IN-USE EMISSONS MEASUREMENT AND DATA POST-PROCESSING

Daniel K. Carder, Arvind Thiruvengadam, Marc C. Besch, Hemanth Kappanna, Zac Luzader, Mridul Gautam

Center for Alternative Fuels, Engines and Emissions

Department of Mechanical and Aerospace Engineering

West Virginia University

Content

- Off-Cycle Light-Duty Diesel Vehicle Emissions Measurement with PEMS
- In-Use Data Post Processing
- Remote PEMS Control and Data Acquisition

Light-Duty In-Use Testing

- Quantifying off-cycle NOx emissions from diesel engine powered LDV's that are certified to Tier 2 Bin 5 or LEV-II (CA) during typical driving conditions pertinent to major US population centers
- Quantifying particulate matter mass (PM) and/or particle number (PN) concentrations
  - comparison of off-cycle NOx emissions with Tier 2 Bin 5/LEV-II emissions standards
  - evaluation of fuel economy in comparison to standardized chassis dynamometer test cycles
  - evaluation of NOx after-treatment conversion efficiency as a function of driving conditions, traffic density, ambient conditions and exhaust gas thermodynamic properties
  - calculation of in-use emissions factors based on the "Averaging Windows Method" (either work or distance based window thresholds)
  - quantification of particle number concentrations with regard to the particle number limit as will be introduced by the Euro 5b/b+ legislation starting in 2013
  - evaluation of Diesel particle filter (DPF) filtration efficiency and frequency of regeneration events
  - quantification of maximum route emissions to identify emissions hotspots

Methodology - Test Vehicle Specifications

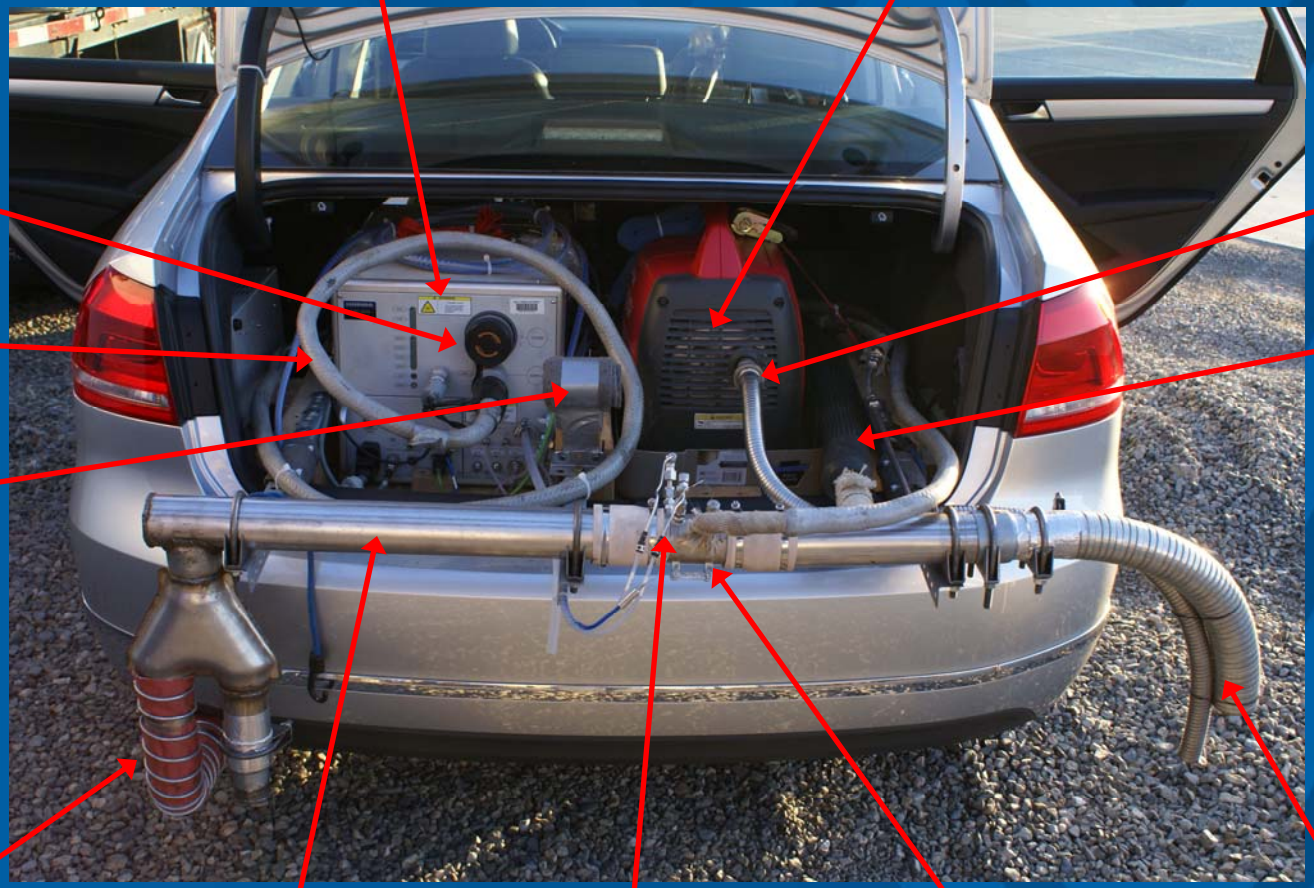
- Three Diesel fueled vehicles of European make
- All vehicles are equipped with Diesel particle filters (DPF)
- Two different NOx control technologies
  - Liquid urea based selective catalytic reduction (SCR) system => two test vehicles
  - Lean NOx trap (LNT) => one test vehicle

Vehicle	Model year	Mileage at test start [miles]	Fuel	Engine capacity [ccm]	Engine Type	Max. Engine Power [hp]	Emissions after-treatment technology	Applicable emissions limit	
								U.S. EPA	CA
A	2012	4710	Diesel	2000	In-line, 4 cycl.	140	OC, DPF, LNT	T2B5 (LDV)	ULEV II (PC)
B	2012	15226	Diesel	2000	In-line, 4 cycl	140	OC, DPF, urea-SCR	T2B5 (LDV)	ULEV II (PC)
C[1)]	2012		Diesel	3000	V-6	210	OC, DPF, urea-SCR		

