

Alternative Heavy-Duty Engine Test Procedure for Full Vehicle Certification

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ABSTRACT

In 2015 the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) proposed a new steady-state engine dynamometer test procedure by which heavy-duty engine manufacturers would be required to create engine fuel rate versus engine speed and torque "maps".[1] These maps would then be used within the agencies' Greenhouse Gas Emission Model (GEM)[2] for full vehicle certification to the agencies' proposed heavy-duty fuel efficiency and greenhouse gas (GHG) emissions standards.

This paper presents an alternative to the agencies' proposal, where an engine is tested over the same duty cycles simulated in GEM. This paper explains how a range of vehicle configurations could be specified for GEM to generate engine duty cycles that would then be used for engine testing. This paper discusses a numerical scheme by which GEM could interpolate these cycle average results instead of the steady-state map the agencies proposed. This paper explores this alternative via simulation and numerical analysis. Engine and powertrain testing of this alternative are described as a companion SAE Technical Paper entitled "Alternative Engine Mapping Approach for Simulation of Vehicle CO₂ Emissions." [3]

These two papers demonstrate how this alternative could successfully integrate cycle average engine test results into GEM for full vehicle certification. Advantages include capturing measured transient engine performance within GEM and avoiding disclosure of potentially proprietary engine control strategies, which could be revealed by the agencies' proposed procedure. This alternative might also lead to a more robust process for de-normalizing test cycles for engine certification.

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INTRODUCTION

In 2011 EPA and NHTSA issued the first-ever U.S. regulatory program to control greenhouse gas (GHG) emissions and improve the fuel efficiency of medium- and heavy-duty vehicles and engines (HD Phase 1).[4] Under HD Phase 1, starting in model year 2014, heavy-duty tractors and vocational vehicle chassis must be certified via GEM.

Similar to other vehicle simulation computer programs, GEM combines various vehicle parameter inputs with physical laws and assumptions to predict vehicle performance over a given vehicle route or drive cycle. HD Phase 1 GEM's required vehicle inputs include vehicle aerodynamics information (for heavy-duty tractors), steer and drive tire rolling resistances, and whether or not a vehicle is equipped with lightweight materials, a tamper-proof speed limiter, or tamper-proof idle reduction technologies. All other vehicle and engine characteristics were assigned fixed values in GEM by the agencies, and these cannot be altered by the GEM user. These fixed values included tabulated data of engine fuel rate as a function of engine speed and torque (i.e., default "engine fuel map(s)"), transmission number of gears and gear ratios, axle ratios, and vehicle payload. For tractors, GEM for HD Phase 1 simulates a tractor pulling a fixed 53-foot dry van box trailer. For vocational vehicle

chassis, GEM for HD Phase 1 simulates a fixed aerodynamic drag coefficient and vehicle frontal area to represent a nominal complete vocational vehicle. HD Phase 1 drive cycles for both tractors and vocational vehicles include a steady-state 55 mi/hr cycle without road grade, a 65 mi/hr cycle without road grade, and a transient drive cycle called the "ARB Transient." [5, 6] Figure 1 illustrates the ARB Transient drive cycle's vehicle speed versus time. The 55 mi/hr and 65 mi/hr cycles are not illustrated because they are simply test cycles operating at those constant vehicle speeds. A weighted average of these three cycles is output by GEM in units of grams of CO₂ (and gallons of fuel) per ton-mile.

