

Cycle-Average Heavy-Duty Engine Test Procedure for Full Vehicle Certification - Numerical Algorithms for Interpreting Cycle-Average Fuel Maps

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ABSTRACT

In June of 2015, the Environmental Protection Agency and the National Highway Traffic Safety Administration issued a Notice of Proposed Rulemaking to further reduce greenhouse gas emissions and improve the fuel efficiency of medium- and heavy-duty vehicles. The agencies proposed that vehicle manufacturers would certify vehicles to the standards by using the agencies' Greenhouse Gas Emission Model (GEM). The agencies also proposed a steady-state engine test procedure for generating GEM inputs to represent the vehicle's engine performance. In the proposal the agencies also requested comment on an alternative engine test procedure, the details of which were published in two separate 2015 SAE Technical Papers [1, 2]. As an alternative to the proposed steady-state engine test procedure, these papers presented a cycle-average test procedure. The papers also explored how a range of vehicle configurations could be defined and selected for generating the engine duty cycles for this test procedure. In addition, these papers described and used a simple interpolation-based numerical algorithm for determining the fuel consumption of a vehicle configuration based on a cycle-average engine "fuel map" that was generated via the cycle-average engine test procedure.

This paper is a continuation of this earlier work [1], and this particular paper presents a more comprehensive evaluation of a range of numerical algorithms for determining fuel consumption values from a cycle-average engine fuel map. These numerical algorithms include interpolation and extrapolation schemes as well as different linear and non-linear equations, where the equations' coefficients were fitted via least-squares regression. The selection of independent and dependent variables for all of these numerical methods was explored in detail. It is shown that the most robust numerical algorithm that we explored specifies fuel mass as the dependent variable, and a linear combination of the ratio of average engine speed to average vehicle speed and cycle work as the two independent variables. It is demonstrated that the cycle-average test procedure, combined with a robust numerical algorithm for interpreting the cycle-average fuel map, can effectively predict the fuel consumption of an engine in different vehicle configurations, including configurations with different parent and child engine ratings and a wide range of transmissions. It is also shown that the cycle-average test procedure represents transient engine performance more accurately than the agencies' proposed steady-state test procedure.

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INTRODUCTION

The Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued a Notice of Proposed Rulemaking to further reduce greenhouse gas emissions and improve the fuel efficiency of medium- and heavy-duty vehicles in June of 2015 [3]. Under this rule, the agencies proposed that vehicle manufacturers would certify vehicles to the standards by using the agencies' Greenhouse Gas Emission Model (GEM) with using the steady state engine fuel map to characterize the engine [4]. In the proposal the agencies requested comment on an alternative engine test procedure named the cycle average test procedure to replace this steady state map approach, the details of which were published in two separate papers [1, 2]. The first paper [1] also

provided a fairly comprehensive overview on the existing certification cycles and how engines and vehicles are certified under the current regulation. Both papers [1, 2] show that this alternative test procedure is a viable alternative to the steady-state engine mapping test procedure recently proposed in the heavy duty Phase 2 rule. It shows that this alternative has the advantage of representing measured transient engine performance within a full vehicle simulation software like GEM [4]. It also has the advantage of protecting potentially proprietary engine calibration strategies that could otherwise be revealed within a detailed data set of steady-state engine dynamometer test results. In addition, both of the papers explored how a range of vehicle configurations could be defined and selected for generating the engine duty cycles for this test procedure.

One of the important topics of the first papers [1] is the discussion of an interpolation-based numerical algorithm for determining the fuel consumption of a vehicle configuration based on a cycle-average engine “fuel map” that was generated via the cycle-average engine test procedure. It shows that with the vehicle configurations selected, this simple numerical scheme can produce fairly accurate results to predict engine performance for the purpose of full vehicle certification.

Significant progresses have been made since the publications of these two papers [1, 2], which covers a large number of engine dynamometer tests to prove the concept. A wide range of industry supported activities, and significant refinement on numerical schemes for interpreting cycle average engine fuel map are also conducted. The engine dynamometer tests includes Cummins’ medium duty ISB engine, Navistar’s heavy duty N13 engine, and Volvo’s heavy duty D13 engine in addition to the Cummins’ heavy duty ISX engine tests reported in the papers [1, 2]. All testing results strongly support the concept of the cycle-average test procedure and the findings resulted from the early work [1, 2].

