Regulation of emissions
from commercial hybrid vehicles

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I) Executive Summary

Hybrids yield significant fuel consumption reduction over conventional powertrains in part because the engine is used *less* and in part because the engine is operated *differently* than those in conventional vehicle powertrains. The ability to use the engine less and to operate the engine differently results from the interactions between the engine and hybrid components and the ability to decouple the engine operation from the vehicle speed and torque requirements. These interactions between engine and hybrid components affect criteria emissions output, in addition to reducing fuel consumption and CO_2 emissions. Because of these interactions, the engine and the hybrid components should be certified as a set, for both criteria and CO_2 emissions. This is the best way to get the most CO_2 reduction while maintaining strict controls over criteria emissions.

Dynamometer-based certification of engines has proven to be successful in achieving the desired reductions of criteria emissions output for a wide range of vehicles and applications. It makes sense to build upon the proven track record based on existing test procedures, test equipment and compliance and enforcement measures of the existing engine-based program to develop a hybrid CO_2 and criteria emissions regulatory program.

For pre-transmission parallel hybrid architectures, the hybrid powerpack (engine, motor-generator, battery, power electronics and hybrid controls) can be certified using the engine dynamometer based test procedure, along with a modified version of the FTP test cycle. This methodology can also be extended to create a post-transmission FTP test cycle that could then be used for all other hybrid configurations (e.g. transmission-integrated, post-transmission or series hybrids, to name a few).

This paper describes the hybrid powerpack certification concept and associated FTP-based test protocol in more detail.

II) Introduction

This paper is a follow-up to Cummins' paper titled "Framework for the Regulation of Greenhouse Gases from Commercial Vehicles" which was submitted in August 2009 in support of the National Academy of Sciences (NAS) study to assess fuel economy technologies in medium and heavy duty vehicles[1].
In that paper, a framework for the regulation of CO_2 was put forth that was based on two commercial vehicle segments: "Line Haul" and "Vocational".

- Separate engine performance standards are an important part of a successful regulatory program for commercial vehicles. When the regulations for criteria pollutants were first established, EPA faced the same diversity of medium- and heavy-duty applications and duty cycles as confronted for dealing with greenhouse gases and fuel efficiency today, and the Agency addressed them in a manner that created a solid foundation for future regulation – by establishing an engine-based regulatory program. Building upon the existing test procedures, test equipment and compliance and enforcement measures of the existing engine-based program will ensure robust introduction and acceptance of a future regulatory program.

- In Line Haul, the engine, vehicle and operation all play an important role in reducing CO_2 emissions. Consequently, the engine (the "Power Supply" or "Active" part of the system) and the vehicle (the "Power Demand" or "Passive part of the system) should be regulated. Because of the steady-state operation and the relatively low percentage of "stop and go" operation, hybrids are not typically utilized in this segment.

- Vocational vehicles experience lower average speeds and relatively low rolling resistance, resulting in the engine contributing the major CO_2 reduction potential. As a result, the engine (the "Active" part of the system) should be the most significant regulated entity for conventional Vocational applications.

- Because of the high percentage of "stop and go" operation, Vocational applications are ideal for hybrid powertrains. Hybrids introduce additional "Power Supply" or "Active" components into the powertrain which offer additional CO_2 reduction potential and which require hybrid specific certification. This paper builds on the Framework to develop a specific certification protocol for the "Power Supply" components of hybrid powertrains in Vocational applications.

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[1] See NAS Report: "Technologies and Approaches to Reducing Fuel Consumption of Medium and Heavy Duty Vehicles", 2010, National Academy Press

Hybrid Powertrains and Engine Operation

A hybrid powertrain has the capability to meet vehicle wheel and auxiliary power requirements from multiple sources. The hybrid system commonly includes an internal combustion engine, and an electrical power system (battery, power electronics and motor) or hydraulic power system (hydraulic energy storage and pump). Hybrids reduce fuel consumption by capturing and storing vehicle braking energy[2] which is then utilized later to meet vehicle power requirements – allowing the engine to be operated less and to be operated differently than conventionally.

Fundamentally, hybrids achieve fuel consumption reduction through modification of engine operation. Hybrid powertrains allow engine operation to be decoupled from the vehicle power requirements, thereby affecting the traditional relationship between engine output and the work accomplished by the vehicle. The use of stored braking energy allows a reduction in engine work while meeting the same vehicle power requirements. Additionally, hybrids present an opportunity to modify engine operation to meet power requirements in a more efficient way. Consequently, the hybrid engine duty cycle can be significantly different from the conventional engine duty cycle. The changes in engine duty cycle impact both CO_2 and criteria emissions.

The hybrid engine duty cycle can include reduced cycle work, the ability to start and stop the engine independently from vehicle power requirements, increased average load and the opportunity to manage transient loads and exhaust temperatures. Figure 1 depicts engine torque for an engine in a conventional powertrain (blue curve) over a portion of a vehicle duty cycle, and engine torque for a hybrid powertrain (red curve) over the same vehicle duty cycle. In the hybrid case, the engine torque has been managed to reduce transients, reduce peaks and eliminate low load and idle operation. The capability of the hybrid system to capture braking energy and modify engine operation will impact the fuel consumption reduction and impact criteria emissions.

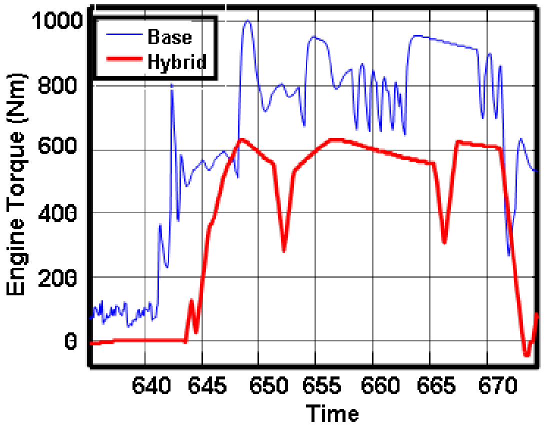

Figure 1: Engine Torque in Conventional Vehicle versus Hybrid Vehicle.

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[2] Regenerative braking is the process of using the generator to slow or stop the vehicle, instead of using the standard friction brakes. Electricity is generated as the generator slows the vehicle.