The HD Phase 1 standards also include separate brake-specific fuel consumption and CO₂ emissions standards for the engines installed in tractors and vocational chassis. For certification to these standards, the agencies require that engine manufacturers follow the existing EPA heavy-duty engine dynamometer test procedures for certification of total oxides of nitrogen (NO_x), particulate mass (PM), non-methane hydrocarbons (NMHC), and carbon monoxide (CO) emissions. These emissions standards must be met by all heavy-duty on-highway engines over the 13-mode steady-state "Supplemental Emissions Test" (SET) cycle (now run as a contiguous "Ramped Modal Cycle" or RMC) and over a composite of a cold-start and a

hot-start transient “Federal Test Procedure” (FTP) cycle. For HD Phase 1 the agencies require that engines specifically installed in tractors meet fuel efficiency and CO₂ standards over the steady-state SET. This requirement was intended to reflect that tractor engines typically operate near steady-state conditions versus transient conditions. In contrast engines specifically installed in vocational vehicles must meet fuel efficiency and CO₂ standards over the hot-start portion of the transient FTP. This requirement was intended to reflect that vocational vehicle engines typically operate under transient conditions versus steady-state conditions.

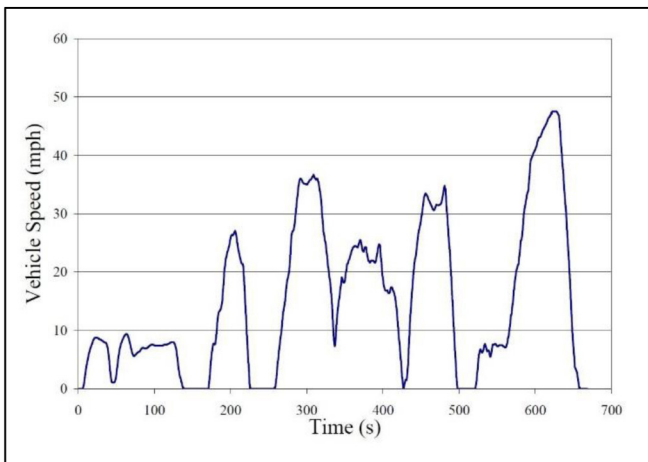


Figure 1. ARB Transient Drive Cycle in GEM.

Comparison of Heavy-Duty Engine Operation over HD Phase 1 Engine Test Cycles and Vehicle Drive Cycles

Figure 2 shows the SET and FTP engine dynamometer cycles de-normalized onto a typical engine torque versus engine speed plot. In Figure 2, the 13 mode SET steady-state modes are shown for the tractor engines and the FTP cycle is shown second-by-second for vocational engines. Note the locations of the so-called “A Speed”, “B Speed” and “C Speed” columns of steady-state points of the SET.

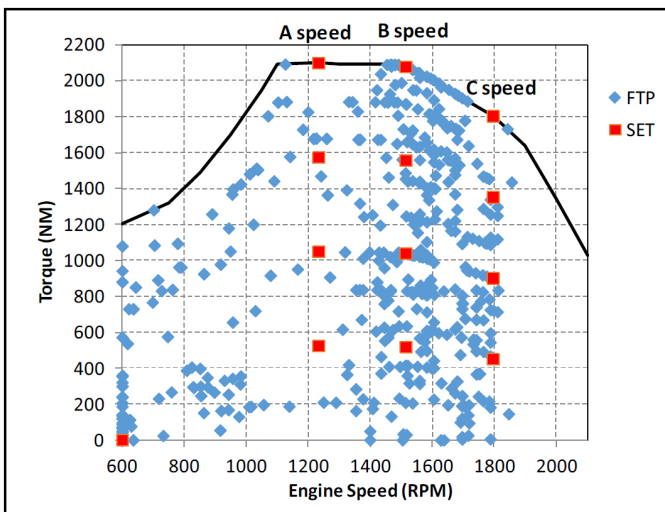


Figure 2. Typical engine operating points over SET and FTP.

Figure 2 can be compared to Figure 3, where Figure 3 depicts how an engine simulated in GEM typically operates over the GEM vehicle drive cycles. Within GEM for HD Phase 1 an engine fuel rate map versus the engine torque and speed demanded by the simulated vehicle is interpolated and each of the fuel rates at the points depicted in Figure 3 is integrated over the GEM cycles to determine total fuel consumed over a given drive cycle.