Because this alternative approach is new and not currently used within the heavy-duty engine and vehicle industry for any other purpose, the agency actively reached out to a number of heavy-duty engine, transmission, and vehicle manufacturers for assistance in evaluating this alternative. Initially, the agency collaborated with a group of five companies who voluntarily assisted the agencies in the development and evaluation of this new approach. Since then, the group has grown into a collection of ten organizations, including the initial five - Cummins Inc., Paccar Inc., Navistar Inc., Eaton, and Allison Transmission, and another five - Volvo, Daimler, Hino, Caterpillar, and Engine Manufacture Association. A bi-weekly industry group meeting has been held since late 2014. This industry group not only contributes many useful and constructive comments and suggestions of how the cycle average map test procedures can be improved, but also contributes significant engine dynamometer tests with their own testing facilities, further consolidating the concept and keeping the program moving forward.

One of the most significant areas of progress is in the development of the numerical scheme that is used to interpret engine fuel map through a very well designed dependent variable domain. Although interpolation and extrapolation scheme developed in the paper [1] is simple and accurate under the assumptions used in that study, it shows that there are many fundamental issues in accuracy when the application is extended to cases where the to-be-certificated vehicles are outside the cycle average engine fuel map boundary. The examples of the issues include the cases with unique vehicle configuration, such as high or very low axle ratio, and the case when the transmissions down shift during the cruise cycle that causes one of independent variables of the cycle average map, such as average engine speed over vehicle speed, to overlap. For those cases, this simple scheme becomes very sensitive to small variations of the independent variable, thus resulting in high numerical errors that are beyond the acceptance of the certification. This means that this simple numerical schemes would not be accepted at the current form

as far as full vehicle certification is concerned, since a certification tool must be accurate enough to cover the whole range of on highway vehicles covered by the rule.

In light of the situation where the numerical algorithm had to be improved to be acceptable for certification, significant development of the numerical algorithms has been made. These numerical algorithms not only include interpolation and extrapolation schemes, but also different linear and non-linear equations, where the equations’ coefficients were fit via least-squares regression called global regression. More than twenty four numerical schemes have been investigated. The large amount effort is also made to select independent and dependent variables for all of these numerical methods. Most significantly, all the numerical schemes have been validated against a large number of the engine tests, including one medium duty diesel engine, and three heavy duty diesel engines under many different scenarios, such as testing parent and child ratings.

This paper will focus on this latest development and progress on the numerical scheme including selection of dependent and independent variables. It will be shown that the cycle-average test procedure, combined with a robust numerical algorithm for interpreting the cycle-average fuel map, can effectively predict the fuel consumption of an engine in different vehicle configurations. It will also show that the proposed cycle average mapping procedure is effective at covering the cases with different parent and child engine ratings and a wide range of transmissions.

The following section summarizes the cycle average map test procedure before giving the technical details on engine tests and development of numerical algorithms for the sake of clarity.

CYCLE AVERAGE ENGINE FUEL MAP TEST PROCEDURE

The proposed test procedure has been summarized in a previous paper [1]. The main difference between the description in that paper and the present paper is no longer limited to engine BSFC as dependent variable and engine work and average engine speed over average vehicle speed (N/V) as two independent variables. Rather, cycle average map variable is extended to fuel mass as dependent variable and engine torque and engine speed as independent variables. For the sake of completeness of this paper, the cycle average engine fuel map test procedure is summarized in the following six steps for full vehicle certification using GEM [4]:

1. Define vehicle configuration. Eight representative vocational vehicle and nine representative tractor configurations are defined in 40 CFR §1036.540, which cover the range of vehicles in which a parent engine of a heavy-duty engine family would be installed in. The range of representative vehicles span the range of to be certified vehicle configurations.
2. Generate steady-state fuel map, lug and motoring curves. Steady-state fuel map is created by following 40 CFR §1036.535. 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 [5].

3. Simulate all eight or nine vehicle configurations with GEM using the engine data of the parent engine, which includes the lug curve, motoring curve and steady-state fuel map. Since GEM for HD Phase 2 has been configured to output engine duty cycles as torque and engine speed versus time (at 10Hz), running GEM this way creates up to 24 or 27 engine cycles (three GEM drive cycles for each of up to 8 or 9 vehicles).
4. Create cycle average fuel map by testing engine over the 24 or 27 GEM engine cycles in an engine dynamometer. A cycle average map in terms of dependent variables, which could be BSFC or fuel mass as function of two independent variables for each certification cycle, will be generated. 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 or fuel mass 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 or fuel mass vs. two independent variable maps.
5. Enter GEM values for a particular vehicle that is to be certified. With all of the cycle average BSFC or fuel mass values entered into GEM for a particular engine family, enter values for the remaining vehicle parameters for a particular vehicle for which GEM simulation are desired: $C_d A$, C_{rr} , transmission and axle parameters, specific engine ratings’ lug curve and motoring curve, etc. However, the fuel map of the parent rating is used.
6. Run GEM to determine a particular to-be-certified vehicle’s results. GEM automatically calculates the cycle average BSFC or fuel mass values for each of the three cycles, based on numerical algorithm and two independent variables from the particular vehicle configuration that was entered. GEM automatically multiplies the calculated BSFC or fuel mass by the independent variables. This value is also converted by GEM into grams of CO₂ per ton-mile. These last two values can be compared directly to the agencies’ vehicle standards, which are specified with the same engineering units.