III) Certification and Hybrid Powertrains

The regulation of CO_2 emissions from hybrid powered vehicles is complex. The EPA and industry faced similar complexity in the late 1970s in addressing engine criteria emissions across a wide range of vehicle applications, duty cycles and engine technologies[3]. The issue was resolved by creating a laboratory engine test cycle that was synthesized from actual operating data taken over a number of representative duty cycles, vehicles and engines. While the Federal Test Procedure (FTP) was not specifically representative of an individual duty cycle, it was deemed adequately representative of all of them. This approach, essentially "engine-in-the-loop simulation", has been used to successfully regulate criteria pollutants since the late 1980s.

This paper presents an analysis of how the essential elements of the FTP can be used to regulate CO_2 and criteria emissions from hybrid powertrains using an engine dynamometer based certification of the "Active" components of the hybrid system (these are also known as the powerpack – see the next section for more explanation of the powerpack concept). There are several advantages to developing a hybrid test protocol by building on the existing FTP base:

- Using the existing emissions structure for CO_2 removes the significant overhead associated with developing a new regulation from scratch.
- Building on the existing framework enables use of current regulatory protocols such as test procedures, production line and in-use compliance audits, averaging, banking and trading flexibility, family emissions levels and emissions useful life.
- Regulating the powerpack allows companies to certify a single hybrid system for a wide variety of vehicles which lowers cost and increases adoption of hybrids in the marketplace while utilizing a proven robust process to certify and regulate CO_2 and criteria emissions.

As previously mentioned, the FTP criteria pollutants certification cycle is a reasonable approximation of engine operation in conventional powertrains. Because of the interactions between the engine and other active power supply components of the hybrid system, the resulting engine operation *in a hybrid application* can be very different from the traditional engine certification cycle. If the hybrid engine duty cycle is significantly different from the certification cycle, then the certification cycle results will not be representative of its fuel efficiency or its CO_2 or criteria emissions in real world operation.

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[3] Refer to Cummins' 2009 white paper for more thorough explanation of the history of emissions regulation and the suitability of the FTP and SET cycles.

Applying an engine that has been dynamometer certified for conventional powertrain in a hybrid powertrain can result in unintended CO_2 and criteria emissions output. Figure 2 illustrates results from an NREL study that quantify this aspect. The tests resulted in 25% reduction in CO_2 emissions with an accompanying 29% increase in NOx emissions.

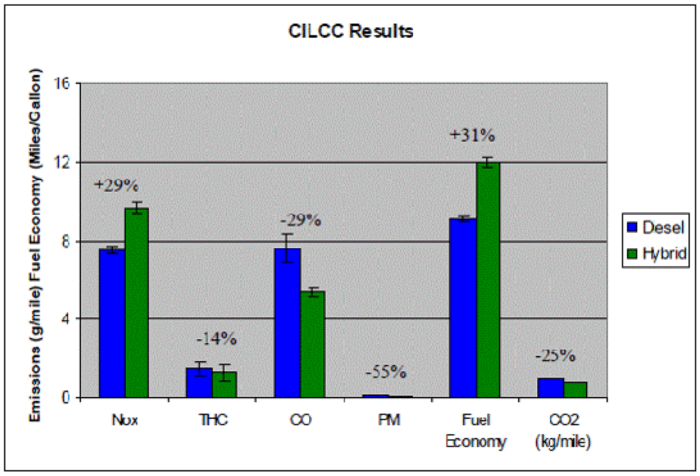

Figure 2: NREL study showing a decrease in CO_2 with accompanying increase in Nox.

An unrepresentative certification duty cycle can result in an engine designed to meet the certification requirements but does not perform to the standard in the real world. In the figure below, point A1 represents the CO_2 and criteria emission level of a conventional engine which has been dynamometer certified for use in a conventional powertrain and then applied in a conventional powertrain. For this case, the certified emission levels and in-use emission levels match. Point A2 represents the case where the same conventional engine is applied in a hybrid powertrain. Because the certification duty cycle is not representative of how the engine operates in the hybrid powertrain, the in-use criteria levels (A2) are not likely to match the certified levels (A1).

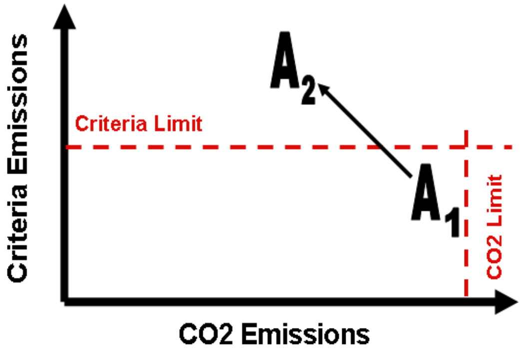

Figure 3: Relationship between CO_2 and criteria emissions when engine is certified for conventional and then applied in hybrid application.

Hybrid Certification for CO_2 and Criteria Emissions

The appropriate system-level certification protocol will ensure that in-use criteria emissions meet the standards and will also ensure that certification optimization efforts are properly focused. There are two critical elements to appropriate hybrid certification:

1) Alignment of certification cycle and real world operation (i.e. representative duty cycle)
2) Alignment of CO_2 and criteria emissions (i.e. CO_2 and criteria emissions determined on the same duty cycle)

For hybrid powertrains, one representative certification duty cycle for both CO_2 and criteria emissions would not only ensure low criteria emissions, but it could also enable additional CO_2 emissions reductions beyond what is possible today (reference point B1, 2 in Figure 4, below).

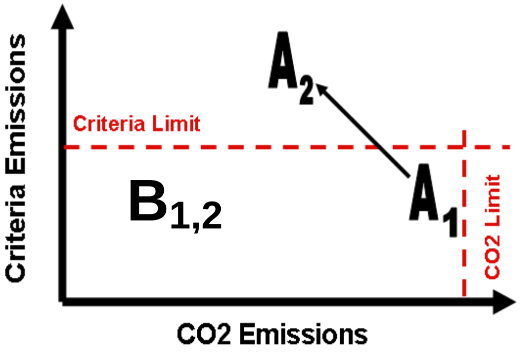

Figure 4: Certification of CO_2 and Criteria allows reduction in CO_2 while maintaining Criteria levels (point B1, 2).