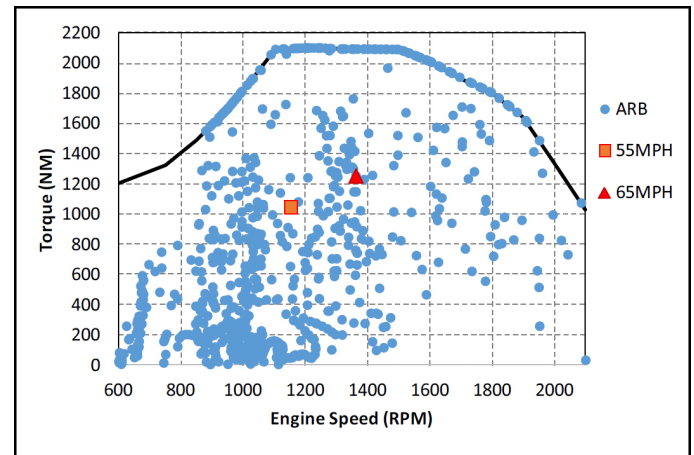


Figure 3. Typical engine operating points over GEM vehicle cycles.

Figure 3 shows that for tractor certification, the 55 mi/hr and 65 mi/hr cruise cycles without road grade each sample engine performance at one steady-state operating point. Also, neither of these two points are near the C Speed of the engine SET cycle in Figure 2 (in fact, there are very few ARB Transient engine operating points located near an engine's C speed either). The engine operating points for the 55 mi/hr and 65 mi/hr cruise speed cycles without road grade are typically located in the region near the “A50” point (i.e., A speed at 50% load) and in the middle of A50, A75, B50, and B75 points, respectively.

Figure 2 also shows that for vocational engine certification, the engine operating points over the FTP are mostly located at high torque and high speed, but Figure 3 shows that the ARB Transient drive cycle in GEM results in engine operation that is mostly located at low torque and low speed engine operation.

Comparison of Heavy-Duty Engine Operation over HD Phase 1 Test Cycles and Typical In-Use Operation

Figure 4 compares SET engine speeds to typical in-use engine operation in today's heavy-duty tractors.[7]

Figure 4 shows that typical tractor engine operation tends to be in the speed range between the SET's A and B speeds. Also, typical tractor operation spans the full range of engine torque within this speed range, instead of remaining at one fixed torque point like the 55 mi/hr and 65 mi/hr drive cycles in GEM for HD Phase 1.

For vocational vehicles Figure 5 compares FTP engine speeds with typical in-use Class 8 vocational vehicle engine speeds gathered from over 7,500 vocational trucks. Figure 5 shows that the FTP cycle has a larger percentage of time operating at high engine speeds in comparison to the in-use data.[8]

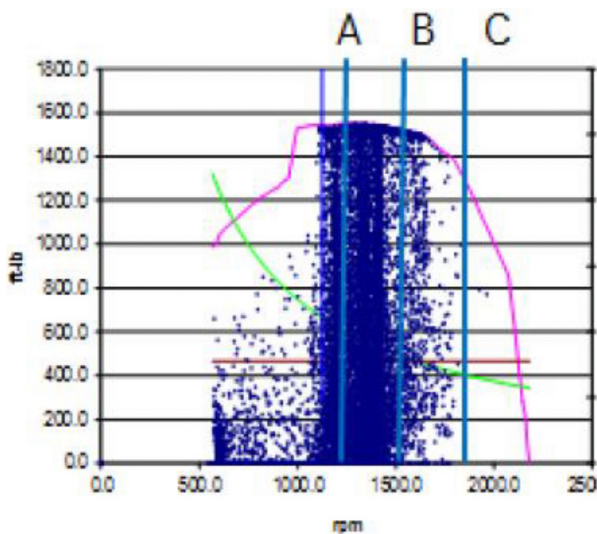


Figure 4. Comparison of SET engine speeds and typical in-use tractor engine operation. The scattered data points indicate in-use tractor engine operation.