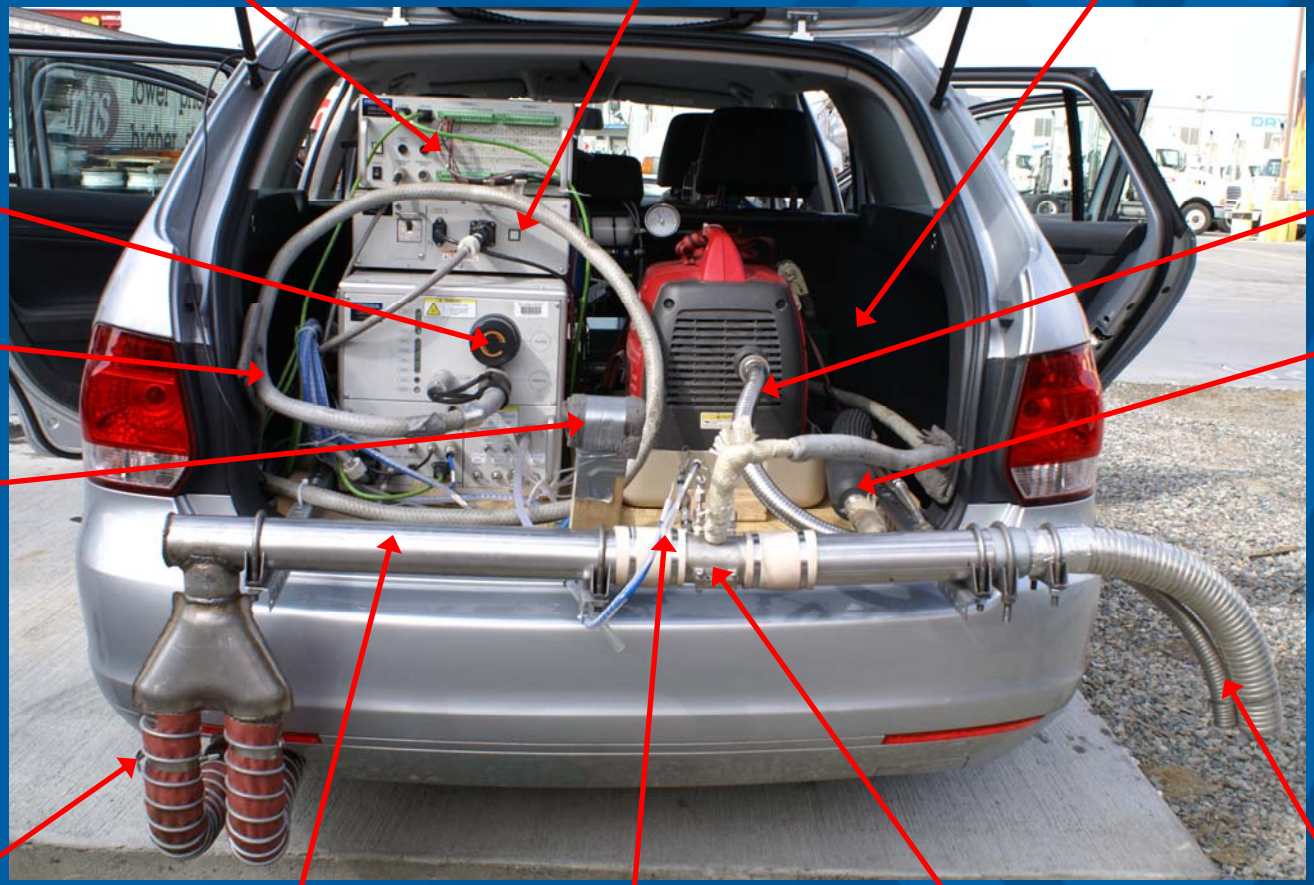
Methodology - Measurement Instruments

- Gaseous emissions
  - Horiba OBS-2200 for NOx (CLD), THC (FID), CO and CO2 (heated NDIR)
  - All constituents sampled on wet basis
- Particulate matter (PM) emissions
  - Pegasor Particle Sensor (PPS) for real-time particle number/mass concentrations
  - Horiba PBS-TRPM for gravimetric PM
- Exhaust flow via Pitot tube type flow meter
- GPS
- ECU interrogation for engine/aftertreatment parameters
- High precision barometric pressure for altitude calculation

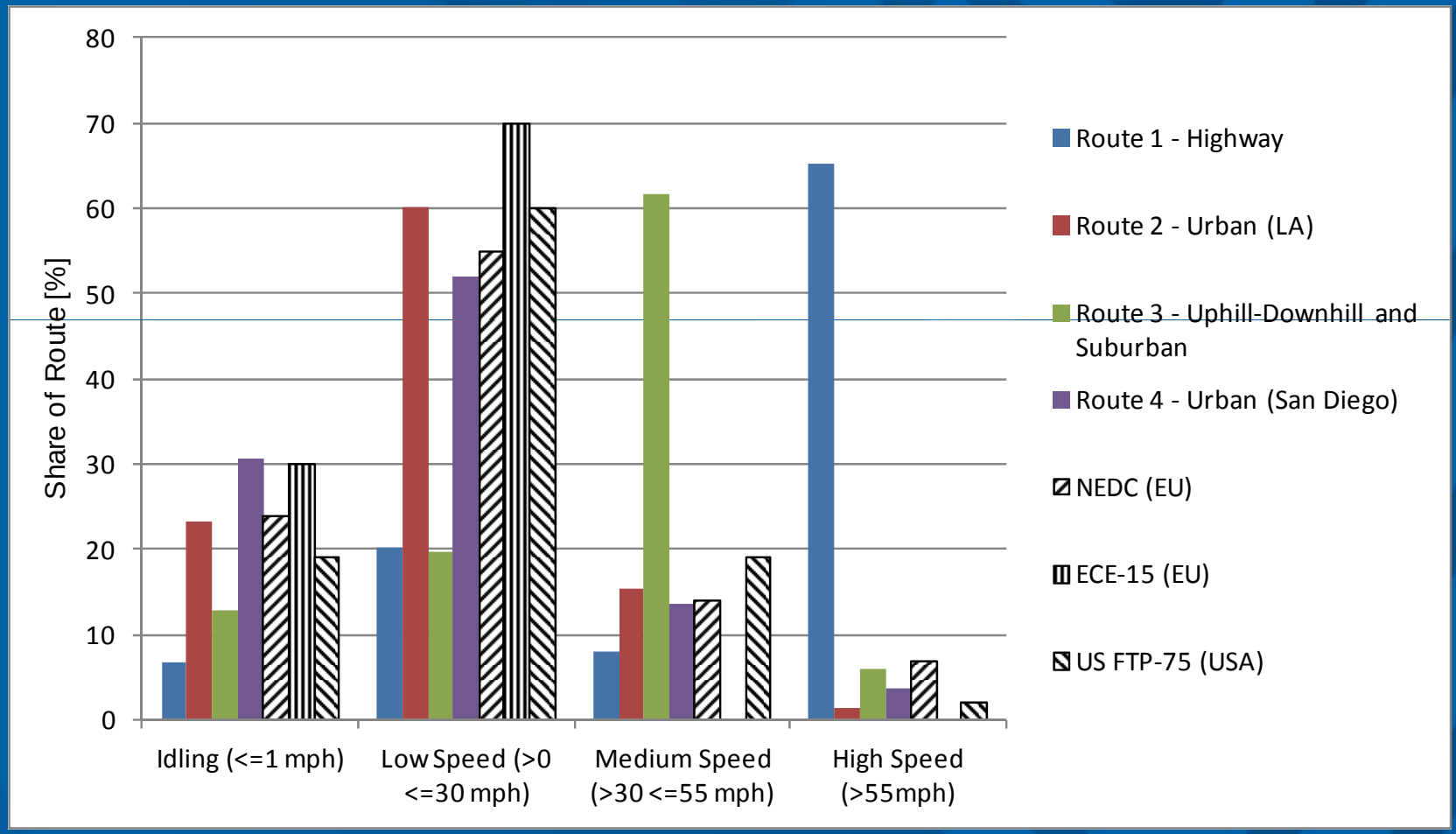
Methodology - Test vehicle with single exhaust tip



