GRPE/HDH-03-06

Cummins Hybrid Certification White Paper Overview

Cummins Hybrid Certification White Paper

- Evaluation and certification of hybrids presents unique challenges
  - Regulatory development efforts in US, EU, and China
  - One prominent proposal is HILS

- Cummins hybrid white paper proposes concept for hybrid certification
  - Proposal was developed in response to EPA's CO_2 regulation development, but may be applicable to EU and China
  - Hybrid concept builds on HD CO_2 regulatory framework described in Cummins CO_2 white paper

Overview: Hybrid Certification Paper Key Points

- **Critical Questions:**
  - **What is certified?**
  - **How much will be simulated?**

- **Main points of Cummins hybrid white paper**
  - **Certify Engine and Hybrid Components as a Set (called a Powerpack)**
  - **Certify the Powerpack for both CO2 and Criteria**
  - **Utilize the dyno-based engine test cycle* to certify the Powerpack**

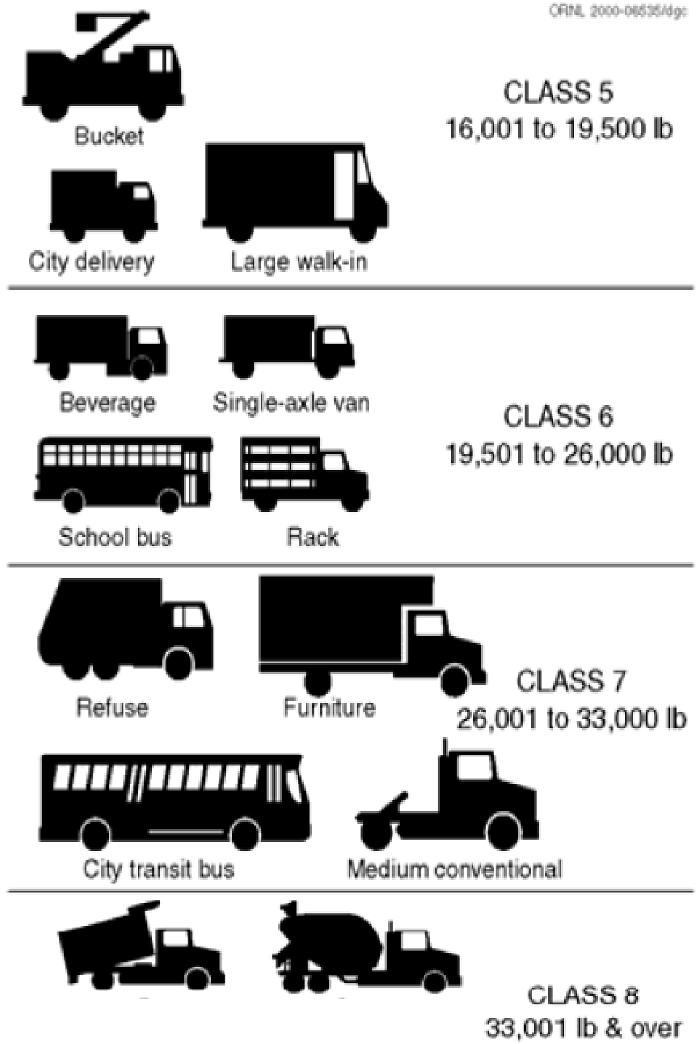
*** Some modifications are required to appropriately account for the additional hybrid components**

Cummins Guiding Principles for Regulation: Conventional & Hybrid

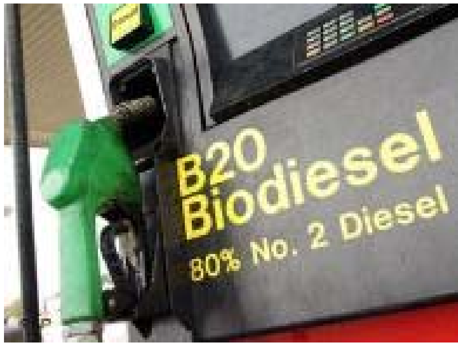
- Simplicity: Find the right balance between real world fidelity and regulatory complexity.
- Speed: Re-use existing vehicle, engine and component regulations and protocols.
- Incentives: Utilize an incentive program to bring CO2 reduction technologies to the market earlier.
- Technology: Use regulations to deliver CO2 reductions by driving technology into the vehicle, engine and critical sub-systems.
- Fairness: Avoid unintended consequences and maintain a level playing field.
- Compliance: Provide for verifiable procedures and results.
- Feasibility: Ensure the implementation of best available technology with current lead time and stability requirements.
- Flexibility: Employ flexibility mechanisms in the current emissions program such as averaging, banking and trading.
- Phase-In: Provide for a progressive approach to scope and stringency of standards.

Vocational Market

- Vocational market has a wide range of applications that could be suitable for hybridization
- A vehicle based certification program could lead to significant proliferation of certifications
- Small volumes for many applications could make individual vehicle certifications impractical

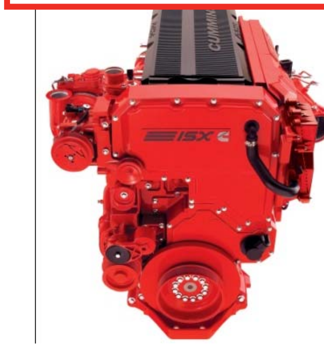


Hybrids are "Active" Part of the System



- **Fuels**
  - Reduced carbon intensity
  - Bio Diesel, CNG, LNG

Power Supply
"Active"



- **Engines**
  - Efficiency improvements
  - Reduced Carbon Fuels
  - Hybrids / Waste Heat Recovery

Power Demand
"Passive"

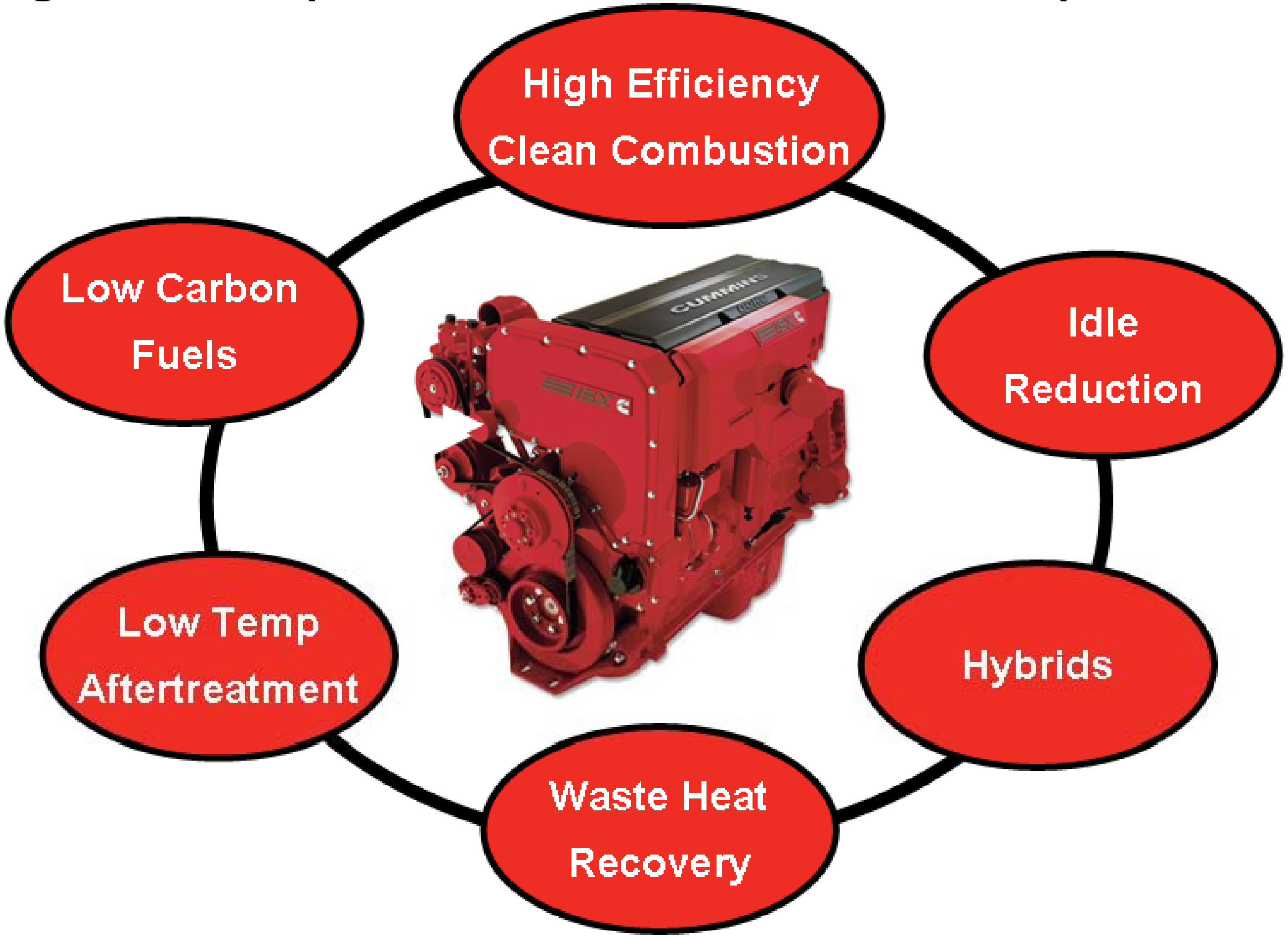
- **Vehicles**
  - Transmissions / Axles / Tires
  - Aerodynamics
  - Tractor & Trailer - Smartway