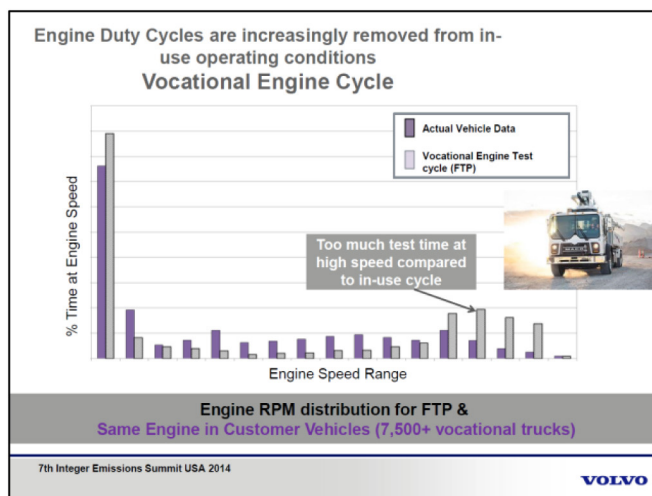


Figure 5. Comparison of FTP engine speeds and typical in-use vocational vehicle engine operation.

Proposed Revisions for Full Vehicle Certification

In 2015 the agencies proposed a second phase of fuel efficiency and GHG emissions standards (HD Phase 2), where the agencies proposed to require vehicle manufacturers to enter a number of additional vehicle parameters into GEM to recognize additional fuel efficiency technologies, as part of a revised “full vehicle” certification. These new inputs would replace many of the fixed values in GEM for HD Phase 1. These would include details of the vehicle's powertrain, such as the type of transmission, number of gears and gear ratios, axle ratio, and revolutions per mile of the drive tires. The agencies also proposed to represent the installed engine's performance within a vehicle, instead of the fixed fuel rate map(s) that were specified in GEM for HD Phase 1.

Because the SET and FTP engine certification test cycles evaluate engine performance at different operating points as compared to engine operating points over the GEM cycles (or as compared to typical in-use engine operation for that matter), results from these

separate engine tests would be challenging to use in GEM to represent engine performance. Therefore, the agencies proposed a new mandatory engine dynamometer test procedure to create a point-by-point steady-state fuel rate map versus engine output torque and engine speed. This requirement would also incorporate the full load and motoring torque engine curves that are already required to be generated under 40 CFR §1065.510.[9] The agencies proposed this particular engine mapping test procedure in part because engine manufacturers and other researchers have traditionally generated engine maps in a similar way for engine development purposes. This is a well-understood and repeatable approach to characterizing engine performance. Another reason for proposing this test procedure was because it would generate a map that is similar to the fixed maps already used in GEM for HD Phase 1.

However, the proposed test procedure does have some disadvantages. For example, only steady-state engine performance is evaluated, even though significant technology investments are being made today to improve heavy-duty engine fuel consumption under transient engine conditions. An example is physics model-based or neural network-based engine controls to replace the traditional look-up table approach to engine calibration[10]. This means that the HD Phase 2 proposed steady-state mapping approach would not capture the fuel efficiency improvements of these types of technology, especially over the ARB Transient drive cycle.

Because the proposed test procedure assumes that transient engine performance is equal to steady-state engine performance, an inherent negative bias to test results is introduced because transient engine performance is almost never superior to steady-state engine performance. The agencies have therefore proposed a constant multiplier of 1.05x as a first order correction to this inherent bias for the ARB Transient cycle,[1] but it remains to be seen how robustly applicable and accurate this fixed correction factor would be—especially as engine and vehicle technologies advance.

Another disadvantage to the proposed steady-state engine mapping procedure is that it takes many individual test points to create an engine map with reasonable fidelity for use in GEM. This means that the time needed in an engine dynamometer laboratory to complete this test can be long; upwards of 8 to 9 hours to complete one map.

And because the resulting map would contain significant detail of engine performance over a wide range of engine operation, engine manufacturers could be concerned about sharing this data with vehicle manufacturers and others involved in the pre-production full-vehicle certification process. These concerns could stem from the potential that proprietary engineering information could be disclosed within the data set of a detailed steady-state engine map.