Methodology - Test vehicle with double exhaust tip



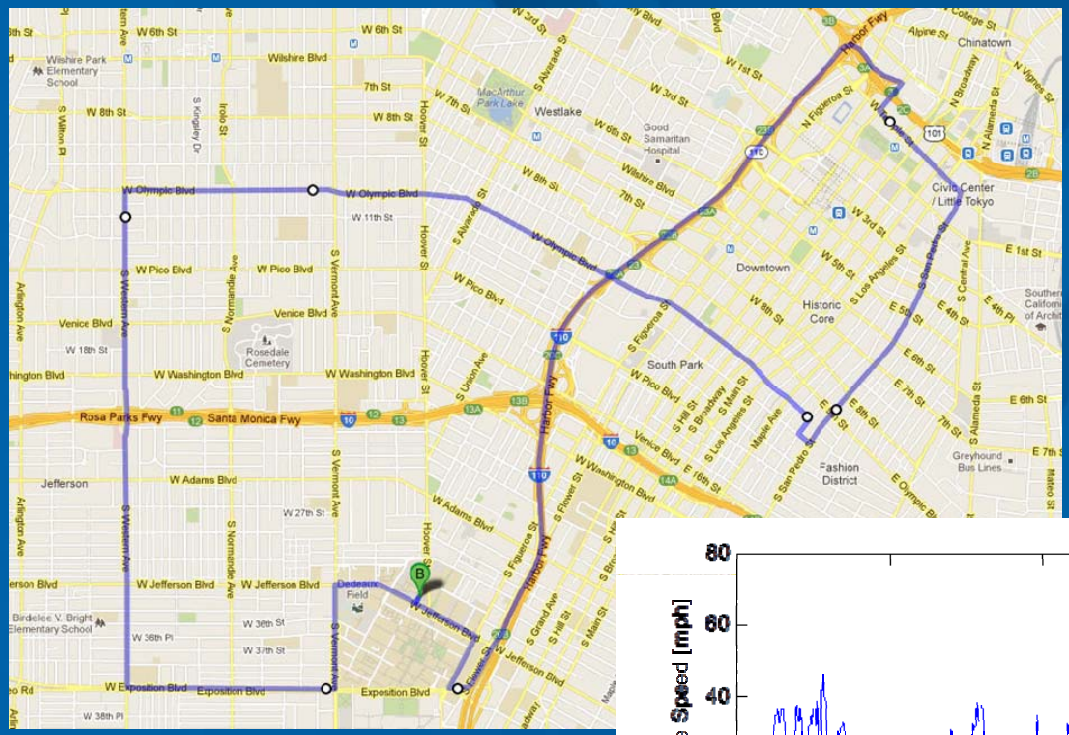
Methodology - Test Routes



Methodology - Test Routes

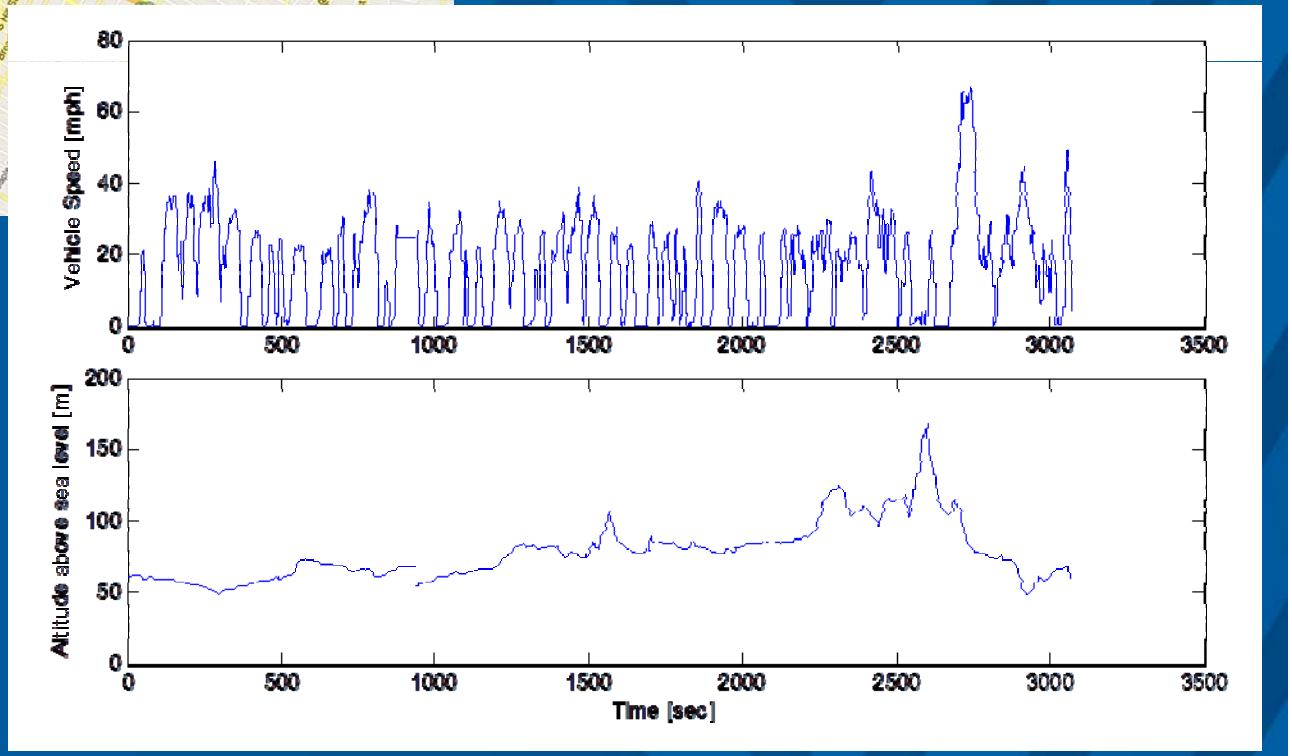
- Test routes cover a wide variety of
  - topography
  - road and ambient conditions
  - traffic densities in major urban areas along the West coast
- Urban driving routes in LA and San Diego,
- Highway driving in LA under free-flowing and congested traffic
- Up/downhill driving in the foothills of San Bernardino County
- Driving extended distance of ~2500 miles from LA to Seattle using one SCR vehicle

Parameter	Route 1 Highway	Route 2 Urban (LA)	Route 3 - Up/Downhill and Suburban	Route 4 Urban (San Diego)
Route duration [sec]	2948.6	3066.7	3917.6	2984.9
Route distance [miles]	42.59	14.42	36.65	13.21
Average vehicle speed [mph]	51.99	16.92	33.68	15.94
Maximum vehicle speed [mph]	87.74	67.55	73.85	72.03
Maximum vehicle acceleration [m/s^2]	1.98	3.01	2.44	2.99
Share [%]				
- Idling (<=1 mph)	6.62	23.17	12.91	30.64
- Low Speed (>0 <=30 mph)	20.22	60.09	19.58	52.09
- Medium Speed (>30 <=55 mph)	8.04	15.29	61.58	13.51
- High Speed (>55mph)	65.12	1.45	5.93	3.75