- A1) Conventional engine certification result
- A2) Real world result when traditionally certified engine is applied to hybrid
- B1) Hybrid certification result
- B2) Real world hybrid result with appropriate certification

The additional reductions in CO_2 would be possible through optimization of engine hardware and calibration for hybrid engine duty cycles. Estimates of these benefits range from 5-10% additional fuel consumption improvement and hardware cost reductions – both of which could contribute to increased hybrid technology adoption.

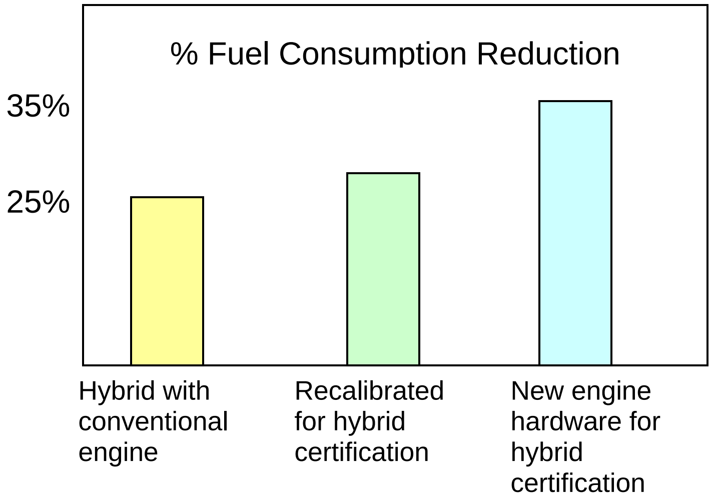

Figure 5: CO_2 Benefit Associated With Combined CO_2 and Criteria Certification.

One example of potential hybrid engine optimization is the selection of a turbocharger. In a conventional powertrain, the engine duty cycle will require fast transient torque response. In a hybrid powertrain, the torque capability of an electric motor might reduce engine transient torque requirements. A reduction in transient engine torque requirements could enable the selection of a larger turbocharger frame size for improved efficiency with slower engine response but equivalent power system response.

An appropriate hybrid certification procedure will allow evaluation of CO_2 and criteria emissions in a way that is representative of how the system will operate in the real world. This will require consideration of not only the engine but also hybrid components like energy storage (batteries) and energy conversion devices (motor, pumps, converters).

IV) Hybrid Powerpack Certification

This paper suggests a hybrid certification procedure, hybrid powerpack certification, which can provide representative evaluation for CO_2 and criteria emissions for hybrid powertrains. This concept is very attractive for pre-transmission hybrids, which will likely be a majority of the systems in the market in the future. Powerpack certification for pre-transmission hybrids would properly evaluate performance and would allow application of hybrid systems to a wide range of applications based on a single certification – as is the case with conventional engines.

Review of Existing HD Criteria Certification Framework

Consider a vehicle fitted with a conventional powertrain, as shown in Figure 6.

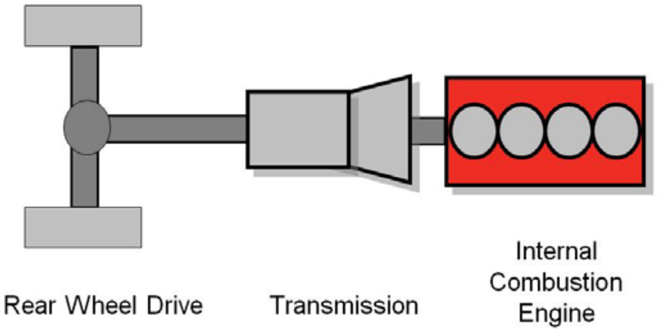

Figure 6: Conventional Powertrain.

The vehicle power is a function of the vehicle and the vehicle drive cycle. The engine speed and torque output are the same as the speed and torque input to the transmission. For the conventional power requirements, the engine is the only component which can meet vehicle power requirements.

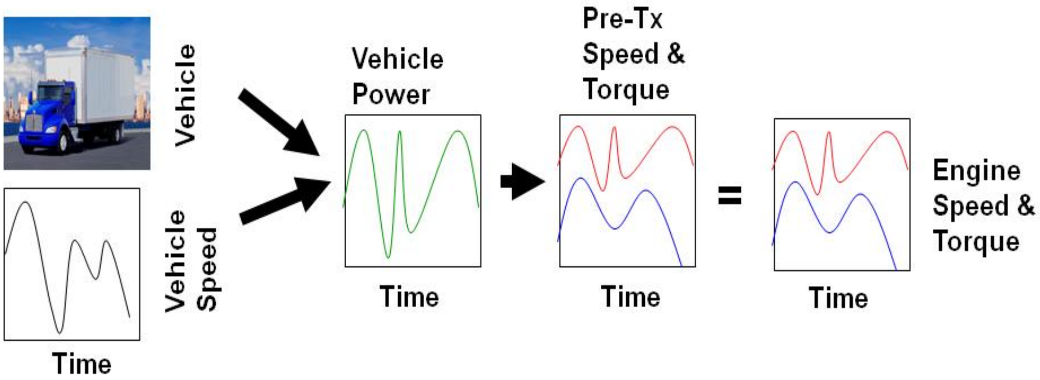

Figure 7: Conventional Vehicle - Pre-Transmission (Pre-Tx) Speed and Torque = Engine Speed and Torque.

Conventional engines are dynamometer certified for criteria emissions using FTP and SET protocols. The certified engine can be installed in many different vehicles. The certified engine operation will meet the criteria emission standards across a range of applications because as previously noted, the certification cycles take into account a representative range of vehicle characteristics and drive cycles. The certification cycles define normalized torque which scales with each particular engine torque curve, assuring that the cycle will be appropriate for a given engine. This approach works well for the commercial market because it provides representative evaluation and reduces certification proliferation.

Now consider the same vehicle and drive cycle, but this time fitted with an engine and hybrid system, as shown in Figure 8 below.

