California Environmental Protection Agency

AIR RESOURCES BOARD

DRAFT
TECHNOLOGY ASSESSMENT: LOWER NO_X HEAVY-DUTY DIESEL ENGINES

September 2015

State of California
AIR RESOURCES BOARD

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Executive Summary

This report is part of a series of technology and fuels assessment reports that evaluate the state of technology to further reduce emissions from the transportation sector including trucks, locomotives, off-road equipment, ships, commercial harborcraft, aircraft, and transportation fuels. The purpose of the assessments is to support the Air Resources Board's (ARB) planning and regulatory efforts, including the development of California's Sustainable Freight Strategy, the State Implementation Plan, funding plans, the Governor's Zero Emission Vehicle Action Plan, and Governor's petroleum reduction goals. The reports focus not only on zero and near-zero emission technologies that will ultimately be necessary to meet long-term air quality and climate goals, but also on improvements to conventional technologies that could provide near-term emissions reductions and help facilitate the transition to zero and near-zero emission technologies.

Specifically, this technology assessment report is intended to provide a comprehensive evaluation of the current state and projected development over the next 5 to 10 years of lower oxides of nitrogen (NO_X) heavy-duty diesel engines. For each technology, the assessment will include a description of the technology, its suitability in different applications, current and anticipated costs at widespread deployment (where available), and emission levels.

Overall, the assessment finds that emissions from heavy-duty diesel engines can be significantly reduced utilizing a systems approach combining advanced aftertreatment systems with engine management strategies. Reducing NO_X emissions to the 0.02 grams per brake horsepower-hour (g/bhp-hr) level will require reducing emissions significantly during cold start and during low load, low speed operations and also maintaining high selective catalytic reduction (SCR) conversion efficiency at high speed-high temperature operation. A variety of strategies can be used to achieve these reductions. However, the final solution will depend on ensuring no adverse impacts on greenhouse gas (GHG) emissions.

Presented below is an overview which briefly describes technologies to further reduce NO_X emissions from on-road heavy-duty diesel engines and staff's proposed next steps. For simplicity, the discussion is presented in question-and-answer format using commonly asked questions about the technology assessment. It should be noted that this summary provides only brief discussion on these topics. The reader should refer to subsequent chapters in the main body of the report for more detailed information.

Q. What are the current emission certification standards of on-road heavy-duty diesel engines?

A. Currently, on-road heavy-duty diesel engines are required to meet the 2010 emission limits of 0.20 g/bhp-hr NO_X emissions and 0.01 g/bhp-hr particulate matter (PM) emissions, on the heavy-duty transient federal test procedure and on the ramped modal cycle supplemental emission test. To further reduce NO_X emission emissions, ARB also adopted optional low NO_X standards that are 50 percent, 75 percent, and 90 percent lower than the current NO_X standard of 0.20 g/bhp-hr. The optional low NO_X standards were developed to encourage engine manufacturers to develop new technologies and also to provide them with a mechanism to optionally certify engines to lower NO_X standards. Certification to lower optional standards would also enable certified low-NO_X engines to become eligible for incentive funding.

Depending on vehicle weight class, heavy-duty diesel engines are also required to reduce GHG emissions by 5 to 9 percent relative to 2010 GHG emission levels by 2017.

Q. What are the market characteristics of heavy-duty trucks and engines?

A. The majority of the heavier trucks are diesel engine powered, while the lighter trucks are predominantly gasoline engine powered. There are approximately 10 manufacturers of Class 4 to 8 trucks in the U.S. Two of these manufacturers only produce Class 4 to 6 trucks.

Sales of Classes 4 to 8 heavy-duty trucks increased by 17.6 percent, from a total of 345,876 in 2013 to 406,747units in 2014 (See Figures ES-1 and ES-2). For these truck classes, in 2014, Freightliner had the biggest market share with 31 percent, while International had 14 percent. For Class 8 trucks, in 2014, Freightliner had the biggest market share, with 36 percent market share, while International had 14 percent market share (Davis et. al, 2015).[1]

Although many of the heavy-duty truck manufacturers produce the engines used in their trucks, they also purchase and install engines made by other manufacturers such as Cummins, Inc. As shown in Figure ES-3, Cummins leads the heavy-duty diesel engine market with 47 percent followed by Detroit Diesel with 11.1 percent and Volvo with 10.9 percent of the market share in 2013 (Davis et. al, 2015).[2] A detailed description of the truck market analysis is provided in a companion report, Technology Assessment: Truck Sector Overview.

[1] *Annual Financial Profile of America's Franchised New-Car Dealerships*, NADA Data, 2014 <https://www.nada.org/nadadata/>.

[2] Davis, Stacy C., S. W. Diegel, R. G. Boundy, and S. Moore, *2014 Vehicle Technologies Market Report*, Oak Ridge National Laboratory, U.S. DOE. ORNL/TM-2015/85 <http://cta.ornl.gov/vtmarketreport/index.shtml>.

Figure ES-1: Class 4 to 7 Truck Sales, 2013 and 2014

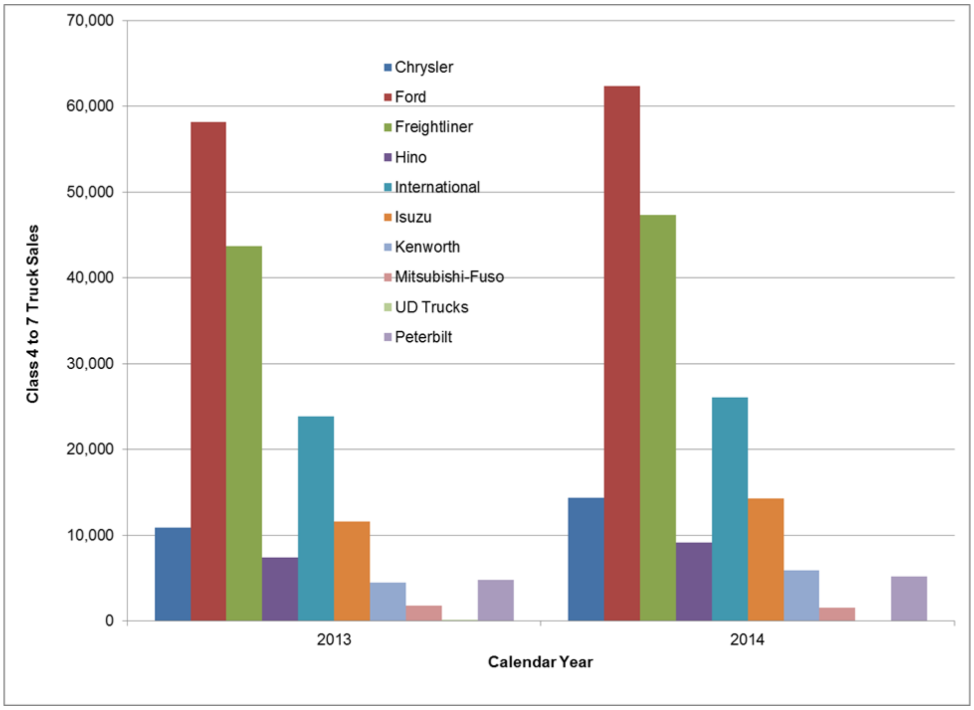


Figure ES-2: Class 8 Truck Sales, 2013 and 2014

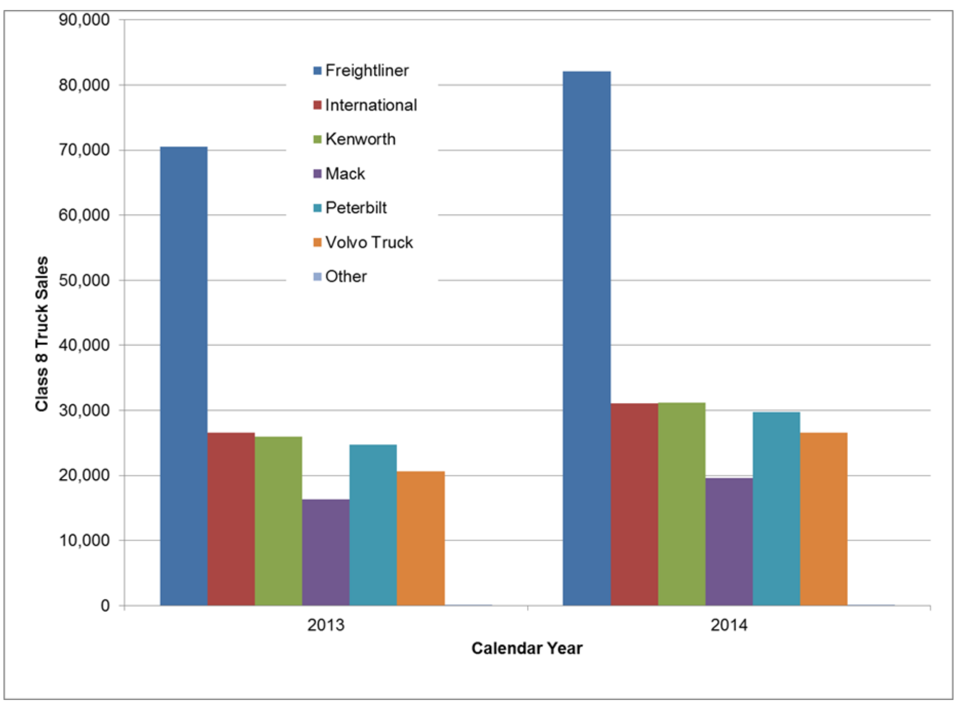
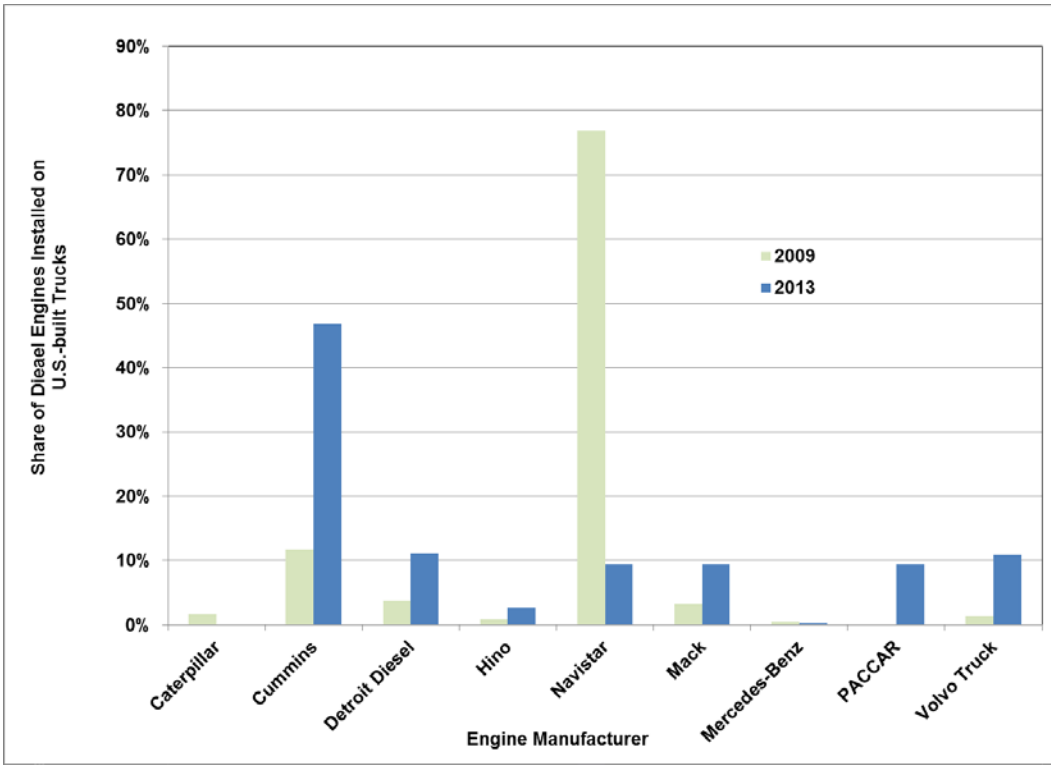


Figure ES-3: Diesel Engine Manufacturers Market Share, 2009 and 2013



Q. How do current diesel vehicles compare to current natural gas vehicles?

A. Heavy-duty diesel-fueled engines are based on lean combustion, compression ignition (CI) engine technology and use SCR to control NO_X and a diesel particulate filter (DPF) to control PM. Heavy-duty natural gas engines, on the other hand, can either use spark-ignited (SI) stoichiometric combustion engine technology or CI dual fuel high pressure direct injection (HPDI) engine technology. SI natural gas engines are similar to gasoline engines and use a similar aftertreatment system, the three-way catalyst, to control NO_X, carbon monoxide, and hydrocarbons, without the need of a DPF to meet PM standards. HPDI natural gas engines are based on the conventional CI diesel engine, but use a small amount of diesel fuel injected at the end of the compression stroke to initiate ignition. As with diesel engines, HPDI natural gas engines require SCR to control NO_X and a DPF to control particulate matter emissions. SI natural gas engines are currently the only original-equipment manufacturer natural gas heavy-duty engines produced for on-road applications.