One of the key steps of the test procedure is Step 4, where a numerical scheme with proper selection of variables must be used to populate a map from 8 or 9 test points, covering the entire map domain that can be used for certification. Two key issues will be addressed here. The first one is the selection of dependent and independent variables, while the second is to form the equation used to describe the cycle average map. These become the key talking points of the next section.

It should be mentioned that three GEM certification cycles mentioned above will be used throughout the study when cycle average test procedure is explored. These cycles are similar to the HD Phase 1 drive cycles for both tractors and vocational vehicles, which include a steady-state 55 mph cycle without road grade, a 65 mph cycle without road grade, and a transient drive cycle called the “ARB Transient.” [6, 7]. However, one of the main differences between Phase 1 and Phase 2 is addition of the road grade into the 55 and

65mph cycles. Because the road grade has not been finalized for the final rule at the time when this paper is written, two road grades have been investigated.

The first one is derived from a section between San Antonio and Junction, Texas, which is about 20 km long as shown in Figure 1 Figure 2. The peak road grade of this cycle is about 2.4%. The second road grade cycle is based on a data set that includes the grade of all the limited access highways in the United States and the vehicle miles traveled (VMT) of heavy-duty vehicles by county. Combining these two data sets of VMT and road grade a 20 km long synthetic road grade profile was created. This road grade profile is shown in Figure 2. The peak grade of this profile is about 5%, so even though the profile is national representative, it is more aggressive than the first road grade profile. Although the final rule may not adopt such aggressive road grade profile, this road grade profile can be viewed as an extreme case, making the validation harder. In other words, a less aggressive road grade profile could be used in the final rule even if the more aggressive road grade profile is used to verify the cycle average test procedure.

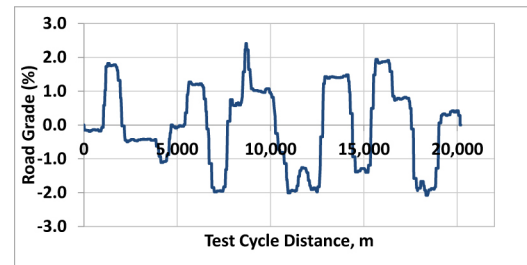


Figure 1. Road grade profile from part of route from San Antonio to Junction to Uvalde to San Antonio

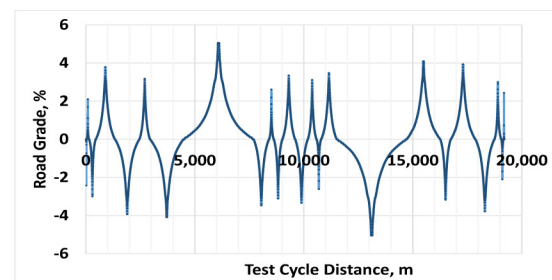


Figure 2. A more aggressive road grade used for 55 and 65mph cycles

DEVELOPMENT OF CYCLE AVERAGE MAP

The cycle average map developed under the paper [1] uses brake specific fuel consumption (BSFC) in g/kW-hour as the dependent variables, and the work and ratio of average engine speed to average vehicle speed (N/V) as two independent variables. The numerical scheme used the 8-9 tests points to interpolate/extrapolate other vehicle points that are to-be-certified. This approach is simple, but has two noticeable drawbacks when it is applied to some of the extreme cases.

The first drawback is shape of the BSFC map. When the fueling is low, the shape of BSFC surface can have a strong non-linear behavior, which can make interpolation and extrapolation fail due to the large errors between the actual BSFC and the predicted values. The second issue is the limitation of extrapolation when it is applied to the points that are out of boundary of the map. The triangular scheme can be very sensitive to the points that are even slightly out of map boundary. Figure 3 shows the example of this behavior for a transient cycle over a medium duty engine.

