March 2011

HD Hybrid Powertrain Testing

Working Paper N° HDH-05-10

HDH informal working group
5th session
March 16-18, 2011, Ann Arbor, USA

Agenda

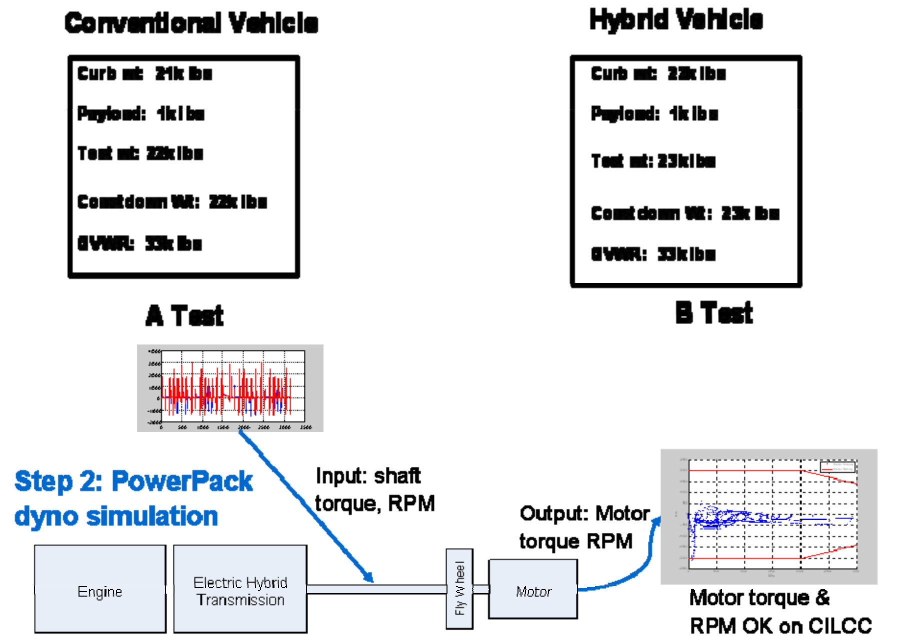
- Hybrid Powertrain Testing Overview
- Presentation of Hybrid System Development
- Potential Test Cell Set-up – for Hybrid Powertrain Testing
- Q&A

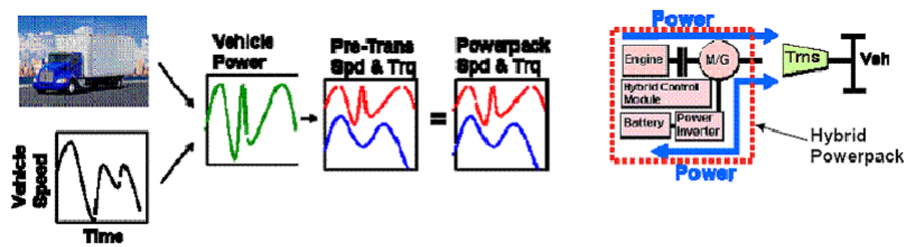
Hybrid Powertrain Testing Overview

- Testing conducted to develop the appropriate protocol for evaluation of hybrid and convention hybrid system performance
- Evaluation of pre- and post- transmission powertrain options
- Applicability of the protocol to various system architectures and energy storage strategies
- PTO evaluation for quantifying hybrid benefit
- Hardware-in-the-loop that incorporates actual system components

Proposed Certification Strategies

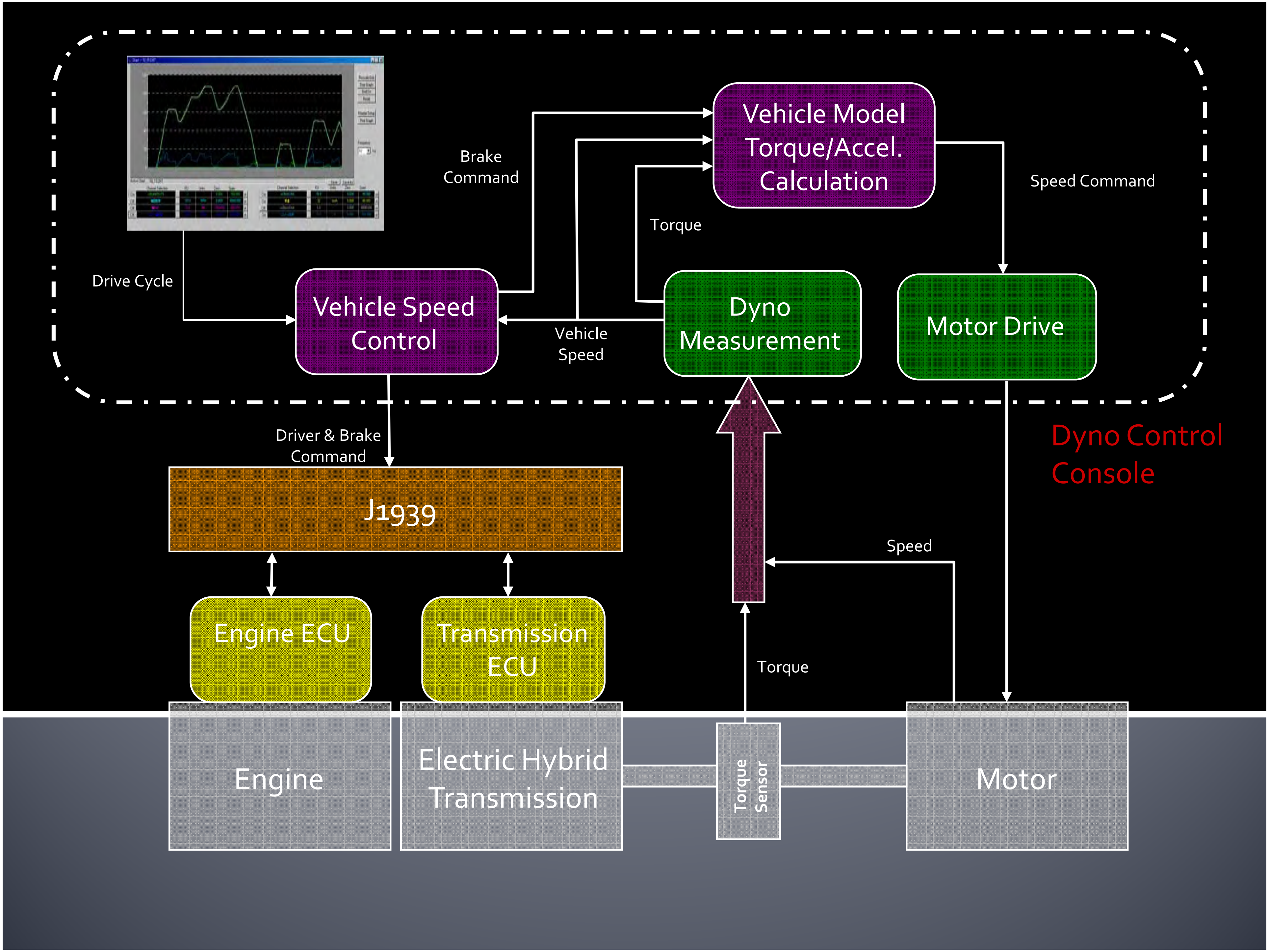
- A to B Testing for Vehicles – chassis test
- A to B Testing for Powertrains (Engine, Hybrid Power System, and Transmissions) – powertrain test cell
- Power Pack Testing (Engine and Hybrid Power System) – engine test cell