In general, heavy-duty SI natural gas engines are expected to be certified to today's optional low-NO_X emission standards (0.02, 0.05, and 0.1 g/bhp-hr) sooner than will diesel engines since recent in-use emissions test data show that natural gas engines do not appear to suffer the control challenges experienced by diesel engines in low temperature, low speed operations. Recently, a Cummins Westport Inc., 8.9 liter (L) SI natural gas engine was certified by ARB to the 0.02 g/bhp-hr optional NOx standard and the 2017 heavy-duty GHG standards for urban bus, vocational truck, and tractor applications.[3]

Besides the different engine technologies used in diesel and natural gas vehicles, other characteristics also distinguish these vehicles and their uses. Unlike diesel vehicles, current use of natural gas vehicles has largely been limited to urban vocational applications rather than line-haul applications. This difference is primarily driven by the lower energy density of natural gas, which requires larger and heavier on-board fuel storage systems. Other factors driving differences in the adoption of diesel and natural gas vehicles include the differences in the extent of development of the refueling infrastructure and current engine offerings. In addition, purchasing prices of heavy-duty diesel vehicles are currently lower than those of comparable heavy-duty natural gas vehicles; however, owners of natural gas vehicles can realize a return on investment due to the lower cost of natural gas fuel compared to diesel fuel. For more details about the differences between diesel vehicles and natural gas vehicles, please refer to a companion report: “Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines.”

Q. How are emissions from on-road heavy-duty diesel engines currently controlled to meet the 2010 standards?

A. In order to meet the 0.20 g/bhp-hr NO_X and 0.01 g/bhp-hr PM standards, engine manufacturers are using engine controls such as cooled exhaust gas recirculation (EGR), variable geometry turbochargers, high pressure fuel injection, and other associated electronic controls, as well as aftertreatment controls such as diesel oxidation catalysts, DPF, urea-SCR, and ammonia slip catalysts. In addition to reducing NO_X emissions, the introduction of SCR technology enabled engine manufacturers to overcome the NO_X/PM and NO_X/GHG trade-off design issues that existed prior to the introduction of 2010-compliant SCR-equipped engines. The inclusion of the highly effective SCR aftertreatment system enables the optimization of engine performance for lower PM emissions and improved fuel efficiency; in other words, low PM and GHG emissions can be achieved at the expense of high engine-out NO_X, but lower tailpipe NO_X can also be realized with an effective SCR aftertreatment system.

Q. Can NO_X emissions be lowered further from current levels?

A. Yes. Reducing cold start emissions and emissions during low speed, low load operations can significantly lower NO_X emissions from current levels since the current urea-SCR system is ineffective at the low exhaust temperatures that

[3] ARB Executive Orders, September 15, 2015. http://www.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2016/2016.php

occur during cold start, extended idling, and low speed operations. This will require the employment of strategies that raise exhaust gas temperatures and advanced catalysts with much higher NO_X control at low temperatures such as NO_X storage catalysts and advanced SCR catalysts. Further NOx reductions can also be achieved during high-speed/high-load driving via advanced SCR catalysts with high cell density and high porosity substrates and better urea injection control.

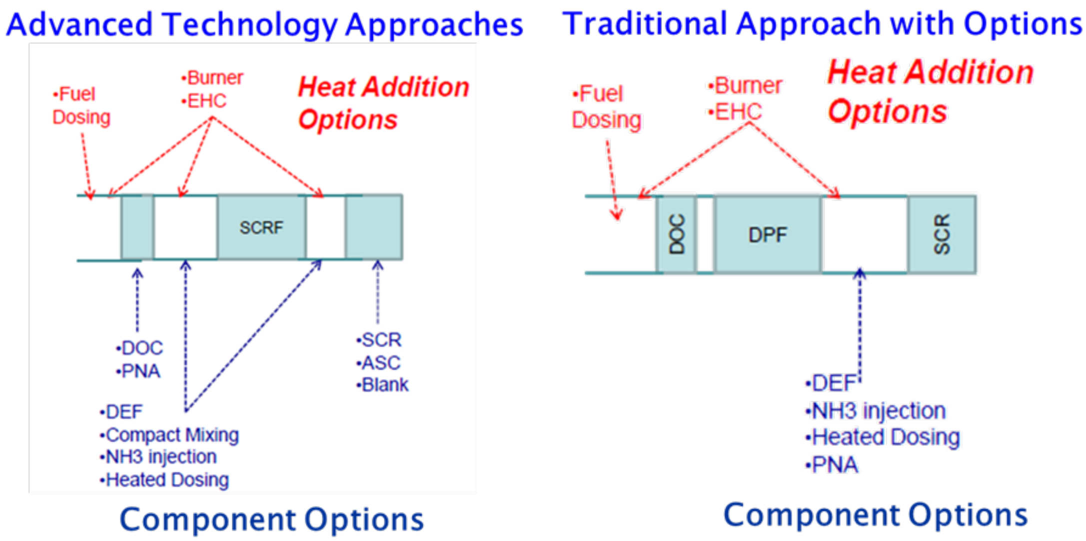
Q. What technology development and demonstration programs are currently in progress to demonstrate the feasibility of low NO_X?

A. In 2013, ARB initiated a project with Southwest Research Institute (SwRI) to demonstrate maximum NO_X reductions possible from heavy-duty engines through a combination of engine tuning practices, exhaust gas thermal management strategies, and aftertreatment strategies[4]. The target NO_X emission rate for this project is 0.02 g/bhp-hr while continuing to meet all applicable standards for hydrocarbons, carbon monoxide, and PM and not incur a GHG penalty.

Figure ES-4 shows some of the technology options that SwRI is investigating. The approach includes screening of a wide range of aftertreatment components and exhaust gas thermal management strategies using a low cost diesel-based burner test rig capable of simulating test cycles and exhaust conditions from a diesel engine. The screening will identify technology packages with the greatest potential to provide maximum NO_X and GHG benefits. The final technology packages selected will then be evaluated on an engine dynamometer over the heavy-duty engine certification cycles and three other low-temperature/low-load vocational cycles. The project is expected to be completed by the end of 2016.

[4] ARB funded SwRI Low NOx Program: *Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles* (http://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm)

Figure ES-4: Advanced Technology Approaches and Options (SwRI)



Q. What technologies seem most promising for further reducing NO_X emissions from heavy-duty diesel engines?

A. This technology assessment evaluated technologies and strategies that when packaged may have the greatest potential to significantly reduce NOx emissions without impacting GHG emissions. These technologies include advanced aftertreatment technologies that improve NO_X conversion efficiency at both low and high exhaust temperature operation and strategies designed to raise the exhaust gas temperature during low temperature operations. Advanced aftertreatment technologies evaluated include advanced SCR catalysts, NO_X storage catalysts, alternative ammonia sources, urea delivery and injection control, and ammonia slip catalysts. Exhaust gas thermal management strategies evaluated include exhaust system thermal insulation, EGR, and turbocharger, idle speed, and injection timing control. Other supplemental heating strategies were also evaluated such as fuel burners and electrically heated catalysts.

It is not expected that a single strategy or technology will reduce NO_X significantly on its own. Maximum NO_X reductions can be realized from integrating engine control strategies with advanced catalysts and aftertreatment system control. Many of the engine control strategies and fuel burners designed to add heat to the exhaust may require additional fuel consumption during cold starts or low temperature operations. However, it is imperative that the technology package must have minimal or no impact on fuel consumption and GHG emissions over the vehicle's entire duty cycle.

Although the package that provides maximum benefits of both NO_X and GHG emissions is currently not yet determined, technology development is progressing and showing promising signs that these objectives will be realized. In fact, some of the technologies evaluated in this document are currently being commercialized for light-duty applications. For heavy-duty applications, currently ongoing development and demonstration programs such as the ARB-sponsored SwRI Low NO_X program are expected to identify technology packages that will provide significant further reductions of both NO_X and GHG emissions by the end of 2016.

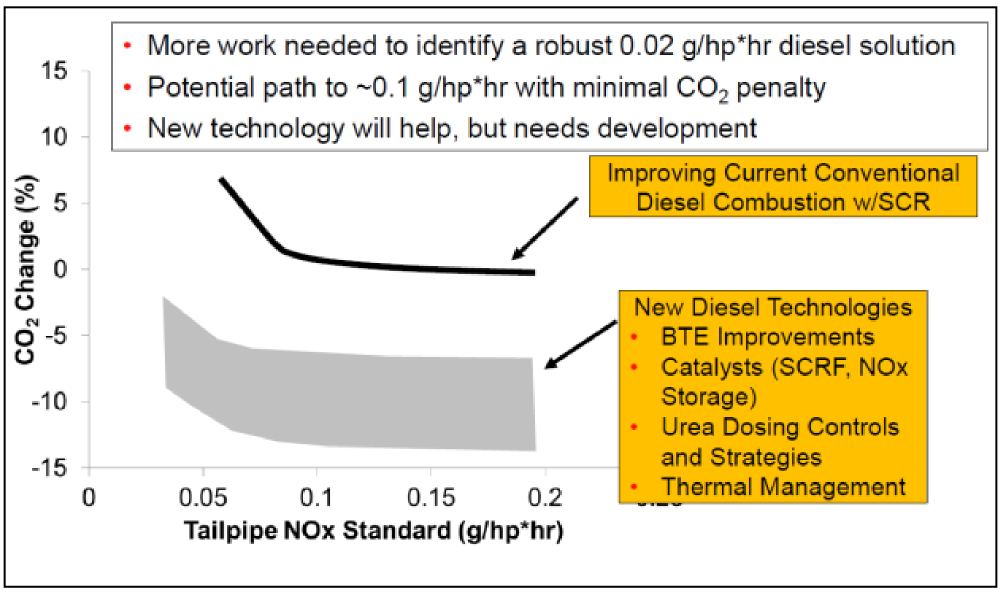
Q. Can NO_X and GHG be reduced simultaneously at lower NOx levels?

A. Yes. To comply with the pre-2010 model year NO_X standards, engines were designed to reduce in-cylinder NO_X at the expense of in-cylinder PM emissions and fuel consumption or GHG emissions (NO_X/GHG trade-off). However, continued developments in combustion systems, fuel injection systems, turbochargers, and electronic controls allowed engine manufacturers to partially mitigate the excess PM and fuel consumption. The introduction of the SCR and DPF aftertreatment systems to meet the 2010 NO_X standards further enabled engine manufacturers to optimize engine fuel economy, while minimizing both PM and NO_X emissions, thus overcoming the NO_X/GHG trade-off. The same engine optimization strategy will be used with future advanced SCR technologies, providing greater NO_X and GHG reductions, especially at high speed and high load operations.