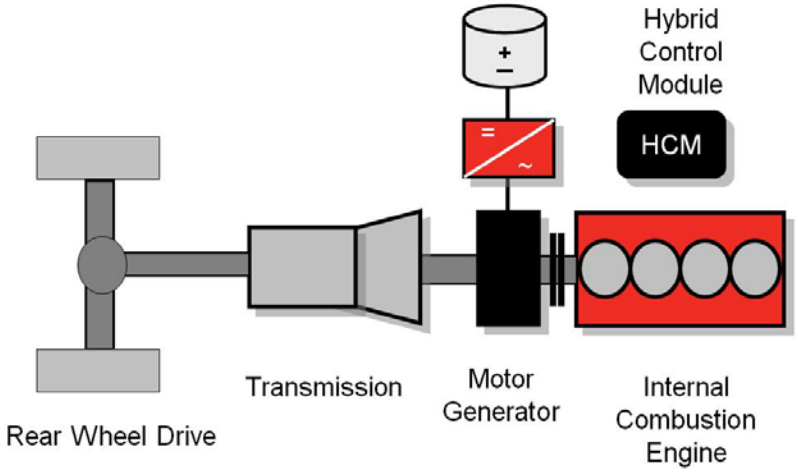

Figure 8: Pre-Transmission Hybrid Configuration.

The engine and hybrid drive both have capability of delivering power to the wheels or deliver power to meet auxiliary power requirements. Both are responsive to operational demands and have complex and active control systems that adjust many parameters dynamically during operation. They are also both controlled by a Hybrid Control Module (HCM) that determines the instantaneous proportion of power to be delivered from the engine and from the hybrid drive motor to meet the instantaneous power requirement of the vehicle.

In a hybrid system, the engine burns less fuel and produces less CO_2, not only because it does less work but also because it is operating differently. The engine speed and torque are no longer equal to the speed and torque input to transmission because of the other active components in the system.

In Figure 9, below, the standard FTP accurately describes the vehicle power requirements, but no longer accurately describes the engine-only speed and torque. In other words, the vehicle power requirements are the same for conventional and hybrid vehicles: both accelerate and decelerate at the same rates, and in both cases auxiliary power requirements must be met. For a pre-transmission hybrid, the FTP would accurately describe the transmission input positive power requirements.

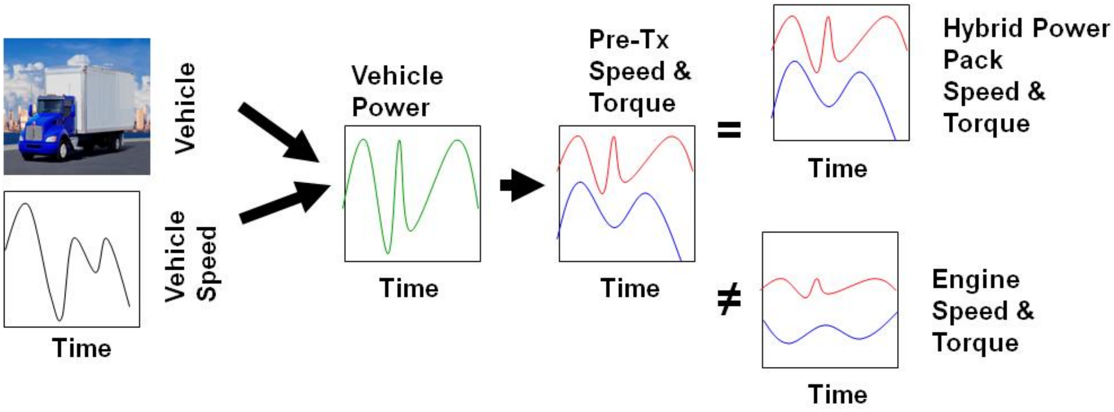

Figure 9: Hybrid Application - Pre-Transmission (Pre-Tx) Speed and Torque = Hybrid System Output Speed and Torque; but Pre-Tx Speed and Torque does not equal Engine Speed & Torque for Hybrid.

The hybrid powerpack certification concept would certify pre-transmission powertrain systems by building on existing heavy-duty engine dynamometer certification procedures, and in particular the FTP Transient test.

Dynamometer certification of hybrid powerpack

The powerpack concept will allow certification of the hybrid powerpack on the engine dynamometer, using a modified version of the FTP test protocol. Figure 10 shows a pre-transmission parallel hybrid.

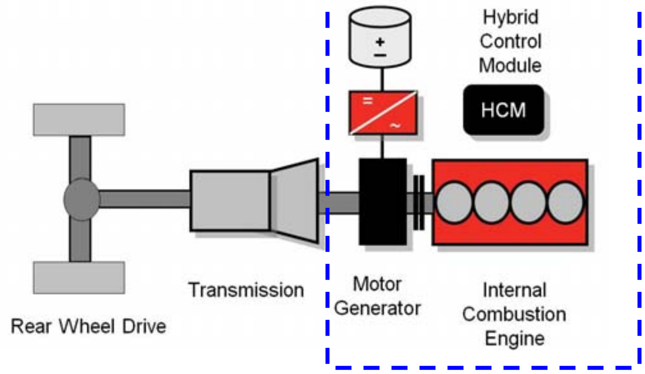

Figure 10: Hybrid Powertrain (Powerpack components outlined in blue dashed area).

The powerpack output shaft will experience the same positive torque and speed requirements as the output shaft of the engine experiences in conventional vehicles. The vehicles, missions and drive cycles have not changed.

This certification protocol would test the physical hardware of the powerpack, in a test cell, for both criteria and CO_2 emissions, utilizing a modified FTP process. Because powerpack components are part of the certification package, they would be subject to On-Board Diagnostics (OBD) requirements.

Hybrid powerpack certification would require some modifications to the engine-only FTP certification. At a high level, these changes fall into four areas:

A. The powerpack system torque curve defines the cycle, not just the engine torque curve.
B. Allow zero engine speed during the idle portions of the FTP.
C. Use only the positive work output in the calculation of cycle work (as is the case in conventional engines).
D. Allow capture of energy during the “motoring” portions of the FTP as reasonable approximation of the regenerative braking that will occur in-use.

A) Powerpack system torque capability defines the cycle

The FTP transient cycle was developed for engine certification based on data from a range of vehicles and provides a representative description of engine operation for a conventional powertrain. The FTP defines speed and torque versus time as a function of the engine torque curve. As vehicle size and power requirements change by application, engine torque curves change and the FTP speed and torque change.

