0	146	73.47321	43.41358	196	43.77679	65.51138
47	5.767857	6.01903	96	0	0	147	61.99107	46.79867	197	46.63393	68.30717
48	0	0	97	0	0	148	63.17857	45.44172	198	50.13393	68.8704
49	0	0	98	0	0	149	32.61607	-1	199	52.00893	-1
50	0	0	99	0	0	150	31.59821	11.32443	200	47.64286	-1
			100	0	0						

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
201	34.8125	-1	251	44.51786	9.358948	301	41.11607	38.1061	351	63.02679	27.66597
202	22.70536	-1	252	44.23214	9.355486	302	37.83036	-1	352	28.16964	17.72963
203	39.41964	-1	253	41.26786	-1	303	36.375	-1	353	26.05357	-1
204	28.46429	-1	254	39.25	8.421607	304	30.375	-1	354	24.91964	-1
205	20.61607	-1	255	38.97321	5.194152	305	21.98214	-1	355	23.34821	-1
206	28.52679	-1	256	38.375	5.254429	306	39.3125	-1	356	21.84821	-1
207	3.294643	8.036392	257	37.64286	5.293883	307	26.34821	-1	357	14.77679	-1
208	0	0	258	37.0625	6.424629	308	36.05357	-1	358	30.42857	-1
209	0	0	259	36.36607	5.362522	309	20.10714	-1	359	21.82143	-1
210	0	0	260	35.51786	-1	310	7.348214	12.55245	360	7.241071	11.23564
211	0	0	261	32.11607	-1	311	2.321429	11.09565	361	0	0
212	0	0	262	30.04464	-1	312	0	0	362	0	0
213	0	0	263	27.32143	-1	313	0	0	363	0	0
214	0	0	264	16.04464	-1	314	0	0	364	0	0
215	0	0	265	23	-1	315	0	0	365	0	0
216	0	0	266	5.607143	7.811011	316	0	0	366	0	0
217	0	0	267	0	0	317	0	0	367	0	0
218	0	0	268	0	0	318	0	0	368	0	0
219	0	0	269	0	0	319	0	0	369	0	0
220	0	0	270	0	0	320	0	0	370	0	0
221	0	0	271	0	0	321	0	0	371	0	0
222	0	0	272	0	0	322	0	0	372	0	0
223	0	0	273	0	0	323	0	0	373	0	0
224	0	0	274	0	0	324	0	0	374	0	0
225	0	0	275	0	0	325	0	0	375	0	0
226	2.651786	51.89371	276	0	0	326	0	0	376	7.160714	47.80019
227	33.03571	42.06337	277	0	0	327	0	0	377	38.27679	40.84179
228	57.08036	55.05928	278	0	0	328	0	0	378	64.67857	59.94883
229	70.46429	49.385	279	0	0	329	18.84821	52.20534	379	83.39286	65.73445
230	74.77679	53.84564	280	0	0	330	47.33036	41.53946	380	76.52679	67.65192
231	62.40179	45.36519	281	0	0	331	59.54464	48.72673	381	56.41071	68.90376
232	36.41964	30.4467	282	0	0	332	57.30357	33.20694	382	45.63393	64.58897
233	32.58929	36.96152	283	0	0	333	72.69643	46.59429	383	63.08036	61.95338
234	41.54464	37.14239	284	0	0	334	54.14286	35.32831	384	42.0625	69.95466
235	47.25893	39.40986	285	0	0	335	48.60714	30.54214	385	48.98214	65.99679
236	53.74107	37.45556	286	1.8125	39.64937	336	31.86607	25.93765	386	56.4375	66.13122
237	57.94643	30.94614	287	29.58036	46.07852	337	36.58036	32.27602	387	62	67.62714
238	59.33929	18.25522	288	45.80357	36.0833	338	42.49107	35.97966	388	65.29464	72.57425
239	60.70536	17.10864	289	67.11607	53.43328	339	48.40179	37.16944	389	34.25	62.66994
240	34.98214	36.3868	290	80.52679	64.60138	340	54.02679	36.41789	390	38.27679	58.14478
241	38.07143	32.7708	291	78.23214	70.27203	341	59.5	36.8624	391	41.66071	63.51442
242	40.92857	30.46419	292	50.14286	77.87595	342	49.67857	39.57639	392	45.29464	64.66392
243	43.24107	31.51385	293	58.99107	73.93225	343	37.52679	37.09415	393	48.375	68.58599
244	45.98214	32.5464	294	64.15179	64.07291	344	42.73214	34.78719	394	51.99107	69.17373
245	48.24107	28.28985	295	42.17857	64.48703	345	45.64286	35.97076	395	54.65179	68.04299
246	50.24107	27.17963	296	52.58036	69.27063	346	48.625	36.02016	396	57.17857	56.20688
247	52.41071	28.41281	297	60.24107	74.23807	347	51.51786	36.18501	397	58.79464	23.99161
248	52.54464	12.55852	298	65.15179	73.46609	348	55.20536	36.53177	398	57.29464	15.92996
249	47.90179	-1	299	34.91071	80.70232	349	57.77679	35.51306	399	58.80357	40.23439
250	47.375	-1	300	39.52679	60.19222	350	61.0625	35.66447	400	60.5625	53.3038

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
401	61.55357	-1	451	71.50893	63.25197	501	27.45536	5.072874	551	51.69643	28.3699
402	58.3125	-1	452	76.58929	67.49466	502	26.32143	-1	552	53.27679	21.63086