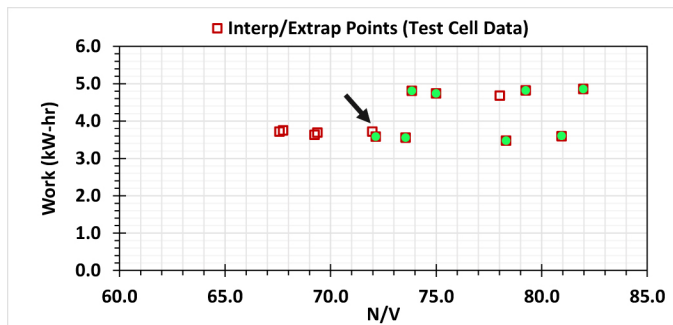


Figure 3. Issues with extrapolation scheme

In this figure, x-axis is the ratio of the average engine speed to average vehicle speed and the y-axis is the work in kW-hr over the cycle. The dependent variables for this map is BSFC in g/kW-hr. The eight green marks are those obtained from engine dynamometer tests representing the cycle average map. The red square points are the assumed-to-be-certified vehicles that are selected carefully in order to illustrate the issue facing in certification.

Table 1 shows the interpolation and extrapolation results. In this table, the first 8 points show the 0.0% error between testing data and test points that are considered being to-be-certified vehicles. This is because when interpolation is applied to the points that are the exactly overlapped on those to-be-certified points, the results should be the same. However, when those first eight points are used to interpolate or extrapolate the points, especially outside the first 8 point boundary, the errors are large. As a matter of fact, the errors vary, ranging from 2.27% to 12.93% differences between testing points obtained from engine dynamometers and the values interpolated and extrapolated from the map. The scheme is extremely unstable for those points that are just a little bit outside of the map domain, such as the point shown with a pointed black arrow in Figure 1. Such large errors ranging from 2.27% to 12.93% would be unacceptable as far as certification is concerned.

In view of these situations, the investigation and development of cycle average map are further explored with different dependent and independent variables as well as more broad numerical schemes in the hope that optimal combinations and robust schemes can be found for use of full vehicle certification.

Table 1. Interpolation and extrapolation results over transient cycle

Interp/Extrap Points (Test Cell Data)			Test Points	Error
$\Sigma N/\Sigma V_i$	W_i	$BSFC_i$	$BSFC_i$	%
72.13	3.58	278.56	278.56	0.00%
73.84	4.81	254.63	254.63	0.00%
73.55	3.56	286.69	286.69	0.00%
75.00	4.74	254.15	254.15	0.00%
78.31	3.47	297.42	297.42	0.00%
79.24	4.82	265.18	265.18	0.00%
80.94	3.59	302.59	302.59	0.00%
81.97	4.86	268.59	268.59	0.00%
78.02	4.68	267.15	265.06	-0.78%
71.98	3.72	271.54	236.44	-12.93%
69.24	3.63	269.57	263.45	-2.27%
69.37	3.69	269.35	244.50	-9.23%
67.58	3.72	265.09	236.70	-10.71%
67.75	3.75	259.62	226.65	-12.70%

Cycle Average Map Domain and Numerical Algorithm

As pointed out in the previous section, BSFC as dependent variable has a non-linear trend when the fueling is small for some vehicle cases. On the other hand, it is well known that the fuel mass in gram is a fairly linear behavior if independent variables are properly selected. Three sets of variables are explored for the two independent variables. The first is N/V and work as two separate independent variables for the cycle average map studied, which has been used in the paper [1]. The second set is the average engine speed (N) and engine torque (T). The third one is N and work. Since interpolation/extrapolation has a fatal flaw when it is applied to the vehicles that are outside the points used to define the cycle average map from the engine dynamometer tests, this approach is not further explored.

In this paper, regression algorithm will be investigated. Table 2 shows that twelve regressions are under consideration with different combination of linear and non-linear terms with and without interaction and interception.

Table 2. Regression model with twelve forms

	#	Without intercept	#	With intercept
With interaction	1	$\sim 0 + NV + W + NV * W$	5	$\sim 1 + NV + W + NV * W$
	2	$\sim 0 + N + T + N * T$	6	$\sim 1 + N + T + N * T$
	9	$\sim 0 + N + W + N * W$	11	$\sim 1 + N + W + N * W$
Without interaction	3	$\sim 0 + NV + W$	7	$\sim 1 + NV + W$
	4	$\sim 0 + N + T$	8	$\sim 1 + N + T$
	10	$\sim 0 + N + W$	12	$\sim 1 + N + W$

As can be seen, Table 2 does not include other second order terms such as N^2 . This is mainly because any more nonlinear terms require more testing data, thus more testing burden, where the agency would like to avoid. As a general rule the number of experimental points should be at least twice the number of model coefficients. This rule limits our consideration to models with an intercept and an interaction to give a maximum of four coefficients. The representation of model forms in Table 2 is typical of any statistical software packages such as SAS, R; e.g. “1” in the last

column of the table means that there is intercept to y-axis. The dependent variable on the left side of equations can be BSFC (g/kWh) or fuel mass (g), which results in a total of 24 regression models to be studied under this paper. In summary, the following equations will be studied:

- BSFC as function of N/V and work
- Fuel mass as function of N/V and work.
- BSFC as function of N and T
- Fuel mass as function of N and T
- BSFC as function of N and work
- Fuel mass as function of N and work

The calculation of model coefficients from the 8 or 9 map cases is fairly straightforward within the available frameworks of regression analysis; e.g., one could use the “LINEST” function in Microsoft Excel or the “lm” function in Gnu R. Packaged functions such as these often provide various metrics to assess quality of fit. The common metric is R^2 , the so-called “coefficient of determination,” interpreted as the variation in the dependent variable explained by the model. Usually a high value of R^2 is considered desirable. However, it is important to note that R^2 does not indicate whether a model is biased, so one must examine the plot of the residuals with respect to the fitted values. Furthermore, it is important to determine whether a high value of R^2 occurred by chance when in fact no relation exists between the dependent and independent quantities. That is, whether a model can be relied upon to predict values of the dependent quantity for cases not used in model construction. This question is usually posed as a test for the null hypothesis - hypothesis that no relationship exists between the dependent and the independent quantities. The question is answered by computing the F-statistic and comparing it with a threshold. The threshold is determined from the number of degrees of freedom (one less than the difference between the number of cases and the number of model coefficients) and the so-called significance level α - the probability of erroneously concluding that a relationship exists; usually 0.05. The question could be equivalently answered by the p-value - roughly the probability that the null hypothesis is true given the observations [8, 9, 10, 11]. The authors recognize that the p-value by itself is not sufficient to draw such conclusion [12], but it remains a useful metric when used in conjunction with a priori domain knowledge.

More will be discussed when the results are presented.

Engine Test Matrix Used for Model Validations

In order to validate the regression model discussed above, three different engines with both parent and child ratings are tested. They are listed as follows.

- 2012 Cummins medium duty ISB engine with parent rating at 300hp and child rating at 200hp tested at Southwest Research Institute (SwRI), San Antonio, Texas
- 2014 Navistar heavy duty N13 engine with parent rating at 450hp and child rating at 365hp tested at SwRI

- 2013 Volvo D13 engines with parent rating at 500hp and child rating at 400hp tested at The National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan

The numbers of test points for generation of the cycle average map follow the test procedure defined in 40 CFR §1036.540. In addition, a large number of the test points are also needed to check the fidelity of the regression. Those points must be beyond the map points, which could be inside or outside the map boundary, covering many possible extreme cases for full vehicle certification. For the sake of completeness of this paper, some of the key parameters used for cycle average map created by GEM simulation are listed in Table 3 and 4. Due to a large number of vehicles, the table is split into two tables for each application.

Table 3a. Defined Class 2b through Class 7 vocational vehicle configurations for GEM engine duty cycle generation, engine testing and GEM interpolation

	Test 1	Test 2	Test 3	Test 4
M (kg)	7,257	11,408	7,257	11,408
C_{rr} (kg/metric ton)	6.7	6.9	6.7	6.9
Set Tire size and axle ratio at engine speed	A	A	B	B

Table 3b. Defined Class 2b through Class 7 vocational vehicle configurations for GEM engine duty cycle generation, engine testing and GEM interpolation

	Test 5	Test 6	Test 7	Test 8
M (kg)	7,257	11,408	7,257	11,408
C_{rr} (kg/metric ton)	6.7	6.9	6.7	6.9
Set Tire size and axle ratio at engine speed	C	C	Maximum test speed	Maximum test speed

Table 4a. Defined Class 8 vocational vehicle and tractor configurations for GEM engine duty cycle generation, engine testing and GEM interpolation

	Test 1	Test 2	Test 3	Test 4
M (kg)	31,978	25,515	19,051	31,978
C_dA	5.4	4.7	4	5.4
Set Tire size and axle ratio at engine speed	Minimum NTE exclusion speed	Minimum NTE exclusion speed	Minimum NTE exclusion speed	B

Table 4b. Defined Class 8 vocational vehicle and tractor configurations for GEM engine duty cycle generation, engine testing and GEM interpolation

	Test 5	Test 6	Test 7	Test 8	Test 9
M (kg)	25,515	19,051	31,978	25,515	19,051
C_dA	4.7	4	5.4	4.7	4
Set Tire size and axle ratio at engine speed	B	B	Maximum test speed	Maximum test speed	Maximum test speed