Hybrid vehicles have the same duty cycles as vehicles with conventional powertrains (hybrid buses drive the same routes as conventionally powered buses). For a given vehicle, the positive torque input to the transmission will be defined by the driving requirements and will be the same for conventional powertrains and for pre-transmission hybrids. The critical difference is that in the pre-transmission hybrid case, speed and torque requirements are met by the hybrid system instead of by the engine alone. The powerpack certification concept proposes to use the hybrid system to meet the FTP torque and speed requirements, so it follows that the system torque curve should define the cycle and not the engine alone.

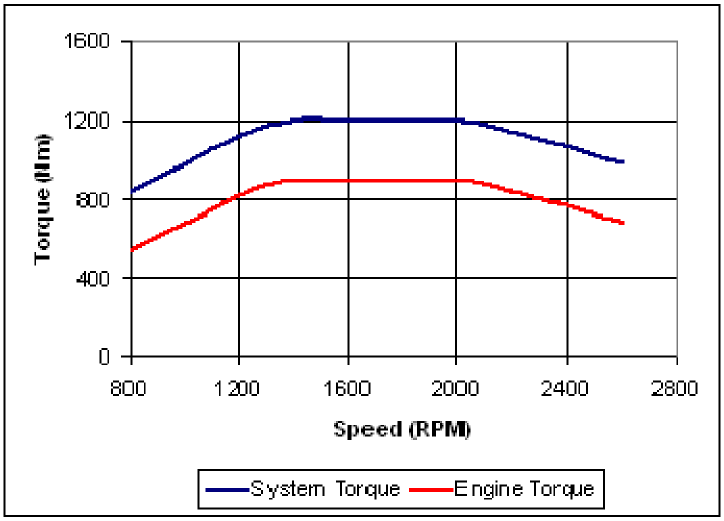

Figure 11: Example of a system torque curve and engine torque curve. The system torque curve exceeds the engine torque curve because of the additional torque provided by the hybrid system (motor, battery, etc.).

B) Allow zero speed during the idle portions of the FTP.

The FTP contains operating conditions that simulate when the vehicle is at rest and the engine is idling (e.g. at a stop light). In the conventional FTP, the engine goes to idle speed for this portion of the test.

Hybrid vehicle duty cycles also contain portions where the vehicle is at rest. Some hybrids take advantage of this reduced vehicle power demand to turn off the engine to reduce fuel consumption. During these zero vehicle speed conditions, if the engine is turned off, the transmission input speed is zero. The alternative power source (most commonly a battery) can meet auxiliary power demands in these circumstances while the engine is off. For the hybrid FTP, it is appropriate to allow the option for the transmission input speed to go to zero during the “idle” portions, as would be the case in the real world.

C) Use only the positive work output (as is the case in conventional engines)

In a traditional FTP test, the work is calculated by integrating the positive work over the cycle, and motoring work (negative work) is not included. Emissions levels are calculated by dividing the total emissions by the positive work and have units of g/hp-hr.

In the powerpack FTP, the emissions calculation should be conducted in the same way as for a traditional engine. That is, the emissions output should be divided by the positive work done. Motoring work is not included in the traditional

FTP calculation and similarly negative work should not be included in this calculation (see Appendix B for further discussion).

D) Allow capture of energy during the "motoring" portions of the FTP as a reasonable approximation of the regenerative braking that will occur in-use

Since the FTP cycle was derived from actual in-use operation of real vehicles, the FTP contains engine operation consistent with a range of vehicle operation – including deceleration (braking / motoring). While the FTP does include a complete description of the positive power required by a vehicle for propulsion, it does not include information related to friction braking requirements. The motoring portions of the FTP properly describe the negative torque that an engine would supply to a transmission, but the FTP does not include the additional negative torque applied to the wheels by the brakes.

In a pre-transmission hybrid, the hybrid system can in many cases supply negative torque to the wheels that exceeds the negative torque of engine motoring. In a hybrid powertrain braking energy is captured, stored and re-used to displace engine operation and reduce fuel consumption. During the motoring portions of the FTP, the powerpack could capture and store energy – in the same way regenerative energy is captured during a vehicle braking event. All critical components would perform in the same manner in the test cell as in real world operation (motor/generator, engine, power electronics, battery and controllers).

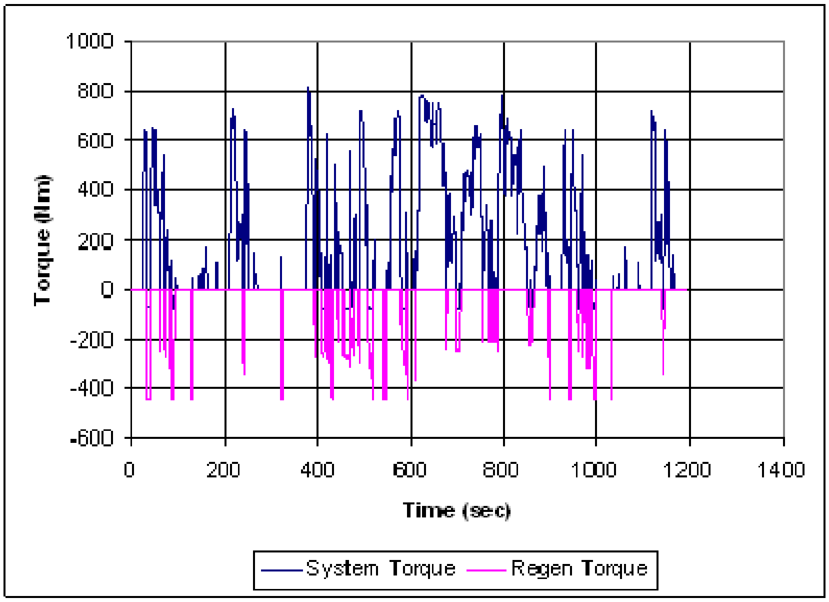

Figure 12: Example of hybrid power pack torque over the FTP. Negative torque during motoring portions of FTP is defined by capability of motor and battery.

To ensure that the actual amount of regenerative energy is representative, the generator, batteries and controls all need to be part of the system under test and the battery state of charge at the end of the tests needs to be the same as the beginning of the test.

The amount of energy to be captured during the motoring portion of the FTP can be limited in one of the following three methods:

1. Allow capture up to capability of system
2. Place upper limit on energy captured over cycle based on available brake energy in real world cycles
3. Calculate second-by-second available regeneration torque based on FTP

These methods for capturing energy during the motoring portion of the FTP are discussed in more detail in Appendix A.