403	47.44643	-1	453	46.83929	70.80942	503	24.78571	-1	553	53.58036	17.09018
404	35.77679	-1	454	59.08929	65.13724	504	17.77679	-1	554	54.25	17.08864
405	22.76786	-1	455	64.02679	65.60551	505	32.47321	-1	555	55.08036	23.94477
406	40.86607	-1	456	42.00893	69.96965	506	23.09821	-1	556	56.625	21.67705
407	23.84821	-1	457	52.49107	60.126	507	32.88393	-1	557	57.0625	18.22932
408	33.90179	-1	458	55.83036	36.54086	508	7.473214	9.928353	558	57.91071	18.24126
409	10.61607	11.67497	459	58.29464	30.87716	509	0	0	559	58.25893	17.08583
410	0	0	460	60.73214	35.8075	510	0	0	560	58.88393	17.09666
411	0	0	461	62.27679	21.83467	511	0	0	561	59.33036	15.93809
412	0	0	462	63.09821	19.47946	512	0	0	562	56.99107	-1
413	0	0	463	29.26786	30.36262	513	0	0	563	54.02679	-1
414	0	0	464	26.61607	-1	514	0	0	564	51.17857	-1
415	0	0	465	26.11607	7.440305	515	0	0	565	51.625	10.33694
416	0	0	466	26.42857	13.48866	516	0	0	566	47.38393	-1
417	0	0	467	27.48214	22.81891	517	0	0	567	45.32143	-1
418	0	0	468	27.61607	15.67385	518	0	0	568	42.64286	-1
419	0	0	469	26.39286	7.477582	519	0	0	569	28.29464	-1
420	0	0	470	25.91071	11.23299	520	0	0	570	20.07143	-1
421	0	0	471	26.60714	19.47763	521	0	0	571	27.40179	-1
422	0	0	472	27.00893	27.74906	522	0	0	572	0	9.35424
423	0	0	473	27.50893	28.79591	523	0	0	573	0	0
424	0	0	474	28.16071	27.25956	524	0	0	574	0	0
425	0	0	475	28.94643	26.97727	525	0	0	575	0	0
426	0	0	476	29.51786	26.81963	526	0	0	576	0	0
427	0	0	477	30.11607	26.65612	527	2.276786	45.44882	577	0	0
428	3.401786	51.06639	478	30.76786	26.47972	528	32.23214	40.68532	578	0	0
429	47.95536	58.941	479	31.33036	26.32892	529	59.20536	56.57086	579	0	0
430	72.1875	66.18903	480	31.79464	26.20545	530	74.63393	59.72065	580	0	0
431	76.34821	50.26887	481	32.22321	18.27771	531	53.35714	32.21444	581	0	0
432	72.41071	63.66632	482	31.19643	8.116217	532	62.6875	50.11266	582	0	0
433	54.53571	61.50505	483	30.82143	6.982686	533	65.30357	37.67458	583	0	0
434	45.57143	67.1621	484	30.26786	9.385006	534	38.82143	32.66033	584	0	0
435	61.41964	60.7136	485	29.14286	3.680459	535	45.77679	39.30872	585	0	0
436	40.58929	66.92398	486	29.08036	10.70237	536	52.49107	42.04021	586	0	0
437	46.72321	59.40254	487	28.76786	14.19419	537	59.35714	41.22999	587	0	0
438	50.64286	-1	488	28.63393	13.01771	538	62.33036	43.18505	588	0	0
439	45.39286	-1	489	28.53571	15.43282	539	38.09821	44.86935	589	7.982143	50.48077
440	29.30357	-1	490	29.03571	16.51012	540	42.78571	28.15612	590	38.44643	40.36581
441	17.41071	-1	491	28.53571	15.38557	541	44.35714	23.74025	591	43.70536	27.07457
442	25.28571	-1	492	29.0625	15.34499	542	44.66071	14.89643	592	45.72321	30.4259
443	1.633929	9.018932	493	29.07143	16.51865	543	45.21429	16.00304	593	49.40179	-1
444	0	0	494	28.41964	15.46722	544	45.63393	15.9977	594	12.57143	8.528328
445	0	0	495	29.01786	15.35309	545	45.08036	10.46222	595	2.883929	0
446	0	0	496	28.38393	15.47495	546	46.01786	15.99912	596	0	0
447	0	0	497	28.30357	15.49235	547	46.75893	17.10675	597	0	0
448	23.24107	51.16553	498	28.33929	15.48461	548	47.3125	17.10429	598	0	0
449	62.24107	68.85576	499	28.83036	15.38719	549	47.91964	17.10311	599	0	0
450	74.11607	50.15711	500	28.10714	13.08897	550	49.28571	27.20229	600	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
601	0	0	651	52.0625	-1	701	33.86607	12.32544	751	57.97321	37.87833
602	0	0	652	40.4375	-1	702	33.85714	-1	752	60.85714	22.93395
603	0	0	653	39.875	-1	703	30.30357	-1	753	33.5	16.78521
604	0	0	654	32.38393	-1	704	30.5	7.162584	754	33.34821	10.0621
605	0	0	655	21.4375	-1	705	27.85714	1.508937	755	34.90179	21.0125
606	0	0	656	37.38393	-1	706	25.6875	-1	756	36.25	22.01993
607	0	0	657	22.17857	-1	707	23.47321	-1	757	33.32143	-1
608	0	0	658	35.42857	-1	708	20.75	-1	758	32.66964	9.074949
609	0	0	659	8.848214	10.02614	709	37.25893	-1	759	31.77679	2.334438