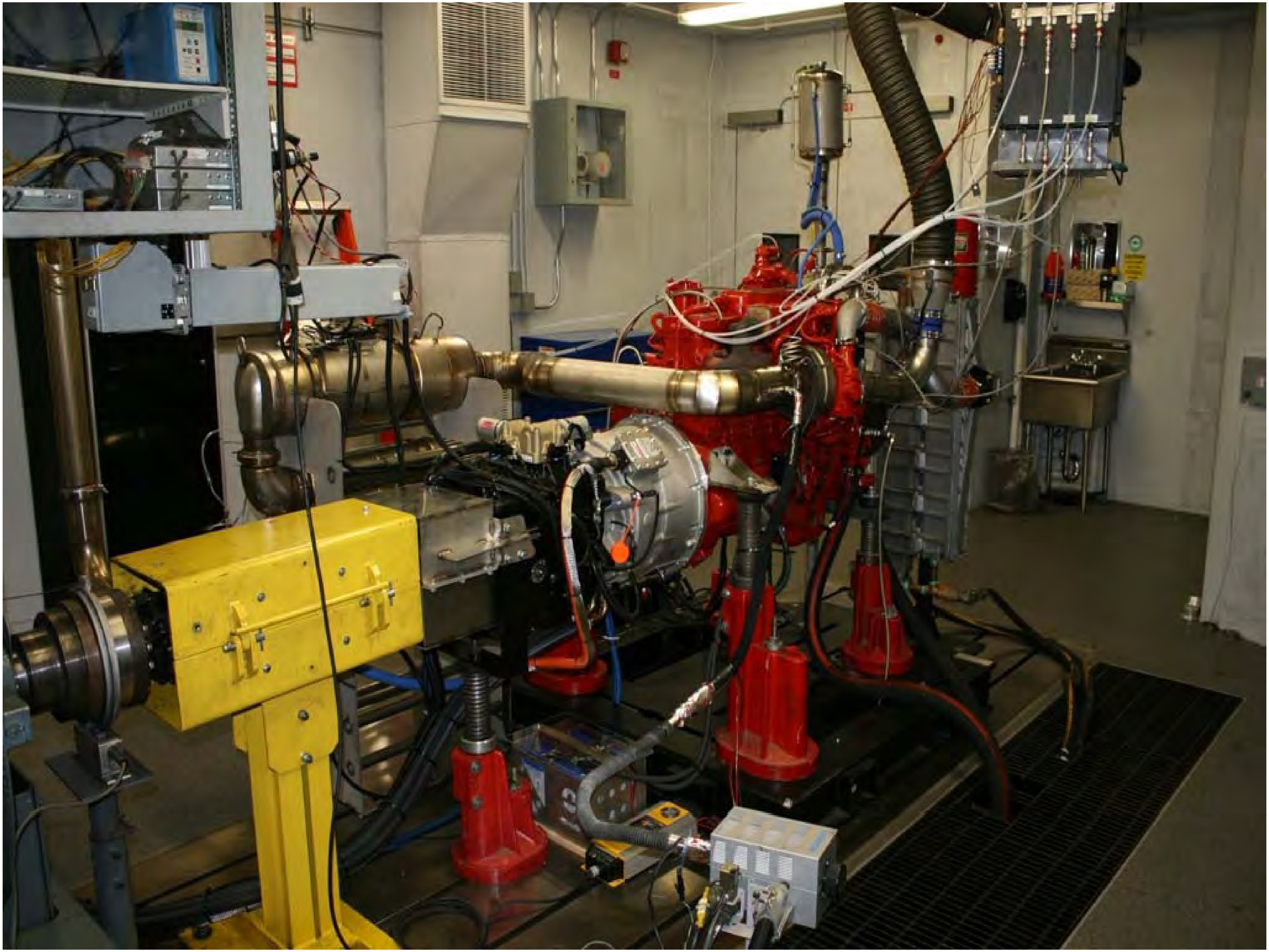


•*PTO evaluation in place with a specific duty cycle and test rig for vehicle testing.*

•*PTO test method fully resolved for powertrain or power pack testing.*



Vehicle Model Torque/Accel. Calculation
Brake Command
Speed Command
Torque
Drive Cycle
Vehicle Speed Control
Vehicle Speed
Dyno Measurement
Motor Drive
Driver & Brake Command
Dyno Control Console
J1939
Speed
Engine ECU
Transmission ECU
Torque
Engine
Electric Hybrid Transmission
Torque Sensor
Motor



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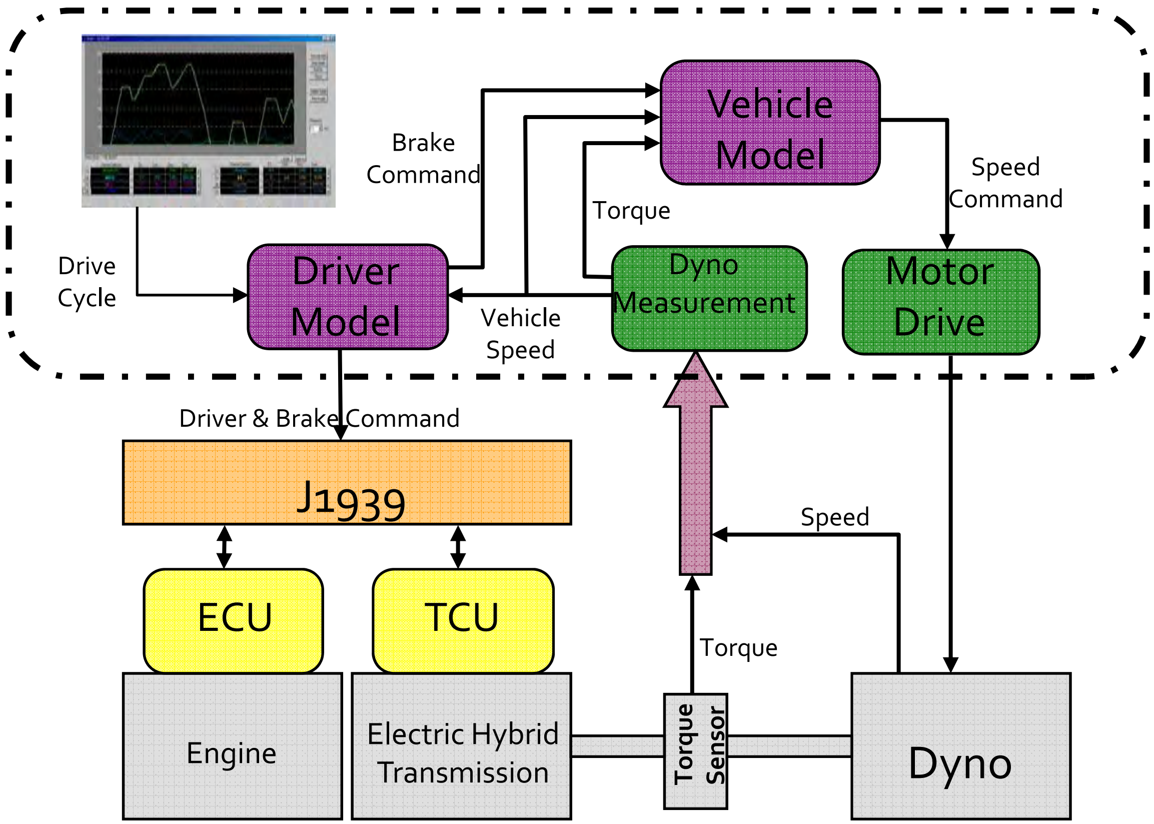
Post-Transmission Power-pack Test Procedures

