

Emissions Certification Vehicle Cycles Based on Heavy Duty Engine Test Cycles

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ABSTRACT

This paper describes the development vehicle cycles based on heavy duty engine test cycles for emissions certification. In the commercial vehicle and industrial equipment markets, emissions are evaluated using engine test cycles. For the on-highway market in the United States, these cycles include the transient heavy duty engine FTP test, and the steady state heavy duty engine SET test. Evaluation of engine only emissions is a practical approach given the diversity of applications, small volumes, and lack of vertical integration in the commercial vehicle market. However certain vehicle and powertrain characteristics can contribute significantly to fuel consumption and emissions. A number of approaches have been proposed to evaluate vehicle performance, and all of these vehicle evaluation methodologies require the selection of a vehicle cycle. If the engine test cycles and vehicle test cycles are not aligned, a technology evaluation will give different results depending on whether an engine test or vehicle test is used. With future regulations potentially allowing engine or vehicle test options, the alignment of the vehicle and engine test cycles is especially important.

In this work, a vehicle FTP cycle and a vehicle SET cycle were created based on the transient engine FTP and engine SET tests. The vehicle cycles are the same duration and have similar power requirements to the engine cycles. Simulation and test results are presented showing similar performance over the engine and vehicle cycles. Alignment of vehicle test cycles with the engine FTP and engine SET cycles will maintain consistency of vehicle and engine emissions evaluations, and will provide a link between future vehicle evaluations and existing experience with engine emissions testing.

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INTRODUCTION

Standard vehicle drive cycles and engine duty cycles are critical development tools. These cycles provide common metrics for evaluation of performance, whether the evaluation is used to determine compliance with an emissions standard or to compare performance of two technologies. In most cases these standard cycles seek to describe the behavior of a typical vehicle, or the operation of a typical engine. However the value of the cycles is not that all real world operation precisely matches the standard cycle, but that they provide a widely used measure that customers, regulators, and development engineers all understand. This is particularly valuable in the heavy duty vehicle industry given the diversity of applications and duty cycles.

This paper proposes heavy duty vehicle cycles for performance evaluation that are based on the existing heavy duty engine cycles. Characteristics of these cycles have been compared to the engine cycles and other heavy duty vehicle cycles. These cycles not only align vehicle and engine

testing, but also extend the functionality of the existing HD emissions testing framework.

STANDARD CYCLES

Standard cycles have been developed for a variety of different purposes, but the most widely used cycles are those used to evaluate performance against regulatory standards. In the US light duty industry, among the most commonly used cycles are the FTP75, the US06 and the SC03 [1] [2] [3]. All of these vehicle cycles are used to evaluate vehicle emissions in chassis dynamometer testing. These cycles do not describe perfectly the operation of all vehicles, but these cycles do include vehicle speeds and acceleration events that are common in the real world. More importantly, the use of these cycles to measure emissions of all vehicles allows comparison of performance versus standards, as well as comparison between vehicles, and comparison between technologies.

In the heavy duty industry, as in the light duty industry, a wide range of cycles have been developed. Some of the

cycles are designed for evaluation of many different types of vehicles, like the HD UDDS or ARB Transient cycle. Some cycles have been developed for specific applications such as pick-up and delivery trucks or specific technologies like hybrids [4]. However perhaps the most widely used cycles in the heavy duty industry are the engine cycles.

For Heavy duty vehicles in the U.S on-highway market, current federal regulations require only the engine to be certified for criteria emissions instead of the complete chassis, using the Transient Heavy Duty Engine FTP cycle (Figure 1).

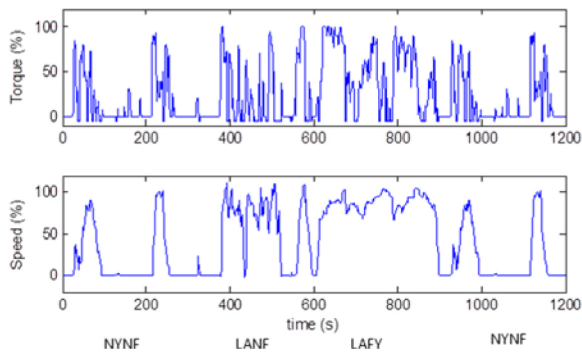


Figure 1. Heavy-Duty FTP Transient Cycle

Additional testing requirements were introduced in 1988 [5] that include the Supplemental Emissions Test (SET) and the Not-To-Exceed (NTE) Testing.