- **Fleets / Operators**
  - Incentives for low GHG vehicles
  - Logistics, Driver training & aids

- **Highways / Infrastructure**
  - Highway Construction / Congestion
  - Speed limits
  - GVW

Cummins

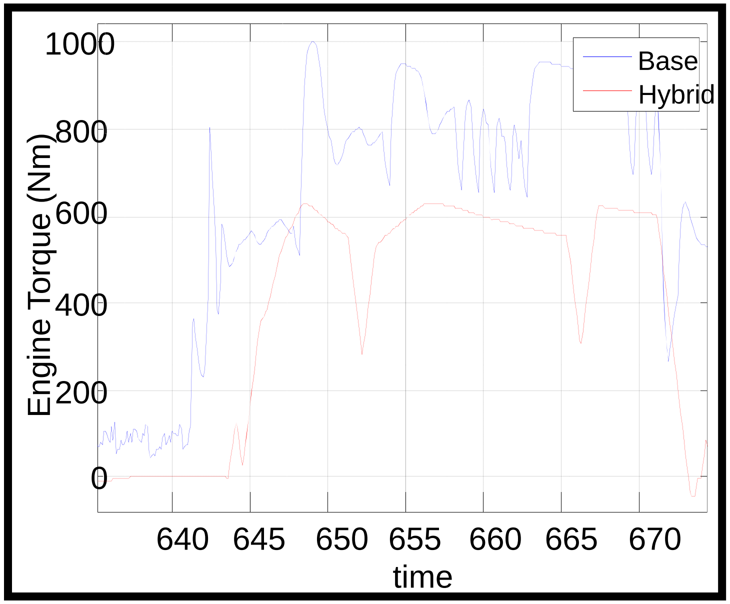
Key CO_2 Reduction Technologies are Engine Dependent and Interdependent



Hybrids have significant interaction with the engine and significant interaction with other engine-based CO_2 reduction technologies

Hybrid CO_2 Reduction Results from the Fact that the Engines in Hybrid Systems Operate Differently than Conventional Diesel Engines

Conventional vs Hybrid



Hybrid Decouples Engine Power from Vehicle Power

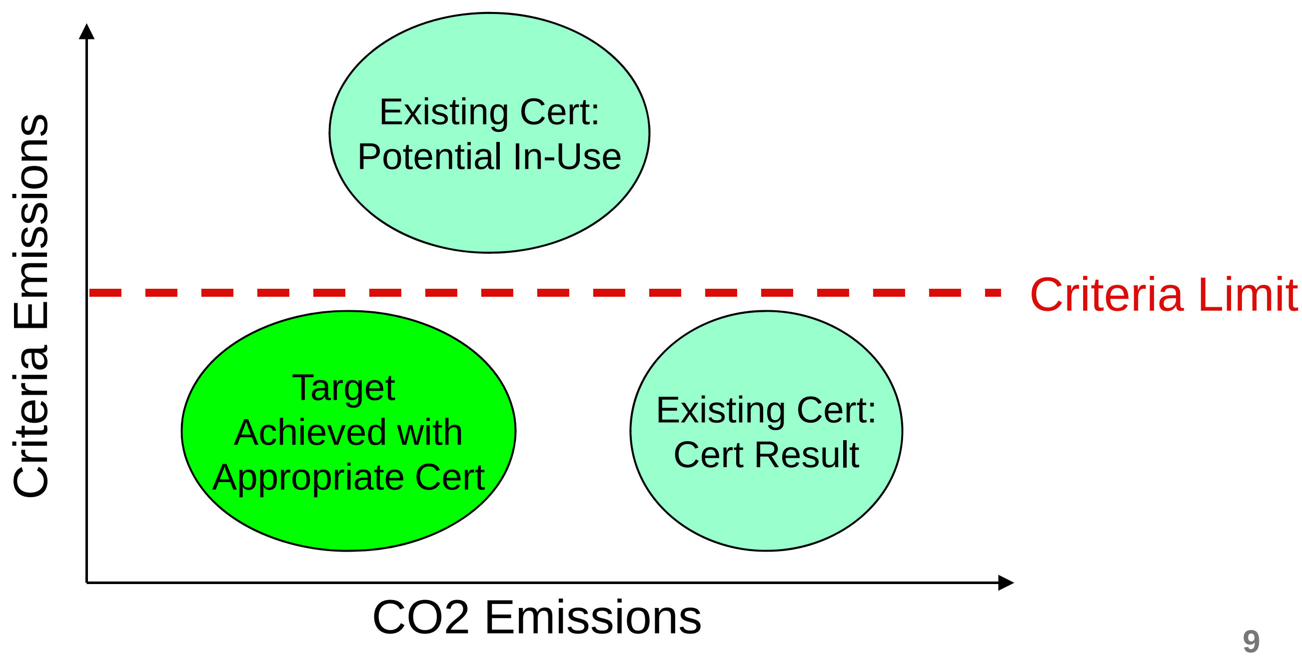
- Reduced Cycle Work (from Regenerative Braking)
- Start / Stop Operation
- Increased Average Load
- Opportunity to Manage Transient Load & Exhaust Temperatures

The amount of CO_2 is dependent upon the engine and upon the interaction of key components within the Hybrid Power Pack:

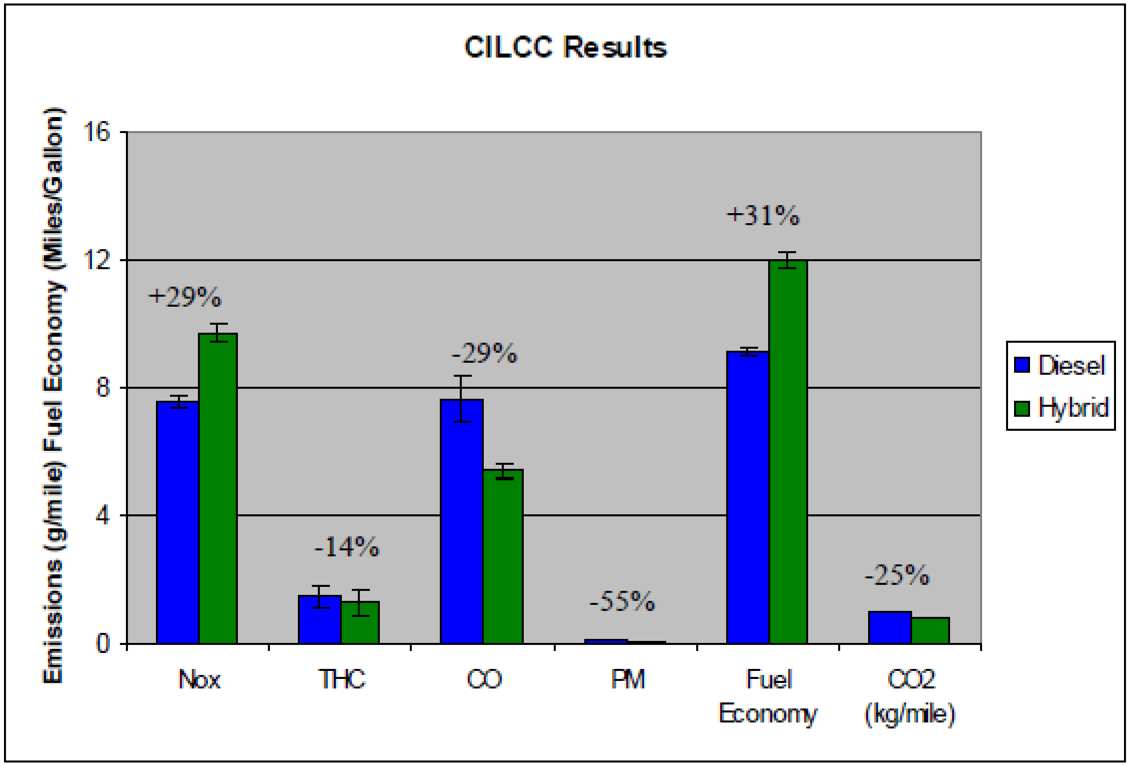
Hybrid Should be certified for both criteria and CO2 together.