Outline

- Additional Aspects of Power-Pack Testing
- Vehicle Model
- Performance Criteria for Driver Model
- Performance Criteria for Torque Control
- Correcting for Stored Battery Energy
- Conclusion

Additional Aspects to Post-Transmission Power-pack Testing

- Vehicle model
- Driver model
- Drive cycle



Vehicle Model Parameters

- Vehicle Mass (m)
- Coefficients of mechanical drag, A_m, B_m, and C_m
- Final Drive Ratio
- Loaded Tire Radius (r)

Vehicle Model

$$F_{\mathrm{RL}} = F_{\mathrm{f}} + F_{\mathrm{J}}$$

$$F_{\mathrm{f}} = C_{\mathrm{m}} v^2 + B_{\mathrm{m}} v + A_{\mathrm{m}}$$

$$F_{\mathrm{J}} = m \frac{dv}{dt}$$

Where:
F_{RL} = road load force
F_{f} = friction and aerodynamic drag forces
F_{J} = force from inertia
v = vehicle velocity

Torque and Speed at Transmission Output

$$n_{\mathrm{ds}} = \frac{v \cdot k_{\mathrm{d}}}{2 \cdot \pi \cdot r}$$

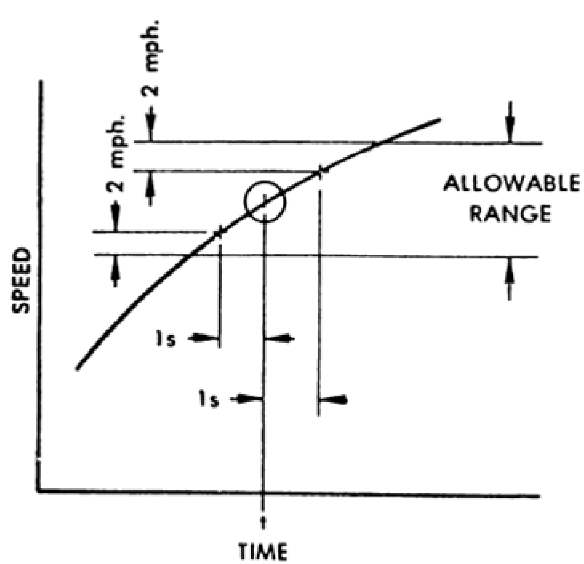
$$T_{\mathrm{ds}} = \frac{r \cdot F_{\mathrm{RL}}}{k_{\mathrm{d}}}$$

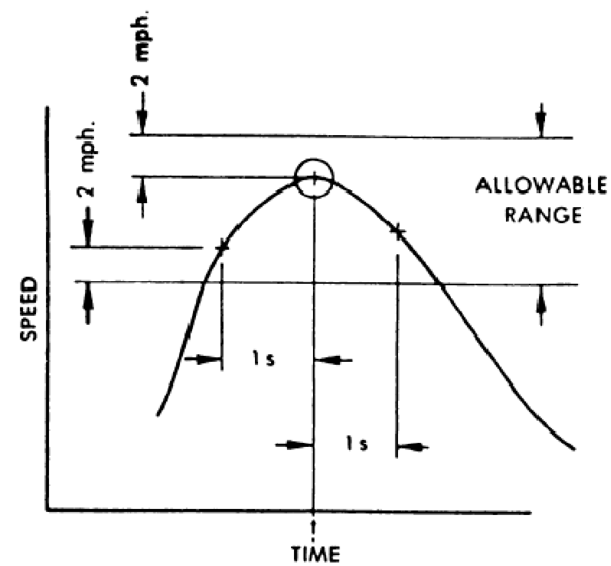
Where:

n_{ds} = rotational speed of drive shaft
T_{ds} = torque at the drive shaft
r = radius of loaded tire
k_{d} = final drive ratio

Performance Criteria
Driver Model

- ±2 mph in a 2 second window
- Actual average power has be within ± 1.5% of scheduled average power





$$\overline{P} = \frac{\sum_{\mathrm{i}=1}^{N} v_{\mathrm{i}} \cdot \left(\left(A_{\mathrm{m}} + B_{\mathrm{m}} \cdot v_{\mathrm{i}} + C_{\mathrm{m}} \cdot v_{\mathrm{i}}^{2}\right) + \left(\frac{dv}{dt} \cdot m\right)\right)}{N}$$

Performance Criteria
Torque Control

Table 2 of §1065.514—Default statistical criteria for validating duty cycles

Parameter	Torque
Slope, a_1	$0.830 \leq a_1 \leq 1.030$
Absolute value of intercept, $\lvert a_0 \rvert$	$\leq$ 2.0 % of maximum mapped torque
Standard error of estimate, *SEE*	$\leq$ 10 % of maximum mapped torque
Coefficient of determination, r^2	≥ 0.850

Methods we are Evaluating to Calculate Net Energy Change (NEC) in Battery

- SAE J1711 and J2711

$$NEC = \left(SOC_{\text{initial}} - SOC_{\text{final}}\right) \cdot V_{\text{nominal}}$$

- Integrating power for measured current and voltage

$$NEC = \sum I \cdot V \cdot \Delta t$$

Correcting for Stored Electrical Energy Using J2711

$$\left|\frac{NEC}{\text{total cycle energy}}\right| \cdot 100\% \leq 1\%$$

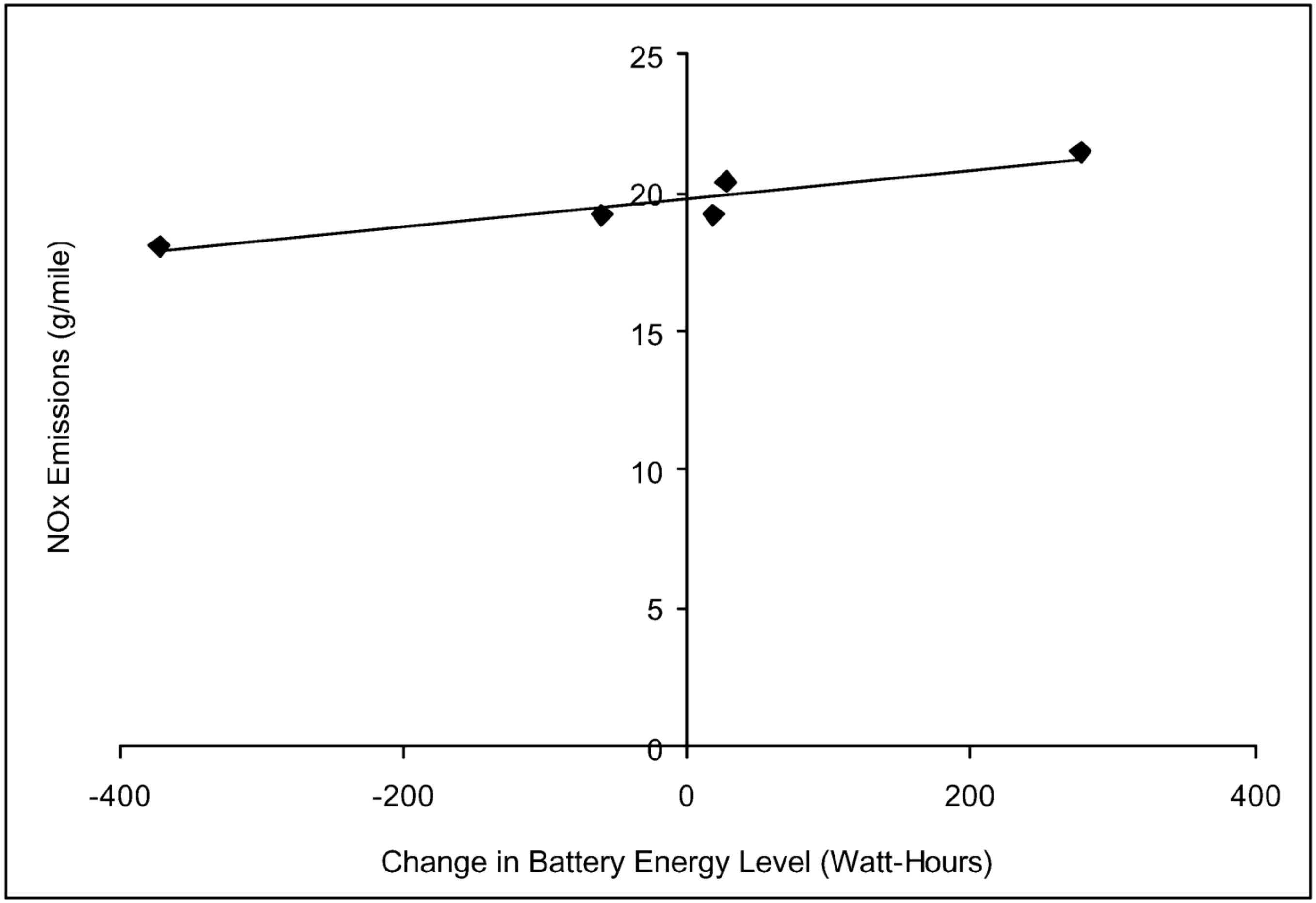
Valid test, no correction need.