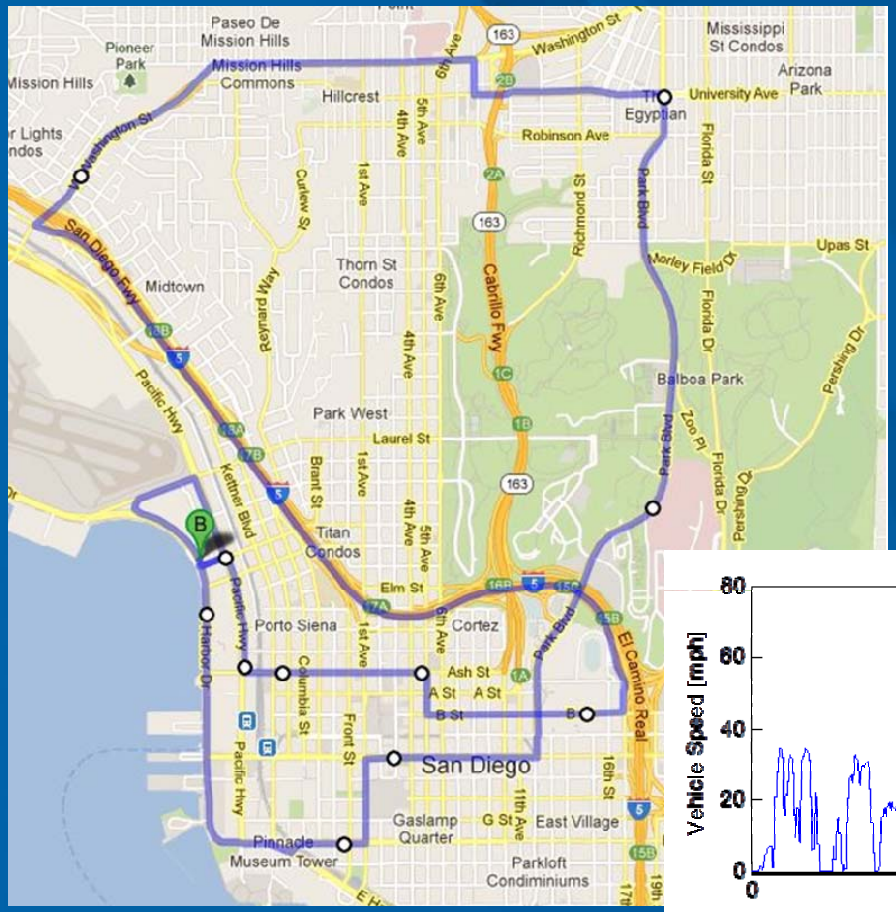
Route 2

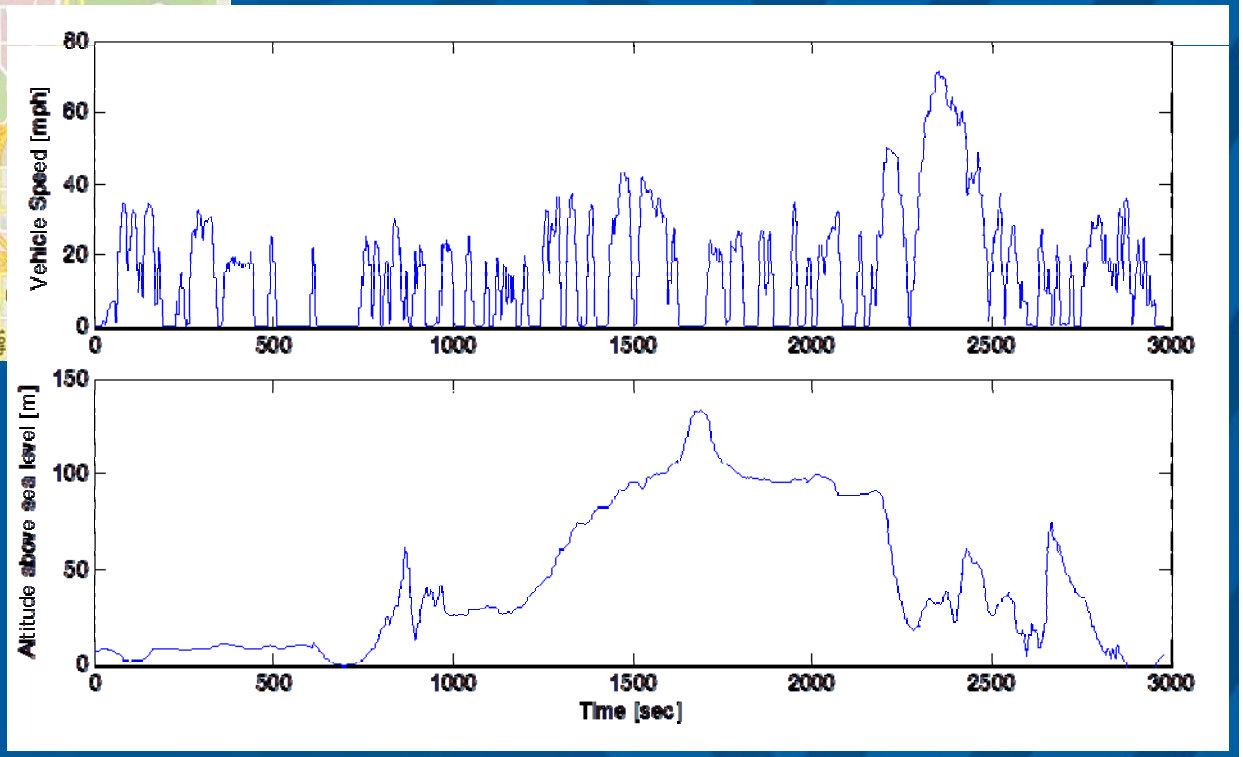
Los Angeles Urban Driving
=> original LA-4 cycle



Route 4

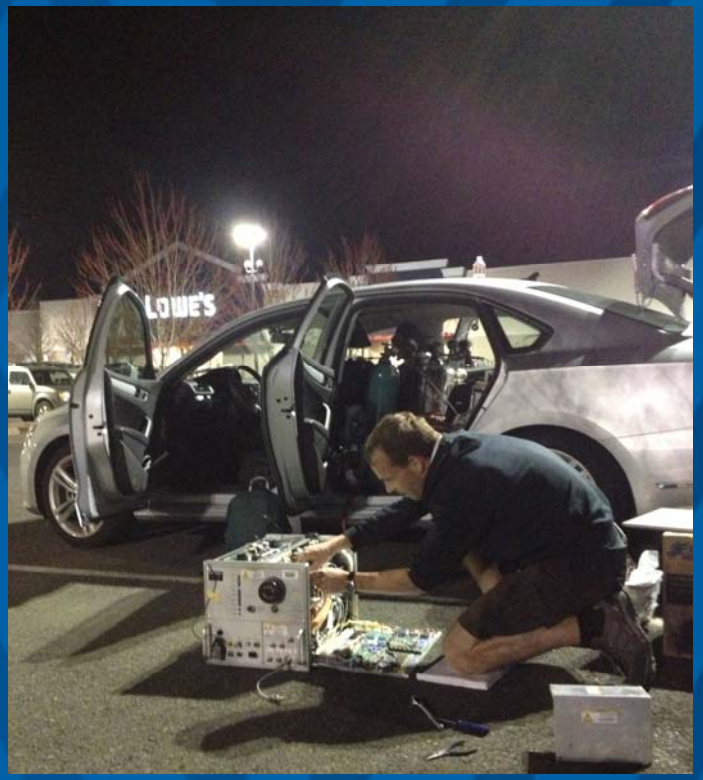
San Diego Urban Driving





HDIUT – What are the Challenges?