Decoupling Engine Power from Vehicle Power Could Have Unintended Consequences

- Existing engine dyno cert assumes engine power matches vehicle power.
- If hybrid decouples engine power from vehicle power, FTP cycle no longer appropriate for hybrid engine certification.
- Mis-match between certification & real world operation could lead to higher criteria emissions, and less than optimal CO_2 emissions reduction.



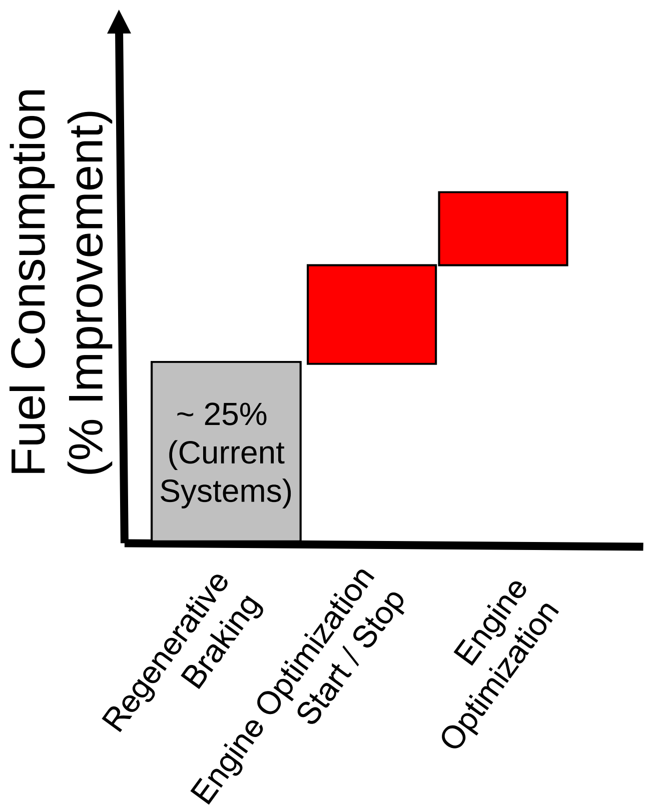
Hybrid with Engine Certified Over Traditional FTP may Produce Higher Criteria Emissions



- DOE / NREL chassis test evaluation of hybrid P&D vehicle CO_2 & criteria emissions
- Eaton hybrid system
- P100 van
- CILCC Cycle

In this case hybridization resulted in lower PM emissions, but higher NO_x emissions.

Hybrid should be Certified Jointly for Both Criteria and CO_2 Emissions



Ensure real world critieria emissions equivalent to conventional

Maximize opportunities for CO2 reduction

Allow for future technology development (engine electrification & integration with hybrid system)

Alignment of CO2 & criteria certification is consistent with CO2 regulatory concepts for conventional powertrains.

Alignment of CO2 & criteria cert can enable 5-10% additional CO2 reduction, that is not available today

Greater optimization can also reduce engine hardware cost and improve reliability of system

Hybrid Certification Should Build on Existing Engine Certification

- Existing FTP transient engine dyno test accurately describes vehicle power requirements for a wide range of vocational applications
- Significant industry experience with FTP procedures and protocols

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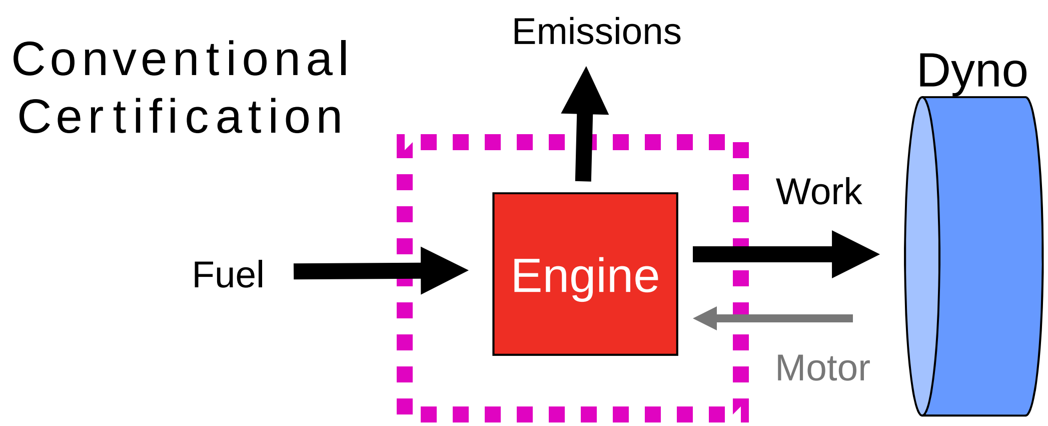
- Use the normalized engine form of the cycle
- Engine torque curve defines actual speed and torque for certification test
- Emissions: g/hp-hr
- Integrate only positive work (motoring work not included)

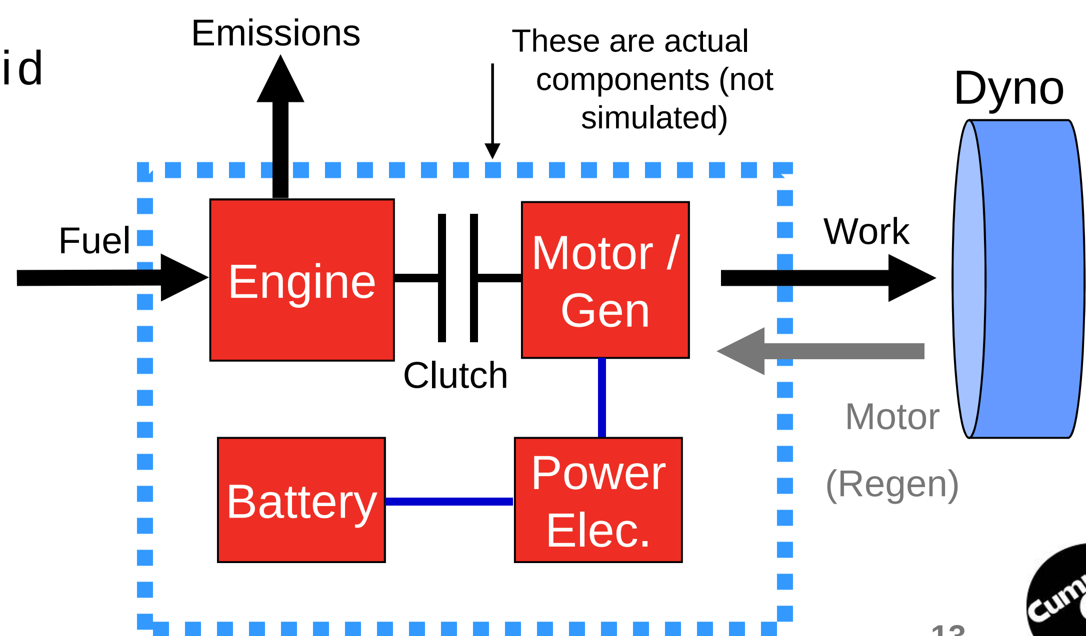


Hybrid Certification of Pre-Transmission Hybrids

- Pre-transmission powerpack could utilize existing procedures and protocols with minor modifications
- For many hybrid systems this approach would allow hardware evaluation of engine, motor, battery, etc.
- One certification, many applications
  - Uses same simplifying assumptions as conventional certifications
- Allow comparative performance evaluation with conventional engine

