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Creation of the "Heavy Heavy-Duty Diesel Engine Test Schedule" for Representative Measurement of Heavy-Duty Engine Emissions

July 2007

COORDINATING RESEARCH COUNCIL, INC.
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Center for Alternative Fuels, Engines & Emissions
West Virginia University

ACES-1 FINAL REPORT

Creation of the "Heavy Heavy-Duty Diesel Engine Test Schedule" for Representative Measurement of Heavy-Duty Engine Emissions

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Executive Summary

The objective of the ACES-1 project was to develop an engine test schedule representative of modern truck usage, and to demonstrate their application in an engine test cell. The motivation for developing a new test schedule was to include a broad range of engine activity in the heavy-duty diesel engine emissions study. The ACES test schedule includes four active modes of truck operation including Creep, Transient, Cruise, and High-Speed Cruise (HHDDT_S). The ACES modes were created using engine data collected on the Heavy Heavy-Duty Diesel Truck (HHDDT) Chassis Schedule, which was in turn developed from in-use data taken from 84 heavy heavy-duty diesel trucks. The project had two phases, namely test mode creation (Phase 1) and test mode demonstration and modification (phase 2).

In phase 1, all available engine speed and torque data were converted to percent engine speed and percent torque. Each mode was separated into four microtrips and a numeric code system was adopted to organize the data. The average database statistics were compared to every possible combination of microtrips to determine the best candidate combination for each of the four modes. The modes created in this phase reproduce exact engine behavior in the real vehicle operation in HHDDT Chassis Schedule.

In phase 2, each final mode was modified to perform properly on the engine dynamometer. This modification included the addition of “closed rack” (zero fueling) operating points. The modes were tested at the West Virginia University (WVU) Engine Research Center. Testing was performed using only the Transient mode to obtain preliminary results. Later all four modes, along with the Federal Test Procedure, were tested in triplicate on a 2004 model year heavy-duty on-road engine. During the final runs, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), particulate matter (PM), and total hydrocarbon (HC) emissions were measured. In addition, TEOM continuous PM data and ECU data were recorded.

All emissions and fueling data, and all regression performance data were reviewed. The new ACES modes should not adopt the Federal Test Procedure (FTP) regression criteria to determine compliance with target torque and speed. New regression criteria were developed for each mode using the data obtained during testing.

Introduction

This final report describes the creation of a Heavy Heavy-Duty Diesel Engine (HHDDE) Test Schedule based on engine data gathered during chassis testing. The new test schedule was intended to correspond to the Heavy Heavy-Duty Diesel Trucks (HHDDT) Chassis Schedule used in the E-55/59 program. This new HHDDE Test Schedule is being considered for application in the ACES program that is addressing 2007 and 2010 diesel engine health effects.

The creation of the new HHDDE Test Schedule was based on the four active modes of the HHDDT Chassis Schedule, which include Creep, Transient, Cruise, and High-Speed Cruise (or HHDDT_S). The HHDDT Chassis Schedule was created from in-use data from 84 HHDDT. These data represented about 5.8 million second records, taken from about 1,600 hours of HHDDT activity in the state of California. The HHDDT Chassis Schedule was used in the E-55/59 program to measure truck emissions on a chassis dynamometer. Engine data were captured from a subset of these trucks, and these data were used to create the engine test modes.

Objectives

The objectives were to develop a schedule of engine cycles representative of modern truck usage, and to demonstrate their application in a test cell.

To meet the objectives, the following tasks were identified:

- Perform a quality-check on all available chassis dynamometer and engine data, eliminating runs that have missing or incorrect data
- Separate the data for each mode into four microtrips (definition addressed in detail below) having time lengths determined by the behavior of the speed trace
- Create all possible candidate cycles for each test mode using these microtrips
- Apply the pre-selection process to eliminate candidate modes that do not meet certain criteria (discussed in detail below)
- Rank the candidate modes in each mode based on how closely they represent that mode's database statistics
- Choose the candidate mode for each mode that best represents database behavior as the final mode
- Test each mode at WVU using transient engine dynamometer facilities
- Examine the test results for the final modes, and determine regression parameters

Figure 1 to Figure 4 show the target speed traces for the four active modes, Transient, Creep, Cruise, and High-Speed Cruise (or HHDDT_S). These modes have been discussed by Gautam et al. [1] and Clark et al. [2] and in the E-55/59 program reports (see www.crcao.com). The modes were derived originally from in-use truck data gathered by Battelle and Jack Fawcett Associates under California Air Resources Board (CARB) contracts. The Creep mode shown in Figure 2 consists of four repetitions of a single creep event.

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[1] GAUTAM, M., CLARK, N.N., RIDDLE, W., NINE, R., WAYNE, W.S., MALDONADO, H., AGRAWAL, A. and CARLOCK, M, "Development and Initial Use of a Heavy Duty Diesel Truck Test Schedule for Emissions Characterization", SAE Spring 2002 Fuels & Lubricants Meeting, Reno, NV, SAE Paper 2002-01-1753

[2] CLARK, N.N., GAUTAM, M., RIDDLE, W., NINE, R.D., and WAYNE, W.S., "Examination of a Heavy-Duty Diesel Truck Chassis Dynamometer Schedule," SAE Powertrain Conference, Tampa, Fla., Oct 2004, SAE Paper 2004-01-2904.

