CALIFORNIA AIR RESOURCES BOARD

HEAVY-DUTY LOW NOx PROGRAM WORKSHOP

JANUARY 23, 2019

LOW LOAD CYCLE DEVELOPMENT

MOBILE SOURCE CONTROL DIVISION

CALIFORNIA AIR RESOURCES BOARD

OBJECTIVE

- Current engine certification cycles (HD-FTP and RMC-SET):
  - Do not account for sustained low load operations
  - Too short to adequately test for active thermal management of aftertreatement system
- Objective is to develop a new Low Load Cycle (LLC) that:
  - Is representative of real-world urban tractor and vocational vehicle operations that are characterized by low engine loads
  - Has average power and duration adequate for demonstrating that hardware and controls needed to deal with low load challenges are present and functional
  - Has emission standard that balances the need for NOx emission reductions and any associated GHG emission impacts
- Work performed under Stage 2 of the Low NOx Demonstration program by SwRI (with support from NREL)

LOW LOAD CYCLE DEVELOPMENT STEPS

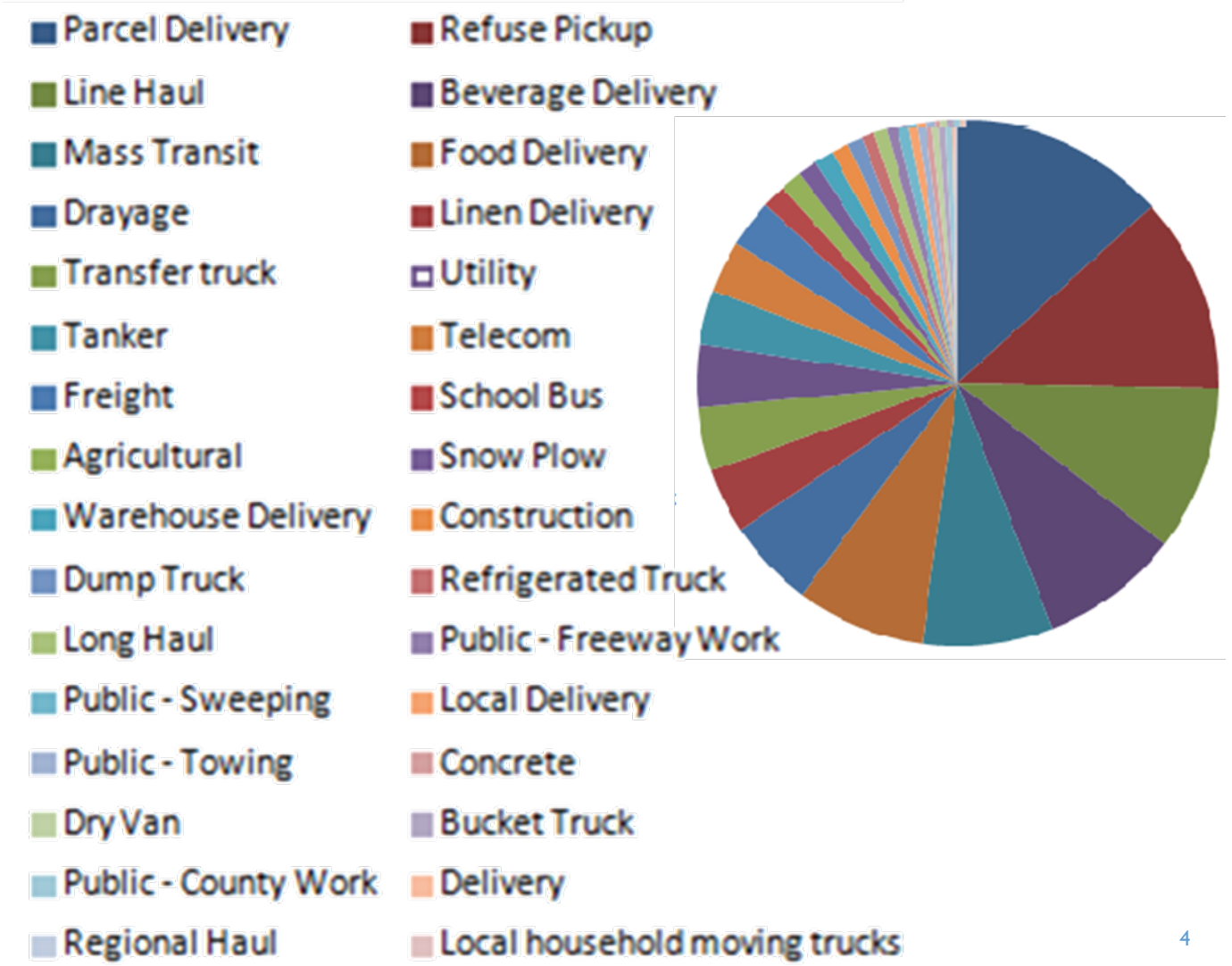
1. Development of Low Load Vehicle Profiles (NREL) ✔
2. Translation of Vehicle-Based Profiles to Engine-Based Ones (SwRI) ✔
3. Testing of Low Load Engine Profiles (SwRI) ✔
4. Development of Candidate Low Load Cycles (NREL / SwRI) ✔
5. Testing of Candidate Low Load Cycles (SwRI) ✔
6. Selection of Final Low Load Cycle (CARB / SwRI) – In Progress