610	0	0	660	0	8.021185	710	28.46429	-1	760	29.28571	-1
611	0	0	661	0	0	711	18.83036	-1	761	20.58929	-1
612	0	0	662	0	0	712	8.589286	8.452531	762	15.82143	-1
613	0	0	663	0	0	713	0	0	763	25.58929	-1
614	0	0	664	0	0	714	0	0	764	2.625	7.455677
615	26.55357	47.58171	665	0	0	715	0	0	765	0	0
616	50.76786	42.36394	666	0	0	716	0	0	766	0	0
617	73.4375	65.13319	667	0	0	717	0	0	767	0	0
618	79.6875	52.01566	668	0	0	718	0	0	768	0	0
619	66.5625	59.93991	669	0	0	719	0	0	769	0	0
620	71.89286	59.28734	670	0	0	720	0	0	770	0	0
621	45.5625	69.3999	671	0	0	721	0	0	771	0	0
622	61.64286	60.58661	672	0	0	722	0	0	772	0	0
623	43.84821	64.55634	673	0	0	723	0	0	773	0	0
624	41.05357	61.53006	674	0	0	724	0	0	774	0	0
625	52.03571	61.01659	675	0	0	725	0	0	775	0	0
626	58.07143	62.15382	676	0	0	726	0	0	776	0	0
627	63.91071	69.23424	677	0	0	727	0	0	777	0	0
628	37	91.12847	678	13.08036	46.35168	728	0	0	778	0	0
629	35.03571	82.28042	679	36.32143	36.16492	729	0	0	779	0	0
630	42.20536	84.26292	680	40.50893	27.17048	730	0	0	780	0	0
631	47.0625	86.20888	681	37.91964	23.95876	731	0	0	781	0	0
632	50.71429	81.36443	682	52.77679	30.71204	732	0	0	782	25.10714	47.82612
633	53.24107	43.21764	683	64.47321	31.40277	733	0	0	783	48.89286	40.46973
634	53.80357	21.64323	684	51.69643	34.40298	734	0	0	784	58.89286	39.95032
635	55.78571	53.75802	685	47.8125	36.12466	735	0	0	785	70.58036	43.93547
636	58.25	66.81408	686	57.35714	42.37649	736	0	0	786	61.45536	45.06165
637	62.84821	85.49221	687	35.39286	32.59952	737	0	0	787	47.13393	29.5387
638	37.875	92.18138	688	39.55357	31.59077	738	0	0	788	50.71429	36.26554
639	35.82143	80.05684	689	43.10714	25.91394	739	0	0	789	36.04464	41.64238
640	39.28571	50.30622	690	47.47321	25.93913	740	0	0	790	41.99107	33.65855
641	40.5625	56.83613	691	49.00893	19.33913	741	0	0	791	46.25	34.81922
642	42.27679	66.67797	692	51.63393	22.73145	742	0	0	792	51.25	30.61609
643	43.75893	68.95562	693	53.23214	19.35604	743	13.61607	45.64984	793	54	26.16485
644	45.24107	69.19424	694	55.60714	21.66517	744	42.41964	38.73265	794	57.46429	25.08599
645	46.97321	-1	695	57.4375	20.52088	745	70.46429	61.68734	795	60.30357	25.25219
646	43.6875	-1	696	58.67857	13.62105	746	82.86607	65.27981	796	40.69643	29.36517
647	42.88393	-1	697	59.61607	14.77855	747	76.20536	67.37328	797	35.02679	17.48551
648	41.1875	-1	698	60.21429	14.77902	748	77.23214	56.34257	798	37.03571	20.73375
649	37.65179	-1	699	53.79464	13.61856	749	48.98214	35.0428	799	38.16964	20.6655
650	30.32143	-1	700	33.00893	14.65026	750	52.89286	24.9765	800	39.10714	15.1178

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
801	38.25	8.526963	851	0	0	901	52.65179	11.41918	951	1.580357	9.580799
802	38.01786	8.573684	852	0	0	902	49.25	-1	952	1.982143	9.471313
803	39.24107	18.40767	853	0	0	903	36.59821	-1	953	18.67857	3.052202
804	39.5625	10.70284	854	0	0	904	24.22321	-1	954	41.92857	27.11385
805	37.45536	-1	855	0	0	905	41.625	-1	955	33.60714	12.84436
806	34.78571	-1	856	0	0	906	28.5	-1	956	40.25893	-1
807	31.95536	-1	857	0	0	907	22.94643	-1	957	11.30357	-1
808	29.52679	-1	858	0	0	908	30.80357	10.49132	958	2.589286	5.591062
809	25.91071	-1	859	0	0	909	0	0	959	1.776786	0.682279
810	16.23214	-1	860	0	0	910	0	0	960	0	9.123313
811	26.76786	-1	861	0	0	911	0	0	961	0	0
812	14.53571	-1	862	10.60714	47.77278	912	0	0	962	0	0
813	4.339286	10.29529	863	40.95536	40.65568	913	0	0	963	0	0
814	6.848214	5.916003	864	67.28571	60.71795	914	15.27679	48.93047	964	0	0
815	0	0	865	83.57143	69.61366	915	57.75	69.01544	965	0	0
816	0	0	866	82.55357	84.00766	916	87.875	86.38564	966	0	0
817	0	0	867	91.45536	91.04705	917	74.29464	49.8518	967	0	0
818	0	0	868	67.33929	86.45793	918	76.1875	67.35098	968	0	0
819	0	0	869	77.3125	94.14078	919	54.8125	60.83411	969	0	0
820	0	0	870	100	94.54979	920	48.83036	68.23428	970	0	0