Reducing NO_X emissions to the 0.02 g/bhp-hr levels will require significant emissions reductions during cold start and during low load, low speed operations. There are a variety of strategies which may be used to achieve these reductions. One approach is to provide greater exhaust gas thermal management. Close coupled SCR on DPF formulations and low thermal mass catalyst substrates can efficiently utilize existing heat in the exhaust gas, allowing better thermal management under a broader range of low speed, low load operations. Start-stop technology allows the engine to shut off rather than idling, which conserves heat in the catalyst and allows for higher catalyst control efficiencies. Another approach would be to use NO_X storage catalysts. These catalysts temporarily capture NO_X emissions at low temperatures and release NO_X at higher temperatures when they can be effectively controlled by the SCR system. A third approach involves advanced catalyst formulations and ammonia injection techniques that provide increased control efficiencies under a wide range of engine operating conditions. All of these strategies can provide additional NO_X reductions while allowing for optimal fuel economy. Finally, some strategies may involve providing supplemental heat to the exhaust gas which requires the use of external heat source. Such a strategy may impact fuel economy, but the impact will be minor. For further discussion on the NO_X/GHG trade-off, the reader is referred to the companion report: Draft Technology Assessment: Engine/Powerplant and Drivetrain Optimization and Vehicle Efficiency.

Figure ES-5 shows an assessment of the feasibility of achieving lower NOx emissions and the impacts on GHG emissions by Cummins Inc., the largest manufacturer of heavy-duty diesel engines in the U.S. (Eckerle, 2015). The solid black line in the figure represents current diesel technology. The chart shows that Cummins believes a 0.1 g/bhp-hr NO_X level is feasible with some improvements to the current SCR technology and the conventional diesel combustion process while still allowing for fuel economy optimization. According to Cummins, reducing NO_X further to the 0.02 to 0.05 g/bhp-hr levels and simultaneously reducing GHG emissions (shaded grey curve) would require more improvements in engine combustion efficiency, thermal management strategies, and advanced aftertreatment technologies such as NO_X storage catalysts, SCR coated on DPFs, and urea dosing control strategies. These strategies and technologies are discussed in chapter III of this document.

Figure ES-5: Cummins' Assessment of GHG and NOx Reduction Opportunities with New Engine Technologies



(Eckerle, 2015)

Manufacturers normally certify their engines with a compliance margin at levels below the numerical standard to protect themselves against non-compliance due to minor increases in emissions in use. The certification levels also include deterioration factors to account for any increase in emissions over the useful life of an engine. An analysis of NO_X certification levels indicates that the compliance margins for the latest diesel engines are 10 percent to 60 percent below the 2010 NO_X certification standard, depending on engine size. Hence, based on the above assessment and the current certification levels, staff believes diesel engines are likely to be certified to the optional NO_X emission standard of 0.1 g/bhp-hr by 2016, while engines meeting 0.05 g/bhp-hr or below are likely to be certified later.

Q. How much will these technology packages cost?

A. Engine manufacturers are using the urea-SCR aftertreatment system to comply with the current 0.20 g/bhp-hr NO_X standard. Depending on engine size, the added cost for the current urea-SCR system is estimated to be approximately $3,000 to $4,500 relative to the 2007 model year engine.[5] ARB staff believes further NO_X reductions to lower levels of approximately 90 percent below current standards will be possible through a combination of newer diesel engine designs, advanced diesel aftertreatment technologies, improved SCR catalysts with advanced substrates, and improved controls. It is expected that there will be costs associated with the development of these technologies. The Manufacturers of Emission Control Association estimates that the incremental cost of future advanced technologies needed to achieve NO_X levels of 0.02 g/bhp-hr to be approximately $500 per vehicle averaged over the medium and heavy-duty fleet.[6] Such an increase in cost is small compared to the initial introduction of SCR systems in 2010. Staff expects the cost-effectiveness of these technologies to fall within the cost-effectiveness range of previous NO_X reduction requirements from new engines.

Q. What next steps does staff recommend?

A.

- ARB should continue to support incentive funding for low-NOx heavy-duty engines to encourage engine manufacturers to develop and certify engines that meet the optional NO_X standards.

- Given California's criteria pollutant, GHG, and petroleum reduction needs, staff recommends that ARB implement statewide strategies that employ lower NO_X combustion engines coupled with the use of renewable fuels in order to attain near-term air quality and climate goals.

- In order to achieve air quality goals, ARB intends to begin the development of lower mandatory NO_X standards applicable to all California-certified heavy-duty vehicles. Since out-of-state registered heavy-duty vehicles that operate in California contribute significantly to the emissions inventory, it is also critical that ARB petition the United States Environmental Protection Agency to require lower NO_X standards applicable to all heavy-duty vehicles nationally.

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[5] Blumberg, K., F. Posada, and J. Miller. *Revising Mexico's NOM 044 standards: Considerations for decision-making* International Council on Clean Transportation, Working Paper 2014-5. May 2014. <http://www.theicct.org/series/heavy-duty-vehicle-policies-for-mexico>.

[6] *MECA's Written Statement on the U.S. EPA's Proposal to Revise the NAAQS for Ozone.* Manufacturers of Emission Control Association. March 16, 2015. <http://www.meca.org/attachments/2560/MECA_EPA_ozone_NAAQS_testimony_031715.pdf>.

I. Introduction and Purpose of Assessment

This report is part of a series of technology and fuels assessment reports that evaluate the state of technology to further reduce emissions from the transportation sector including trucks, locomotives, off-road equipment, ships, commercial harborcraft, aircraft, and transportation fuels.

Air Resources Board's (ARB) objective is to transform the on- and-off-road mobile source fleet into one utilizing zero and near-zero emission technologies to meet air quality and climate change goals. This assessment is intended to provide a comprehensive evaluation of the current state and projected development over the next 5 to 10 years of lower oxides of nitrogen (NO_X) heavy-duty diesel engines. For each technology, the assessment will include a description of the technology, its suitability in different applications, current and anticipated costs at widespread deployment (where available), and emissions levels.

This technology assessment will support ARB planning and regulatory efforts, including:

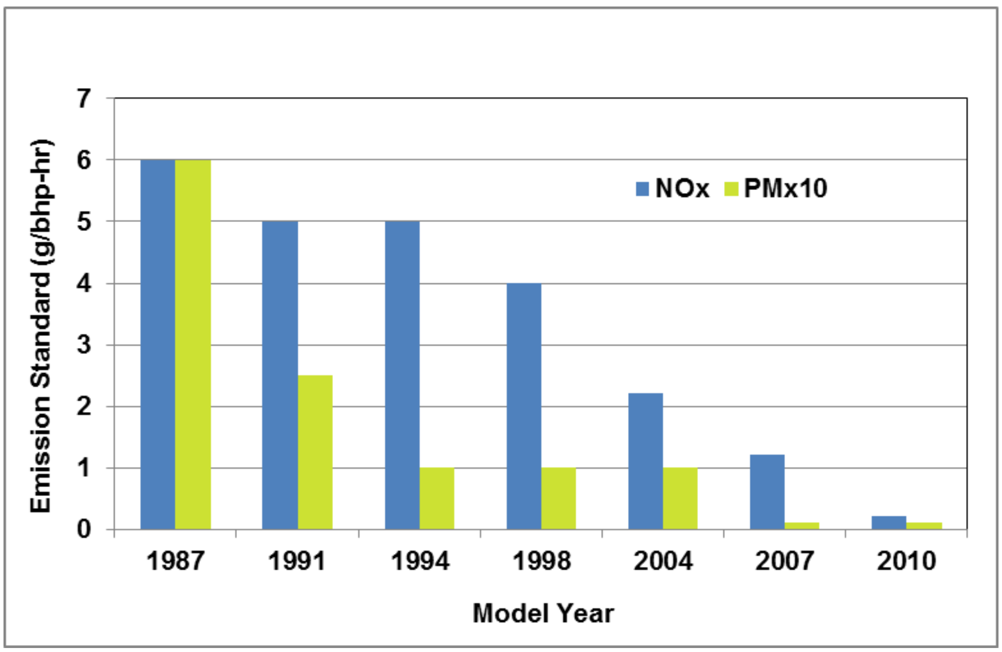
- California's integrated freight planning
- State Implementation Plan (SIP) development
- Funding Plans
- Governor's Zero Emission Vehicle Action Plan
- California's coordinated goals for greenhouse gas (GHG) and petroleum use reduction

Chapter II discusses the history and current status of emission control for heavy-duty diesel engines. Chapter III discusses advanced aftertreatment technologies and the diesel engine control strategies that have the potential to reduce NO_X emissions. Chapter IV discusses system suitability and infrastructure needs. Chapter V discusses currently ongoing technology development and demonstration programs. Chapter VI and VII discuss the cost of the new technologies and the level of emissions reduced by these technologies, respectively. Chapter VIII discusses the impacts of NO_X control on GHG emissions and vice versa (NO_X/GHG trade-off). Finally, Chapter IX and X discuss staff's recommended next steps and conclusions.

II. History of Emission Control for Heavy-Duty Diesel Engines

Regulations to control pollutant emissions from on-road heavy-duty diesel engines (HDDE) have been getting more and more stringent since the 1970s, beginning with smoke controls, and continuing in the 1990s through 2010, with increasingly stringent standards for NO_X and particulate matter (PM) emissions. Figure II-1 illustrates the evolution of California NO_X and PM standards for on-road HDDEs. Most of the NO_X and PM standards that were implemented in the early years prior to the 2007 and 2010 standards were met using in-cylinder emission controls that reduced engine-out NO_X emissions. For example, during the late 1980s and early 1990s, the main strategies used for NO_X control were injection timing retard together with charge air cooling to reduce intake manifold temperatures. These strategies reduce NO_X by lowering peak combustion temperatures. However, reducing NO_X using injection timing control also tends to increase fuel consumption and PM emissions. Thus, other strategies such as increased injection pressures and increased intake manifold pressures had to be used to offset the increased fuel consumption and PM.

Figure II-1: California – On-Road HDDE NO_X and PM Standards



The 1998 NO_X standard of 4 grams per brake horsepower-hour (g/bhp-hr) was met with continued improvement of the previous control strategies and advances in electronic controls which allowed a more flexible and accurate control of engine operating parameters including fuel injection timing, fuel injection pressures, fuel metering, and turbocharger control.

Compliance with the 2004 NO_X standards required the use of exhaust gas recirculation (EGR) coupled with higher fuel injection pressures to mitigate potential increases in PM and fuel consumption and the use of variable geometry (VG) turbochargers to control and ensure the required EGR flow.

Beginning in 2007, heavy-duty engine manufacturers were required to meet a PM standard of 0.01 g/bhp-hr, a NO_X standard of 0.20 g/bhp-hr, and a non-methane hydrocarbon (NMHC) standard of 0.14 g/bhp-hr. Specifically, the PM standard took full effect beginning in 2007, while the NO_X and NMHC standards were phased-in on a percent of sales bases; 50 percent from 2007 to 2009 and 100 percent in 2010. To comply with the phase-in NOx standards, engine manufacturers opted to certify engines to a fleet average NOx standard of approximately 1.2 g/bhp-hr, rather than certifying engines to two different standards (50 percent at 0.2 g/bhp-hr NOx and 50 percent at 2.4 g/bhp-hr NOx+NMHC standard).

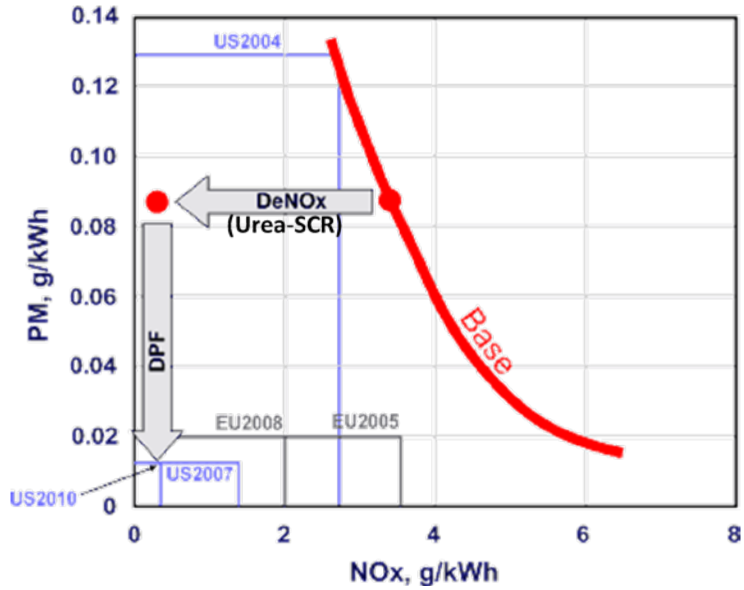
The 2007 PM standard was met using diesel particulate filters (DPF). Higher rates of cooled-EGR, VG turbochargers, high pressure fuel injection and electronic controls were used to comply with the 2007 through 2009 fleet average NOx standard of 1.2 g/bhp-hr, and diesel oxidation catalysts (DOC) were used to meet the NMHC standard.