ANALYSIS OF VEHICLE ACTIVITY DATA

Source Datasets

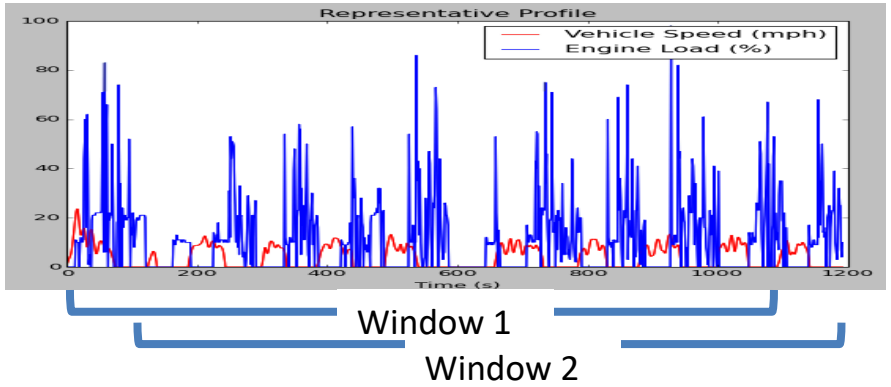
Fleet DNA + CARB HDDV Activity Data

- 751 vehicles
- 25 Locations across the US (predominantly in CA)
- 55 Fleets
- 44 Vocational Designations
- ~600+ GB of raw data