Because of these disadvantages, the agencies also initiated the development of an alternative engine dynamometer test procedure.[3] The main idea underpinning this alternative is to leverage the capabilities of GEM to generate a set of engine dynamometer test cycles and then use the results from testing an engine over these cycles to represent that engine within GEM for a full range of vehicles. This paper describes this alternative test procedure and explores its viability to accurately represent engine performance in

GEM. This work was done primarily through GEM simulation and numerical analysis. The results of a comprehensive experimental test program to explore this test procedure are described in the companion paper mentioned in the abstract of this paper.

Because this alternative approach is new and not currently used within the heavy-duty engine and vehicle industry for any other purpose, the agencies reached out to a number of heavy-duty engine, transmission, and vehicle manufacturers for assistance in evaluating this alternative. Ultimately, the agencies collaborated with a group of five companies who voluntarily assisted the agencies in the development and evaluation of this new approach.

The following sections of this paper describe the alternative test procedure and its development and explore some of the key questions that were raised during its development.

ALTERNATIVE HEAVY-DUTY ENGINE TEST PROCEDURE FOR FULL VEHICLE CERTIFICATION

The following 6 steps outline the alternative heavy-duty engine test procedure for full vehicle certification using GEM:

1. Define vehicles. Define eight representative vocational vehicle and/or nine representative tractor configurations that cover the range of vehicles in which a parent engine of a heavy-duty engine family would be installed. The range of representative vehicles is spanned by defining vehicle configurations that result in different GEM cycle work (W , hp-hr) and different quotients of GEM cycle average engine speed over average vehicle speed (N/V , rpm/(km/hr)). W is varied from one representative vehicle configuration to another by varying the vehicle parameters of gross vehicle weight class (vehicle mass), the product of vehicle aerodynamic drag coefficient and frontal area, C_dA , and the steer and drive tires' coefficients of tire rolling resistance, C_{rr} . N/V is varied by varying vehicle configurations drive tires' size (revolutions per mile), drive axle ratio and transmission gear ratios. Figure 7. Parent engine rating (450 hp) data and surface fit of BSFC as a function of W and N/V for the 65 mi/hr cycle with road grade. Table 1 and Table 2 show how these representative vehicle configurations could be defined.
2. Map lug and motoring curves. Map the parent engine's maximum brake torque versus engine speed (i.e., the "lug curve") and the engine's motoring torque versus engine speed (i.e., the "motoring curve"), according to 40 CFR §1065.510.
3. Enter vehicle configurations and engine data into GEM. Enter the parent engine's lug curve and motoring curve into GEM and run GEM for the 8 or 9 vehicle configurations. Since GEM for HD Phase 2 has been configured to output engine torque and engine speed versus time duty cycles (at 10Hz), running GEM this way creates up to 27 engine cycles (three GEM drive cycles for each of up to 9 vehicles).
4. Test engine over GEM cycles. In an engine dynamometer laboratory test the parent engine of the engine family using up to 27 engine cycles that were created by GEM, and enter the cycle average BSFC results of these tests back into GEM. GEM for HD Phase 2 has been configured to accept these inputs to create the three cycles' 8-point or 9-point BSFC vs. W and N/V maps.
5. Enter GEM values for a particular vehicle. With all of the cycle average BSFC values entered into GEM for a particular engine family, enter values for the remaining vehicle parameters for a particular vehicle for which GEM results are desired: C_dA , C_{rr} , transmission and axle parameters, specific engine ratings' lug curve and motoring curve, etc.
6. Run GEM to determine a particular vehicle's results. GEM automatically interpolates or extrapolates the cycle average BSFC values for each of the three cycles, based on the particular W and N/V results from the particular vehicle configuration that was entered. GEM automatically multiplies the interpolated BSFC by the cycle W per ton-mile result to determine fuel consumed per ton-mile. This value is also converted by GEM into grams of CO_2 per ton-mile. These last two values can be compared directly to the agencies' vehicle standards, which are specified with the same engineering units.