$$1\% < \left|\frac{NEC}{\text{total cycle energy}}\right| \cdot 100\% \leq 5\%$$

Correction need

Greater than 5% the test is considered charge depleting

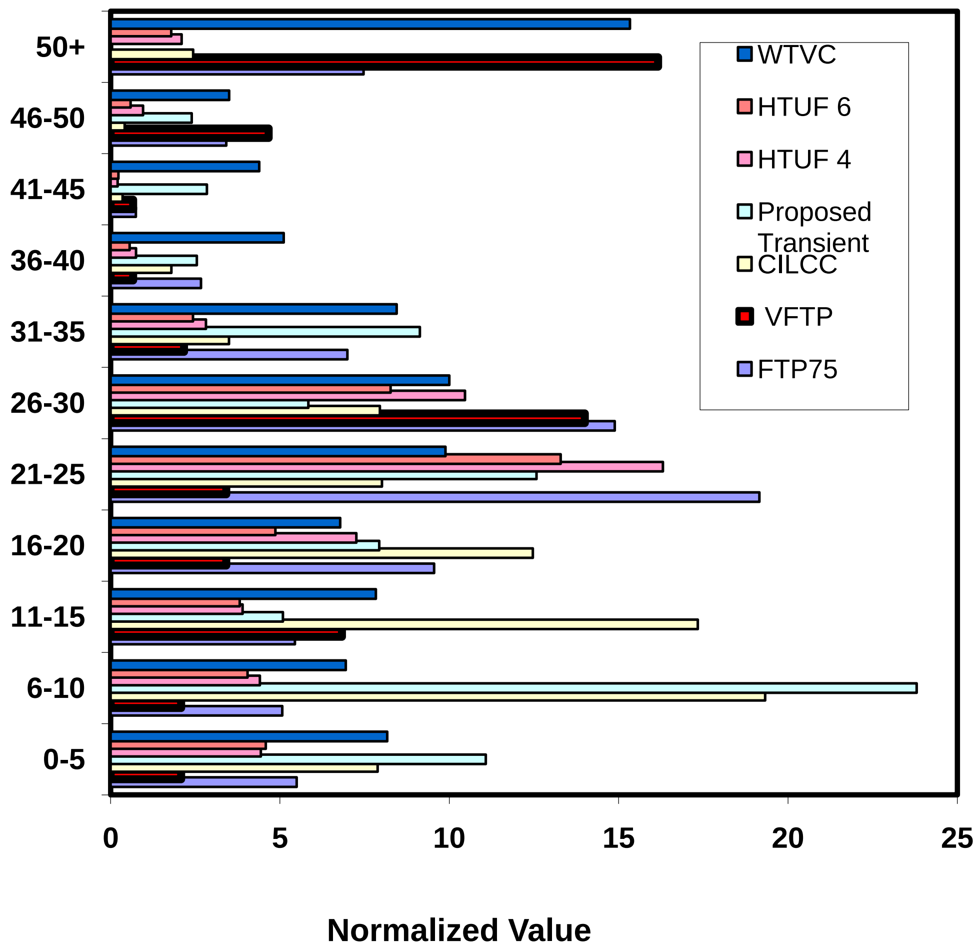
Example of Correction Curve for NEC



Conclusion

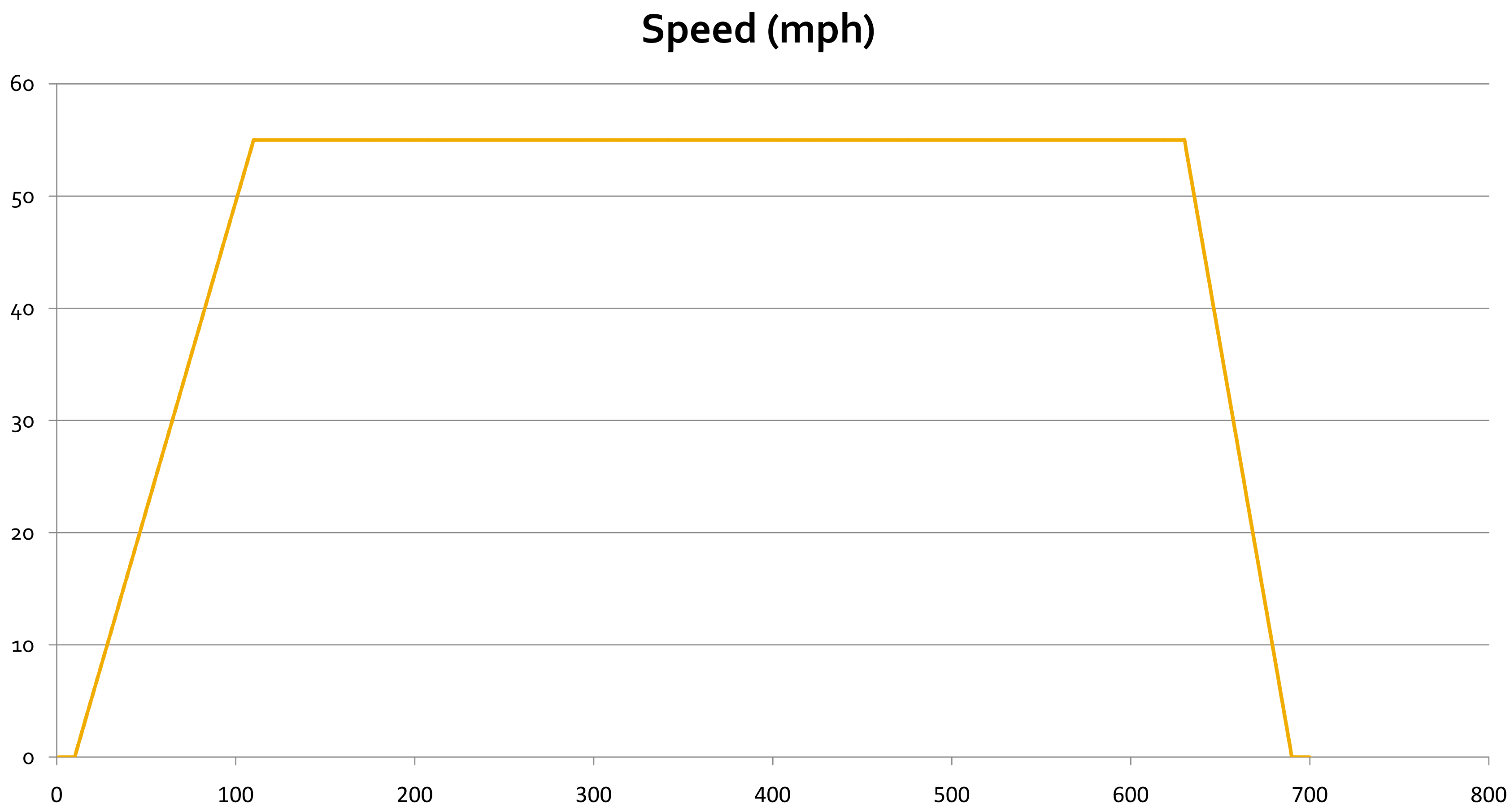
- EPA continues to refine test procedures for power-pack testing
- Test procedures from both engine and chassis testing are being used to develop power-pack test procedures
- Looking at using a modified version of SAE J2711 to account for energy stored in Battery