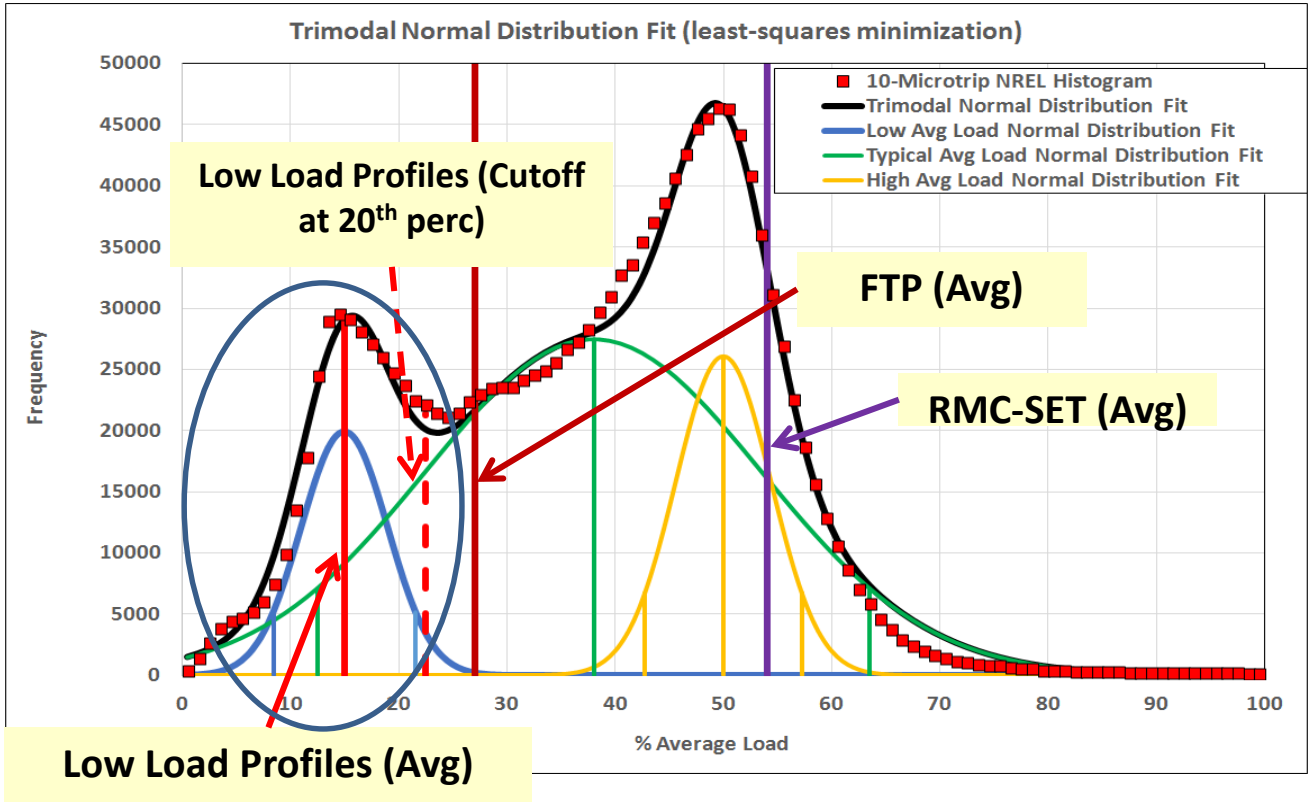


DEVELOPMENT OF LOW LOAD VEHICLE PROFILES

- Data analyzed using moving windows of 10 microtrips

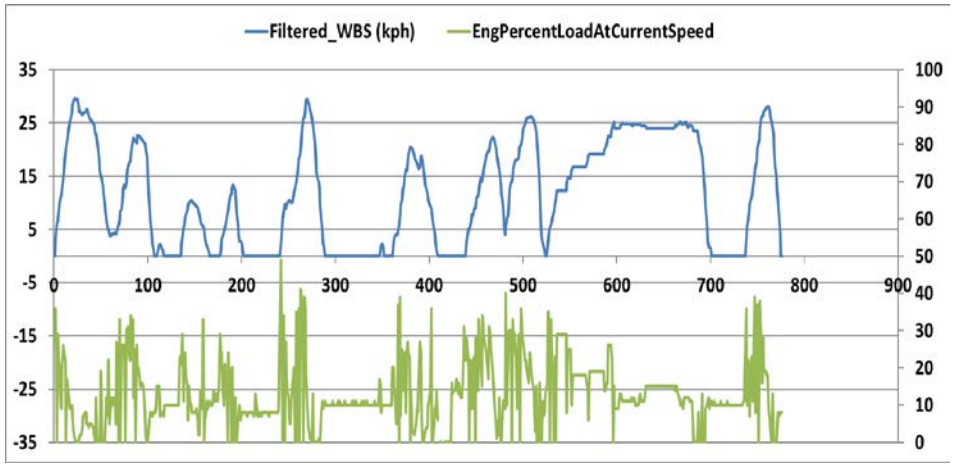


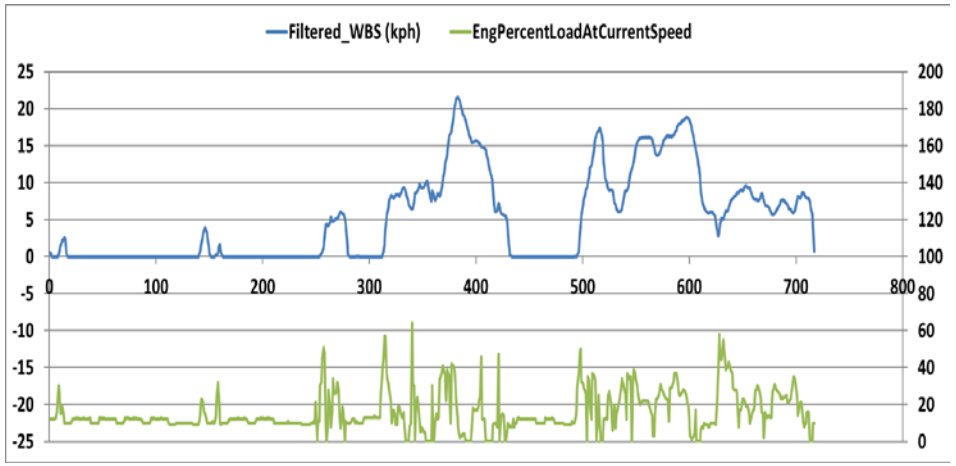
- ~1.25 million windows (profiles) obtained
- Only profiles with average loads below 20% were further considered for constructing the LLC



CLUSTERING AND SELECTION OF REPRESENTATIVE PROFILES

- K-means clustering applied to the population of profiles to identify groups with similar characteristics
  - A total of 3 clusters were identified
- To identify most representative profiles, results for each cluster were ranked based on their distance to cluster center
- Starting with profiles closest to cluster center, profiles examined for behavior and final suitability for testing
- Profiles with outlying behavior removed from list





BASIC EMISSION CONTROL CHALLENGES

- An effective Low Load Cycle will test all three of the following challenges:
  - High Load-to-Low Load Transition
    - Drive to work-site then lower load work or idle period
    - How long can system maintain performance and manage heat during prolonged cool-off?
  - Sustained Low Load
    - Repeated short transients separated by idle (delivery, refuse, transit bus, drayage)
    - Can system maintain heat levels long-term?
  - Low Load-to-High Load Transition
    - Long downhill grade transition to uphill (Tractor)
    - Long idle transition to highway work
    - Can system handle abrupt increases in engine-out emissions?