- Integration of a Number of Systems
  - Exhaust Flow Rate
  - Gaseous and Particulate Matter Concentrations
  - Engine Load/SAE J1939 Parameter Broadcast
  - Ambient Conditions
  - Ancillary Data for Redundancy and Exclusion Justification
- Achieve Trouble-Free PEMS Operation for an 8-hr Period
- Field Evaluation of PEMS Data Validity
- Formal Results QC/QA & Reporting



HDIUT North America– What is Really Involved?

- Defining Not-to-exceed (NTE) zone of the engine being tested using advertized engine map.
- Determine NTE emissions threshold values which is a function of its respective certification standards along with accuracy and compliance margins.
- Identify NTE events from the collected in-use data. Integrate the emissions and engine work for a given NTE event. An NTE event is defined as continuous operation of an engine in an NTE zone for a period of 30s or more.
- Apply allowable exclusions to discount an NTE event or a data point in the NTE zone.

NTE Zone Boundaries

- Torque Upper Bound: is the Maximum Torque at the Given Engine Speed (Advertized Engine Map)
- Torque Lower Bound: 30% of Maximum Torque (constant)
- Speed Lower Bound (n_{15}): 15% ESC Speed

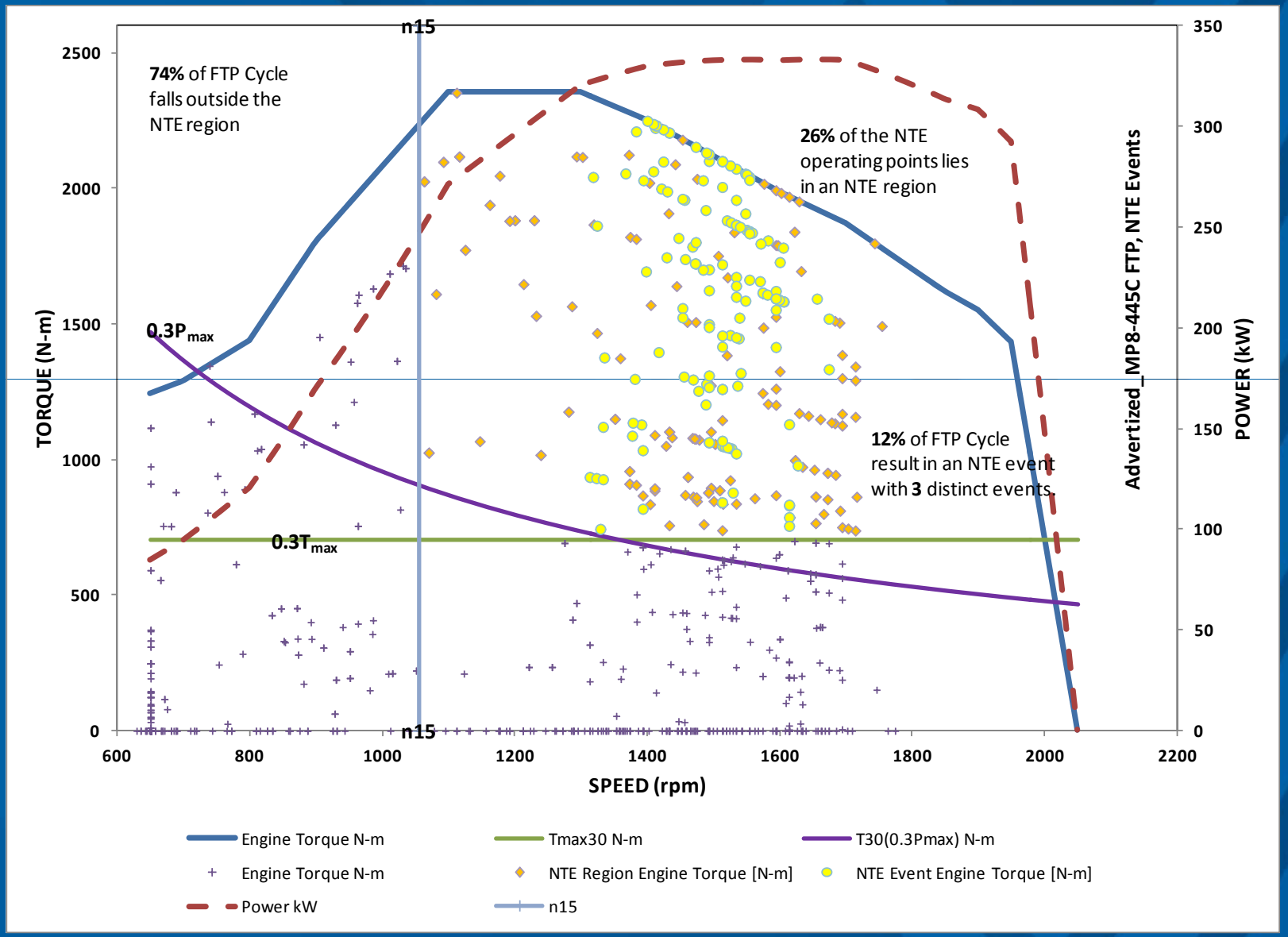
$$n_{15} = n_{lo} + 0.15 \times (n_{hi} - n_{lo})$$

  - n_{hi} – highest engine speed at which 70% of max power is still achievable
  - n_{lo} - lowest engine speed at which 50% of max power is still achievable
- Power Lower Bound = 30% of Maximum Power (constant)