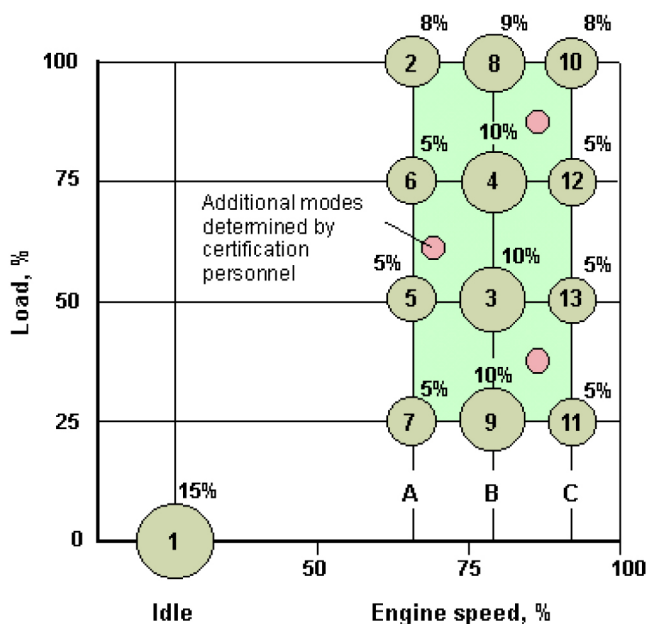


Figure 2. SET Test Points - the number on the circle shows the order of test points, and % shows the time spent at each modal point. A, B, & C lines correspond to speeds for definition of modal points.

Recently there is increasing interest in more integrated approaches to heavy duty vehicle emissions and fuel economy evaluation. New technologies like hybrid powertrains require performance evaluation of components generally not included in traditional engine tests. Examples of this interest include the HILS procedure developed by JAMI & JARI [6], EPA's new CO₂ rule [7] and GTR development efforts for vehicle CO₂ emissions. Each of these new approaches proposes new cycles to evaluate vehicles, but widely used cycles already exist: the engine test cycles. In the US, this means the FTP and SET engine test cycles.

FTP AND SET

The FTP and SET cycles define engine operating requirements in terms of normalized speed and torque, and are used to evaluate engine emissions. The FTP transient test cycle was developed based on data from a range of vehicles operating in different driving conditions. The SET test is a modal steady state test covering the engine operating range. Both cycles include engine operation that is representative of real world operation. A comparison of several vocational vehicles with the FTP show a reasonable match between real world operating point and FTP test cycle operating points as shown in Figure 3.

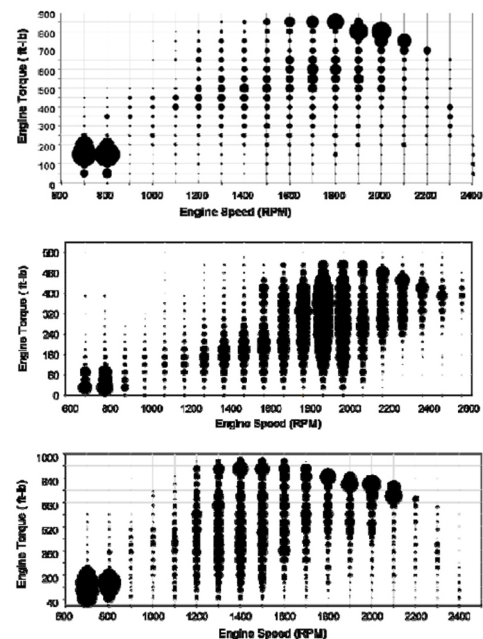


Figure 3. Field data taken from 9 vocational applications with size of circles corresponding to fuel consumed

Upper: 11L engine, refuse truck with PTO

Middle: 8.3L engine, school bus and refuse truck overlaid

Lower: 6.7L engine, pick-up and delivery

Average fuel consumption for these vehicles in the real world is very similar to fuel consumption over the engine FTP on a work specific basis. The difference of CO₂ between the prediction from FTP test (cold and hot composite cycle) and actual field data is only 4.0% [15].

The SET with its steady state operation is not a good match for vocational vehicles, but is a reasonable match for line haul vehicle operation. In Figure 4, the operating points for 13 line haul vehicles are shown.