821	0	0	871	72.65179	63.24927	921	63.59821	57.18699	971	0	0
822	0	0	872	61.15179	30.09855	922	41.19643	54.60174	972	0	0
823	0	0	873	25.25893	-1	923	43.57143	23.71551	973	0	0
824	0	0	874	25.44643	-1	924	40.09821	-1	974	0	0
825	0	0	875	24.08036	-1	925	39.27679	8.504772	975	0	0
826	0	0	876	22.33036	-1	926	39.16071	12.90429	976	0	0
827	0	0	877	22.97321	26.60431	927	39.73214	17.28691	977	0	0
828	0	0	878	24.5	55.26062	928	40.90179	20.53275	978	0	0
829	0	0	879	27.66071	67.69484	929	41.33036	16.09446	979	0	0
830	0	0	880	30.69643	69.13493	930	41.88393	19.38622	980	0	0
831	0	0	881	31.91964	30.8193	931	42.82143	20.41333	981	0	0
832	0	0	882	32.64286	26.08052	932	44.42857	29.26864	982	0	0
833	2	18.28452	883	34.14286	39.19078	933	46.1875	29.30423	983	7.267857	47.76414
834	26.64286	40.21957	884	35.47321	40.03503	934	47.05357	20.43949	984	38.47321	40.95544
835	52.80357	47.74003	885	36.29464	29.58887	935	47.66071	20.45369	985	56.74107	47.78279
836	80.04464	63.96709	886	38.16964	45.98186	936	48.25	20.45875	986	60.39286	35.48894
837	76.24107	66.11994	887	40.96429	59.08014	937	45.26786	-1	987	74.16071	46.49978
838	77.67857	67.87806	888	44.25	59.09138	938	43.83036	-1	988	63.16964	48.63499
839	48.84821	50.72796	889	46.92857	64.98655	939	40.58929	-1	989	41.8125	32.71695
840	51.5625	-1	890	51.17857	74.68681	940	37.5625	-1	990	34.40179	38.33423
841	43.44643	-1	891	54.61607	77.60026	941	34.45536	-1	991	42.29464	33.86502
842	38.83036	-1	892	58.13393	78.34753	942	35.41964	17.76445	992	47.23214	39.17628
843	34.32143	-1	893	62.21429	65.32346	943	36.36607	26.26779	993	51.30357	28.3131
844	23.58036	-1	894	63.00893	-1	944	35.45536	14.18121	994	54.65179	26.21329
845	14.79464	-1	895	59.30357	-1	945	32.41964	-1	995	58.69643	29.83807
846	4.928571	8.786387	896	51.10714	-1	946	31.375	-1	996	61.38393	31.17915
847	0	0	897	48.25	45.33454	947	28.22321	-1	997	36.47321	34.90381
848	0	0	898	53.79464	53.47779	948	17.16964	-1	998	39.10714	24.00494
849	0	0	899	54.32143	21.64566	949	14.78571	-1	999	41.55357	30.45404
850	0	0	900	53.13393	11.40569	950	23.47321	5.795666	1000	44.07143	30.37408

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1001	46.5625	30.45962	1051	10.29464	11.3652	1101	24.15179	-1	1151	57.17857	10.1623
1002	48.86607	30.55263	1052	0	0	1102	21.40179	-1	1152	57.08036	10.17306
1003	51.03571	30.64083	1053	0	0	1103	34.28571	-1	1153	57.53571	11.323
1004	53.54464	30.74358	1054	0	0	1104	42.5	23.7357	1154	57.76786	12.46934
1005	55.83036	29.67952	1055	0	0	1105	44.91071	21.53532	1155	54.17857	-1
1006	58.41964	29.70241	1056	0	0	1106	47.625	22.6865	1156	51.50893	-1
1007	59.34821	20.57127	1057	0	0	1107	49.95536	21.59811	1157	46.48214	-1
1008	60.875	24.13083	1058	0	0	1108	52.33036	22.75992	1158	37.24107	-1
1009	62.14286	25.3559	1059	0	0	1109	54.76786	22.79766	1159	24.84821	-1
1010	30.46429	32.2958	1060	0	0	1110	57.41964	22.84364	1160	13.91071	-1
1011	30.03571	28.97966	1061	0	0	1111	58.71429	15.93632	1161	2.696429	12.30459
1012	30.72321	26.61004	1062	0	0	1112	59.58929	14.77769	1162	0	0
1013	31.52679	32.10422	1063	0	0	1113	56.08036	-0.21737	1163	0	0
1014	32.41071	31.98681	1064	0	0	1114	53	-1	1164	0	0
1015	33.39286	34.94105	1065	0	0	1115	48.54464	-1	1165	0	0
1016	34.72321	33.2065	1066	0	0	1116	43.77679	-1	1166	0	0
1017	35.91071	31.83244	1067	0	0	1117	39.6875	-1	1167	0	0
1018	36.83929	26.26636	1068	0	0	1118	34.5625	-1	1168	0	0
1019	36.39286	16.3419	1069	0	0	1119	20.58036	-1	1169	0	0
1020	36.3125	17.44862	1070	0	0	1120	7.348214	10.82965	1170	0	0
1021	37.39286	21.84526	1071	0	0	1121	0	0	1171	0	0
1022	37.39286	17.40734	1072	21.88393	48.30929	1122	0	0	1172	0	0
1023	36.70536	15.21455	1073	42.32143	34.74057	1123	0	0	1173	0	0
1024	36.39286	5.35725	1074	50.35714	37.37086	1124	0	0	1174	0	0
1025	36.44643	7.572584	1075	65.91071	44.32642	1125	0	0	1175	0	0