Hybrid Certification: Pre-Transmission Hybrid

- Use the normalized engine form of the cycle(s)
- Pre-transmission system torque curve defines actual speed and torque for certification test
- Emissions: g/hp-hr
- Allow capture of energy during "motoring" portions of FTP
- Count only positive work (as with conventional engines)

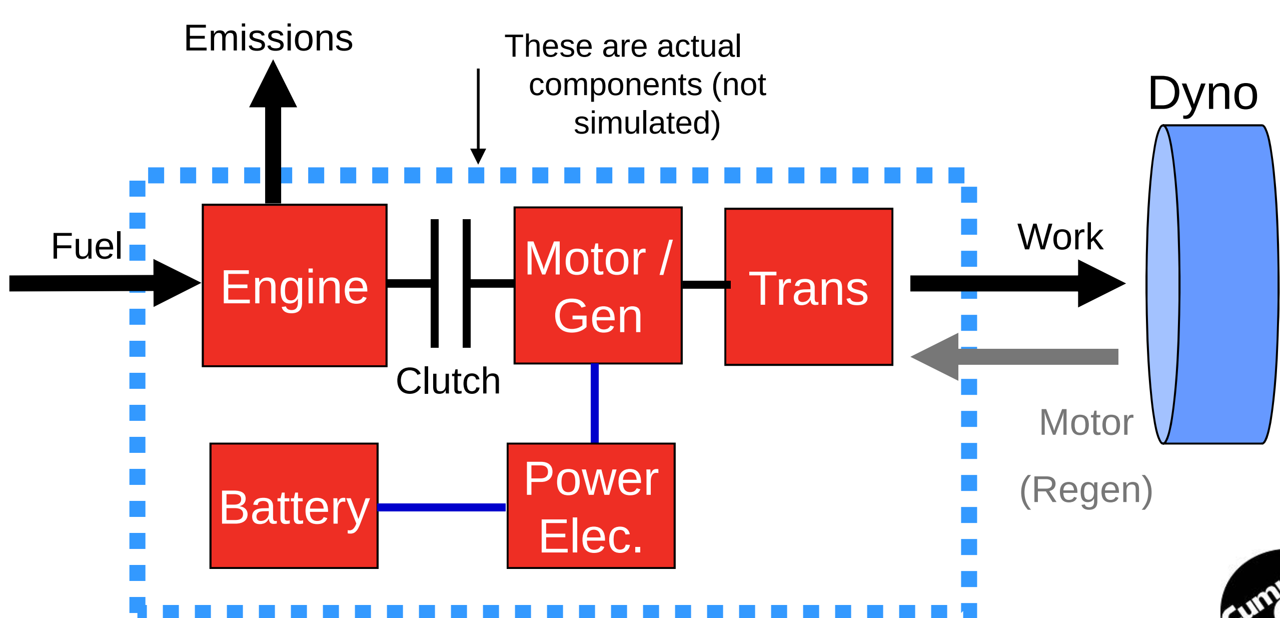


Post-Transmission Power Pack Certification

- Pre-transmission powerpack certification not viable for all hybrid architectures
- Post-transmission powerpack certification would work for series and other transmission integrated hybrid systems
- Cycle based on FTP would allow comparative evaluation with conventional and pre-trans hybrid

- Use normalized post-transmission test cycle(s)
- Post-transmission system torque curve defines actual speed and torque for certification test
- Emissions: g/hp-hr
- Allow capture of energy during braking portions of cycle
- Count only positive work (as with conventional engines)

Hybrid Certification: Post-Transmission Option



Powerpack and HILS

- HILS very attractive, but presents some challenges
  - Development of models for some hybrid components (batteries)
  - Verification of compliance
  - Test cycle selection, standards for new cycles, and comparison with conventional certification results

- Powerpack is a form of HILS
  - Aero, rolling resistance, wheels, differential (+transmission in pre-trans option) all simulated.

- Advantages of powerpack concept
  - Certifying powerpack would reduce proliferation
  - Inclusion of criteria emissions and CO2 allows maximum optimization
  - Inclusion of hybrid HW enables fast implementation

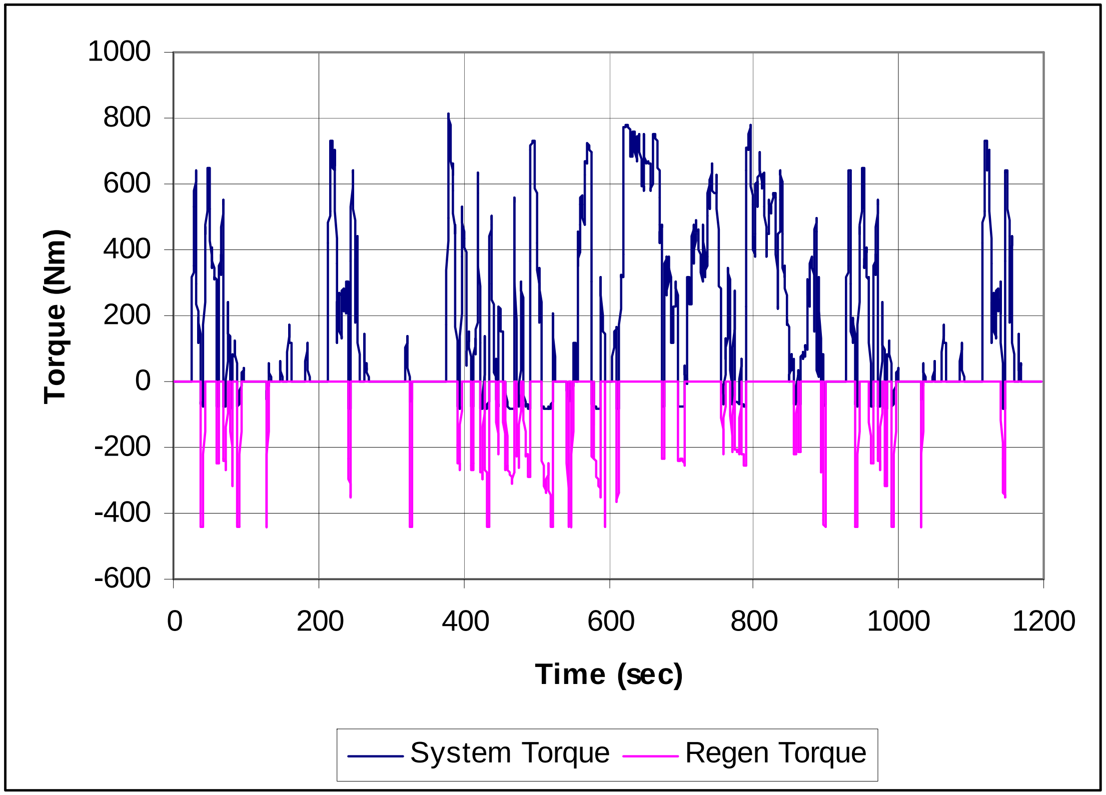
Summary

- Cummins hybrid white paper
  - Certify powerpack
  - Test all hybrid components
  - Certify for both criteria emissions and CO_2
  - Build on existing experience with engine dyno based certification

- Questions:
  - Would powerpack approach be applicable to EU or China?
  - Is powerpack approach compatible with HILS?