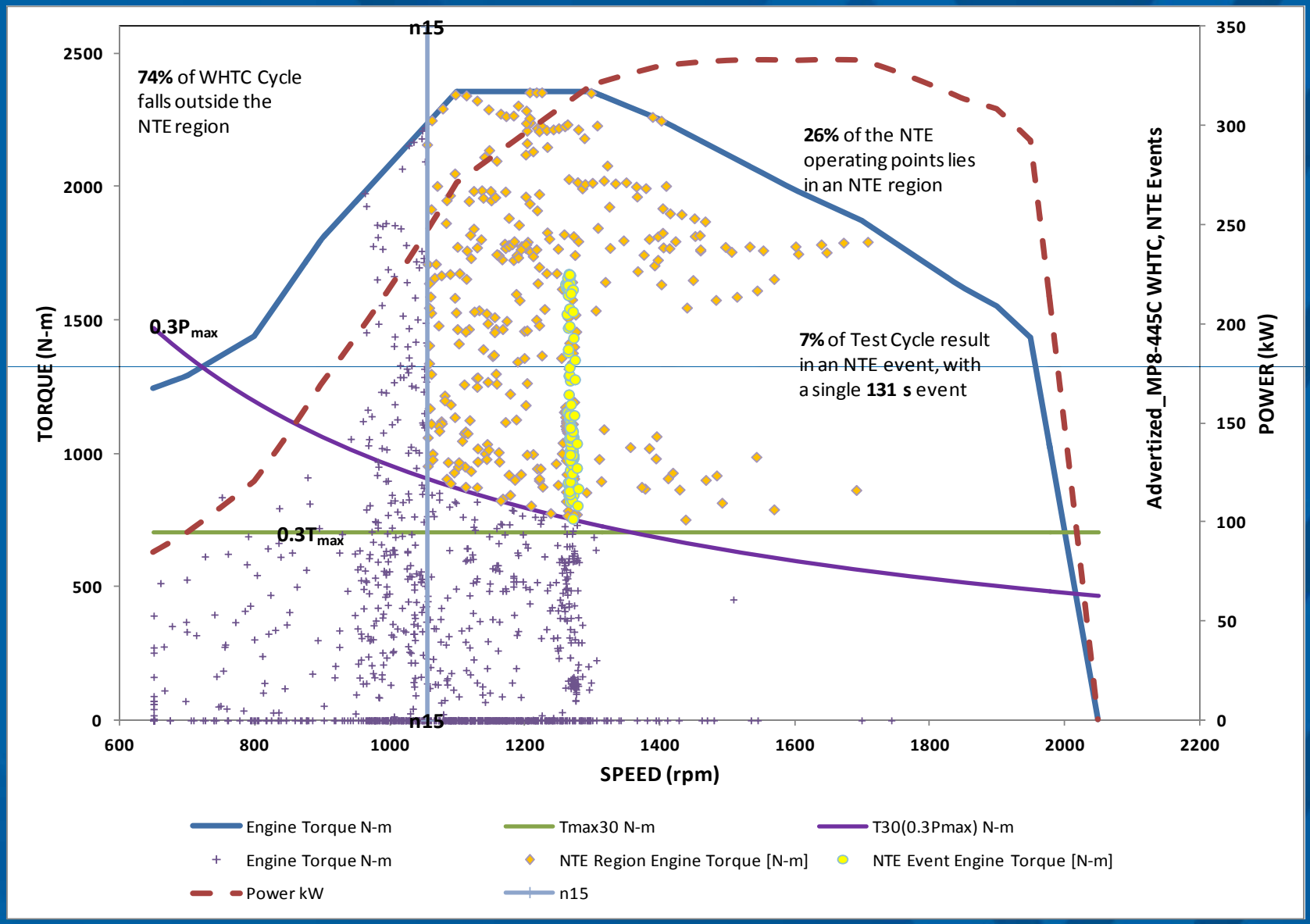
HDIUT Euro – What is Really Involved?

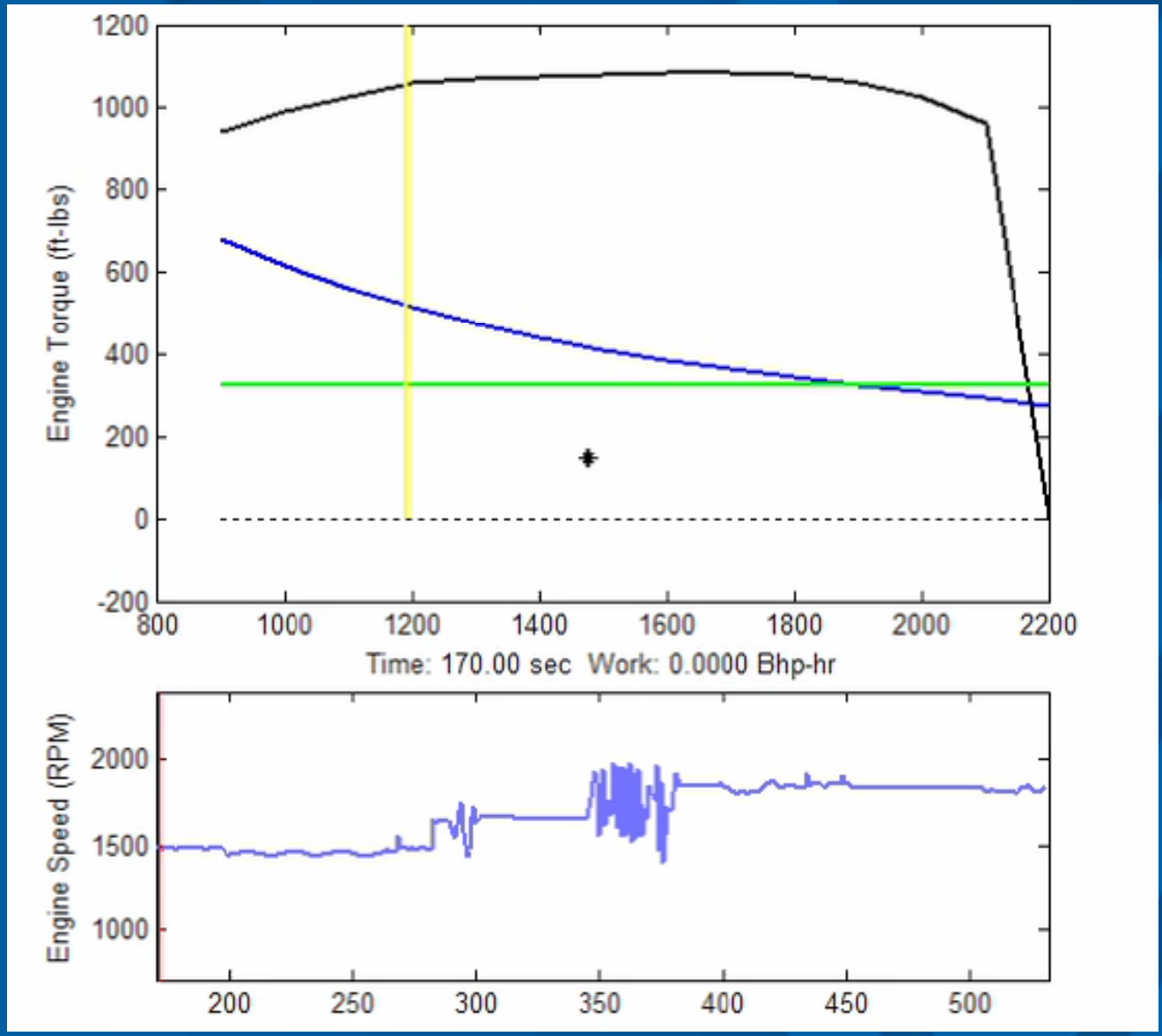
- European Work-Window
  - Work produced over each sampling period (Δt) is integrated until the total work is ≥ W_{ref}, reference cycle work while calculating brake specific emissions for each window
  - The above step is repeated on moving averaging basis, resulting in a large number of overlapping windows.
- Conditions
  - Error in measurement equipment, intake manifold and engine coolant temperature exclusions apply
  - The average power in a work window shall be ≥ $0.2P_{max}$ to be a valid work window
  - Total number valid work windows ≥ 50% for in-use test to be valid
  - Threshold of avg. power of a work window is decreased in steps of 1% till the threshold reaches 15% in order to increase percentage of valid work windows.