It is important to note that method 3 (calculate second-by-second available regeneration torque based on FTP) can also be utilized to develop a post-transmission test cycle that is also based on the FTP. This test cycle could be useful to certify other hybrid architectures (transmission integrated parallel systems, post-transmission systems and series hybrid systems, to name a few).

Powerpack Certification Performance vs. In-Use Performance

Powerpack certification will ensure representative evaluation of the system that accounts for interaction of hybrid components and engine. Component operation over the hybrid FTP cycle will be consistent with operation in the real world, as long as the system duty cycle in the real world is consistent with the FTP cycle. The FTP transient cycle was developed to be a representative duty cycle for a range of applications for engines in conventional powertrains – so it is also a representative duty cycle for pre-transmission hybrid systems. However, the added complexity of hybrid powertrains may raise concerns that hybrid operation in-use may differ from certification operation.

There are a couple of ways to address this concern.

- First, all hybrid components would be tested in hardware in the certification test and so could be subject to OBD requirements. OBD requirements would ensure that all hybrid components (engine, battery, power electronics, motor, etc.) function properly in-use.
- Second, all conventional engines are subject to in-use requirements to ensure that real world performance is consistent with certification results. Similar in-use requirements could be applied to powerpack performance.

These additional requirements would ensure that powerpack operation would be evaluated over a wide range of conditions, covering real world operation over a range of duty cycles. These same procedures are adequate for conventional engine certification and so would also be appropriate for powerpack certification.

V) Summary

New certification procedures are needed to properly evaluate hybrid system performance in commercial vehicles. Today, only engine certification is required in the heavy-duty market. The FTP duty cycle is representative of engine operation in a conventional powertrain. However, engine operation in hybrid systems can differ significantly as compared to conventional engine operation. The CO_2 and criteria emissions measured on a hybrid engine using conventional engine certification FTP duty cycle may not be representative of actual in-use emissions.

An appropriate certification procedure would capture interactions between all hybrid system components including engine, motor, battery and other components. Using the same duty cycle representative of in-use operation for both CO_2 and criteria emissions will ensure that criteria emissions in-use meet expectations and that fuel consumption optimization efforts are properly focused.

The hybrid powerpack certification procedure would test all pre-transmission hybrid components in hardware. The procedure would build on existing engine dynamometer certification procedures, using the hybrid components and engine to meet the FTP transient test requirements. Some minor modifications of existing procedures would be required, including allowing the capture of energy during the motoring portions of the FTP to approximate regenerative braking. A variety of options exist to ensure that regenerative braking energy is consistent with in-use operation.

The powerpack certification, by testing all components in the test cell, would ensure all interactions between hybrid components and engine were properly evaluated for both CO_2 and criteria emissions. Procedures that are available to ensure conventional engine performance (OBD, in-use, etc.) could be applied to powerpack certification.

Powerpack certification would be attractive and could be applicable to all hybrid architectures. The strategy could enable additional CO_2 reduction above what is possible today, reduce hardware cost, and thereby speed of adoption of hybrid technology to reduce fuel consumption and CO_2 emissions.

VI: APPENDIX A - Capture of Energy During Hybrid FTP

The capture of braking energy presents the largest opportunity for hybrid fuel consumption reduction. For the powerpack certification concept, hybrid regenerative braking can be approximated by allowing the capture of energy during the motoring portions of the FTP cycle. During the motoring portions of the cycle, the hybrid motor would act as a generator and send energy to the energy storage device. For a pre-transmission hybrid (powerpack), the components would function in the same way during the FTP as they would in the real world. One potential concern is that the amount of energy captured during the FTP might not be representative of what would be available in vehicle operation.

In the existing HD Transient FTP dynamometer cycle, positive torque is defined by the torque curve, while negative torque is defined by the engine motoring torque. While the FTP accurately describes vehicle positive power requirements, it does not offer a complete description of vehicle negative torque: the FTP does not include a description of vehicle friction braking. If negative torque is limited to conventional engine motoring torque, the total available braking energy will be potentially under-estimated. If the negative torque is not limited, it might be possible to capture too much energy. This proposal identifies three potential options for ensuring that powerpack energy capture during the FTP is consistent with real world regenerative braking:

1) Energy capture will be limited by system capabilities, and economics will drive appropriate matching between system and real world applications.

2) An upper limit for energy capture could be defined as a fraction of the positive traction work. Evaluation of a range vehicle applications and drive cycles could provide an appropriate limit.

3) Available regen torque could be defined second-by-second based on the FTP.

1) System capability constrains energy capture

The simplest strategy would be to allow energy capture during the motoring portions of the FTP up to the capability of the hybrid system. A hybrid system with a smaller motor or battery would be able to capture less energy as compared to a system with larger motor and battery. A convenient way to describe the available energy in the motoring portions of the FTP is by comparing captured energy to positive traction energy as a function of the positive and negative power capabilities. A comparison of available FTP energy and real world regenerative braking energy (PSAT simulation) shows a reasonable match.

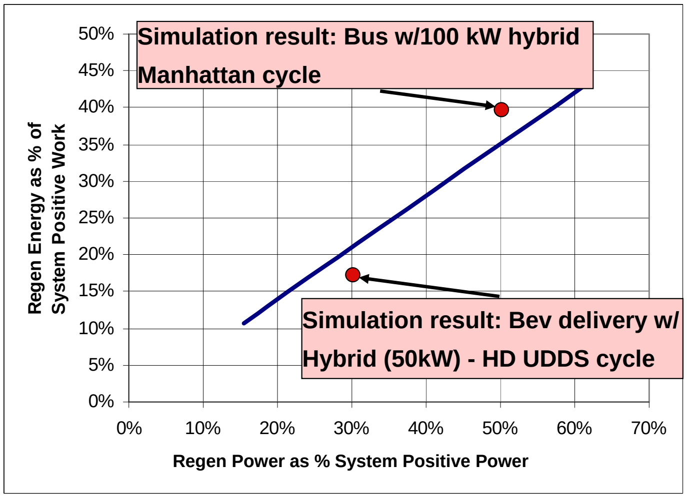

Figure 13: Regenerative Energy as a Fraction of Positive Traction Energy versus Regenerative Power as a Fraction of System Positive Power.