1026	35.49107	14.19748	1076	72.80357	42.33739	1126	0	0	1176	0	0
1027	33.83036	3.303551	1077	70.13393	57.69742	1127	0	0	1177	20.78571	45.72364
1028	34.35714	4.416714	1078	70.58036	51.09533	1128	0	0	1178	44.72321	38.20568
1029	33.52679	6.66012	1079	41.85714	25.948	1129	0	0	1179	71.5625	62.03071
1030	33.04464	6.780888	1080	48.69643	32.78646	1130	0	0	1180	82.41964	58.16869
1031	32.38393	6.852748	1081	56.83929	50.22565	1131	0	0	1181	60.79464	38.15003
1032	31.45536	2.372488	1082	59.44643	22.90761	1132	0	0	1182	36.03571	32.79241
1033	31.03571	5.859125	1083	60.59821	18.23189	1133	0	0	1183	32.85714	38.30121
1034	30.35714	10.5211	1084	33.51786	20.4543	1134	0	0	1184	44.38393	54.68776
1035	30.00893	10.57019	1085	33.08036	7.851043	1135	0	0	1185	55.78571	65.21901
1036	29.74107	10.53115	1086	32.79464	9.059116	1136	0	0	1186	63.16071	77.51563
1037	29.24107	8.335081	1087	32.74107	11.30766	1137	4.598214	44.87647	1187	44.19643	81.5259
1038	28.48214	2.577976	1088	34.29464	23.35014	1138	32.94643	39.39337	1188	55.46429	81.08922
1039	27.6875	3.87207	1089	35.51786	24.43453	1139	52.08929	44.27422	1189	63.82143	83.41378
1040	26.96429	3.942445	1090	36.27679	16.38168	1140	58.30357	34.34875	1190	76.65179	89.2996
1041	26.22321	3.959098	1091	37.05357	17.42559	1141	74.91071	50.46092	1191	80.125	-1
1042	25.48214	4.089841	1092	37.63393	18.49436	1142	69.26786	56.51709	1192	31.58036	-1
1043	24.64286	4.175259	1093	38.47321	17.34913	1143	70.39286	49.01995	1193	32.28571	19.15774
1044	23.14286	-1	1094	38.72321	12.93564	1144	39.58929	30.4492	1194	34.25893	34.65501
1045	21.5625	-1	1095	39.11607	15.12744	1145	42.32143	21.56437	1195	35.97321	51.59413
1046	20.25893	-1	1096	36.46429	-1	1146	45.80357	25.98842	1196	38.83929	59.1631
1047	15.91071	-1	1097	34.28571	-1	1147	49.08929	28.31817	1197	41.41071	-1
1048	38.9375	-1	1098	31.79464	-1	1148	53.48214	29.6034	1198	36.41964	-1
1049	24.72321	-1	1099	29.13393	-1	1149	56.45536	30.82422	1199	24.53571	-1
1050	36	-1	1100	26.25893	-1	1150	57.48214	14.77624	1200	23.61607	-1

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1201	18.625	-1	1251	45.27679	68.31002	1301	0	0	1351	39.39286	70.09946
1202	26.01786	11.65125	1252	60.3125	51.62005	1302	0	0	1352	42.94643	71.17918
1203	0	0	1253	63.03571	56.40457	1303	0	0	1353	46.09821	73.77794
1204	0	0	1254	40.86607	41.32646	1304	0	0	1354	50.24107	77.89473
1205	0	0	1255	47.4375	50.5811	1305	0	0	1355	53.75	79.71119
1206	0	0	1256	52.90179	59.10427	1306	0	0	1356	57.65179	73.56266
1207	21.42857	49.20953	1257	58.375	57.5851	1307	0	0	1357	59.41964	42.59887
1208	48.5	40.06555	1258	63.97321	59.42143	1308	0	0	1358	61.5	56.96988
1209	73.07143	60.66365	1259	33.54464	34.80431	1309	0	0	1359	63.54464	-1
1210	76.33036	36.29507	1260	30.54464	32.01749	1310	13.125	59.08973	1360	58.47321	-1
1211	19.91964	-1	1261	34.33929	56.67718	1311	56.80357	65.52379	1361	45.5	-1
1212	8.892857	5.72433	1262	36.86607	57.81631	1312	74.34821	72.77012	1362	33.03571	-1
1213	6.410714	9.95581	1263	38.46429	33.84961	1313	66.09821	31.73264	1363	21.15179	-1
1214	10.98214	4.489413	1264	38.77679	20.63612	1314	63	55.76755	1364	39	-1
1215	0	0	1265	39.39286	29.41056	1315	67.30357	34.54876	1365	21.99107	-1
1216	0	0	1266	40.25893	30.49995	1316	34.21429	18.74342	1366	29.86607	-1
1217	0	0	1267	40.99107	31.55404	1317	31.19643	-1	1367	3.241071	10.32781
1218	0	0	1268	42.33036	31.44008	1318	27.52679	-1	1368	0	0
1219	2.464286	43.55199	1269	43.76786	45.79142	1319	16.27679	-1	1369	0	0
1220	31.26786	40.78797	1270	46.125	54.89059	1320	5.178571	10.80397	1370	0	0
1221	58.97321	56.53087	1271	48.36607	39.48338	1321	1.910714	5.147371	1371	0	0
1222	81.07143	64.7045	1272	48.66071	-1	1322	0	8.112031	1372	0	0
1223	76.40179	66.15114	1273	44.71429	-1	1323	0	0	1373	0	0
1224	77.24107	-1	1274	34.50893	-1	1324	0	0	1374	0	0