SUMMARY OF REPRESENTATIVE PROFILES

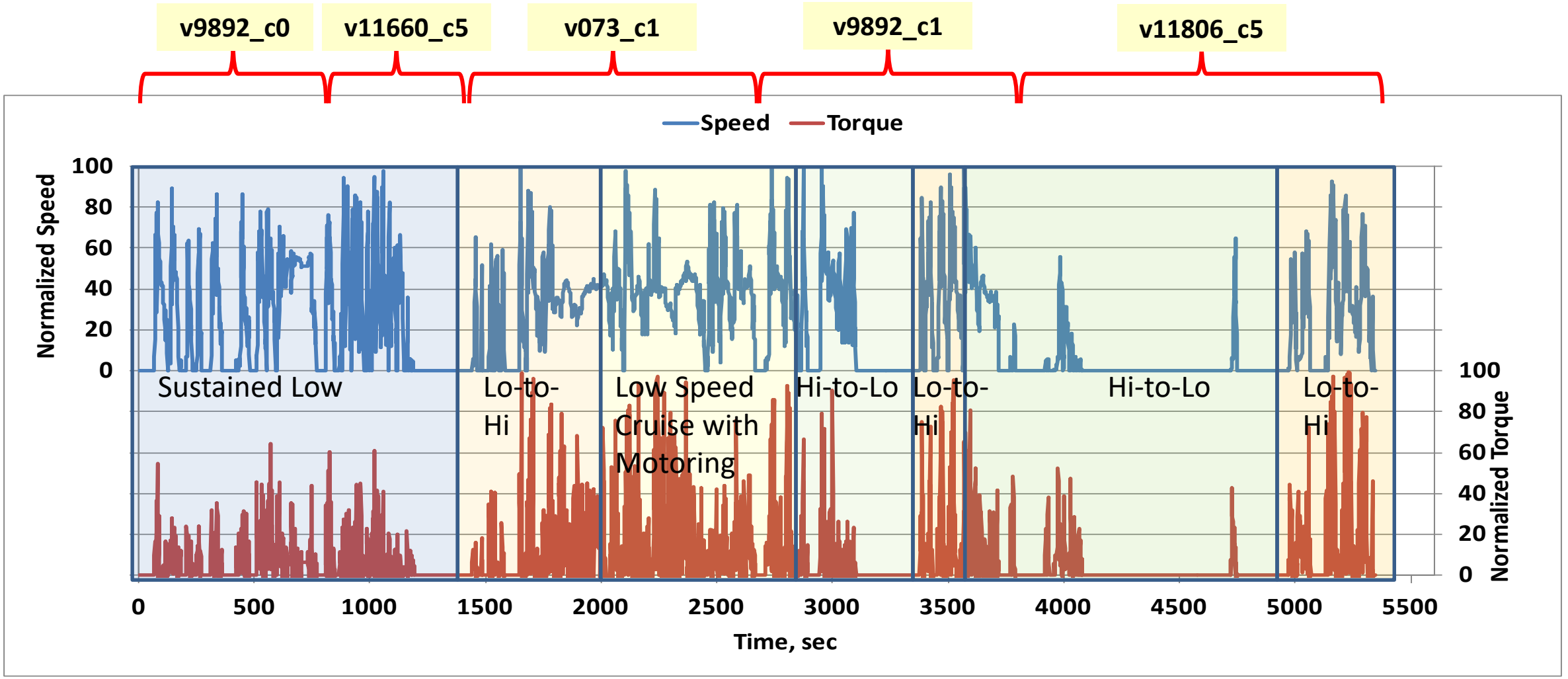
Profile	Vehicle	Cluster	Length	Avg % Speed	Avg % Torque	Repeats in SwRI Test Runs	Class	Chassis	Engine	Trans	Gears	Vocation
1	v9892	0	800	26.9	6.9	4	8	4x2	Volvo D13	AMT	12	Food Service
2	v11660	0	1295	21.4	6.6	3	8	6x4	Mack MP8-415C	MT	13	Drayage
3	v075	0	1130	26.3	7.4	3	8	6x4	Mack MP8-415C	AMT	10	Drayage
4	v11815	1	1949	11.5	8.8	3	8	6x4	Cummins ISX 15	MT	13	Transfer Truck
5	v11646	1	904	15.9	10.7	4	4	4x2	Cummins ISB 6.7	AT	6	Parcel Delivery
6	v073	1	1410	33.8	18.1	3	8	6x4	Mack MP8-415C	AMT	10	Drayage
7	v9892	1	1616	27.0	10.6	3	8	4x2	Volvo D13	AMT	12	Food Service
8	v11660	5	615	16.2	3.5	4	8	6x4	Mack MP8-415C	MT	13	Drayage
9	v11806	5	1810	7.5	6.8	3	8	6x4	Cummins ISX 12	AMT	10	Transfer Truck
10	v11817	5	739	15.3	7.7	4	8	6x4	Cummins ISM 11	AMT	10	Transfer Truck

- Load data broadcast by engines not sufficiently accurate for use directly to create engine cycle, so used Phase 2 Greenhouse Gas Emissions Model (GEM) simulation model to translate vehicle-based profiles to engine-based ones

INITIAL CANDIDATE CYCLES

- Five primary types of events were observed in the low load profiles:
  - Sustained low load
  - Long idle
  - Motoring/short idle cooling
  - Post-cooling breakthrough (high load segments)
  - Mid-speed cruise-motoring
- Initial candidate cycles were constructed to include one example of each of the 5 types of events
- Did not always use the entire profile if the key segment could be completed in a shorter time

EXAMPLE CANDIDATE CYCLE



OTHER CONSIDERATIONS

- Preconditioning procedure to bring engine to temperature and warm aftertreatment
  - 1 FTP + 20 min soak
- Longer duration for long idle segment?
  - Not productive, no change in results
- Longer or shorter sustained low load segment?
  - Pro: countermeasure for higher thermal inertia systems
  - Con: longer cycle time
- Longer or shorter mid-speed cruise/motoring segment?
  - Pro: bridges space from rest of LLC to FTP in terms of power, covers upper corner of low load space
  - Con: inclusion does raise overall temperatures, but minor effect, also longer cycle time