Moreover, in addition to the continued use of existing technologies, NOx aftertreatment control technologies were used to comply with the 2010 NO_X standard of 0.20 g/bhp-hr. For most engine manufacturers, the NOx aftertreatment control system of choice was the urea-selective catalytic reduction (SCR) including ammonia slip catalysts to control ammonia slip at the tailpipe.

Since sulfur can poison and degrade the performance of aftertreatment catalysts, ultra-low sulfur diesel fuel (ULSD) with sulfur content less than 15 parts per million (ppm) was introduced prior to the implementation of the 2007 and 2010 heavy-duty engine NO_X and PM standards. The introduction of ultra-low sulfur diesel fuel also had the additional effect of reducing PM from the entire in-use heavy-duty fleet.

It is well known that simultaneous NO_X and PM control using only engine design changes is very complex and can have offsetting effects (i.e., the so-called NO_X/PM trade-off). Nevertheless, advances in engine development such as electronic controls, combustion chamber design, fuel injection systems, turbocharging, and associated controls have enabled and continue to enable manufacturers to overcome the NO_X/PM trade-off and achieve lower tailpipe levels of both NO_X and PM. Furthermore, the use of aftertreatment systems to control NO_X and PM has also enabled engine developers to overcome the NO_X/PM trade-off. For example, the high NO_X reduction capability of the SCR system enables the engine to be calibrated for high engine-out NO_X emissions, low fuel consumption, and low PM emissions (Figure II-2). An additional benefit of this strategy is that since less PM is collected in the filter, less filter maintenance is required. Also, the presence of higher concentrations of nitrogen dioxide (NO_2) that results from the introduction of DOCs in the exhaust system facilitates passive filter regeneration at lower exhaust gas temperatures.

Figure II-2: Emission Strategy for SCR and DPF Systems

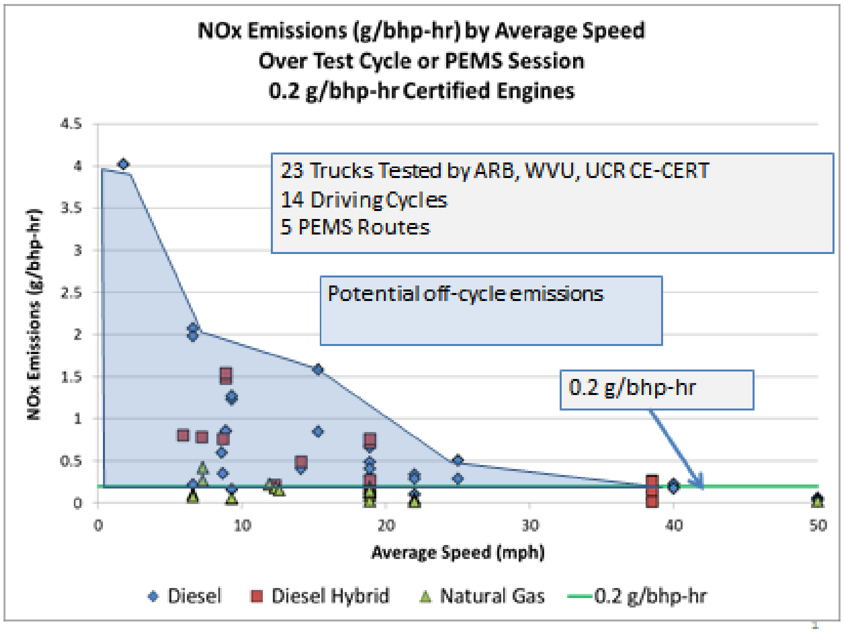


(www.dieselnet.com)

Current SCR systems are providing high NO_X conversion efficiencies during steady-state and high-speed operations. Despite meeting the current standards during certification test cycles, they have poor NO_X conversion efficiency when exhaust gas temperatures are low, such as during cold start, low-speed city driving and during extended idling. This is because SCR performance is limited by urea decomposition and hydrolysis issues at exhaust gas temperatures below 200°C. If urea is injected at exhaust gas temperatures below 200°C, solid deposits, such as ammonium nitrate and/or ammonium sulfate, are formed over the catalyst and exhaust system. The solid deposits degrade the NO_X conversion efficiency of the system.

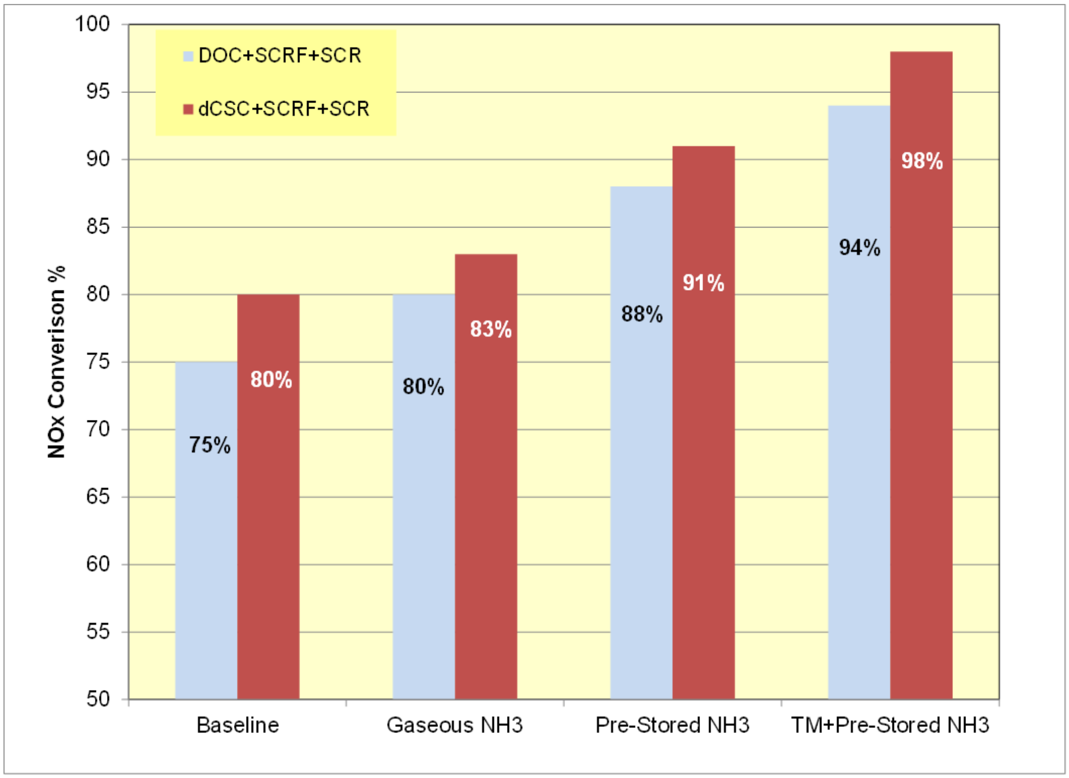
Furthermore, as shown in Figure II-3, recent in-use emissions test data from natural gas, diesel, and diesel hybrid engines certified to the 2010 NO_X emission standard show that diesel engines appear to suffer the control challenge experienced in low temperature, low speed, and low load operations. However, at high speed engine operating temperature, as are seen during cruise and high-load operations, diesel engines appear to emit below the NO_X certification standard.

Figure II-3: In-Use Running Exhaust NOx Emissions Diesel, Diesel Hybrid, and Natural Gas Trucks



Thus, a significant challenge to achieving further emission reductions involves reducing cold start emissions to the lowest possible levels and controlling emissions at light load and low-speed operations. This can be achieved by improving the low temperature performance of the SCR system, which would involve controlling NO_X during cold start and accelerating the catalyst light-off temperatures; controlling emissions at light load and low-speed operations; and once warmed-up, maintaining high conversion efficiency. To meet certification standards lower than 0.20 g/bhp-hr NOx, such as ARB's optional NO_X standards of 0.1, 0.05, and 0.02 g/bhp-hr (ARB, 2013), it may also be necessary to further reduce NO_X emissions at high speed and high load operations. Reducing NO_X at cold start, light load, low-speed, high load and high speed operations may require a combination of strategies including exhaust thermal management methods, advanced catalyst formulations, better control systems, and more effective alternative sources for ammonia. As shown in Figure II-4, Naseri et al. recently demonstrated significant NO_X conversion efficiency improvements of greater than 95 percent during the cold federal test procedure (FTP) transient test using an advanced aftertreatment system that included low temperature NO_X storage catalyst (dCSC), SCR coated on DPF (SCRF) with a downstream high porosity SCR catalyst, ammonia slip catalyst in combination with thermal management (TM) strategies (electrical heater), and early availability of pre-stored ammonia in the system (Naseri et al., 2015). The strategies are discussed in detail in Chapter III.

Figure II-4: Cold-Start Technologies Being Demonstrated



(Naseri et al., 2015)

III. Technologies Evaluated

This chapter discusses a number of measures and technologies currently being explored to reduce cold start and low temperature emissions and improve the NO_X conversion efficiency of SCR aftertreatment systems at all engine operating conditions, including low-speed and high-speed operations. Section A discusses improvements to the aftertreatment system, which may improve NO_X conversion without incurring a fuel consumption penalty. Section B discusses engine-based exhaust gas thermal management and exhaust system thermal management strategies. Strategies that have the potential for reducing NO_X further without a fuel penalty are presented first, followed by strategies that may incur a fuel penalty.

It is not expected that a single emission control strategy will reduce emissions significantly on its own. Maximum NO_X and GHG benefits can result from proper systems integration and optimization of engine management control strategies with advanced aftertreatment systems and their control strategies. For example, one integrated system could include accelerating the catalyst light-off by raising the exhaust gas temperature using engine-based strategies and improving aftertreatment conversion efficiency using advanced catalyst formulations and a urea-SCR control system. Furthermore, as discussed at further length in the ARB's companion report Technology Assessment: In-Use Emissions Truck Technology Assessment, improving the certification and in-use compliance programs would help ensure emission reductions are achieved in the real world and durable.

A. Advanced Aftertreatment Systems

1. Advanced SCR catalysts

Table III-1 shows urea-SCR catalysts in commercial use today. Vanadia based catalysts are not currently used for on-road applications in North America due to the possibility of emissions of vanadium compounds being produced at elevated exhaust gas temperatures that may occur during active DPF regeneration.

SCR catalyst formulations and designs have been undergoing continuous development to improve the durability and the overall NO_X conversion performance of the SCR system. To improve the temperature operating window, catalysts with high cell density and thinner durable substrate walls are being developed. The high cell density and increased porosity provide increased surface area to allow sufficient contact area between the exhaust gas and the active catalytic materials. The thin substrate walls also reduce the catalyst thermal mass allowing rapid warm-up. Other catalyst formulations such as chemical mixtures of copper and iron zeolites have also been shown to improve the low temperature performance versus copper-zeolite alone (Yang & Narula, 2011). High cell density substrates are also being evaluated and are showing faster reactions than current substrates (Johnson, 2014a). Furthermore, low temperature performance of new generation copper zeolites has also been improving relative to earlier generation copper zeolites (15 percent improvement at temperatures of 175° and 200°C) (Walker, 2012). Moreover, as discussed below in paragraph 3, combined SCR-DPF systems are being developed to improve SCR catalyst light-off, reduce system size, packaging, and cost.