In Figure 13 the blue line shows regenerative energy as a fraction of positive traction energy vs. regen power as a fraction of system positive power. As the size of the motor/generator & battery increases with respect to the system positive power, the regen energy captured would increase as well. For a system capable of outputting 100 kW of traction power (engine + motor), and capable of capturing 25 kW of regenerative braking (25 kW battery), the amount of regen energy captured on the FTP would be equal to approximately 17% of the positive traction work. For a 100 kW traction power system with 50 kW of regen power, energy capture in the FTP would be approximately 35% of the positive work.

Also shown in Figure 13 are simulation results for two cases: a hybrid bus with 100 kW pre-transmission parallel hybrid system over the Manhattan cycle, and beverage delivery vehicle with a 50 kW pre-transmission parallel hybrid system over the HD UDDS drive cycle. In both cases, the energy captured in the FTP happens to match the simulation results for real world operation quite well.

Although this approach does appear to give reasonable results for the two cases shown, it is possible to imagine a hybrid system with a very large electric motor and battery that would capture an unrealistic amount of energy over the motoring portions of the FTP. However, just as is the case with conventional powertrains, economics will drive appropriate matching of hybrid system capability (and size) to applications.

2) Define maximum available regenerative energy

An alternative approach could define an upper limit for available regenerative energy over the FTP. Each system would maximize energy capture over the FTP up to the limit. The limit would be defined based on evaluation of available braking energy in real world operation.

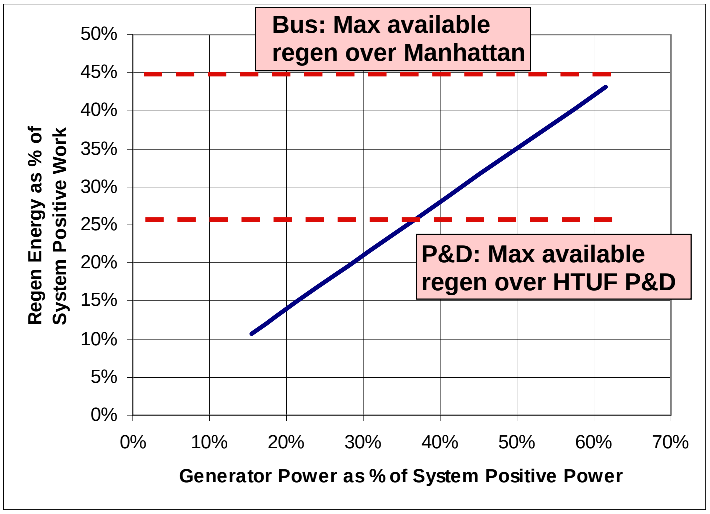

Figure 14: Using a pre-defined limit for the maximum available regenerative energy, based on an evaluation of the available braking energy in real world applications.

The amount of available brake energy will depend on the vehicle and drive cycle. Figure 14 shows available brake energy for a city bus over the Manhattan cycle, and a delivery vehicle over the HTUF P&D cycle (red dashed lines).

In this scenario, a hybrid system would capture energy during the motoring portions of the FTP up to the capability of the system or the limit. Setting an upper limit to available regen energy would ensure that energy capture never exceeds the amount of energy available in the real world.

3) Use FTP to define available regen torque

The third option would define available regen torque second-by-second for the FTP. This approach would link the FTP to vehicle kinetic energy and ensure that available regen energy was constrained appropriately. Although the existing HD FTP dynamometer test is an engine test, it is based on vehicle data. The FTP defines engine speed and torque that is representative of a range of applications for conventional powertrains. The engine power meets vehicle power demands, and so with a few assumptions it is possible to calculate vehicle behavior based on the FTP. This calculation of vehicle behavior can then be used to calculate available regen energy.

The calculation assumes that FTP defined power is used to meet vehicle power demand. By selecting vehicle characteristics, it is possible to calculate the fraction of engine power that is needed to overcome rolling resistance, aerodynamic drag, driveline losses and accessory loads. The remainder accelerates the vehicle, and in this way vehicle speed can be calculated based on power.

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

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

In addition to vehicle assumptions, several cycle assumptions are necessary. The FTP gives a reasonable prediction of positive power requirements for vehicles, but as noted does not include friction braking. Therefore, some assumptions are necessary to calculate deceleration rates. In particular:

1) Vehicle speed is assumed to be zero during portions of FTP which contain extended idling.
2) Vehicle is assumed to use friction brakes to decelerate to zero speed. An average deceleration rate of 1.5 m/s^2 is assumed.
3) During motoring portions not leading to zero vehicle speed, the vehicle is assumed to coast down (no friction brakes, only engine friction to slow vehicle).

Figure 15 shows the FTP speed and torque for an engine, and assumptions are highlighted. During the acceleration and coast down portions of the cycle, the vehicle acceleration is calculated based on the power and vehicle characteristics. During idle, vehicle speed is zero, and during deceleration to zero speed a constant deceleration rate is assumed.

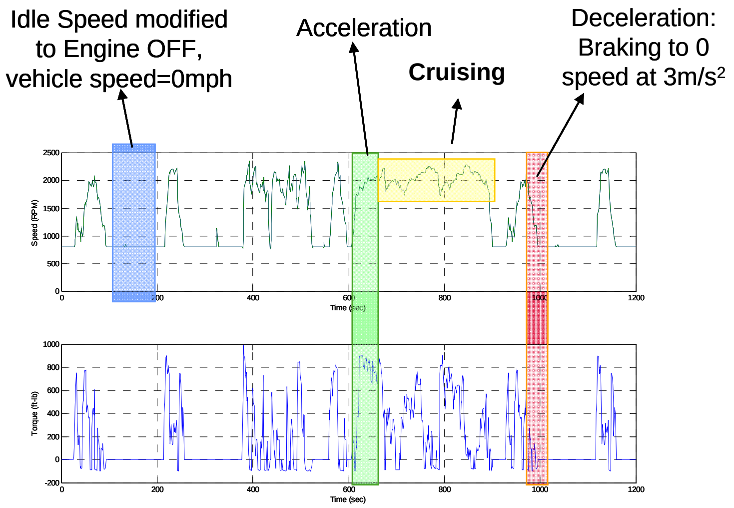

Figure 15: FTP Speed and Torque Curve. Portions of the Curve are highlighted to indicate Idle, Acceleration, Cruising and Deceleration.