Appendix:
Limiting of regen braking

Capture of Regen Energy could be Approximated by Capturing Dyno Energy during Motoring Portions of FTP

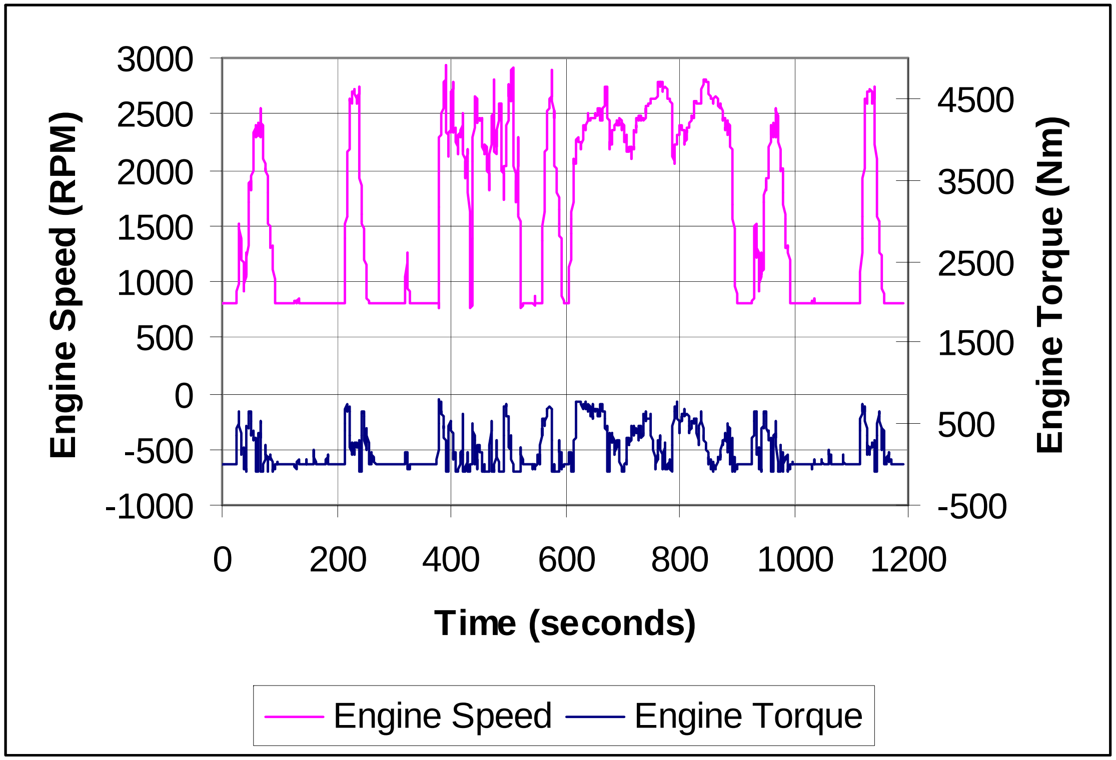


- FTP torque based on system torque (blue)
- Regen torque based on capability of 60kW motor/gen during motoring portions of FTP

This strategy would allow capture of energy in a battery, which is a key feature of hybrids.

Definition of a "Vehicle FTP" Will Allow Hybrid Certification of All Hybrid Systems

FTP for 260 hp 6.7L ISB



- FTP defines speed and torque requirements for engine
- Engine speed and torque can be used to determine power going to wheels to accelerate vehicle
- Engine power combined with engine speed can define vehicle speed

Engine speed and torque can be used to define vehicle speed.

Definition of a Post Transmission FTP Will Allow Hybrid Certification of All Hybrid Systems

FTP defines speed and torque requirements for engine

Acceleration: If engine torque positive, engine speed and torque can be used to determine power going to wheels to accelerate vehicle

$$Force_{Engine} - Force_{Load} = Mass_{Veh} * Acceleration$$

$$Accel = \frac{P_{Eng}}{MV} - \frac{\frac{1}{2} C_d * Area * \rho_{air} * V^2 + Mgf_{rolling} + \frac{P_{accessory}}{V}}{M}$$

Deceleration: Engine torque negative

- If engine speed ~ constant assume coasting and calculate deceleration based on motoring engine torque.
- If engine speed decelerates quickly, assume braking.
  - At > 15 mph, calculate vehicle deceleration based on engine deceleration
  - At < 15 mph, decelerate vehicle at 1.5 m/s2

Engine speed and torque can be used to define vehicle speed.

Definition of a Post Transmission FTP Will Allow Hybrid Certification of All Hybrid Systems

"Average" cycle could be defined based on calculated vehicle speed for a range of engines & vehicles.

Vehicle speed could also be used to calculate maximum regen energy available to ensure powerpack energy capture is realistic.

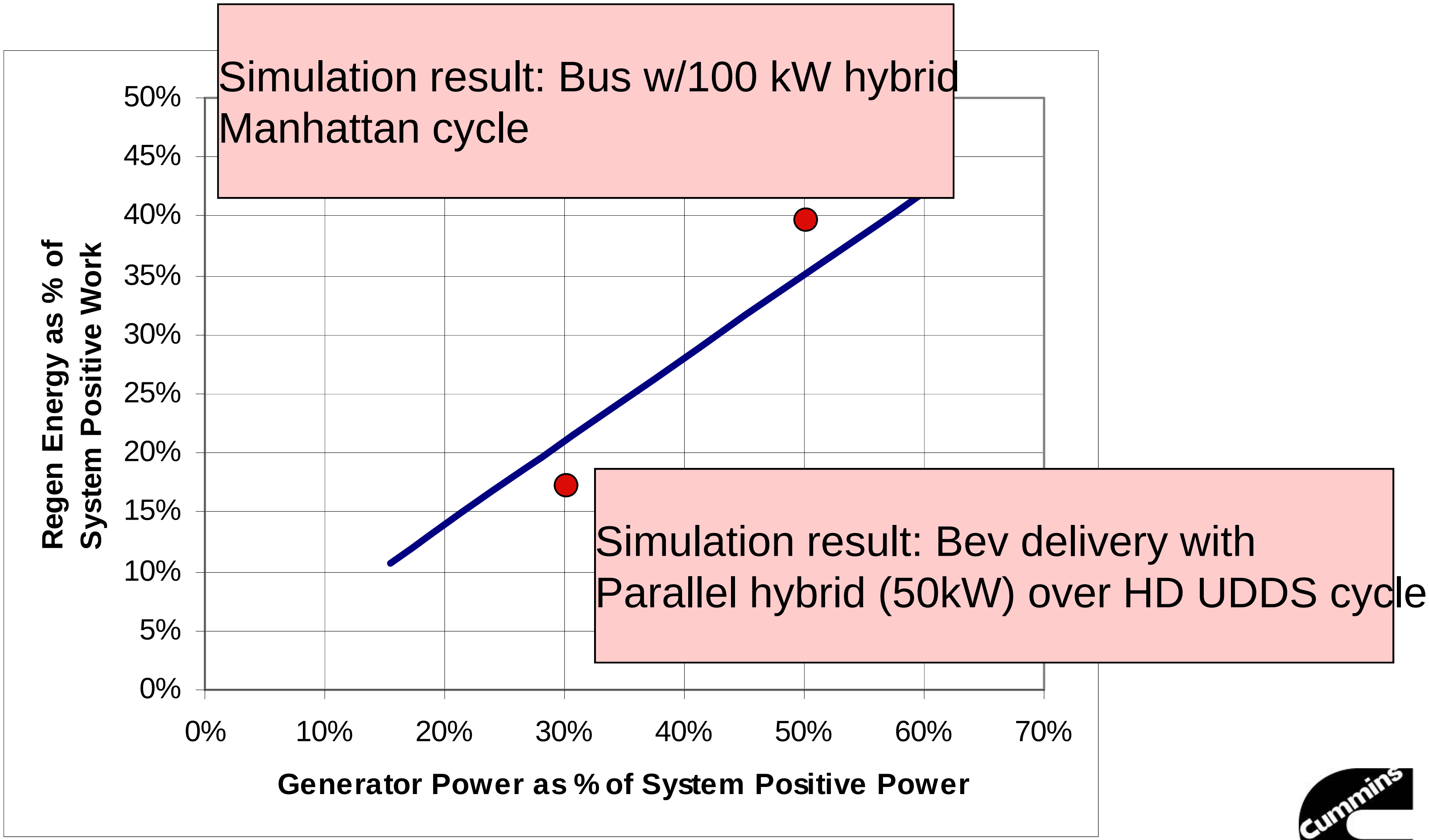
Vehicle speed vs. time will be consistent with FTP in terms of engine power requirements.