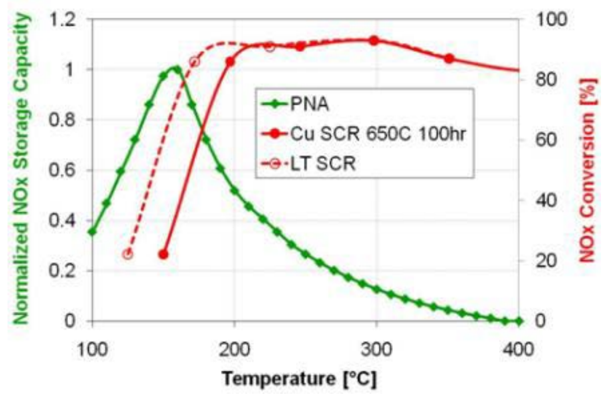
Table III-1: Urea-SCR catalysts in commercial use today

Copper-zeolite	- High performance at low temperatures - Temperature window 150°C to 450°C - High efficiency at high space velocity - Little sensitivity to NO_2 concentration - Susceptible to sulfur poisoning /requires occasional desulfation - Does not create dioxins
Iron-zeolite	- High performance at high temperature - Temperature window 350°C to 600°C - NO_2 management of the inlet gas needed for improved low temperature performance - No sulfur poisoning but susceptible to moderate HC poisoning
Vanadia	- Cheapest of the catalysts - Temperature window: 300°C to 450°C - Poor high temperature durability (deteriorates at 550°–600°C) - Not utilized in systems with DPFs that require active regeneration - Low temperature performance strongly depends on NO_2 availability

2. Passive NO_X adsorber

A passive NO_X adsorber (PNA) is a NO_X storage device that is placed upstream of an SCR to store NO_X during cold start and during low temperature operations and then release the NO_X at higher temperatures when the downstream SCR catalyst becomes active. Figure III-1 illustrates the NO_X storage capacity of the PNA and the NO_X conversion efficiency of a urea-SCR system during the cold start segment of the light-duty FTP-75 (Henry et al., 2011). In this illustration, the PNA stores approximately 65 percent of the NO_X at temperatures less than 150°C. The majority of the stored NO_X is released at temperatures of around 150°C to 200°C when the SCR activity is still very low. Thus, a low temperature SCR catalyst (e.g., close-coupled SCR coated on DPF) and/or ammonia gas injection or using pre-stored ammonia in the catalyst can be used to bridge the gap and improve NO_X conversion at the lower temperatures. The technology is currently under research and development and more work is needed to optimize the PNA to improve the NO_X storage efficiency (≥ 90 percent) and to increase the NO_X release temperature (> 150°C).

Figure III-1: PNA Strategy to Improve Low Temperature Performance

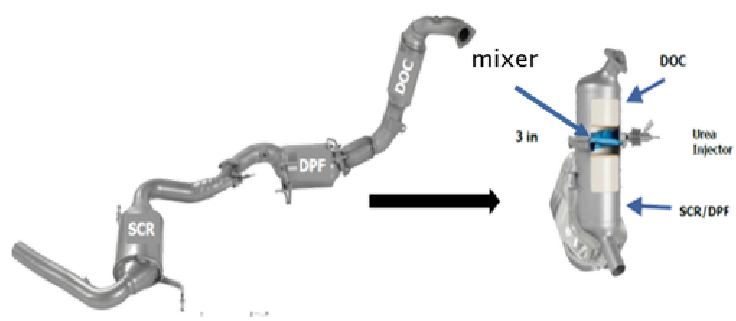


(Henry et al., 2011)

3. Combined SCR-DPF systems

A technology that is receiving considerable attention is the combined SCR-DPF system (also referred to, by different manufacturers, as SCRF, SDPF, or SCRoF), in which the porous walls of the DPF substrate are impregnated with SCR catalytic material. As shown in Figure III-2, it combines the functionalities of two systems, the SCR and the DPF, into one aftertreatment system, reducing system size, weight, complexity, and cost. With the addition of a compact urea mixer, the system can be close-coupled to the DOC for faster light-off and improved cold start emissions. To maximize NO_X conversion, the system may also require an additional SCR system downstream of the combined system. Copper and iron-based catalysts are more appropriate for use as SCR catalysts on the DPF due to their higher thermal stability (Karamitros et al., 2014).

Figure III-2: Close-coupled combined SCR-DPF System



There are competing requirements that need to be considered in the development of combined SCR-DPF systems. These include the impacts of competitive NO_2 consumption by the SCR and the DPF, the effect of soot loading on NO_X conversion, and the effect of NO_X conversion activity on filter regeneration. For improved NO_X conversion, it is desirable to have the highest possible amount of active SCR sites on the pores of the filter, so a high porosity filter substrate would be required. Furthermore, filter performance such as pressure drop, filtration efficiency, and thermal durability may also limit the amount of catalyst washcoat loading.

The technology is still under research and development for heavy-duty applications. Catalyst manufacturers are currently investigating the performance of the technology on HDDEs and have reported some promising results, although more work needs to be done to optimize the performance of the system at low temperatures (Naseri et al., 2014; Naseri et al., 2015).

4. Close-coupled SCR catalyst

Placing the SCR catalyst upstream of the DPF and closer to the DOC exposes the SCR to higher exhaust gas temperatures compared to a conventional DPF-SCR system (see Figure III-3). This enables faster SCR light-off and therefore better cold start NO_X conversion efficiency. However, the exhaust gas reaching the DPF will be cooler and will have relatively lower concentration of NO_2, thus minimizing the passive regeneration potential and increasing the potential for needed active regeneration. As a result, the filter may require supplemental heat to improve filter regeneration during extended low exhaust gas temperature events, resulting in a potentially higher fuel consumption penalty.

Figure III-3: SCR Upstream of DPF

5. Alternative Sources for Ammonia

In a traditional SCR system, the ammonia gas is generated by injecting urea into the hot exhaust stream upstream of the SCR catalyst. However, current SCR performance is limited by urea decomposition and hydrolysis issues at exhaust gas temperatures below 200°C. If urea is injected at exhaust gas temperatures below 200°C, solid deposits, such as ammonium nitrate and/or ammonium sulfate, are formed over the catalyst and exhaust system. The solid deposits degrade the NO_X conversion efficiency of the system. Furthermore, aqueous urea freezes at an ambient temperature of -11°C, so a heating system may be required to heat the urea tank for low ambient temperatures. Two alternative sources of ammonia that could enable SCR conversion at temperatures below 200°C are discussed below.

a. Solid Ammonia Precursors

The issues with urea may be resolved to a certain extent using solid ammonia precursor compounds, which when heated can deliver ammonia gas. Candidate ammonia storage materials should have high ammonia storage capacity, low decomposition/desorption temperature, and should be safe and easy to handle. Two groups of ammonia storage materials that show a desirable combination of properties are ammonium salts and metal ammines.

Since the density of ammonia is higher in ammonium salts than in urea, ammonium salts require smaller storage containers than urea. Ammonium carbamate and ammonium carbonate are two types of ammonium salts that decompose completely into gases without leaving solid deposits. Both materials release ammonia and carbon dioxide when heated, though ammonium carbonate also generates water upon decomposition. Both compounds generate ammonia at temperatures below 100°C (Fulks et al., 2009).

Solid ammonia storage systems in conjunction with low temperature SCR catalysts can reduce NO_X at temperatures significantly below 200°C. However, continuous ammonia dosing during prolonged low temperature operations may result in the formation of deposits such as ammonium nitrate. As a result, advanced control algorithms are needed to calculate the amount of deposits formed as a function of the ammonia injected and the operating temperature, and then stop ammonia dosing once the maximum allowed deposit mass is reached.

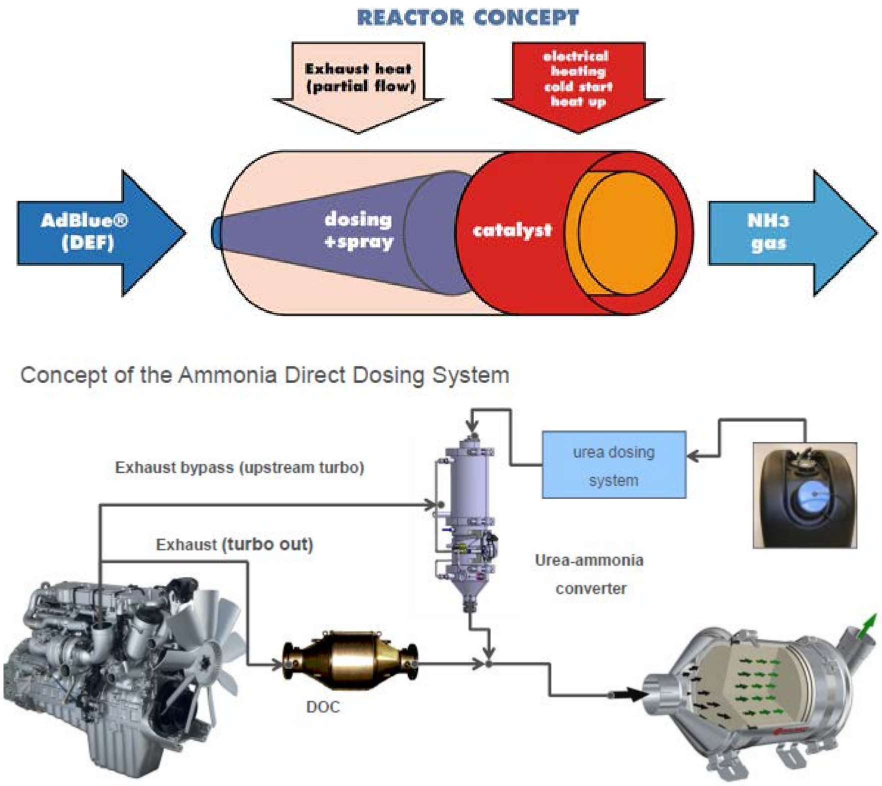
A solid storage system that uses strontium amine chloride has been developed for light- and heavy-duty vehicles. The system starts releasing ammonia at exhaust temperatures of about 100°C. The version for heavy-duty engines consists of two replaceable/refillable dosing systems: an engine coolant heated main cartridge and an electrically heated start-up cartridge for cold start. The technology is currently in pilot demonstration phase.

To become widely used, solid ammonia storage systems would require development of infrastructure for the replacement and recharging of used cartridges.

b. Heated Ammonia Generation from Aqueous Urea

An alternative solution that is gaining commercial acceptance is to convert the urea solution on-board the vehicle to ammonia gas. In this system, shown in Figure III-4, ammonia gas generation occurs in a separate module outside of the main exhaust line (Doelling et al., 2014). Urea solution is injected into the module via a urea dosing system and the heat needed to convert the urea solution is provided via two sources: (1) a partial exhaust flow taken off from the main exhaust upstream of the turbocharger, and (2) an electrically heated catalyst (cold start heat up). The two heat sources can be used either one at a time or together. The ammonia gas generated is then injected into the main exhaust line upstream of the SCR catalyst. This improves the SCR performance at lower exhaust gas temperatures when urea injection into the main exhaust gas is not possible. The drawbacks of this system are it requires a separate device which requires additional space, mounting parts, pipes, connectors, cables, and electrical energy. The system is commercially available and can be used on new engines as well as in retrofit applications.

Figure III-4: The B-NOx System (Ammonia Generator)



6. Urea Delivery System

The urea delivery system comprises of the urea storage tank, heated delivery line, pump, dosing module which includes the injector and mixer, and the control system and associated sensors. The main functions of the urea dosing and injection system include dosing of the precise amount of urea necessary for NO_X conversion and mixing urea and ammonia thoroughly with the exhaust gas. Potential improvements to the urea delivery system are discussed below.