NTE Points & Events under FTP Cycle



NTE Points & Events under WHTC Cycle




Engine Torque (ft-lbs)
1200
1000
800
600
400
200
0
-200
800
1000
1200
1400
1600
1800
2000
2200
Time: 170.00 sec Work: 0.0000 Bhp-hr
Engine Speed (RPM)
2000
1500
1000
200
250
300
350
400
450
500

NTE Data Exclusions

- Operating points must be within the NTE boundaries and must simultaneously satisfy data exclusions for a minimum of 30 continuous seconds:
  - Ambient Conditions
  - Altitude ≤ 5,500 feet (1,700 m)
  - Ambient temperature ≤ 86°F (sea-level) - 100 °F (5,500 feet)
- Brake specific fuel consumption (BSFC) must be less than or equal to 105% of the minimum BSFC if an engine is not coupled to a multi-speed manual or automatic transmission.
- NOx Corrections for Temperature and Humidity
- Engine operation must be outside of any manufacturer petitioned exclusion zone.
- Cold Temperature Operation (EGR-equipped engines)
  - IMT ≥ (1/0.0875)(IMP_Abs + 7.75) [°F], based on intake manifold pressure
  - ECT ≥ (1/0.0778)(IMP_Abs + 9.889) [°F], based on intake manifold pressure.
- Exhaust Aftertreatment T_{exh} ≥ 250°C within 12 inches of Outlet (§86.1370-2007(g))
- Engine Time-Weighted Carve-Out – Limited Testing Region (LTR)
  - Exclude points in any NTE event if duration exceeds 5% of total NTE event duration. (§86.1912(b) & §86.1370-2007 (b)(6)).

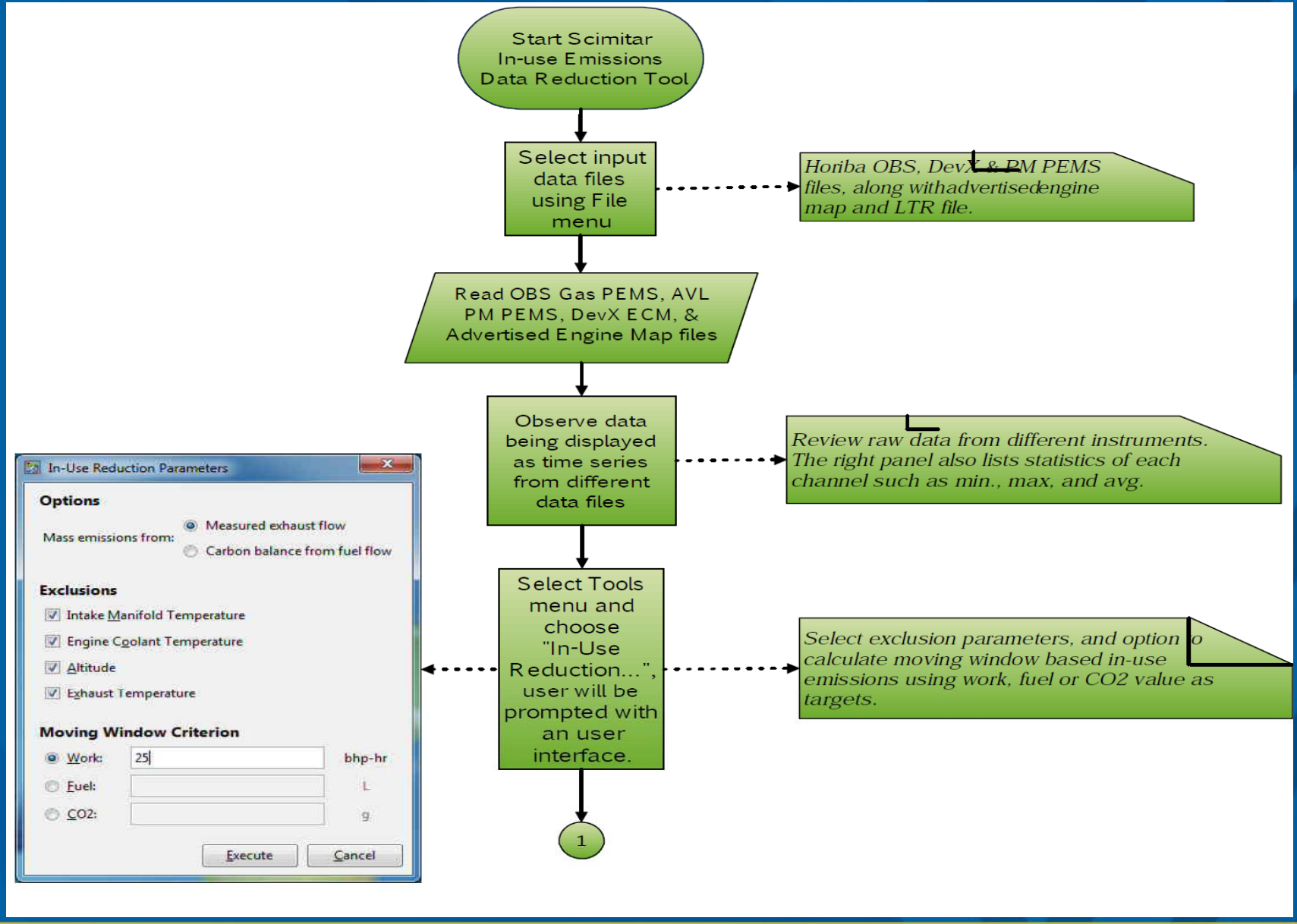
Vehicle Pass Criteria

- Vehicle Pass Ratio

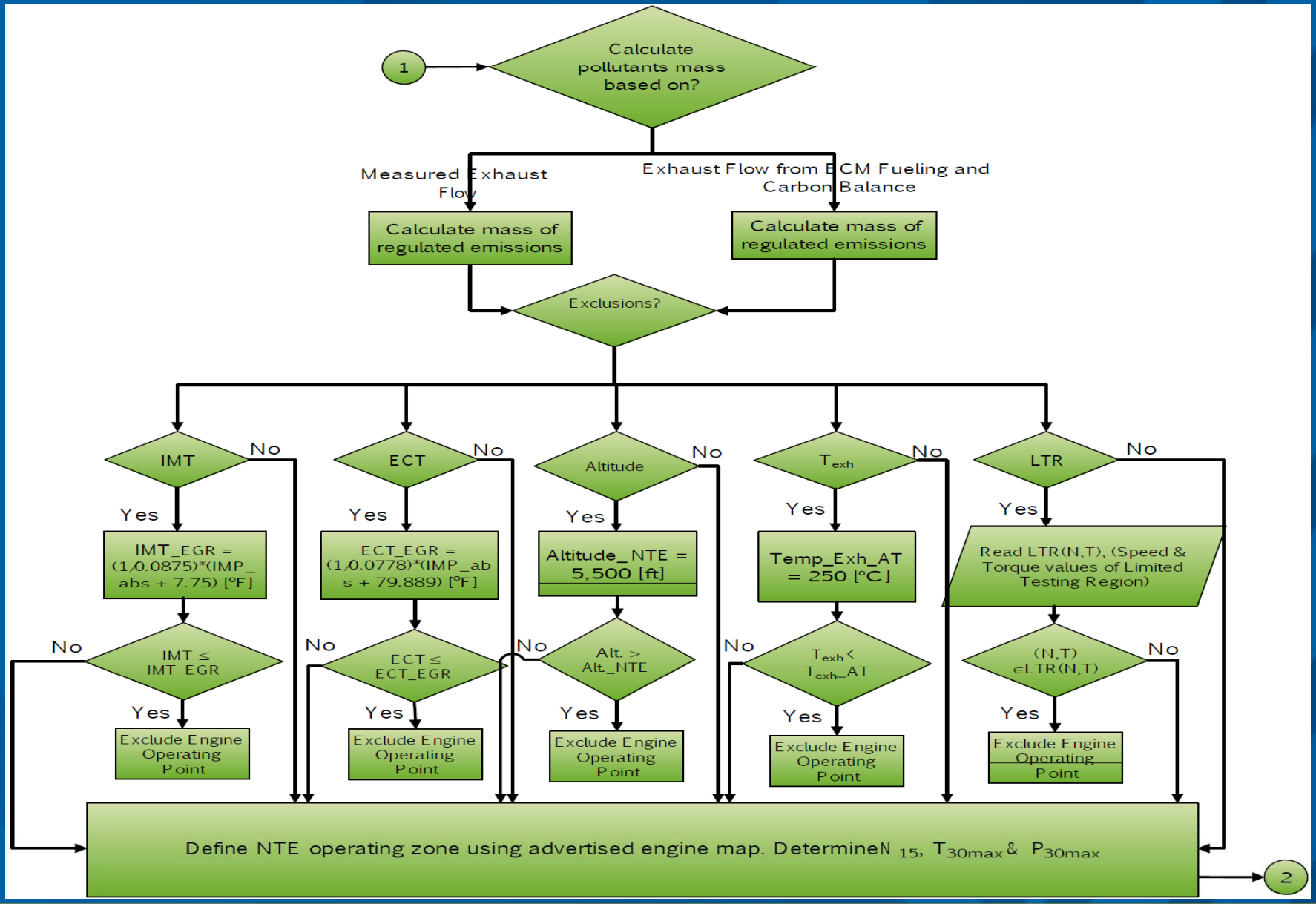
$$(VPR) = \Sigma t_{ntepass} / \Sigma t_{nte}$$