Multitude of Available Driving Cycles

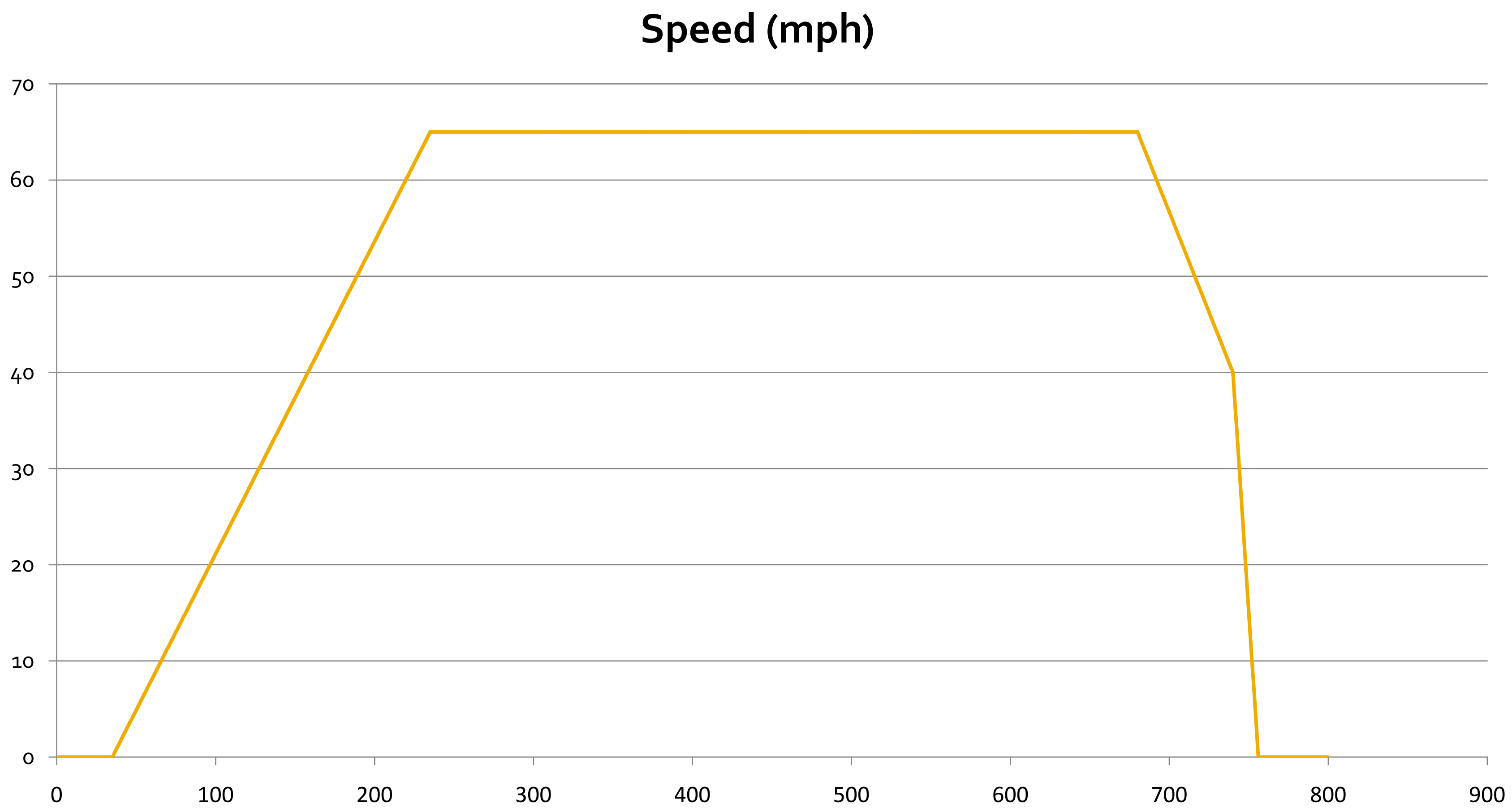


- Cycles are as varied as vehicles tested
- High and low speed traces as well as cycles that encompass all speed ranges
- All tests are used on chassis dyno, as opposed to engine dyno