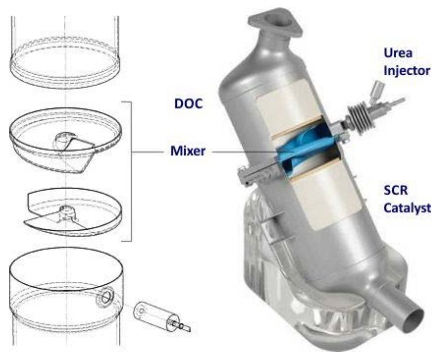
a. Urea Dosing and Injection System

New generations of urea dosing systems are being developed and introduced to enable high SCR conversion efficiencies. Air assisted injectors, which need separate air pumps specific for urea injection are being replaced by airless injectors where the energy for atomization is supplied by the urea pressure. Urea pumps, dosing modules and injectors are moving from separate component designs into integrated designs. For example, Delphi has developed an integrated pump and airless injector system that delivers a peak injection pressure of 50 bar and a highly optimized injection spray. The system is designed to perform well with close coupled catalysts where the mixing length is very short and uniform ammonia distribution at the catalyst inlet is required (Needham et al., 2012).

b. Urea Mixer

Currently, low temperature SCR activity is limited by urea decomposition and hydrolysis issues at exhaust gas temperatures below 200°C. Improved mixers enable urea injections at temperatures as low as 180°C (Alano et al., 2011). For example, compact swirl mixers with very short mixing paths have been developed to enable the SCR catalyst to be placed closer to the engine for faster heat-up (Figure III-5). The technology is in the research and development stage for heavy-duty vehicles.

Figure III-5: SCR BlueBox Compact Mixer



(Faurecia, 2014)

c. Urea Hydrolysis Catalyst

Urea hydrolysis catalysts that use base metal oxide formulations such as titania can be placed between the urea injection point and the SCR catalyst to ensure more complete urea decomposition and to accelerate the formation of ammonia, potentially improving cold start and overall SCR performance.

d. Urea Injection Control

The objective of the urea injection control system is to simultaneously minimize the tailpipe NO_X and ammonia emissions by enabling the urea dosing system to inject the precise amount of urea necessary for NO_X conversion. Closed-loop control SCR systems are used in applications such as 2010 heavy-duty diesel engines, where high NO_X conversion efficiency (>90 percent) is needed (Majewski, 2014). For a closed-loop SCR control system, a NO_X sensor upstream of the SCR and downstream NO_X and ammonia sensors are needed to adjust the amount of urea injected.

Ammonia sensors which recently became commercially available are enabling direct measurements of ammonia slip at the SCR outlet (Majewski, 2014). Thus, the combination of NO_X and ammonia sensors and model-based closed-loop control has significantly improved the precision in urea injection of the SCR system (Wang et al., 2008). The use of ammonia sensors can also provide the flexibility to eliminate or reduce the size of the ammonia slip catalyst.

e. Ammonia Slip Catalysts

Ammonia slip catalysts are precious metal-based oxidation catalysts that are needed to oxidize excess unreacted ammonia that may have slipped through the SCR catalyst and would otherwise be exhausted to the environment. Ammonia slip catalysts are designed to have high selectivity for ammonia, oxidizing ammonia to form nitrogen. However, if the nitric oxide to ammonia ratio coming out of the SCR catalyst is very high, the catalyst may also catalyze undesirable reactions that produce nitrous oxide, a potent greenhouse gas. The latest generations of ammonia slip catalysts with reduced precious metal content are showing much better selectivity for ammonia, while forming less undesirable products at the tailpipe. This technology is commercially available for heavy-duty applications.

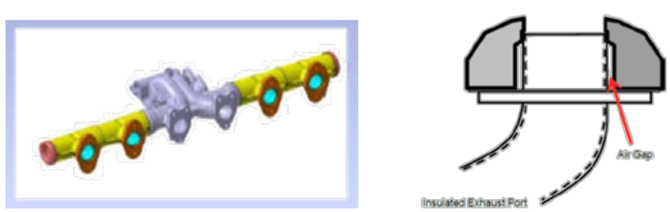
B. Exhaust Gas Thermal Management

This strategy involves increasing and maintaining the exhaust gas temperature through thermal insulation of the exhaust system, direct heat addition to the exhaust using fuel burners or electrically heated catalysts, and increasing the exhaust gas temperature through engine control strategies. Except for the exhaust system heat retention strategy, all of the other strategies discussed in this section involve heat addition and therefore may have negative impacts on fuel consumption.

1. Exhaust system heat retention

The use of exhaust thermal management strategies to reduce cold start emissions has also led to improvements of the exhaust system components upstream of the SCR in order to retain as much heat as possible in the exhaust gases. Reducing the mass of the exhaust system and insulating it from the outlet of the turbocharger to the inlet of the SCR system would reduce the amount of heat lost to the walls. Double walled manifolds and pipes with a very thin inner wall and an air gap separating the inner and outer wall may be used to insulate the exhaust system and reduce the thermal mass, minimizing the amount of heat lost to the walls (Figure III-6). This technology is prevalent in gasoline-fueled engine applications and is in the demonstration phase for diesel engine applications. There is no fuel penalty with this strategy.

Figure III-6: Insulated Exhaust System



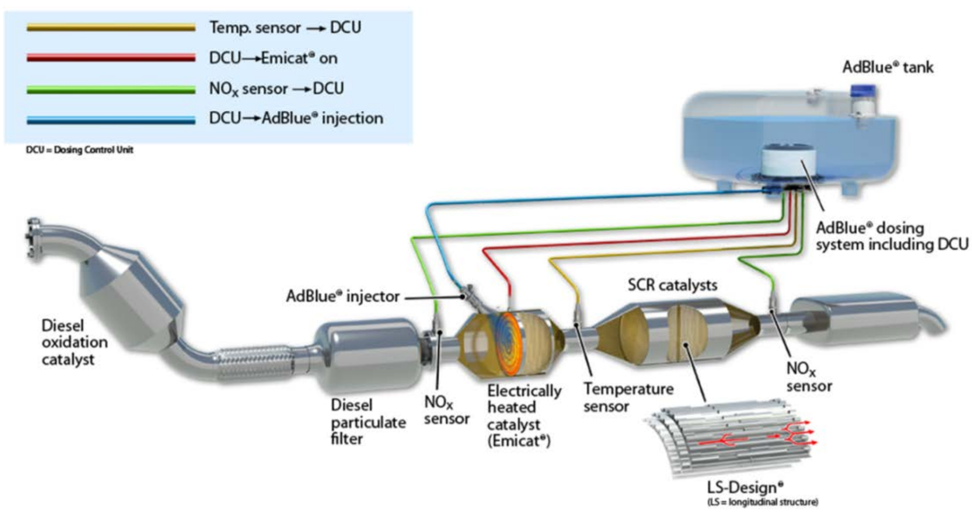
2. Supplemental heat to the exhaust gas

Another approach to raising the exhaust gas temperature to improve SCR conversion efficiency at low temperatures is to directly add heat to the exhaust using electrically heated catalysts or fuel burners.

a. Electrically heated catalyst

Electrically heated catalysts (EHC) use a small catalyst ahead of the main catalyst to deliver heat directly to the exhaust gases. The system can be programmed to activate only when it is needed during cold starts or during light-load operations when the exhaust gas temperature drops below the catalyst light-off temperature. Since EHCs use electricity generated by the engine's alternator, the exhaust gas heating is a parasitic load on the engine and therefore consumes fuel. However, the fuel consumption penalty may become less significant when used in combination with electric hybrid vehicles where the electrical energy used is recovered via braking energy. Heated metal catalysts, with a power rating between 1 and 3 kW, can raise the exhaust gas temperature by 20 to 30°C in commercial vehicles (Emitec, 2013). The technology is widely commercially available in light-duty vehicles and is in the demonstration phase for commercial heavy-duty vehicle applications. Shown in Figure III-7 is Emitec's electrically heated catalyst.

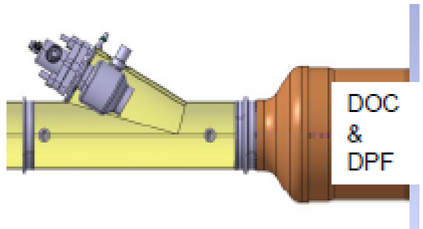
Figure III-7: Electrically Heated Catalyst



b. Exhaust fuel dosing / fuel burners

In this approach, the exhaust gas temperature is increased either by combusting the fuel in the fuel burner with the flame entering the exhaust system or injecting fuel into the exhaust gas and oxidizing it over an oxidation catalyst, or a combination of the two. Similar to the EHC, the fuel burner (Figure III-8) may be operated only when needed during cold start or when the exhaust gas temperature drops below the light-off temperature. The strategy can increase fuel consumption. The technology is widely available commercially to add heat to the exhaust to facilitate diesel particulate filter regeneration.

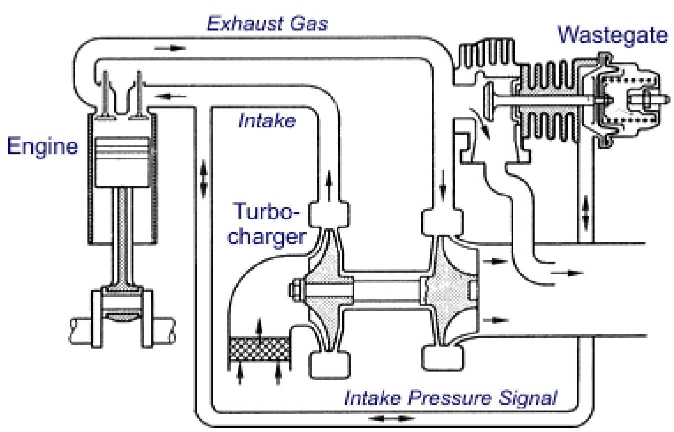
Figure III-8: Fuel Burner



3. Turbocharger bypass (Wastegate)

Turbocharger bypass is simply a valve in the turbine housing that allows some portion of the exhaust gas to bypass the turbocharger and divert it directly to the exhaust system (Figure III-9). Having the exhaust gas bypass around the turbocharger limits the turbine speed and the amount of power delivered by the turbine. This reduces the amount of inlet boost pressure that the compressor provides, resulting in a fuel rich mixture condition. Since there is insufficient oxygen in the mixture, combustion of the fuel rich mixture results in reduced NO_X emissions. In addition to reducing in-cylinder NO_X, this strategy also avoids heat loss across the turbine housing, accelerating catalyst warm-up during cold starts. The bypass valve may be closed during transient operations to minimize effects on drivability and emissions. Using this strategy to increase exhaust gas temperature can increase fuel consumption. The technology is widely available commercially.

Figure III-9: Turbocharger with External Wastegate



(www.dieselnet.com)

4. VG turbocharge control

Electronically controlled VG turbochargers may also be used to increase the exhaust gas temperature by partially closing the VG turbine vane to increase the exhaust manifold pressure. The high exhaust manifold pressure makes the engine work harder thereby increasing the exhaust gas temperature. Since the engine is made to work harder, there could be a fuel consumption penalty with this strategy. The technology is widely available commercially.

5. Increasing idle speed

Increasing idle speed increases the amount of fuel injected during idle, thereby producing a rich exhaust. The unburned hydrocarbons in the exhaust are oxidized in the DOC, providing a moderate increase of exhaust gas temperature. However, this strategy can impact fuel consumption negatively. The technology is widely available commercially.

6. In-cylinder post injection

Injecting fuel late in the combustion process allows some of the unburned hydrocarbons in the exhaust to create an exothermic reaction downstream at the DOC. This increases the exhaust gas temperature, which improves aftertreatment performance during cold start or low temperature operation. This strategy can increase fuel consumption. The technology is widely available commercially.

7. Intake air throttling

A commonly used method of increasing the exhaust gas temperature is intake air throttling. The method involves partially reducing the amount of air entering the cylinder, which in turn reduces the power output of the engine. In a diesel engine, load control is generally accomplished by varying the amount of fuel injected to the engine. Therefore, to maintain the required engine load, fuel consumption increases resulting in fuel rich mixture combustion. This supplies unburned fuel to the DOC creating an exothermic reaction and as a result increases the exhaust gas temperature. This strategy can increase fuel consumption. The technology is widely available commercially.