FINAL CANDIDATE CYCLES

- LLC Candidate #7 – 90 min
  - 30 min sustained low load segment
  - Retains v073 mid-speed cruise/motoring segment
- LLC Candidate #8 – 81 min
  - 30 min sustained low load segment
  - Shorter v073 mid-speed cruise segment for breakthrough only
- LLC Candidate #10 – 70 min
  - 20 min sustained low load segment
  - Shorter v073 mid-speed cruise segment for breakthrough only

Currently favored by CARB Staff

LLC Candidates – Test Results on Engine E

Candidate	Duration [min]	Conversion efficiency [%]	Engine Out NOx [g/bhp-hr]	Engine Out NOx [g NOx/kg CO2]	Tailpipe NOx [g/bhp-hr]	Tailpipe NOx [g NOx/kg CO2]
#7	90	74	3.2	4.4	0.8	1.1
#8	81	77	2.9	4.1	0.7	0.9
#10	70	69	3.2	4.3	1.0	1.3

PLANNED LLC REQUIREMENTS

- LLC standard will be based on:
  - SwRI Stages 2 and 3 calibration test results
  - Potential GHG emission impacts
  - Could be a standalone standard or combined with other test requirements
    - e.g., incorporate idle test within the LLC test (to reduce testing burden)
- Conformity factor for LLC and in-use testing requirements:
  - May be same or different, depending on SwRI LLC optimization results
- May include a CO_2 emissions cap
- Preliminary proposal on LLC standard /CO_2 cap: March 2019 workgroup Meeting