Strategies to Ensure Representative Regen Energy Capture

1. Allow capture up to capability of system
   - Economics will limit system size, which will limit energy captured
2. Place upper limit on energy captured over cycle based on available brake energy in real world cycles
   - Evaluate range of applications and duty cycles to determine appropriate level for brake energy
3. Calculate second-by-second available regen torque based on FTP

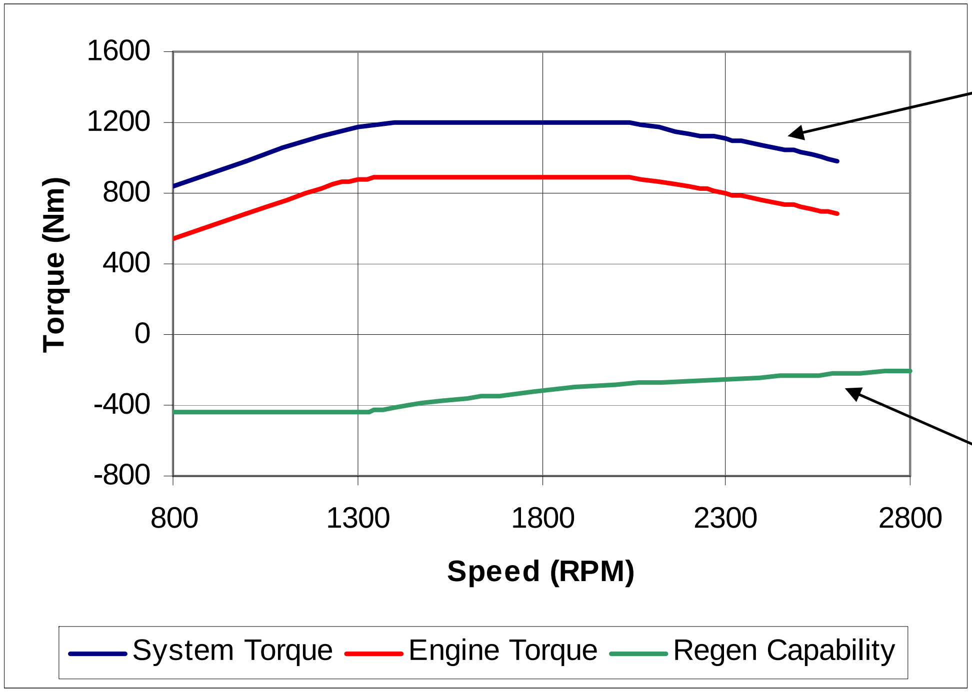
Allow capture up to capability of system

- Allowing energy capture during motoring portions of FTP results in reasonable matches with real world regen for many systems.



Allow capture up to capability of system

Example of system, engine, and regen torque curves

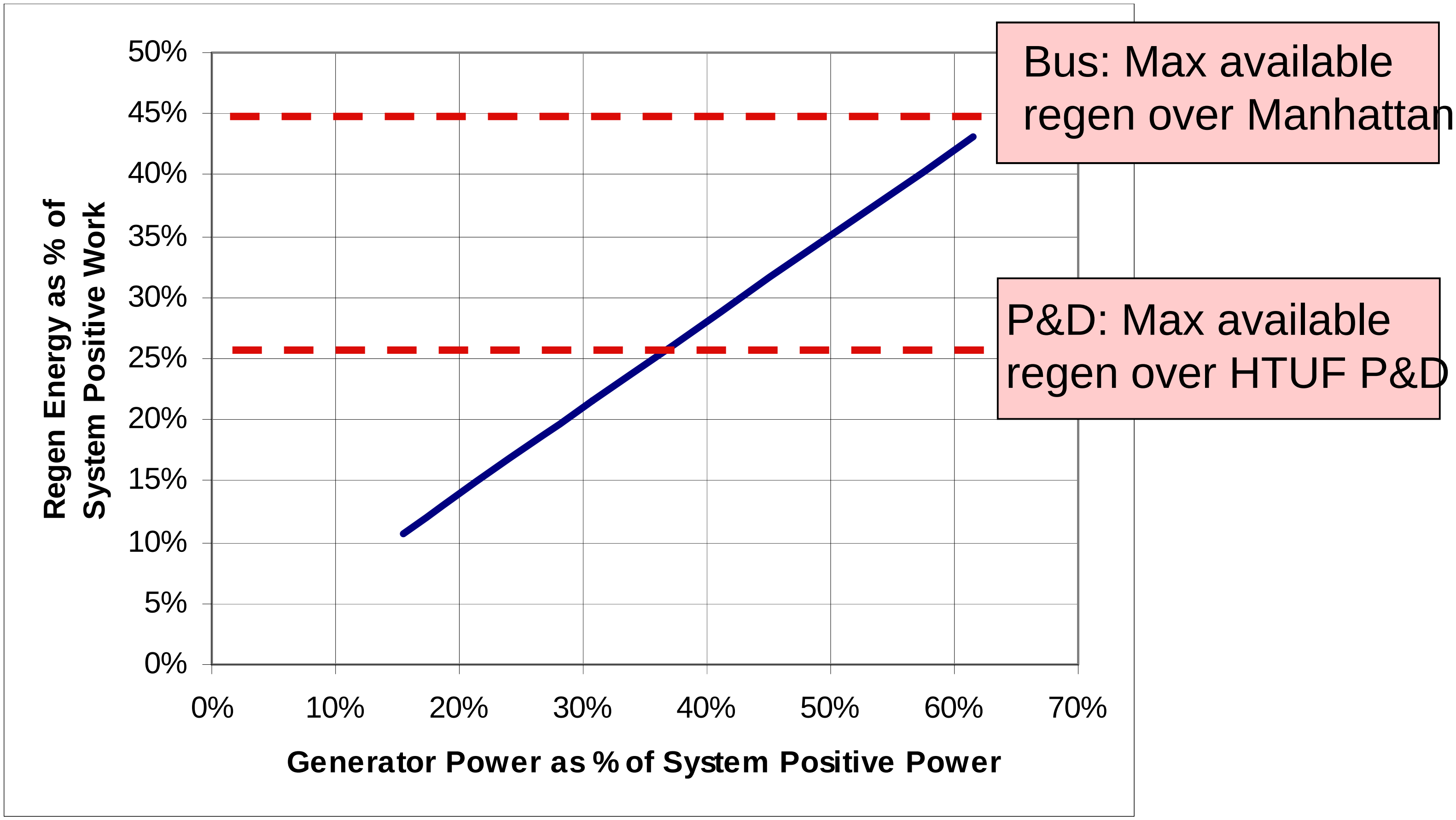


System torque curve defines positive FTP torque & speed requirements

Motor & battery capability define regen torque curve

During motoring portions of FTP, regen torque curve defines torque

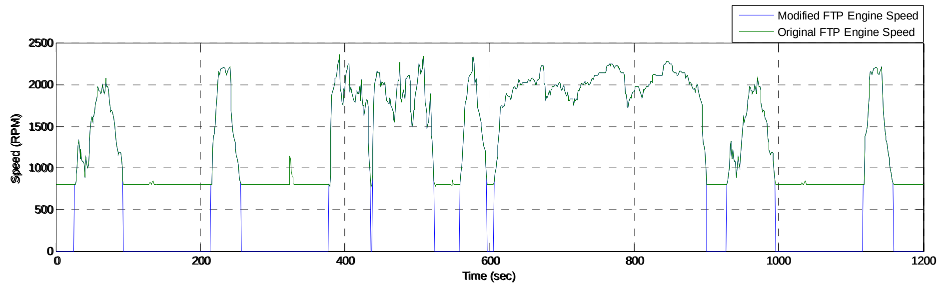
Place upper limit on energy captured over cycle based on available brake energy in real world cycles

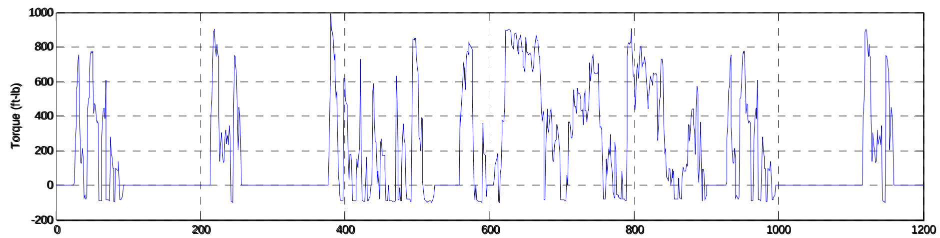


Strategies to Ensure Representative Regen Energy Capture: Calculation of Available Regen Energy

- FTP defines speed & torque – Power
  - Good match between FTP & real world vehicle power requirements
- By making an assumption on a typical vehicle for a given torque curve – it is possible to calculate a second-by-second regen energy limit.