1225	20.72321	-1	1275	29.15179	-1	1325	0	0	1375	0	0
1226	10.6875	5.999145	1276	26.0625	-1	1326	0	0	1376	0	0
1227	0	0	1277	46.64286	-1	1327	0	0	1377	0	0
1228	0	0	1278	27.65179	-1	1328	0	0	1378	0	0
1229	0	0	1279	24.46429	-1	1329	0	0	1379	0	0
1230	0	0	1280	41.16964	-1	1330	0	0	1380	0	0
1231	0	0	1281	24.59821	-1	1331	0	0	1381	0	0
1232	0	0	1282	12.91964	-1	1332	0	0	1382	0	0
1233	0	0	1283	2.803571	11.11568	1333	0	0	1383	0	0
1234	0	0	1284	0.633929	5.433223	1334	0	0	1384	13.47321	49.68878
1235	0	0	1285	5.642857	8.197461	1335	0	0	1385	37.85714	39.69389
1236	0	0	1286	10.33036	0.155909	1336	0	0	1386	59.42857	53.12346
1237	0	0	1287	29.75893	28.17727	1337	0	0	1387	68.41964	37.8338
1238	0	0	1288	47.21429	35.95259	1338	12.1875	49.6299	1388	72.72321	51.0651
1239	0	0	1289	24.10714	-1	1339	40.80357	45.75032	1389	59.6875	42.69563
1240	0	0	1290	10.875	9.866633	1340	65.40179	58.96645	1390	60.16964	43.88789
1241	0	0	1291	15.04464	-1	1341	82.875	73.53291	1391	38.24107	30.49512
1242	0	0	1292	0	0	1342	79.44643	84.85382	1392	44.51786	30.42015
1243	0	0	1293	0	0	1343	86.69643	85.78265	1393	50.8125	40.78297
1244	0	0	1294	0	0	1344	66.27679	87.07572	1394	55.78571	29.68995
1245	2.4375	48.71184	1295	0	0	1345	60.96429	80.26309	1395	59.82143	31.07262
1246	42.76786	56.69031	1296	0	0	1346	45.34821	73.22113	1396	61.70536	36.03924
1247	71.45536	62.29842	1297	0	0	1347	55.52679	69.11222	1397	36.75893	25.1107
1248	78.79464	55.67432	1298	0	0	1348	61.88393	72.29687	1398	38.95536	22.82311
1249	73.92857	65.38731	1299	0	0	1349	65.125	70.44857	1399	39.6875	15.08353
1250	76.66071	62.44551	1300	0	0	1350	34.36607	78.89694	1400	41.21429	28.20949

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1401	42.94643	22.61527	1451	57.8125	27.29246	1501	0	0	1551	28.46429	22.90107
1402	44.32143	24.8446	1452	63.70536	24.14348	1502	0	0	1552	30.96429	24.27475
1403	45.875	25.98912	1453	38.55357	28.46731	1503	0	0	1553	33.97321	22.29247
1404	46.875	14.87726	1454	33.23214	23.27601	1504	0	0	1554	36.48214	22.19835
1405	46.07143	7.103882	1455	32.5625	24.69815	1505	0	0	1555	39.45536	22.79608
1406	46.14286	4.905416	1456	37.61607	26.27498	1506	0	0	1556	42.01786	22.65709
1407	46.03571	18.21622	1457	28.32143	30.66895	1507	0	0	1557	44.75	22.64129
1408	46.79464	28.24168	1458	31.52679	25.13954	1508	0	0	1558	47.46429	22.68398
1409	49.17857	35.01106	1459	34.66964	23.24224	1509	14.39286	48.83838	1559	49.89286	22.72198
1410	50.40179	17.09774	1460	36.77679	18.54047	1510	43.36607	40.46973	1560	49.79464	8.10279
1411	48.05357	1.386896	1461	38.60714	19.59196	1511	56.46429	44.7625	1561	48.64286	5.894628
1412	45.95536	-1	1462	41.83929	28.1668	1512	60.86607	34.37909	1562	50.29464	17.09851
1413	43.33929	7.128379	1463	49.04464	42.83913	1513	72.67857	48.03895	1563	51.28571	17.09578
1414	43.375	10.46961	1464	52.22321	22.75826	1514	19.41964	-1	1564	52.72321	17.09488
1415	43.44643	8.288509	1465	50.60714	4.664468	1515	9.464286	15.67443	1565	53.61607	14.81319
1416	44.79464	18.21531	1466	52.05357	20.48764	1516	3.455357	1.837851	1566	54.625	15.94701
1417	45.23214	15.99976	1467	54.52679	23.93538	1517	8.294643	5.810421	1567	54.8125	10.23316
1418	44.59821	6.049033	1468	57.24107	22.81955	1518	1.107143	9.524619	1568	53.96429	9.096905
1419	43.21429	2.755083	1469	59.03571	14.77768	1519	8.196429	3.377432	1569	53.75	9.1189
1420	40.57143	-1	1470	56.67857	4.41563	1520	0	0	1570	53.42857	10.26546
1421	37.5625	-1	1471	57.05357	10.17375	1521	0	0	1571	53.11607	8.000651
1422	35.04464	-1	1472	58.66071	21.7276	1522	0	0	1572	51.58036	3.499478
1423	26.5625	-1	1473	61.08036	26.47873	1523	0	0	1573	50.83036	6.944872
1424	13.6875	-1	1474	35.41964	29.57689	1524	0	0	1574	50.52679	9.208953
1425	20.69643	8.663656	1475	36.10714	11.99509	1525	0	0	1575	50.13393	5.843545
1426	0	0	1476	36.42857	14.18695	1526	0	0	1576	48.84821	5.886891