DEVELOPMENT OF THE ALTERNATIVE TEST PROCEDURE

The previous section described the step-by-step procedure of the alternative test procedure. This section discusses the development of the alternative test procedure, and it explores some of the key questions that were raised during its development:

1. Would BSFC maps (or equivalently, brake-specific CO_2 maps) be sufficiently well-behaved, such that GEM interpolation and extrapolation could be carried out with sufficient confidence for the purpose of vehicle certification and compliance assurance?
2. Would one map that combines all three certification cycles be adequate to represent the engine, or are individual maps for each cycle be needed?
3. What would be the most suitable independent variable(s) against which BSFC should be interpolated?
4. What is the minimum number of engine tests needed to ensure accurate interpolation over an engine families' full range of vehicles?
5. How would GEM results from using the alternative test procedure compare to the agencies' proposed procedure, and how would these compare to engine dynamometer and powertrain dynamometer experimental results?
6. How significant is the engine dynamometer test burden of the alternative test procedure, and how does this compare to the agencies' proposed test procedure?

Test Matrix of GEM Simulations

In order to explore these questions, a test matrix of 1,152 unique vehicle and engine configurations were simulated in the software version of GEM proposed by the agencies for HD Phase 2.[11, 12] This test matrix was based on the Cummins ISX engine family, coupled with various Eaton automated manual transmissions, as installed in various hypothetical variations of a PACCAR Class 8 Kenworth T700 tractor. Within the test matrix engine, transmission and vehicle parameters were varied as follows

1. Thirty-two hypothetical variations of the Kenworth T700
 - a. C_d : 0.35, 0.45, 0.55, 0.65, and 0.75
 - b. C_{rr} : 0.005, 0.006, 0.007 and 0.008
 - c. Axle ratio: 2.64, 3.36, 3.9 and 4.56
2. Three automated manual transmissions
 - a. 10-speed: Eaton F016E310C-LAS
 - b. 13-speed: Eaton FO_16E313A_MHP
 - c. 18-speed: Eaton FO-16E318B-MXP
3. Two transmission shift strategies for each transmission
 - a. Eaton's proprietary shift strategy
 - b. GEM's HD Phase 2 proposed shift strategy[13]
4. Two engines from the Cummins ISX engine family
 - a. 450 hp parent engine rating
 - b. 400 hp child rating
5. Three GEM drive cycles, as proposed in HD Phase 2[1]
 - a. 55 mi/hr with road grade
 - b. 65 mi/hr with road grade
 - c. ARB Transient

Results of GEM Simulations

The following figures depict the results of the GEM simulations, as follows:

1. Figure 6, Figure 7 and Figure 8 illustrate the parent engine rating's (450 hp) *BSFC* surface fits and data points for the 55 mi/hr, 65 mi/hr, and ARB transient cycles, respectively, with all simulation results used to generate the respective surface fits.
2. Figure 9 illustrates the parent engine rating's (450 hp) *BSFC* surface fit and data points for all cycles combined, with all simulation results used to generate one surface fit.
3. Figure 10, Figure 11, and Figure 12 illustrate the parent engine rating's (450 hp) *BSFC* data points superimposed on a surface fit of the analogous results using an engine child rating of 400 hp; for the 55 mi/hr, 65 mi/hr, and ARB transient cycles, respectively.
4. Figure 13, Figure 14 and Figure 15 illustrate the parent engine rating's (450 hp) *BSFC* data points superimposed on a surface fit of only nine of the same engine's results; for the 55 mi/hr, 65 mi/hr, and ARB transient cycles, respectively.

Discussion of GEM Simulation Results

Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, Figure 14, Figure 15 show individual simulation results as open circles, and computer-generated surfaces are shown to guide the eye. Note that the surfaces shown are not the result of the particular interpolation and extrapolation scheme selected for use in GEM for interpolating and extrapolating the 8-point or 9-point maps described in the previous section.