- Criteria Established for HD On-highway, but Non-Road ruling is yet to be finalized

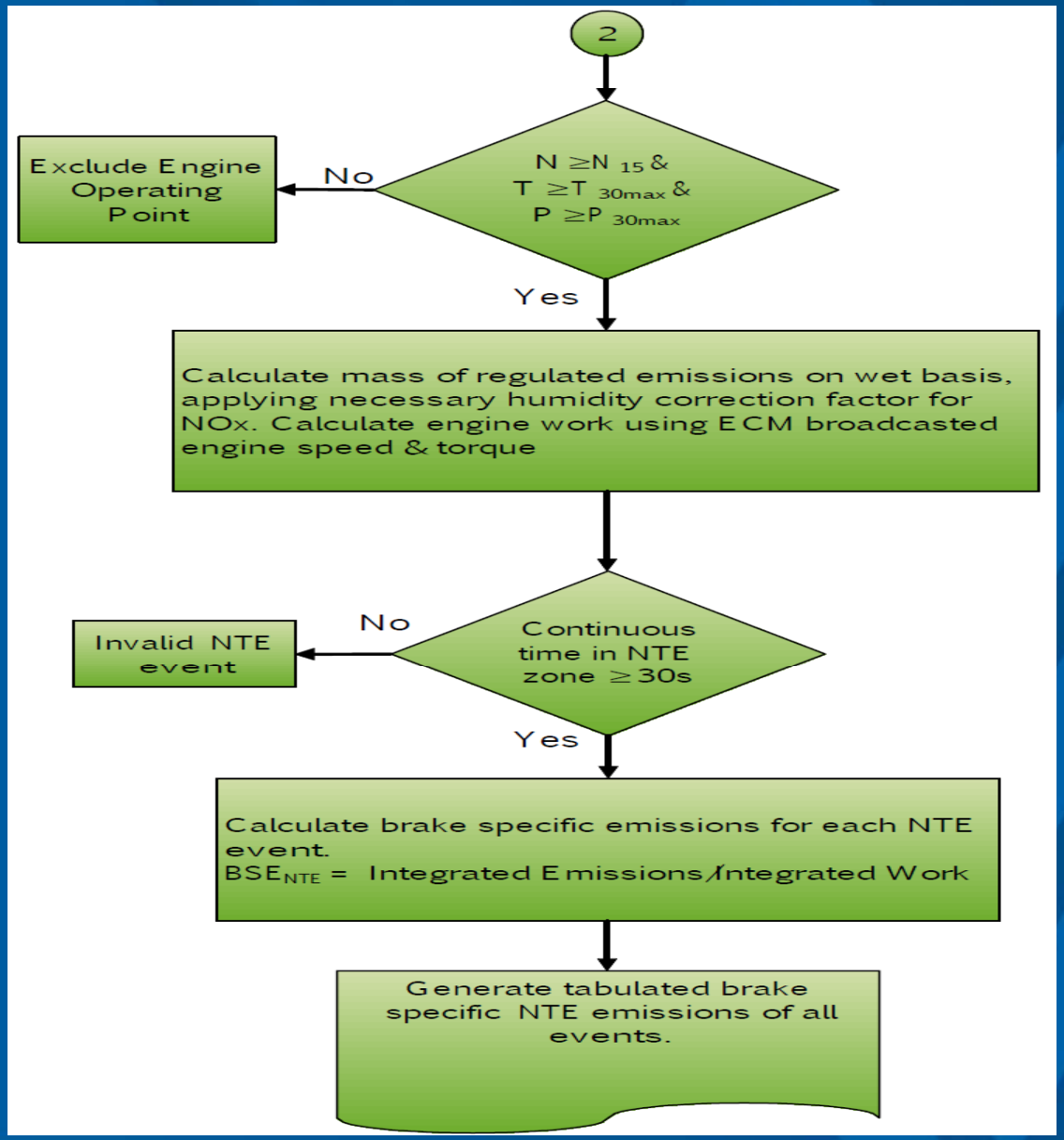
NTE Emissions Data Post Processing Flow Chart



NTE Emissions Data Post Processing Flow Chart Cont…



NTE Emissions Data Post Processing Flow Chart Cont…



Lessons Learned

- HDIUT - NOT an easy, well-defined task
- Off-highway is an order of magnitude above on-highway
- Commercial Post-Processors NOT Thoroughly Vetted
- Exhaust Flow Rate Measurement – Problems and Accuracy
  - Accuracy Determination is Still Needed
  - Vulnerability of Non-Compliance

Lessons Learned

- Time-alignment Sensitivity
- Alignment Criteria
  - Current CFR Procedure: use a constant shift in time based on spike response test of given sampling system which includes sampling lines, interconnects and the analyzers
  - Proposed Procedure: use an engine performance variable (eg. Fueling vs. CO_2) to track emissions sampling system response that varies over test duration. Apply the above determined varying shift in time for all the emissions samples.

Remote PEMS Control

- Wireless telemetry
  - "Remote Desktop" for monitoring
  - Real-time data monitoring (wireless, cellular)
  - Data transfer (test data QC/QA, instrument health checks)
- Eventual wireless component interconnect
- Expedites field QC/QA (scheduling, reporting)

Thank You for Your Attention

Daniel K. Carder: Daniel.Carder@mail.wvu.edu

Arvind Thiruvengadam: Arvind.Thiruvengadam@mail.wvu.edu

Marc C. Besch - Marc.Besch@mail.wvu.edu

Professor Mridul Gautam - Mridul.Gautam@mail.wvu.edu

CAFEE Center for Alternative Fuels, Engines and Emissions