Methodology





Example:

- Engine FTP Cycle to Vehicle FTP Cycle

- ISC 8.3L, 330hp Engine

- 55000 lbs vehicle

- Assumptions on frontal area, drag coefficient, rolling resistance, first gear & final drive ratio

- Assumption on coasting vs. braking regimes

FTP defines speed and torque requirements for engine

Acceleration: If engine torque positive, engine speed and torque can be used to determine power going to wheels to accelerate vehicle

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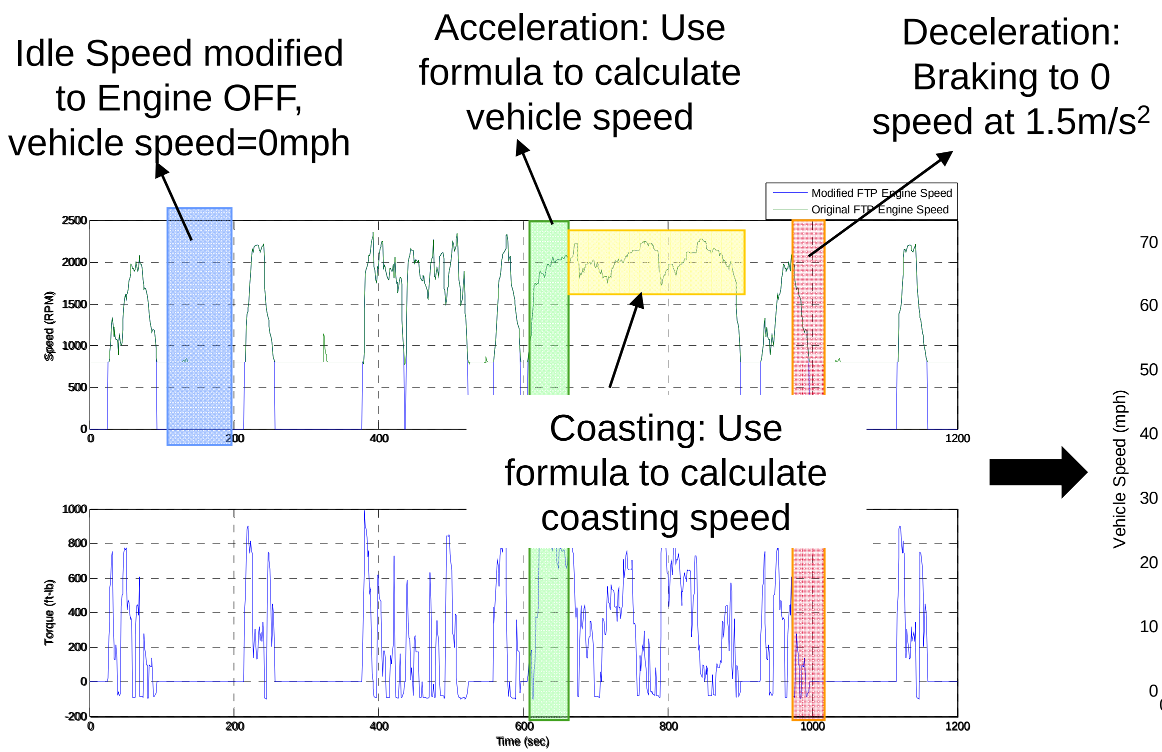
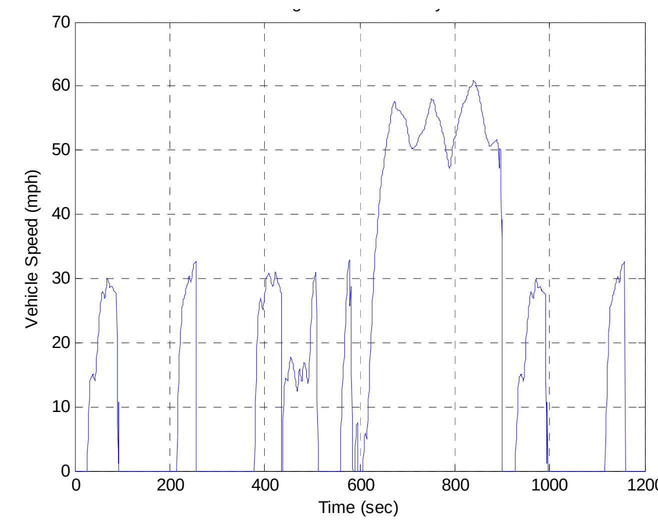
– If engine speed ~ constant assume coasting and calculate deceleration based on motoring engine torque.

– If engine speed decelerates quickly, assume braking at 1.5 m/s^2

Methodology





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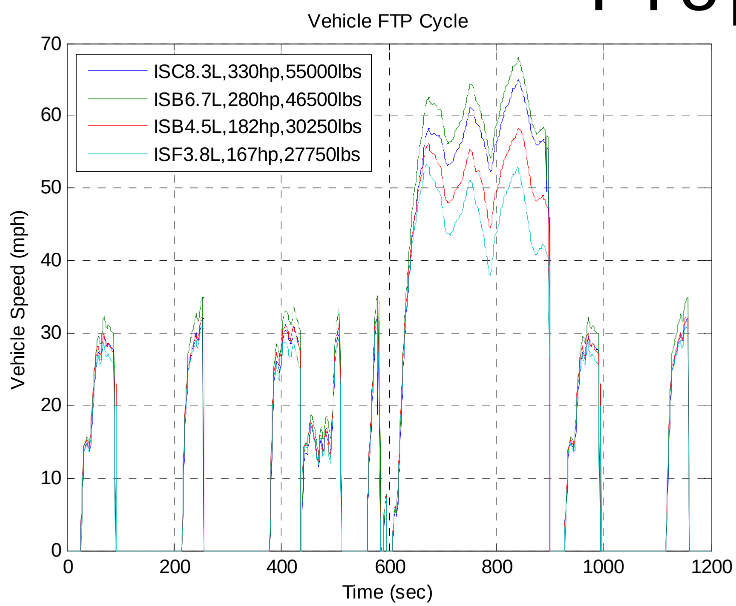
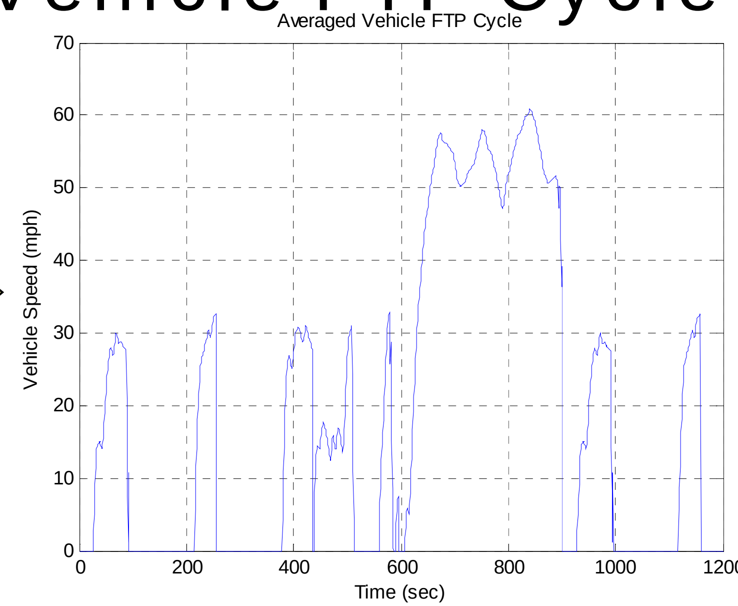
Proposed Vehicle FTP Cycle