Figure 6, Figure 7 and Figure 8 show that for each drive cycle, all *BSFC* results generally collapse onto one well-behaved and predictable surface, when plotted versus W and N/V , even with the

full range different simulated transmissions, transmission shift strategies, drag coefficients, rolling resistance coefficients and axle ratios.

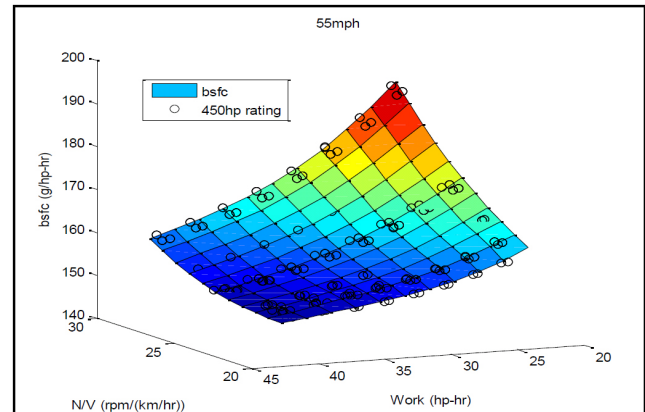


Figure 6. Parent engine rating (450 hp) data and surface fit of *BSFC* as a function of W and N/V for the 55 mi/hr cycle with road grade.

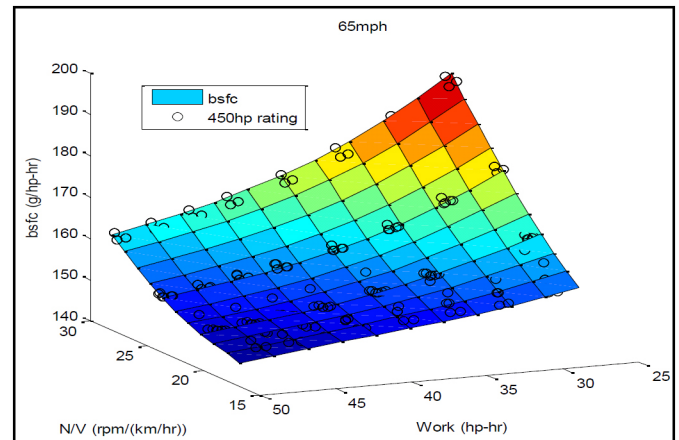


Figure 7. Parent engine rating (450 hp) data and surface fit of *BSFC* as a function of W and N/V for the 65 mi/hr cycle with road grade.

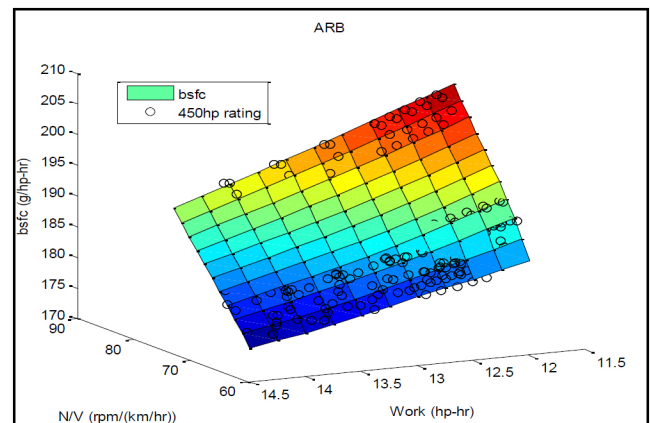


Figure 8. Parent engine rating (450 hp) data and surface fit of *BSFC* as a function of W and N/V for the ARB Transient cycle.

Figure 9 shows the *BSFC* data and surface fit as function of W and N/V with all three cycles' results combined. It can be seen that the individual data points are not as well-behaved along a single surface suggesting that separate maps per cycle may be preferred.