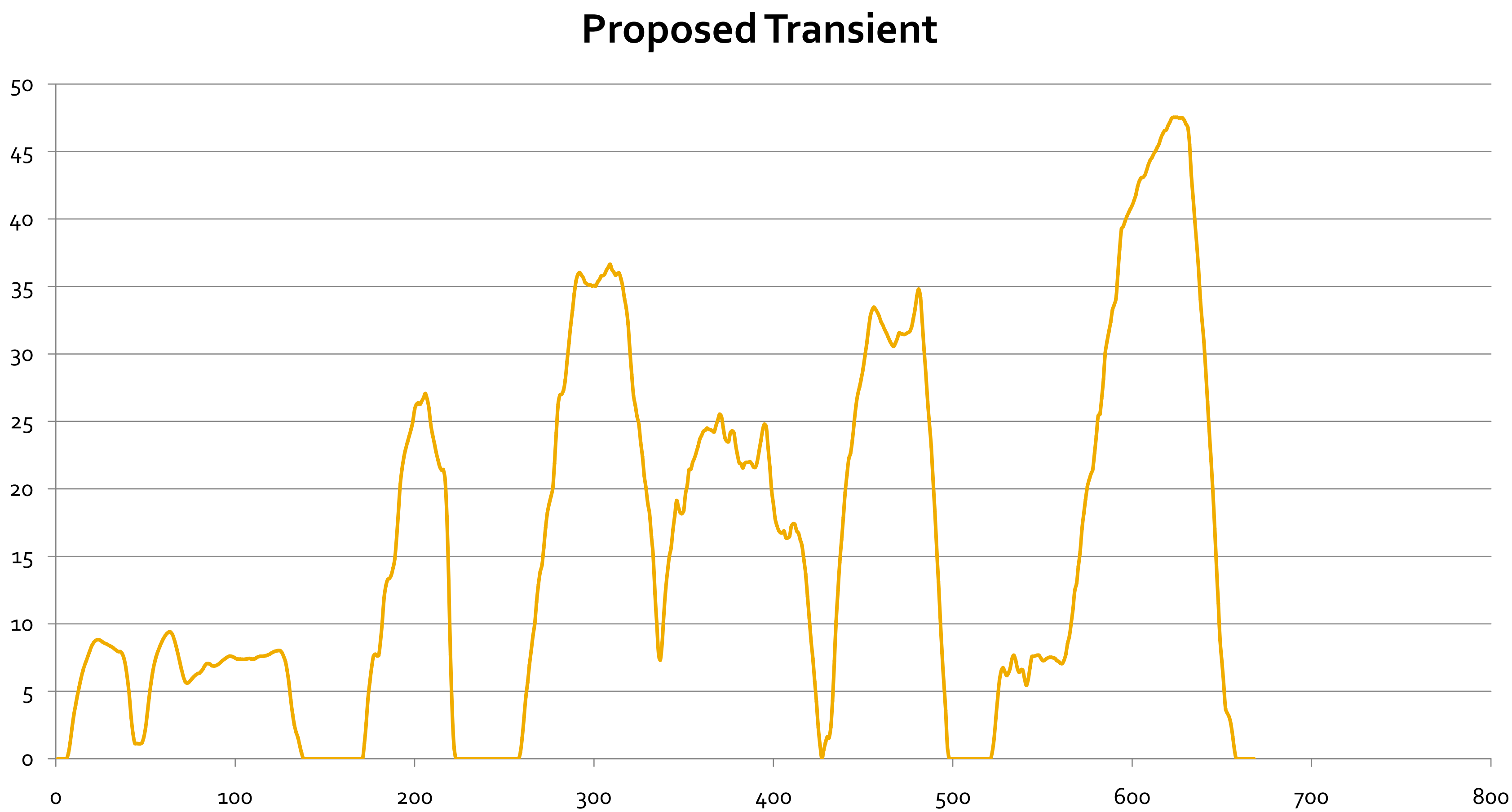
55 Mph Cruise Cert Cycle



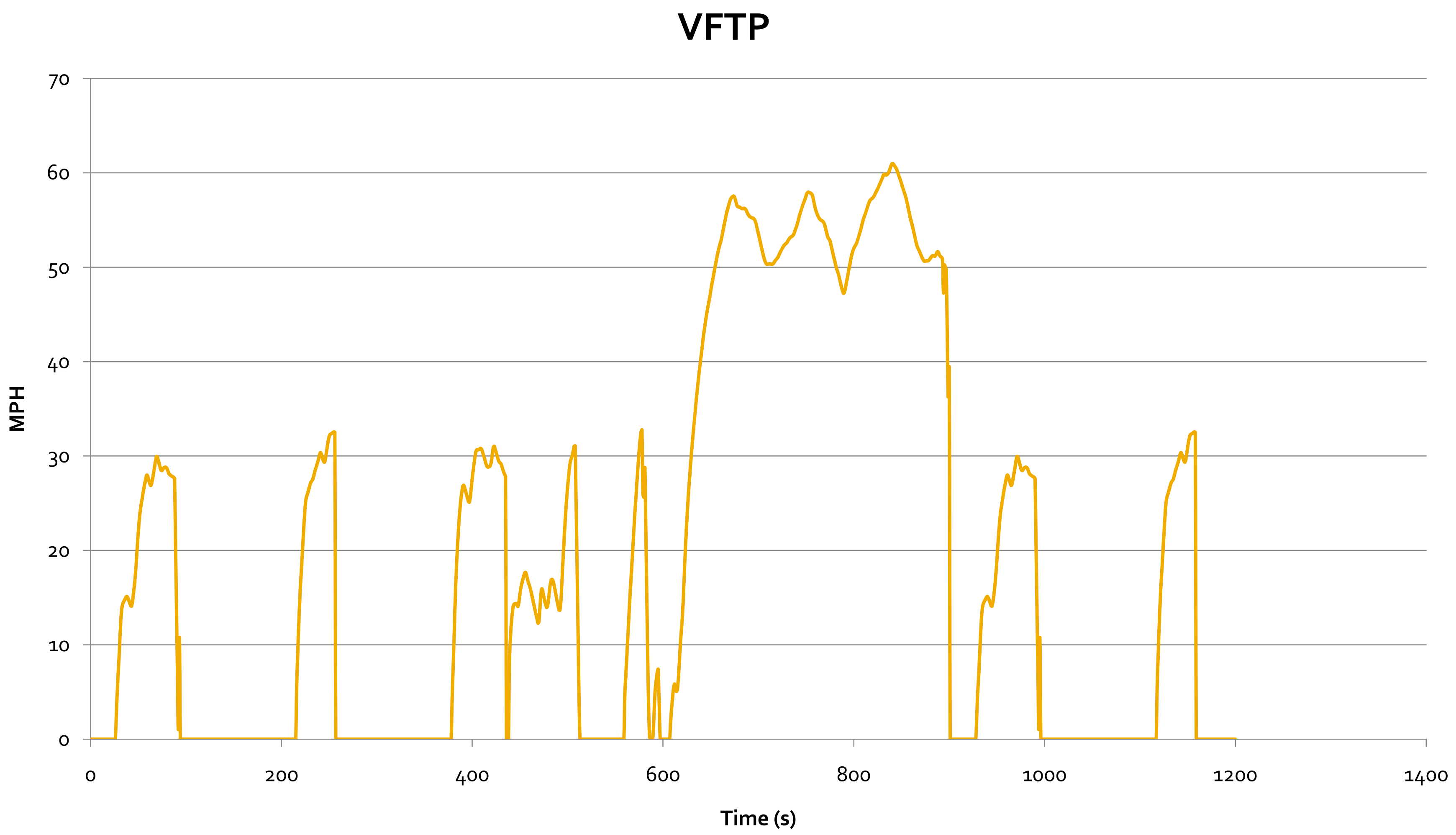
65 Mph Cruise Cert Cycle



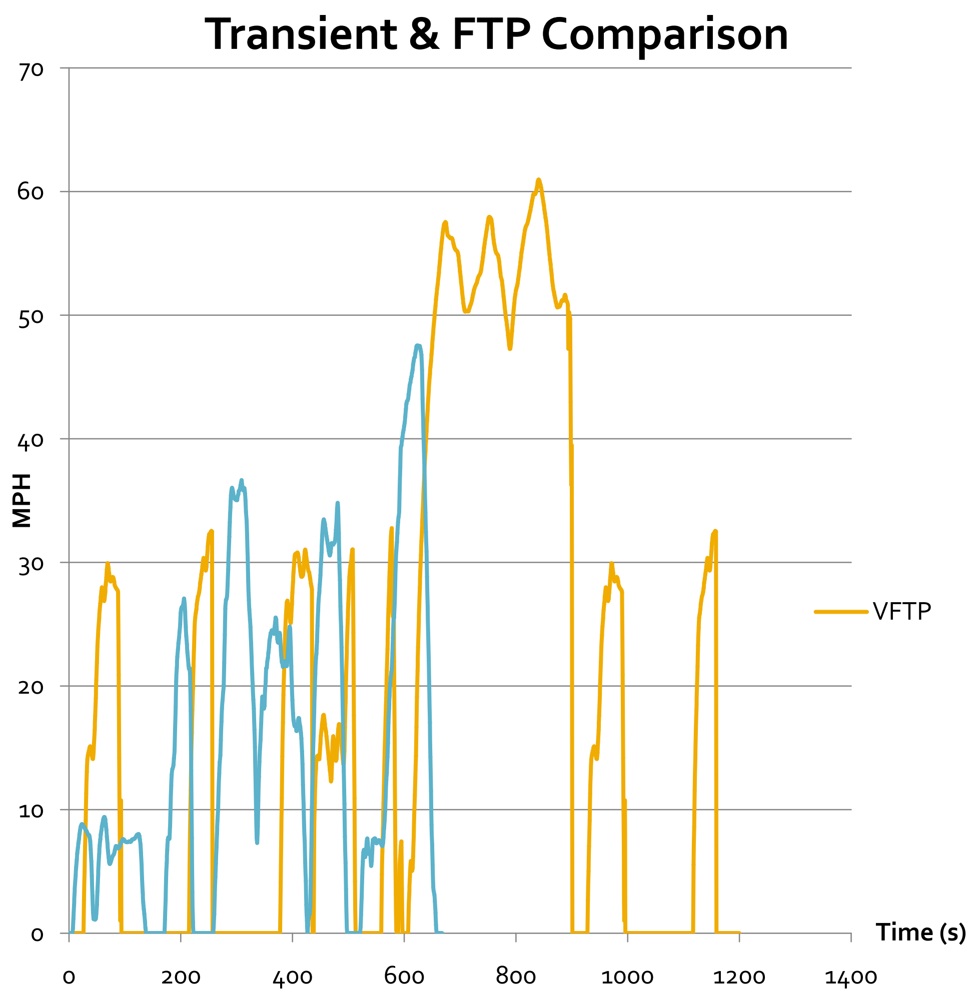
Proposed Transient Cert Cycle



Converted Engine Cycle (vFTP)