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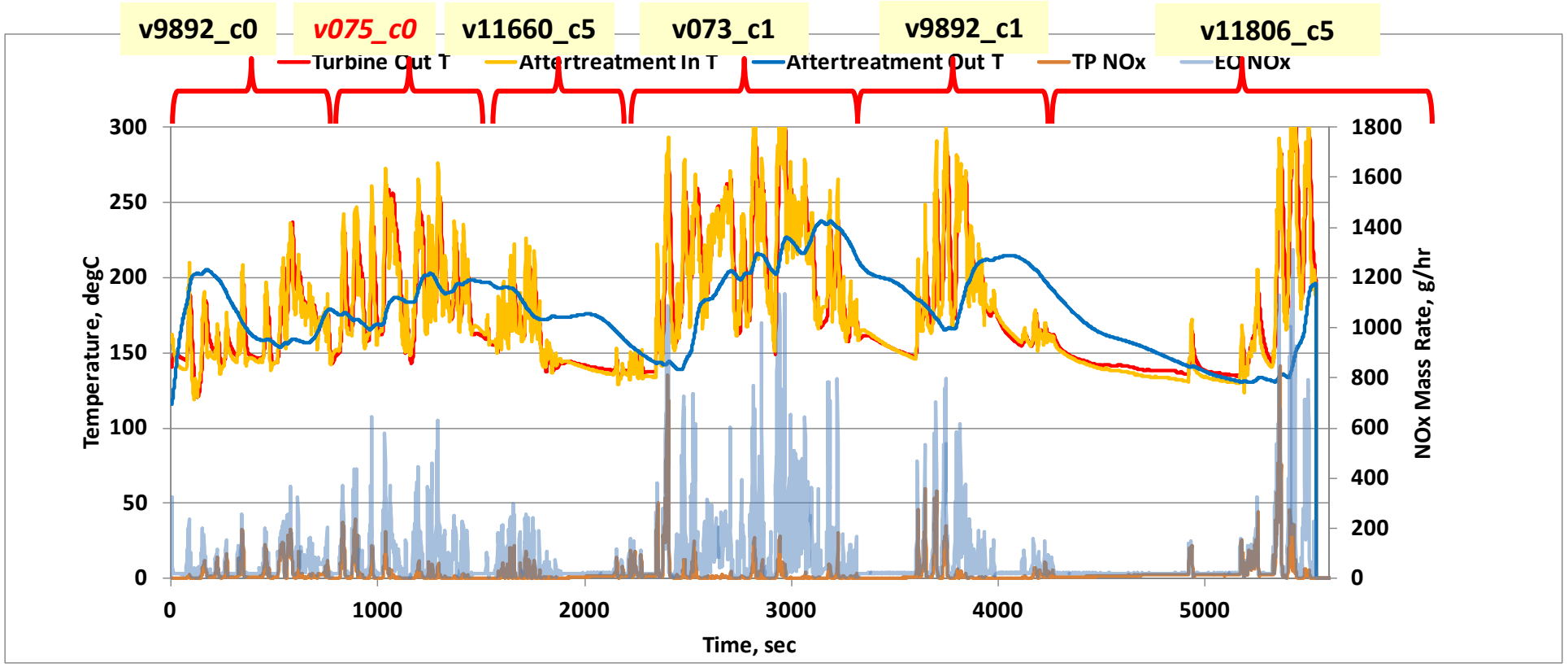
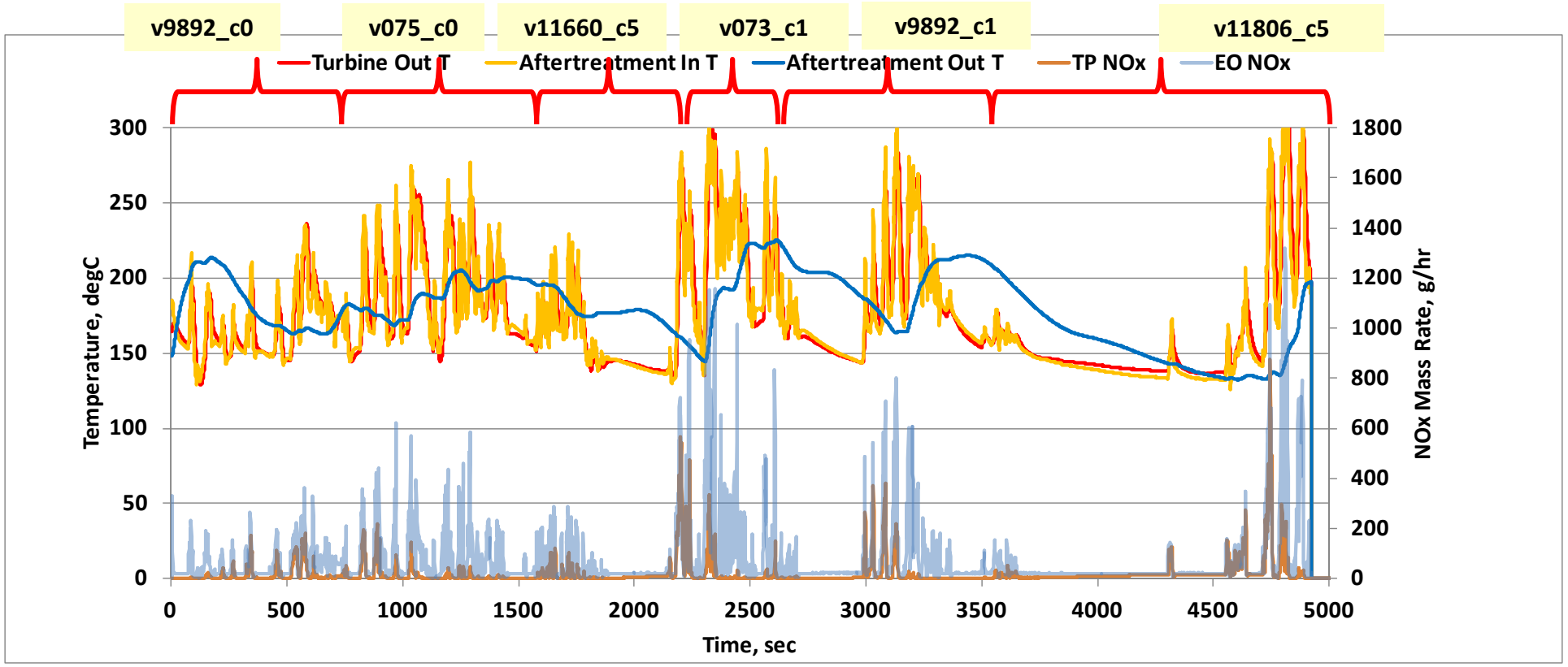
Backup Slides