Using assumptions about drag coefficient, mass, rolling resistance, etc. for a class 8 delivery vehicle, the calculated vehicle speed is shown in figure 16. This calculated drive cycle, based on an engine torque curve and some vehicle assumptions, seems to have many characteristics in common with HD vehicle urban drive cycles including similar speed range, acceleration rates and deceleration rates.

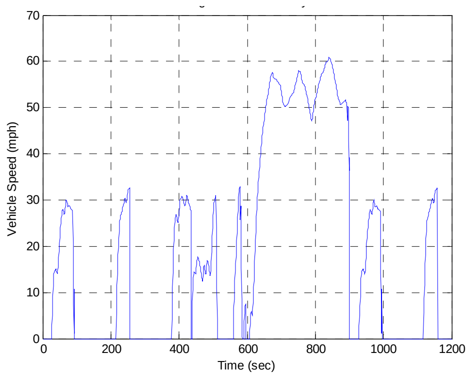

Figure 16: Resulting Vehicle Speed Trace for Class 8 Beverage Truck, per assumptions and methodology put forth in this section.

The calculated vehicle cycle will of course depend on the torque curve initially selected (which defines the FTP speed and torque) and on the vehicle assumptions. Figure 17 shows calculated vehicle cycles for a range of different engines and vehicles. The cycles match reasonably well because the engine power scales with vehicle mass and size.

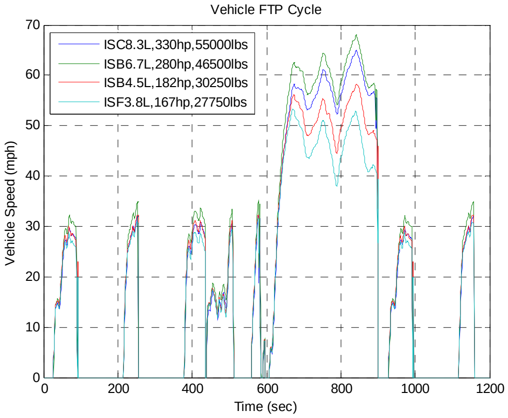

Figure 17: Calculated Vehicle Speed Traces for a range of vehicles and engine combinations.

Using this approach to define vehicle speed based on torque curve, also allows the calculation of required deceleration power the vehicle needs to meet the cycle requirements. During coast down periods, the deceleration power will be much lower than during vehicle braking. This deceleration power will define available regen energy in a realistic way.

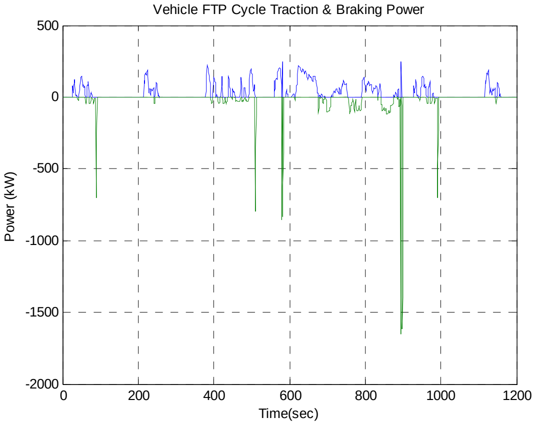

Figure 18: Braking power available for the hybrid system to capture over the cycle. The actual amount captured would depend on the capability of the hybrid system.

A comparison of the calculated available regen energy based on the above method with the available braking energy in the HD UDDS drive cycle shows a good match.

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)

Figure 19: Brake energy as a percentage of positive cycle work for 4 different cases. In each case, vehicle characteristics were selected that were a reasonable match for the engine torque curve (larger vehicle for the 8.3L engine than for the 3.8L engine).

While the calculated available regen energy will depend on the assumptions, preliminary analysis suggests that this approach could provide a reasonable way to ensure regen energy capture during the FTP is appropriately linked to vehicle behavior.

This approach could also provide one way to develop a post-transmission cycle based on the FTP. Assumption of average tire size and final differential would allow calculation of post-transmission speed based vehicle speed. By combining the vehicle power requirements with the post-transmission speed, it would be possible to define a post-transmission torque. The post-transmission speed and torque could then be used for evaluation of a transmission integrated hybrid system, or series hybrid system with a single output shaft. This post-transmission cycle based on the FTP would allow comparison of system performance of conventional engine, powerpack, and other hybrid architectures based on the common foundation of the FTP.

Note: This approach also defines a vehicle cycle based on the FTP that could be used for chassis certification, and would also allow comparison based on a common cycle.

VII: Appendix B – FTP Work Calculation

The FTP speed and torque define the test cycle positive work, and this work is representative of the energy necessary to meet vehicle requirements. This work will remain the same for a given system torque curve whether the system is conventional (an engine) or hybrid (engine + motor + battery…). When emissions levels are calculated for a conventional engine, the total emissions generated over the cycle are divided by the total cycle positive work – which is representative of the work required to propel the vehicle.

The existing regulation includes a provision to modify the work calculation to include negative work if an energy storage device is included in the FTP test (40CFR1065.210, 1065.650(d)). In the case of a hybrid powerpack which could absorb significant negative work, this would reduce the cycle work and increase work specific emissions over the FTP duty cycle This provision would result in an emissions level that would not be representative of system emissions in the real world (emissions divided by work to propel the vehicle) and acts as a disincentive to commercialization of hybrid powertrains in heavy duty vehicles. This provision was added to cover all applications, not just applications where the primary function of the engine/powerpack is propulsion of a land vehicle where the motoring power decelerates the vehicle. It makes no assumption about the source of the motoring power in the application. For land based vehicle applications, the deceleration/braking power is a waste energy stream for a conventional powertrain -- but a hybrid powertrain recovers some of this energy. The current test procedures specify the speed, but not the torque during motoring segments. Thus, this provision protects the agency/environment from systems that might absorb unrepresentatively large amounts of motoring power during the FTP. With representative limits on the available regenerative braking power during the cycle, the negative work should be excluded from the cycle work calculation like a conventional powertrain.

To ensure the powerpack certification emissions evaluation is consistent with the properties that are relevant in the real world (total emissions, total work to propel vehicle), negative work should not be included in the work calculation.