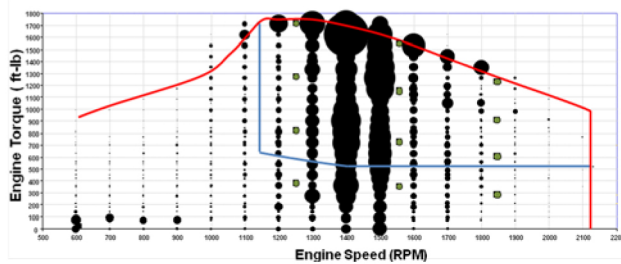


Figure 4. Field data from 8 line-haul trucks running a variety of routes and GVWs. Circle diameter represents fuel used. Red line is torque curve, and blue line shows NTE zone boundary.

There are differences between the SET and the real world line haul operation, but the overall fuel efficiency evaluations are similar (3.7%) [15]. More important though than an exact match between the test cycles and real world operation, is the fact that the test cycles are inclusive of the types of operating duty cycles seen in the real world.

ALIGNMENT OF ENGINE CYCLES AND VEHICLE CYCLES

Although these engine cycles do match real world engine operation reasonably well, they do not include enough information to make them more broadly applicable to the evaluation of vehicles or new powertrain technology. The creation of a vehicle cycle describing vehicle speed versus time based on these engine cycles would allow an equivalent evaluation at the engine or vehicle level.

A set of cycles at both the engine and vehicle levels would be attractive for a number of reasons. It would build on manufacturers' and regulators' experience with existing engine testing. It could provide the option of evaluating performance at either the engine level or the vehicle level. Most importantly it could make possible a comparison between the results of an engine test and a vehicle test. An engine test and a vehicle test which were aligned in terms of power requirements could provide common metrics for evaluation regardless of what type of test is selected. This is very important because, if the cycles are not aligned, evaluation of a particular technology could give different results depending on if it were certified over the engine cycle or over the vehicle cycle. Alignment would ensure a fair comparison between different technologies without increasing testing requirements.

Alignment may also provide the means to extend the applicability of engine testing to include a broader range of technologies. If engine and vehicle cycles are aligned, the vehicle cycle could be used to provide a vehicle speed signal during the engine test for the purposes of optimization of engine performance, or provide a vehicle speed for calculation of available brake energy for a hybrid powertrain. As new procedures for evaluating performance and emissions in the heavy duty industry are developed, alignment of engine and vehicle cycles will provide the flexibility to reduce development costs, and allow technology development to build on past experience.

LITERATURE REVIEW

Every heavy duty truck has a different drive cycle in-use and hence, it is very challenging to develop a common drive cycle which accurately assesses criteria emissions relative to their performance in the real world. O'Keefe et al. [8] proposed some physical-based metrics for drive cycle characterization and evaluation. Most of the metrics developed were independent of the vehicle or application, and allows for comparison of drive cycles.

For the GHG rule making process, EPA considered a variety of cycles including the light duty FTP-75, HWFEC, Heavy Duty UDDS, World Wide Transient Vehicle Cycle (WTV), Highway Line Haul, HTUF cycles and California ARB's Heavy-Heavy Duty Truck 5-mode cycle [9]. While the FTP75 was found to have steep accelerations which are not representative of Class 8 trucks, the HWFEC had a maximum speed of 60 mph, while the national average truck highway speed is 65 mph. WTV characteristics were found to be not diverse enough to represent different types of truck operation in the U.S, apart from not providing the flexibility to vary the weightings of a single cycle. The Highway Line Haul schedule was found to be too long for a typical chassis dynamometer test.

A number of drive cycles have been developed by the Calstart-Weststart Hybrid Truck Users Forum. These include cycles like the Manhattan Bus Cycle, Orange County Bus Cycle, Combined International Local and Commuter Cycle (CILCC), Class 4 Parcel Delivery, Class 6 Parcel Delivery, Utility Service and Neighborhood Refuse. These cycles were developed to match the characteristics of the applications which are expected to be the first hybrids in the market and each cycle is very application specific to be used as a common test procedure. Zou et al. [4] proposed a composite cycle used to evaluate Class 4-6 hybrid electric vehicles, which is one amongst the many proposals for a heavy duty vehicle cycle [10][11][12].

However, most of these cycles are application specific and are not aligned to the existing framework for heavy duty engine testing. The following sections present how a set of vehicle cycles (vehicle FTP and vehicle SET) were created, how these compare to other real world cycles and how these cycles align to existing emissions certification procedures.