LLC Candidate 7 – Test Results on Engine E



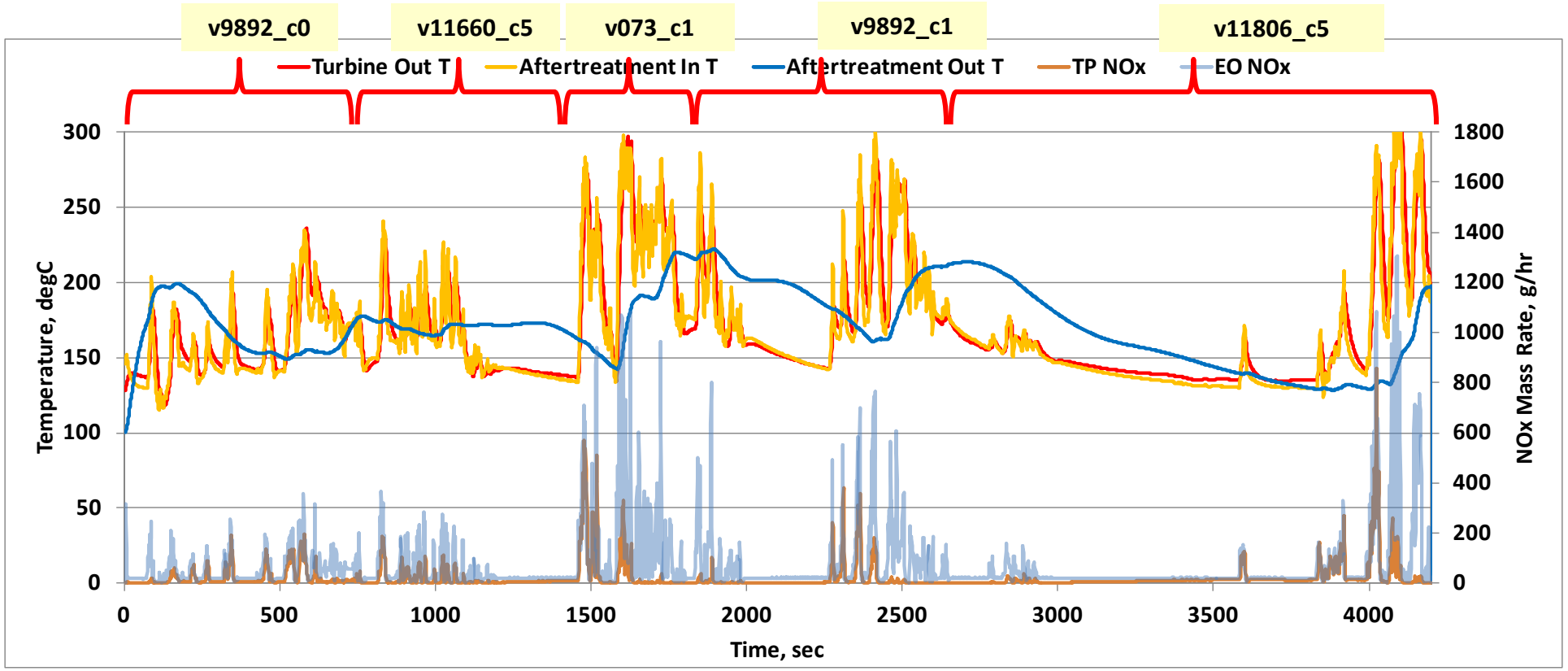
- Overall 74% conversion
- EO NOx (g/hp-hr / g/kgCO2) = 3.2 / 4.4
- TP NOx (g/hp-hr / g/kgCO2 = 0.8 / 1.1

LLC Candidate 8 – Test Results on Engine E



- Overall 77% conversion
- EO NOx (g/hp-hr / g/kgCO2) = 2.9 / 4.1
- TP NOx (g/hp-hr / g/kgCO2 = 0.7 / 0.9

LLC Candidate 10



- Overall 69% conversion
- EO NOx (g/hp-hr / g/kgCO2) = 3.2 / 4.3
- TP NOx (g/hp-hr / g/kgCO2 = 1.0 / 1.3