Averaged

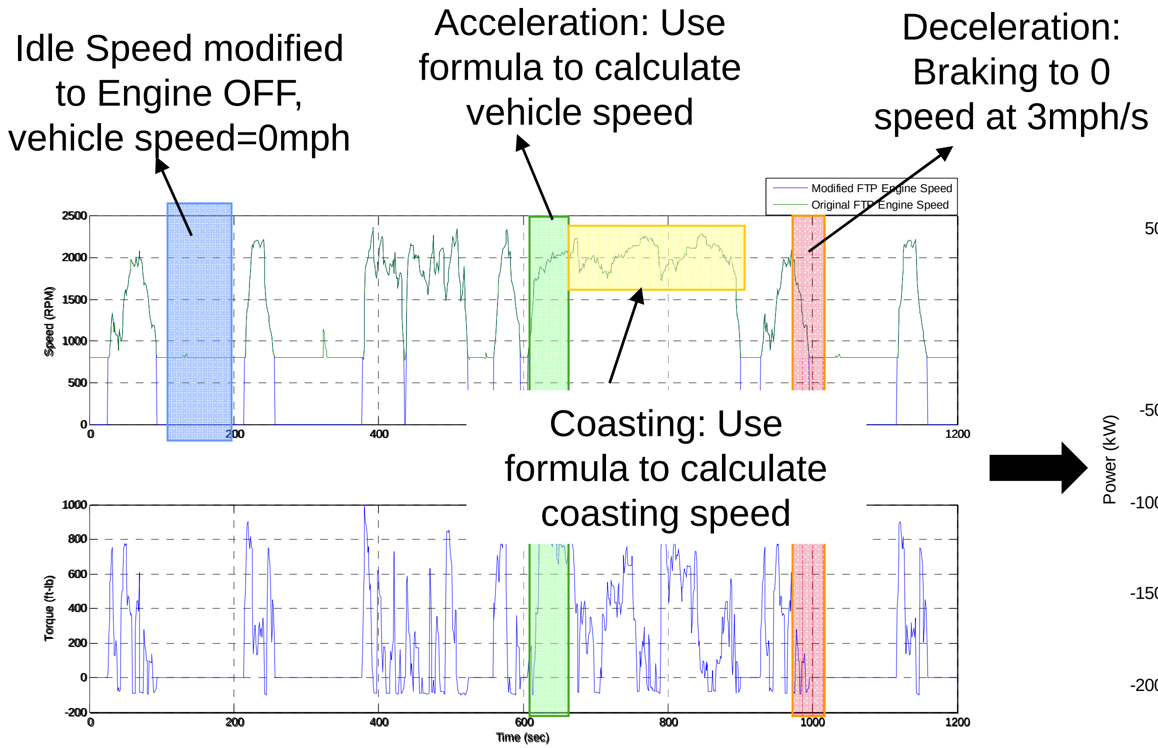


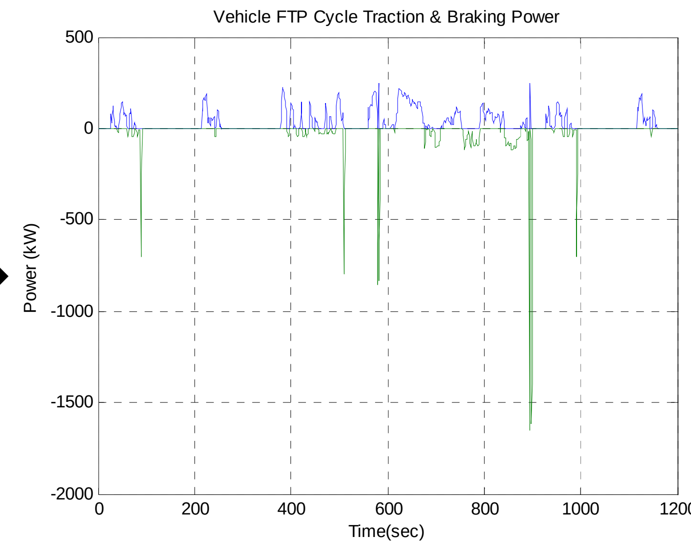
Brake Energy as % of +ve Traction Energy	
Engine for FTP	**Vehicle FTP**
3.8L	39.40
4.5L	39.72
6.7L	44.93
8.3L	45.92
Average	42.49

Matches with HD UDDS cycle potential of about 40 to 45% (based on application)

Conventional Engine FTP Cycle speed and torque can be used to define vehicle speed for Vehicle FTP Cycle

Methodology





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$$Braking\ Power = (M * Accel * V)_{when\ Accel<0}$$

$$Driving\ Power = (M * Accel * V)_{when\ Accel>0}$$

Deceleration: Engine torque negative

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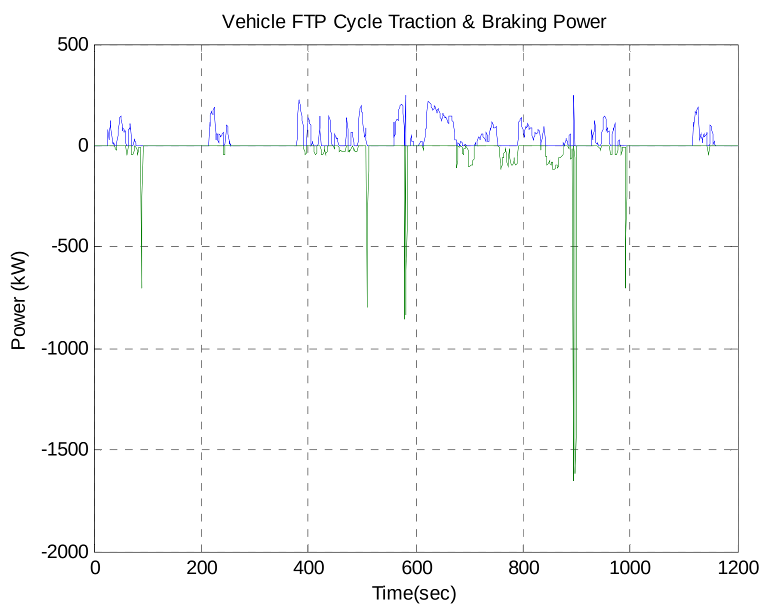
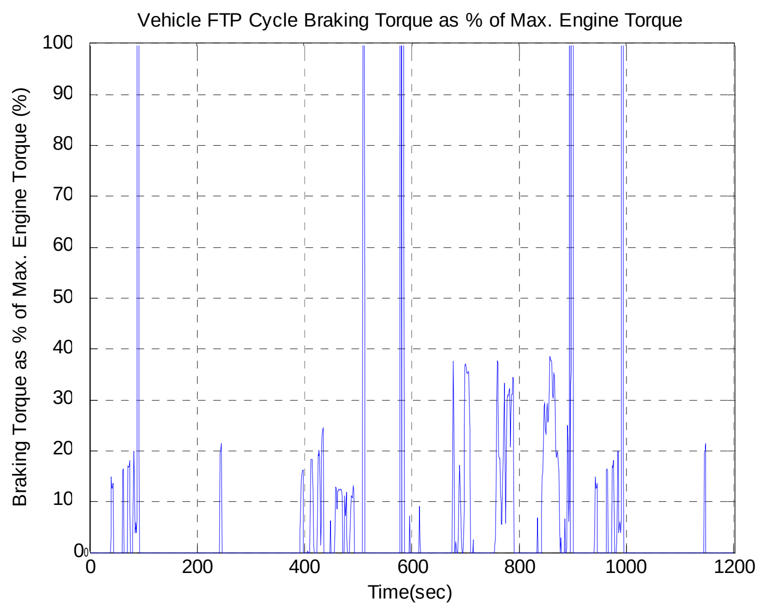
Available Regen Torque



Normalized



Conventional Engine FTP Cycle speed and torque can be used to define a brake limit for the Hybrid FTP Cycle