8. EGR

EGR is used as a NO_X reduction strategy in modern commercial heavy-duty diesel engines. EGR involves routing some portion of the exhaust gas back into the cylinder. The exhaust gas dilutes the oxygen fraction of the inlet charge entering the combustion chamber and reduces the peak combustion temperatures, thereby reducing the formation of NO_X emissions. The use of EGR to reduce NOx emissions can increase fuel consumption and PM emissions. However, as discussed in Chapter II, manufacturers have been mitigating these negative impacts through advances in engine development such as electronic controls, increased fuel injection pressure, and increased intake manifold boost pressure. As discussed in paragraphs (a) and (b) below, in addition to reducing NOx emissions, EGR can also be used to increase the exhaust gas temperature during certain engine operating conditions.

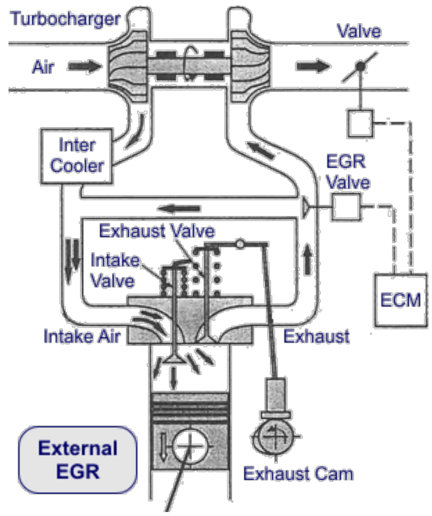
a. External EGR

This method involves routing some portion of the hot exhaust gas from the exhaust manifolds back into the cylinder (Figure III-10). Introducing hot EGR into the intake manifold increases the mixture temperature and reduces the inlet charge mass, or air to fuel ratio. The higher inlet charge temperature due to EGR improves fuel evaporation and air-fuel mixing during the ignition delay period and during combustion, increasing exhaust gas temperature. However, cooled EGR provides better in-cylinder NO_X reduction and lower PM emissions than hot EGR and therefore HDDE applications often use cooled EGR. As a result, the use of hot EGR as a strategy to increase exhaust gas temperature may be limited only to certain engine operating conditions such as cold start, extended idle, and light load operations. An EGR cooler bypass or dual loop systems may be used to allow uncooled EGR into the intake manifold. This strategy can result in additional fuel consumption. The technology is widely available commercially.

b. Internal EGR

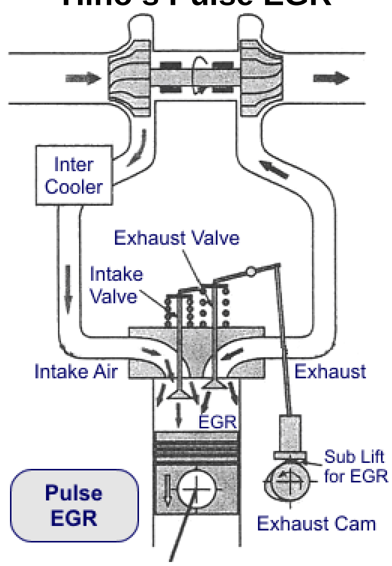
Exhaust temperature can also be increased during cold start and extended idle with internal EGR (Figure III-11). Internal EGR can be achieved with variable valve actuation (VVA) by opening the exhaust valve slightly during the intake stroke and drawing exhaust gas into the cylinder; or by opening the intake valve slightly during the exhaust stroke and pushing some of the exhaust into the intake manifold. The exhaust gas that is left in the cylinder heats up the intake charge and reduces the air-fuel ratio, providing higher combustion temperatures. This strategy can result in additional fuel consumption. The technology is widely available commercially.

Figure III-10: External EGR



(www.dieselnet.com)

Figure III-11: Internal EGR
Hino's Pulse EGR



(www.dieselnet.com)

IV. System/Network Suitability and Operational/Infrastructure Needs

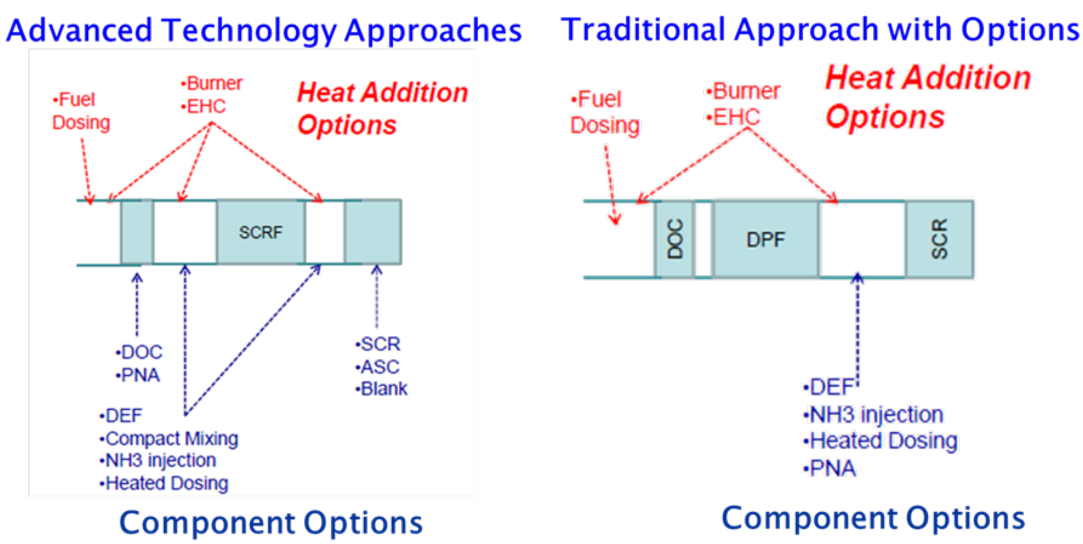
HDDEs require ULSD to enable the use of DPF and SCR control technologies to meet the 2007-2010 standards. Since 2007, almost all diesel fuel sold in the U.S. at facilities where trucks are fueled is ULSD. In addition, these vehicles are equipped with SCR aftertreatment systems and require periodic replenishment of urea for the SCR and the vehicle to function properly. Since 2010, infrastructure for urea (Diesel Exhaust Fluid) distribution has been developed, making it available at truck stops, dealerships, fueling stations, and repair and service operations. Thus, there is no specific infrastructure issue that needs to be addressed that otherwise would be an impediment to enable the lower-NO_X technology options evaluated in this assessment.

V. Demonstration Status / Technology Readiness

In 2013, ARB initiated a project with Southwest Research Institute (SwRI) to demonstrate maximum NO_X reductions from two heavy-duty engines: a stoichiometric natural gas engine and a diesel engine. SwRI will evaluate the feasibility of achieving lower NO_X emissions through a combination of engine tuning practices, exhaust thermal management strategies, and aftertreatment strategies. The engine technology must also continue to meet all applicable standards for hydrocarbons, carbon monoxide, and PM; not incur a GHG penalty; and be consistent with a technological path to meeting the upcoming U.S. Environmental Protection Agency (EPA) GHG standards for heavy duty vehicles. The target NO_X emission rate for this project is 0.02 g/bhp-hr.

The technology strategies for diesel engines are more complex and varied. Figure V-1 shows some of technology options that SwRI is investigating to demonstrate maximum feasible NO_X reductions from the HDDE. SwRI's research plan includes identification and screening of candidate aftertreatment options and engine management strategies using a low-cost diesel-based burner test rig capable of simulating test cycles and exhaust conditions from a diesel engine. The screening will identify optimum technology packages for final on-engine demonstration testing. The demonstration testing will include some but not all of the strategies listed in Figure V-1. SwRI will then perform engine dynamometer tests for the selected strategies in accordance with title 40, Code of Federal Regulations, section 1065. The tests will measure performance over the heavy-duty transient FTP, Ramped Modal Cycle (RMC), World Harmonized Transient Cycle (WHTC), extended idle, and three other low-load, low-temperature vocational cycles. The projected is expected to be completed by 2016.

Figure V-1: Options for Advanced SCR Configurations (SwRI)



VI. Cost

Almost all engine manufacturers are complying with the current 0.20 g/bhp-hr NO_X standard using the urea-SCR aftertreatment system. The incremental cost of the SCR system is estimated to add approximately $3,000 to $4,500 to the cost of the 2007 model year engine (ICCT, 2014).

It is expected that further reductions in NO_X emissions will be achieved through a combination of engine control strategies and the continued development and enhancement of new and existing aftertreatment systems, as were discussed at length in Chapters III through V. As shown in Figure VIII-1, according to Cummins, achieving a 0.1 g/bhp-hr NO_X standard is feasible (with minimal GHG penalty) with improvements to current conventional engine combustion and SCR system. Therefore, staff believes that the additional technology development cost to achieve 0.1 g/bhp-hr NO_X levels to be minimal or zero. However, it is expected that there will be costs associated with the development of technologies and strategies to reduce NO_X to lower levels of about 0.02 g/bhp-hr while at the same time also reducing GHG emissions. The Manufacturers of Emission Control Association estimates that the incremental cost of future advanced technologies needed to achieve NO_X levels of 0.02 g/bhp-hr to be approximately $500 per vehicle averaged over the medium and heavy-duty fleet (MECA, 2015). Staff expects the cost-effectiveness of these technologies to fall within the cost-effectiveness range of previous NO_X reduction requirements from new engines.

VII. Emission Levels

Currently, HDDEs are required to meet NO_X standards of 0.20 g/bhp-hr and PM standards of 0.01 g/bhp-hr on the heavy-duty transient FTP and on the RMS. Although manufacturers are certifying HDDEs to these standards, ARB in-use testing of SCR equipped HDDEs show that these engines may be emitting higher NO_X emissions during sustained real world city driving, which are conditions not covered by the heavy-duty transient FTP (Misra et al., 2013). HDDEs are also required to meet the Phase 1 GHG emission standards that will reduce GHG emissions by 5 to 9 percent by 2017, depending on vehicle weight class. In addition, ARB, U.S. EPA and the National Highway Traffic Safety Administration are currently jointly developing the Phase 2 GHG regulations that will further reduce GHGs from on-road HDDEs.

The technologies evaluated in this assessment report are expected to provide significant NO_X reductions during cold start, low load and low speed operation, and during high speed or high load operations. However, emissions data are currently not available since the current ARB-SwRI Low NO_X Program is still in the early stages of engine and aftertreatment development and no emissions test results have been reported yet.

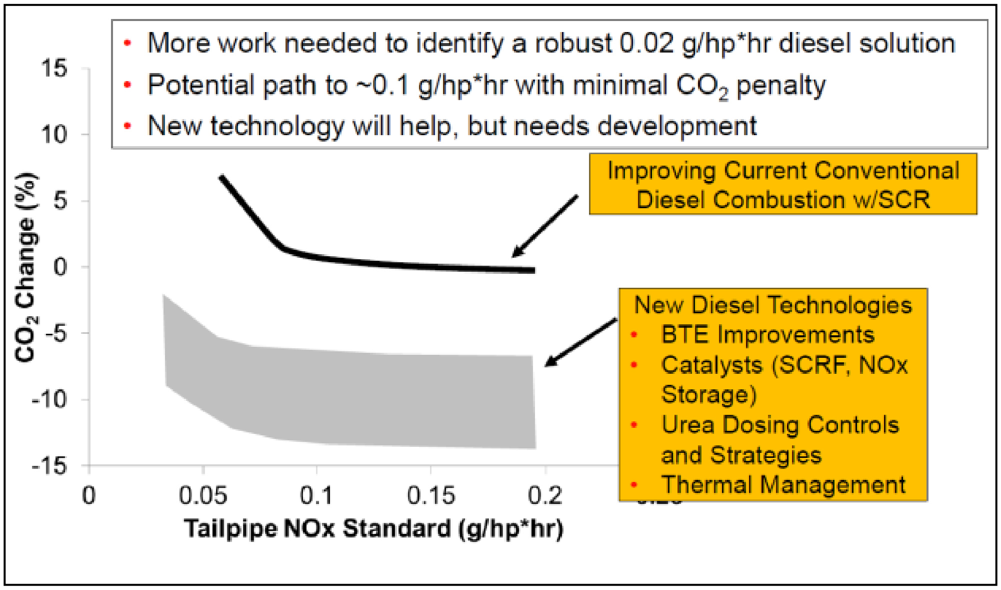
VIII. Potential for Reducing Both NO_X and GHG Emissions

As discussed in Chapter II, to comply with the pre-2010 model year NO_X standards, engines were designed to reduce in-cylinder NO_X at the expense of in-cylinder PM emissions and fuel consumption or GHG emissions (NO_X/GHG trade-off). However, continued developments in combustion systems, fuel injection systems, turbochargers, and electronic controls allowed engine manufacturers to partially mitigate the excess PM and fuel consumption. The introduction of the SCR aftertreatment systems to meet the 2010 NO_X standards further enabled engine manufacturers to optimize engine fuel economy, while minimizing both PM and NO_X emissions, thus overcoming the NO_X/GHG trade-off. The same engine optimization strategy will be used with future advanced SCR technologies, providing greater NO_X and GHG reductions, especially at high speed and high load operations.