CYCLE DEVELOPMENT: VEHICLE FTP

There are a variety of possible approaches to creating a vehicle cycle based on an engine cycle. For the creation of the vehicle FTP (vFTP), the best results were obtained by using the engine power as defined in the engine transient FTP. The engine power is compared to the road load for an assumed vehicle, and the difference defines acceleration.

An alternative approach that was considered is to use the engine speed and model the transmission and driveline. If the shift points could be modeled accurately, changes in engine speed would define changes in vehicle speed. However this approach required many subjective judgments about the location of shift events, and did not give good results. Focusing on the engine power presented fewer challenges and gave more consistent results.

There are several critical assumptions that must be made in order to create the vehicle cycle:

- Vehicle characteristics
- Vehicle deceleration rates / brake power

VEHICLE CHARACTERISTICS

Vehicle characteristics include mass, frontal area, aerodynamic drag, rolling resistance, etc. Many different vehicles were considered, but ultimately one vehicle was selected as the reference vehicle to create the cycle: The class 8 vocational vehicle defined by EPA in the GEM model as part of the new GHG rule.

EPA developed this vehicle model to be representative of a range of class 8 vocational vehicles, and so this made it a good model for the creation of the transient vFTP cycle.

The class 8 GEM vocational vehicle characteristics used in creating the vFTP are shown in [table 1](#). Other GEM vehicle parameter can be found in EPA's description of the GEM model [7]. The GEM class 8 vehicle is a relatively heavy vehicle and its weight to engine power ratio is around 90 kg/kW, which is higher than class 2b-5 and class 6 vehicle. Using a vehicle with a relatively high weight to power ratio ensures that most vehicles will be able to follow the cycle.

Table 1. GEM class 8 vehicle characteristics used in deriving the vehicle FTP

Engine Rated Power	kW	337
Accessory Load	kW	1.36
Rolling Resistance f		0.006
Aero Drag Cd		0.7
Frontal Area	m ²	9.8
Vehicle Mass	kg	30391
Tire Radius	m	0.4892
Transmission Efficiency		0.97
Differential & Driveshaft Efficiency		0.98
Air Density	kg/m ³	2.64

VEHICLE DECELERATION / BRAKING POWER

While we can assume that the FTP completely defines positive vehicle power requirements at the engine, it contains limited information about vehicle negative traction power requirements. There are motoring portions of the engine FTP which define when during the test the engine provides negative torque, but the torque is not actually defined - the engine is motored by the dynamometer using whatever torque is necessary. If we use the engine FTP to create a vehicle cycle, the motoring portions of the engine FTP would correlate to a negative power demand at the wheels. However these motoring portions of the cycle give no indication of friction brake requirements. In order to avoid unreasonably high vehicle speeds, some assumptions about braking must be made.

A range of approaches were tried from assuming a constant vehicle deceleration rate to applying a consistent brake power profile for each braking event. Each of these approaches required a significant number of assumptions about when the vehicle was coasting and when the vehicle was braking, and the vehicle cycle was quite sensitive to changes in the assumptions.

This challenge was avoided by using the HD-UDDS cycle as reference for the vehicle FTP. HD-UDDS is believed to have been created from the same data used to create the engine FTP [9] and is a reasonable representation of real world vehicle operation.

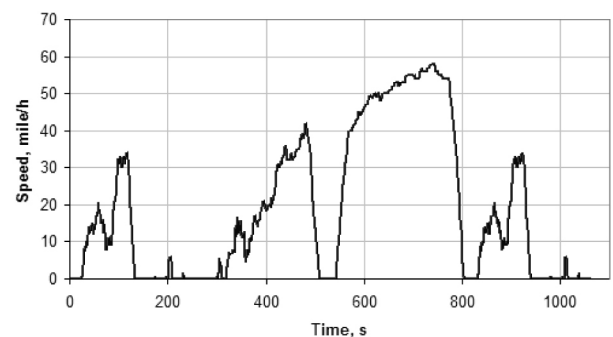


Figure 5. EPA Urban Dynamometer Driving Schedule (HD-UDDS)

CRITICAL CONSTRAINTS

Even with an assumed vehicle and the HD UDDS as a reference, there is still quite a bit of flexibility in creating a cycle. Several critical constraints were applied to bound the problem and ensure that the resulting cycle would meet the basic objectives of aligning with the engine FTP and of providing a reasonable match with real world operation.

The critical constraints for the vehicle FTP included:

- Vehicle travel between 6.3 and 6.5 miles over the cycle per 40 CFR 1036.705(b)91;