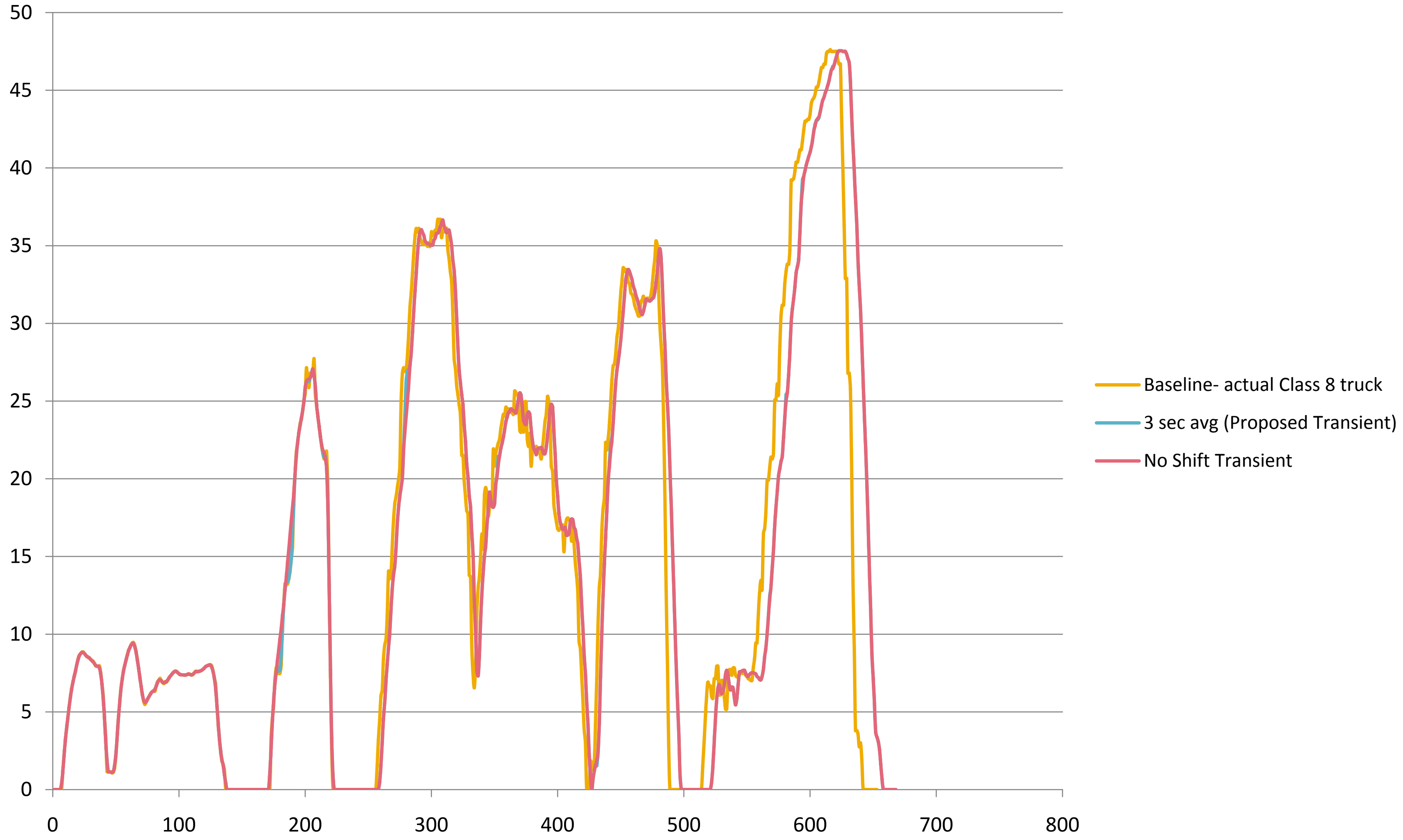


Overlaid Cycles

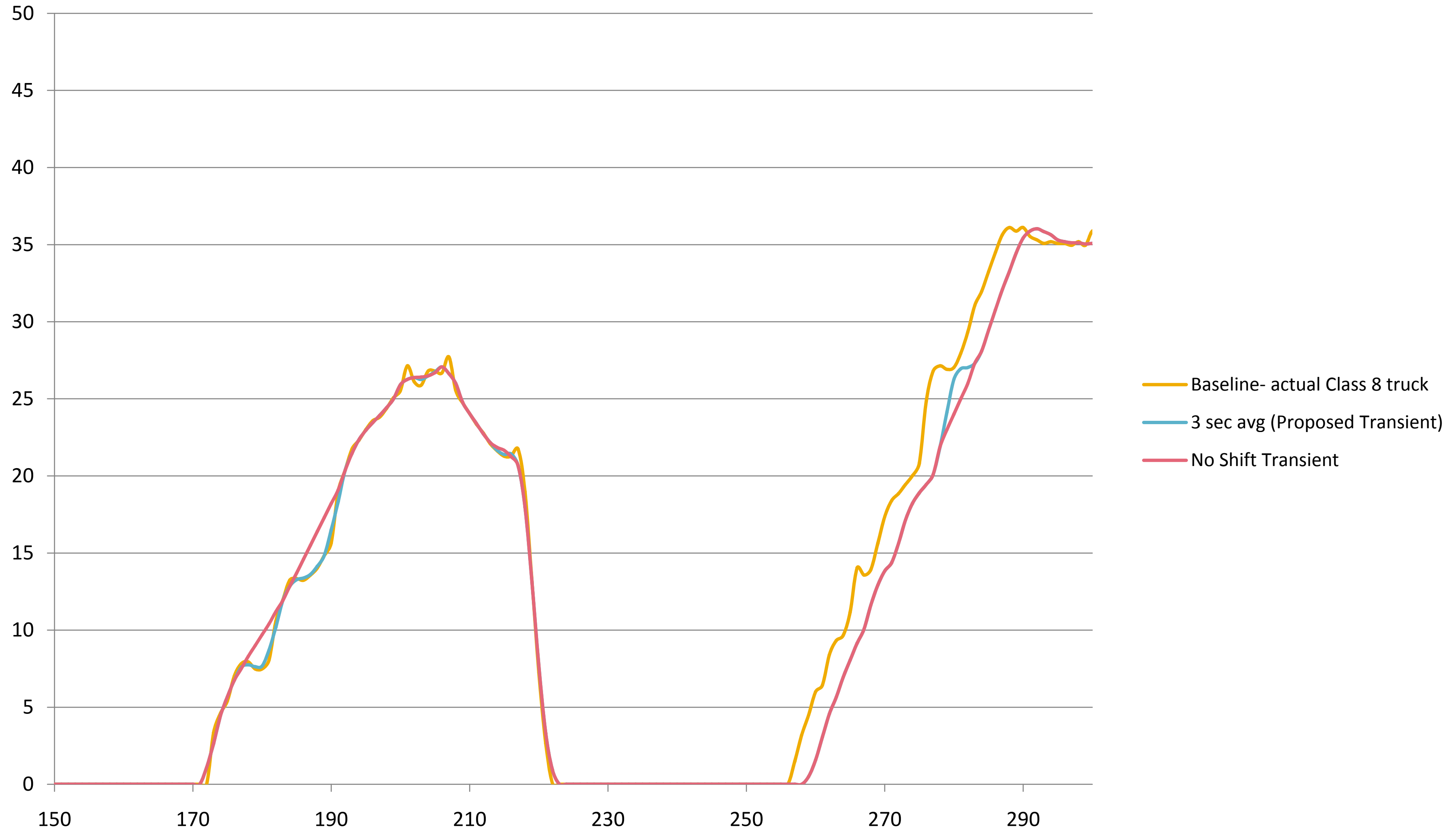


- Chassis derived Proposed Transient Cycle vastly different from engine derived engine FTP cycle
- How will this affect GHG output for similar powertrains?

Transient Cycle Background



Eliminating Vehicle Specific Shift Points



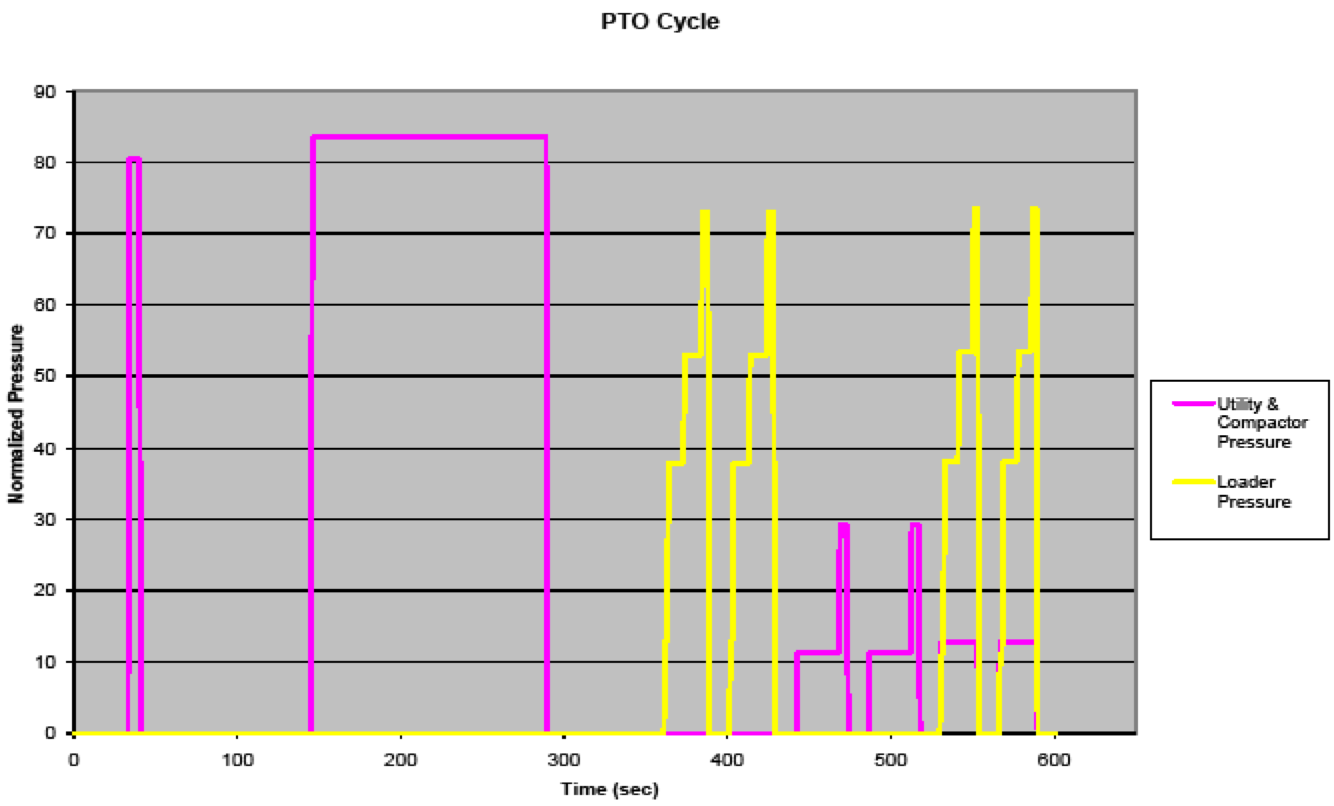
Power Take Off Testing Overview

- The EPA comissioned Southwest Research Institute to study the potential applications for hybrid PTO vehicles in industry and to determine what typical PTO operation would be.
- Survey of industry indicated PTO hybrids were being investigated and developed for utility and refuse applications.
- SwRI obtained a utility truck and a refuse truck, instrumented them, and sent them to their owner for field operation
- The refuse truck was operated for a week on a variety of routes
  - The vehicle was a class 8 residential vehicle with a automated side-load-arm (SLA). This vehicle was owned by a large refuse company.
- The utility truck was operated for two weeks in two different locations
  - The vehicle was a class 8 vehicle with a bucket. This vehicle was in a rental fleet during testing.

Power Take Off Testing Overview

- The testing showed that the utility truck had different duty cycles depending upon the operator and location of the vehicle.
- The testing showed that the refuse truck duty cycle was similar day-to-day for the routes it covered.
- SwRI analyzed the data and using cluster analysis to determine the most appropriate pump operation modes based upon the data for both vehicles.
- Two sub-cycles were developed, one for utility and one for refuse operations. These were combined into one cycle, weighted for time wihtin the cycle based on unit sales.

Power Take Off Testing Overview



Power Take Off Testing Overview

Hybrid Powertrain Testing Overview

- The test rig can test a two-loop or single-loop PTO system.
- The subject vehicle will be put near an emission analyzer and connected to the PTO rig.
- The vehicle will be operated over the cycle while measuring emissions.
- A conventional system will be tested and compared to the hybrid system. The difference will be used to calculate emission credits.