Reducing NO_X emissions to the 0.02 g/bhp-hr levels will require significant emissions reductions during cold start and during low load, low speed operations. There are a variety of strategies which may be used to achieve these reductions. One approach is to improve exhaust gas thermal management. Close coupled SCR on DPF formulations and low thermal mass catalyst substrates can efficiently utilize existing heat in the exhaust gas, providing improved NO_X control during cold start conditions and during low speed and low load operations. In addition, start-stop technology shuts the engine off rather than idling, which allows the latent heat in the aftertreatment system to be retained, improving NO_X emission control when the engine is restarted for operation. Another approach would be to use NO_X storage catalysts during cold starts. These catalysts temporarily capture NO_X emissions at low temperatures and release NO_X at higher temperatures when they can be effectively controlled by the SCR system. Also, advanced catalyst formulations and ammonia injection techniques rather than only relying on urea injection, would provide increased NO_X control efficiencies under a wide range of engine operating conditions. All of these strategies can provide additional NO_X reductions while allowing for optimal fuel economy. Finally, strategies that use external heat source may be used to provide supplemental heat to the exhaust gas. These strategies can impact fuel economy, but the impact should be minor.

Figure VIII-1 shows an assessment of the feasibility of achieving lower NO_X emissions and the impacts on GHG emissions by Cummins Inc., one of the largest manufacturer of heavy-duty diesel engines in the U.S. (Eckerle, 2015). The solid black line in the figure represents current diesel technology. The chart shows that a 0.1 g/bhp-hr NO_X level is feasible with some improvements to the current SCR technology and the conventional diesel combustion process while still allowing for fuel economy optimization. According to Cummins, reducing NO_X further to the 0.02-0.05 g/bhp-hr levels and simultaneously reducing GHG emissions (shaded grey curve) would require more improvements in engine combustion efficiency, thermal management strategies, and advanced aftertreatment technologies such as NO_X storage catalysts, SCR coated on DPFs, and urea dosing control strategies. Most of these strategies and technologies are discussed in Chapter III of this document.

Figure VIII-1: Cummins' Assessment of GHG and NOx Reduction Opportunities with New Engine Technologies



(Eckerle, 2015)

Manufacturers normally certify their engines with a compliance margin at levels below the numerical standard to protect themselves against non-compliance due to minor increases in emissions in use. The certification levels also include deterioration factors to account for any increase in emissions over the useful life of an engine. An analysis of NO_X certification levels indicates that the compliance margins for the latest diesel engines are 10 percent to 60 percent below the 2010 NO_X certification standard, depending on engine size. Hence, based on the above assessment and the current certification levels, staff believes diesel engines are likely to be certified to the optional NO_X emission standard of 0.1 g/bhp-hr by 2016, while engines meeting 0.05 g/bhp-hr or below are likely to be certified later.

IX. Next Steps

- ARB should continue to provide incentive funding for low-NO_X heavy-duty engines to encourage engine manufacturers to develop and certify engines that meet the optional NO_X standards.

- Given California's criteria pollutant, GHG, and petroleum reduction needs, staff recommends that ARB implement statewide strategies that employ lower NO_X combustion engines coupled with the use of renewable fuels in order to attain near-term air quality and climate goals.

- In order to achieve air quality goals, ARB intends to begin development of lower mandatory NO_X standards applicable to all heavy-duty vehicles that operate in California. Since out-of-state registered heavy-duty vehicles that operate in California contribute significantly to the emissions inventory, it is also critical that ARB petition the U.S. EPA to require lower NO_X standards applicable to all heavy-duty vehicles nationally.

X. Conclusion

Even with advanced technologies (hybrid, battery, fuel cell vehicles), heavy-duty diesel internal combustion engines will continue to play a major role in the passenger and freight transportation industry of the nation. Even though HDDEs are significantly cleaner than they were in the past decade, additional reductions are needed to meet air quality and GHG goals. To this end, ARB is contracting with SwRI to demonstrate the feasibility of low-NO_X emissions without incurring a GHG penalty. Aftertreatment system manufacturers are also conducting research to develop technologies that would significantly improve the performance of the aftertreatment system to reduce emissions during cold start, light load, and high-speed steady-state operations, and the developments are showing promising signs that NO_X can be reduced significantly below current standards. To achieve maximum NO_X and GHG reductions, engine management and aftertreatment control integration is necessary. Based on ARB staff's technology assessment, staff is optimistic that with the technologies and strategies discussed in this report, manufacturers will within the next decade be able to certify heavy-duty diesel engines that can be certified to significantly lower than the current 0.20 g/bhp-hr NOx new engine standard. The strategies to be employed and the extent of further NOx reductions remain to be determined, but progress is certainly possible.

XI. References

(Alano et al., 2011) Alano, E., Jean, E., Perrot, Y., Brunel, J. et al. *Compact SCR for Passenger Cars;* SAE Technical Paper 2011-01-1318, 2011, doi:10.4271/2011-01-1318.

(ARB, 2013) Air Resources Board. *Optional Reduced Emission Standards for Heavy-Duty Engines.* Staff Report: Initial Statement of Reasons. Sacramento. October 22, 2013. <http://www.arb.ca.gov/regact/2013/hdghg2013/hdghg2013.htm> (accessed on May 5, 2015).

(Doelling et al., 2015) Doelling, W.S., Y. Zhang, S. Wang, J. Li, J. Margraf, T. Haake, C. Luecking, W. Frank, M. Mrosek, *NH3 Generator for Enhanced Low-Temperature SCR Performance; An Option also for Retrofit.* Proceedings of SAE-China Congress 2014: Selected Papers, Lecture Notes in Electrical Engineering 328, DOI 10.1007/978-3-662-45043-7_21

(Eckerlie, 2015) Eckerle, Wayne. *Engine Technologies for GHG and Low NOx* Presentation at ARB Symposium on Phase 2 GHG. Los Angeles. April 22, 2015. <http://www.arb.ca.gov/msprog/onroad/caphase2ghg/presentations/caphase2ghg_symposium_presentations.htm> (accessed on May 5, 2015).

(Emitec, 2013) EMITEC; Press Release 65th IAA Cars; September 2013. <http://www.emitec.com/fileadmin/user_upload/Presse/Presseinformationen/IAA_2013/Heated_catalyst.pdf> (accessed on September 23, 2014).

(Faurecia, 2014) SCR Bluebox. <http://www.faurecia.com/en/innovations/our-areas-innovation> (accessed on September 25, 2014).

(Fulks et al., 2009) Fulks, G., Fisher, G., Rahmoeller, K., Wu, M. et al. *A Review of Solid Materials as Alternative Ammonia Sources for Lean* NO_X *Reduction with SCR*; SAE Technical Paper 2009-01-0907, 2009, doi:10.4271/2009-01-0907.

(Henry et al., 2011) Henry, C., D. Langenderfer, A. Yezerets, M. Ruth, H. Chen, H. Hess, M. Naseri. *Passive Catalytic Approach to Low Temperature* NO_X *Emission Abatement*; Presented at the 2011 DEER Conference, Detroit, MI.

(ICCT, 2014) Blumberg, K., F. Posada, and J. Miller. *Revising Mexico's NOM 044 standards: Considerations for decision-making* International Council on Clean Transportation, Working Paper 2014-5. May 2014. <http://www.theicct.org/series/heavy-duty-vehicle-policies-for-mexico> (accessed on March 5, 2015).

(Johnson, 2014a) Johnson, T. *Review of Selective Catalytic Reduction (SCR) and Related Technologies for Mobile Applications*; In I. Nova and E. Tronconi (eds.), Urea-SCR Technology for deNOx After Treatment of Diesel Exhausts, Fundamental and Applied Catalysis, DOI: 10.1007/978-1-4899-8071-7_1,_ Springer Science+Business Media New York; 2014.

(Karamitros et al., 2014) Karamitros, D., S. Skarlis, and G. Koltsakis. *Exhaust Gas Aftertreatment Technologies and Model Based Optimization*; In: Automotive Exhaust Emissions and Energy Recovery; Editor: Apostolos Pesiridis © 2014 Nova Science Publishers, Inc.

(MECA, 2015) *MECA's Written Statement on the U.S. EPA's Proposal to Revise the NAAQS for Ozone.* Manufacturers of Emission Control Association. March 16, 2015. <http://www.meca.org/attachments/2560/MECA_EPA_ozone_NAAQS_testimony_031715.pdf> (accessed on May 21, 2015).

(Majewski, 2014) Majewski, A. *Urea Dosing and Injection Systems*; Revision 2014.08a. <www.DieselNet.com> (accessed on October 1, 2014).

(Misra et al., 2013) Misra, C., J. Collins, J. Herner, T. Sax, M. Krishnamurthy, W. Sobieralski, M. Burntizki, and D. Chernich. *In-Use NO_X Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines Equipped with Aftertreatment Devices*; Environmental Science and technology; Volume 47, pages 7892-7898.

(NADA, 2015). NADA Data. Annual Financial Profile of America's Franchised New-Car Dealerships. 2014 <https://www.nada.org/nadadata/> (accessed on September 4, 2015).

(Naseri et al., 2014) Naseri, M., Conway, R., Hess, H., Aydin, C. et al. *Development of Emission Control Systems to Enable High NO_X Conversion on Heavy Duty Diesel Engines*; SAE Technical Paper 2014-01-1525, 2014, doi:10.4271/2014-01-1525.

(Naseri et al., 2015) Naseri, M., Aydin, C., Mulla, S., Conway, R. et al., *Development of Emission Control Systems to Enable High NO_X Conversion on Heavy Duty Diesel Engines*, SAE Int. J. Engines 8(3):2015, doi:10.4271/2015-01-0992.

(Needham et al., 2012). Needham, D., P. Spadafora, and H. Schiffgens. *Delphi SCR Dosing System – An alternative approach for close-coupled SCR catalyst systems*; SIA Diesel International Conference, Rouen; June 2012. <http://delphi.com/images/news/2012/Delphi-SCR-Dosing-System-SIA Diesel-Rouen-2012.pdf> (accessed on October 15, 2014).

(Walker, 2012) Walker, A. (2012) as cited in Johnson, T.; *Vehicular Emissions in Review*; SAE Int. J. Engines 6(2):699-715, 2013, doi:10.4271/2013-01-0538.

(Wang et al., 2008) Wang, D., Yao, S., Shost, M., Yoo, J. et al. *Ammonia Sensor for Closed-Loop SCR Control*; SAE Int. J. Passeng. Cars - Electron. Electr. Syst. 1(1):323-333, 2009, doi:10.4271/2008-01-0919. <www.delphi.com/pdf/techpapers/2008-01-0919.pdf>.

(Yang & Narula, 2011) Yang, X., Narula, C. *Simple Approach to Tuning Catalytic Activity of MFI-Zeolites for Low Temperature SCR of NO_X*; poster at U.S. Department of Energy. <http://energy.gov/sites/prod/files/2014/03/f8/p-18_yang.pdf> (accessed on October 15, 2014).