1427	0	0	1477	36.875	15.23519	1527	0	0	1577	48.10714	8.152008
1428	0	0	1478	37.44643	16.32271	1528	0	0	1578	44.49107	-1
1429	0	0	1479	38.125	16.26791	1529	0	0	1579	43.07143	6.082418
1430	0	0	1480	38.61607	16.24142	1530	0	0	1580	41.10714	0.689613
1431	0	0	1481	38.28571	8.559244	1531	0	0	1581	36.625	-1
1432	0	0	1482	37.08929	2.005418	1532	0	0	1582	32.53571	-1
1433	0	0	1483	34.33929	-1	1533	0	0	1583	25.57143	-1
1434	0	0	1484	32.23214	7.969333	1534	0	0	1584	10.67857	8.935211
1435	0	0	1485	29.66964	-1	1535	0	0	1585	3.089286	5.463421
1436	0	0	1486	20.47321	-1	1536	0	0	1586	1.803571	7.629683
1437	0	0	1487	12.16071	-1	1537	0	0	1587	0	7.815826
1438	0	0	1488	19.44643	11.49407	1538	1.232143	37.74278	1588	0	0
1439	0	0	1489	0	0	1539	18.91964	25.9358	1589	0.526786	50.8185
1440	0	0	1490	0	0	1540	12.41964	18.25452	1590	33.625	39.45735
1441	0	0	1491	0	0	1541	22.8125	27.69584	1591	43.57143	28.12403
1442	0	0	1492	0	0	1542	29.35714	25.9806	1592	32.53571	17.95784
1443	0	0	1493	0	0	1543	37.44643	25.19317	1593	44.27679	27.1787
1444	12.79464	46.66478	1494	0	0	1544	46.84821	27.07053	1594	45.35714	14.8905
1445	23.95536	26.53555	1495	0	0	1545	58.71429	29.76673	1595	51.25893	19.35469
1446	31.6875	34.57148	1496	0	0	1546	65.66071	30.16758	1596	58.3125	21.71737
1447	36.34821	16.8824	1497	0	0	1547	45.03571	32.01725	1597	61.59821	-1
1448	30.65179	17.29802	1498	0	0	1548	42.66071	23.72209	1598	5.267857	18.35125
1449	38.99107	20.62118	1499	0	0	1549	26.21429	17.00921	1599	11.05357	4.640021
1450	47.08036	21.56331	1500	0	0	1550	23.70536	23.24809	1600	4.785714	10.72805

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1601	10.32143	3.109331	1651	39.33036	37.10284	1701	0	0	1751	44.49107	17.1091
1602	0	0	1652	65.47321	55.40504	1702	12.20536	48.31885	1752	45.08929	16.00048
1603	0	0	1653	80.09821	64.42802	1703	38.83929	41.63111	1753	45.5625	15.99807
1604	0	0	1654	75.00893	66.07321	1704	64.10714	58.61641	1754	46.14286	15.99506
1605	0	0	1655	44.75893	39.23964	1705	83.41964	73.71948	1755	46.75893	15.99181
1606	0	0	1656	44.69643	29.23087	1706	80.40179	83.33914	1756	47.26786	17.10526
1607	0	0	1657	53.09821	51.17685	1707	84.3125	81.50621	1757	47.79464	18.22028
1608	0	0	1658	57.60714	30.8805	1708	60.71429	61.50505	1758	48.70536	18.22188
1609	0	0	1659	61.6875	33.54568	1709	57.83036	27.56151	1759	49.3125	18.22274
1610	0	0	1660	36.78571	37.32204	1710	61.35714	20.59974	1760	50.16071	18.22385
1611	0	0	1661	39.3125	26.20638	1711	37.03571	41.59052	1761	50.80357	18.22464
1612	0	0	1662	42.6875	41.39301	1712	39.59821	35.98836	1762	51.61607	18.22556
1613	0	0	1663	39.27679	-1	1713	41.96429	33.71385	1763	52.32143	18.22629
1614	0	0	1664	38.25	-1	1714	44.60714	35.9113	1764	52.98214	18.22692
1615	0	0	1665	35.59821	-1	1715	47.50893	34.84089	1765	53.64286	18.2275
1616	0	0	1666	26.91964	-1	1716	50.16071	35.10749	1766	54.0625	18.22783
1617	14.5625	48.10364	1667	13.58929	-1	1717	53.21429	35.2765	1767	55.04464	18.22852
1618	41.08036	40.16827	1668	21.02679	9.771016	1718	55.9375	34.28232	1768	55.46429	18.22878
1619	63.98214	51.48871	1669	0	0	1719	58.25	30.90967	1769	56.30357	18.22923
1620	71.08929	38.22001	1670	0	0	1720	58.8125	14.77734	1770	56.77679	18.22944
1621	64.25	53.98416	1671	0	0	1721	58.89286	15.93418	1771	57.50893	18.23515
1622	71.05357	58.0817	1672	0	0	1722	54.59821	-1	1772	57.90179	17.08255
1623	48.21429	37.23811	1673	29.125	67.13011	1723	54.76786	12.50185	1773	58.79464	18.25468
1624	40.83929	24.82257	1674	63.5625	49.94999	1724	55.08036	14.79809	1774	58.99107	17.09265
1625	46.6875	30.44885	1675	87.58929	78.06335	1725	55.33036	11.35857	1775	59.625	17.10438
1626	51.375	34.04451	1676	73.57143	61.29617	1726	54.70536	7.933106	1776	60.17857	17.11012
1627	58.99107	46.09496	1677	75.42857	66.59328	1727	54.04464	9.110482	1777	60.70536	17.11558
1628	62.48214	38.86958	1678	65.08036	67.46587	1728	53.55357	7.973697	1778	61.27679	17.12148
1629	37.20536	22.88282	1679	55.02679	71.1769	1729	52.83929	8.009488	1779	61.83036	21.80148
1630	39.94643	28.31298	1680	62.65179	35.0384	1730	52.27679	8.027366	1780	38.49107	29.44817
1631	42.26786	30.39301	1681	32.41071	-1	1731	50.01786	-1	1781	28.54464	32.91566
1632	44.83036	31.49691	1682	20.01786	-1	1732	47.73214	-1	1782	28.11607	4.998164
1633	46.75	25.99661	1683	12.00893	-1	1733	44.61607	-1	1783	27.58036	7.411586
1634	48.73214	28.30624	1684	17.82143	5.665308	1734	29.46429	-1	1784	28.33929	24.90048
1635	50.83036	29.50448	1685	0	0	1735	23.66071	-1	1785	28.79464	26.02715
1636	53.27679	29.59571	1686	0	0	1736	35.96429	12.08178	1786	29.17857	25.83528
1637	55.13393	30.77739	1687	0	0	1737	36.36607	18.66135	1787	29.36607	16.52378
1638	54.46429	6.809247	1688	0	0	1738	31.01786	-1	1788	28.09821	5.002985
1639	51.29464	-1	1689	0	0	1739	32.70536	15.97129	1789	26.80357	-1
1640	48.125	-1	1690	0	0	1740	34.875	25.40827	1790	25.09821	-1
1641	45.38393	-1	1691	0	0	1741	38.91071	30.52552	1791	23.84821	-1
1642	42.48214	-1	1692	0	0	1742	44.16964	36.99076	1792	16.75	-1
1643	31.49107	-1	1693	0	0	1743	50.48214	38.45489	1793	35.52679	-1
1644	19.36607	-1	1694	0	0	1744	53.25893	21.63658	1794	24.125	-1
1645	27.55357	-1	1695	0	0	1745	58.49107	39.08532	1795	31.78571	-1
1646	7.598214	9.656174	1696	0	0	1746	61.99107	39.24493	1796	6.714286	10.04292
1647	3.0625	5.400067	1697	0	0	1747	37.51786	41.58811	1797	0	0
1648	0.946429	6.228128	1698	0	0	1748	39.33036	20.60284	1798	0	0
1649	7.75	1.890668	1699	0	0	1749	41.57143	33.68379	1799	0	0
1650	3.151786	30.25039	1700	0	0	1750	43.85714	28.13964	1800	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz	TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1801	0	0	1851	63.08036	34.83501
1802	0	0	1852	29.24107	18.7633
1803	0	0	1853	26.88393	-1
1804	0	0	1854	26.03571	8.762433
1805	0	0	1855	27.1875	24.25572
1806	0	0	1856	27.26786	26.47329
1807	0	0	1857	27.80357	26.22654
1808	0	0	1858	28.29464	26.16764
1809	0	0	1859	29.02679	28.28045
1810	0	0	1860	29.32143	22.24344
1811	0	0	1861	29.71429	22.15039
1812	0	0	1862	30.15179	22.04744
1813	0.973214	36.20294	1863	30.35714	22.11459
1814	22.80357	47.37405	1864	30.73214	21.91197
1815	34.39286	33.31054	1865	31.03571	21.84159
1816	49.51786	40.43796	1866	31.26786	21.788
1817	56.72321	35.32831	1867	31.70536	21.68752
1818	69.61607	36.94689	1868	32	21.62023
1819	58.66964	43.81481	1869	32.19643	21.57554
1820	62.51786	48.91074	1870	32.50893	21.50472
1821	66.26786	46.65907	1871	32.9375	21.40815
1822	41.20536	28.17166	1872	33.22321	21.34412
1823	50.35714	43.00226	1873	33.49107	20.16499
1824	56.92857	42.07409	1874	31.64286	-1
1825	61.58036	34.66662	1875	30.52679	-1
1826	36.3125	30.64574	1876	28.80357	-1
1827	38.40179	24.02799	1877	27.4375	7.431916
1828	40.47321	27.20622	1878	25.79464	-1
1829	42.48214	27.03181	1879	24.14286	-1
1830	44.30357	28.14849	1880	14.72321	-1
1831	45.39286	21.54267	1881	29.20536	-1
1832	46.59821	21.55743	1882	23.32143	-1
1833	47.59821	21.56961	1883	34.15179	-1
1834	48.82143	21.58444	1884	8.892857	10.49355
1835	50.07143	21.59951	1885	1.75	12.37549
1836	50.83929	18.22454	1886	0	0
1837	51.40179	17.09529	1887	0	0
1838	51.78571	14.83146	1888	0	0
1839	52.11607	13.69558	1889	0	0
1840	51.76786	13.6945	1890	0	0
1841	52.48214	14.83058	1891	0	0
1842	52.875	14.82777	1892	0	0
1843	53.39286	20.50169	1893	0	0
1844	54.47321	22.79035	1894	0	0
1845	55.66964	21.65165	1895	0	0
1846	56.6875	20.52592	1896	0	0
1847	57.57143	20.53149	1897	0	0
1848	58.5	20.56532	1898	0	0
1849	59.46429	20.58913	1899	0	0
1850	61.04464	29.97826	1900	0	0

TIME (seconds)	FINAL SPEED 1hz	FINAL TORQUE 1hz
1901	0	0
1902	0	0
1903	0	0
1904	0	0
1905	0	0
1906	0	0
1907	0	0
1908	0	0
1909	0	0
1910	0	0