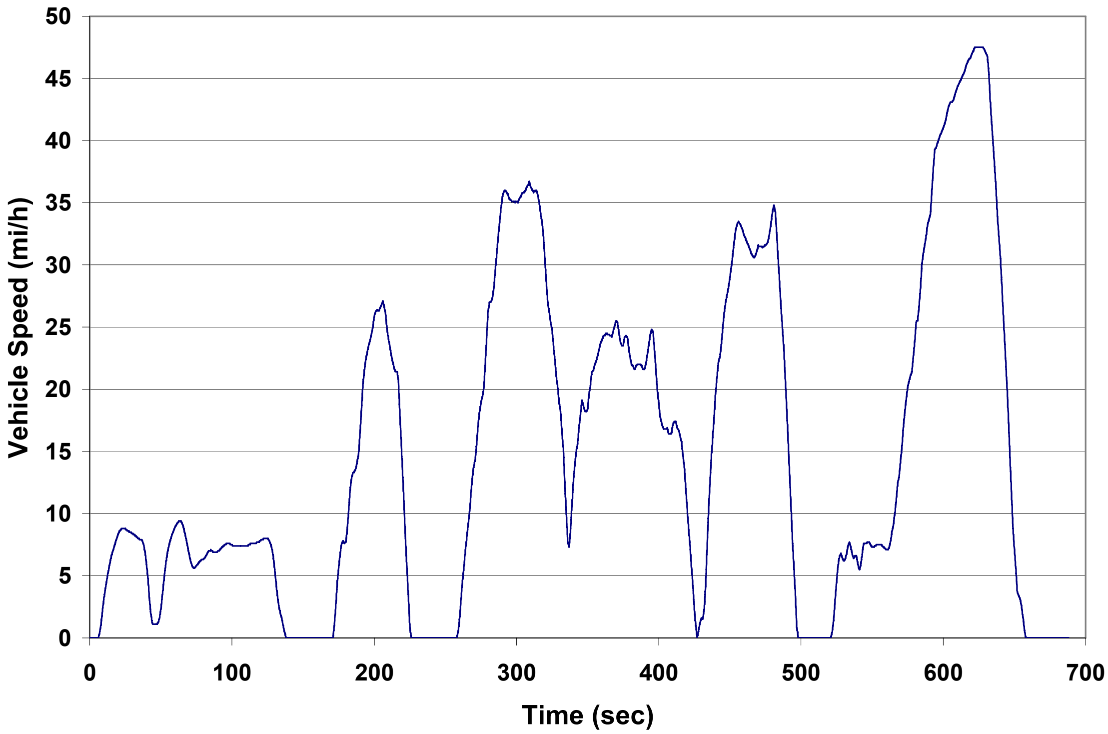

Figure 1: Transient Mode Target Speed Trace

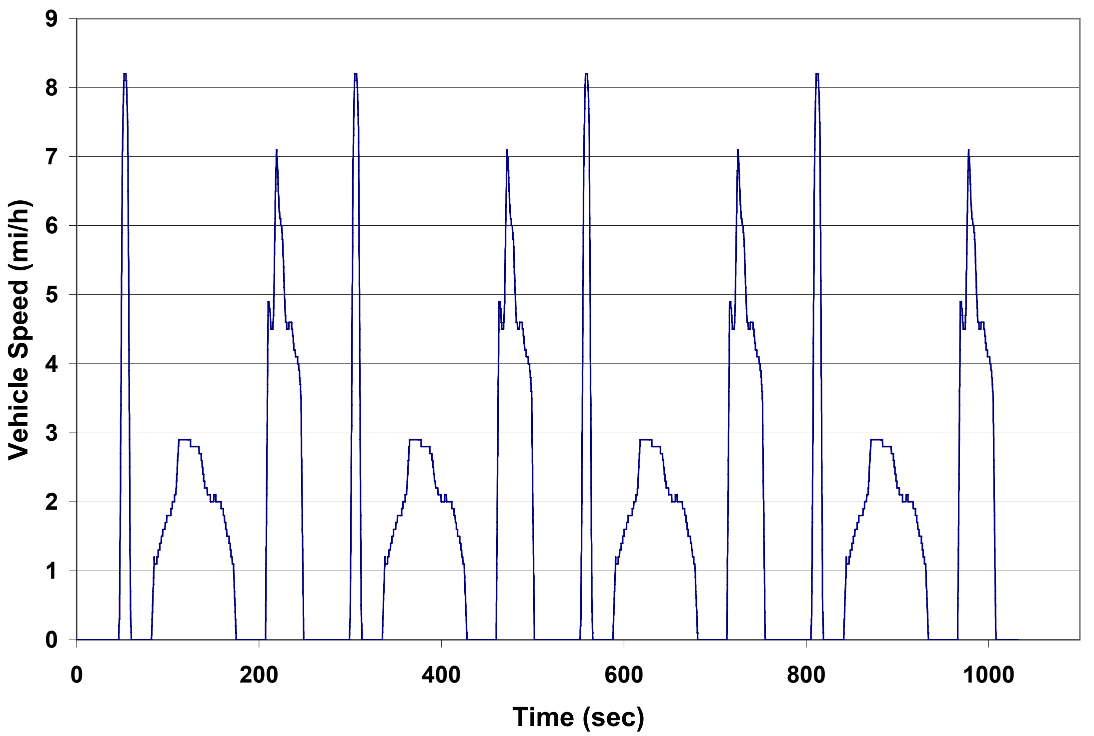

Figure 2: Creep Mode Target Speed Trace

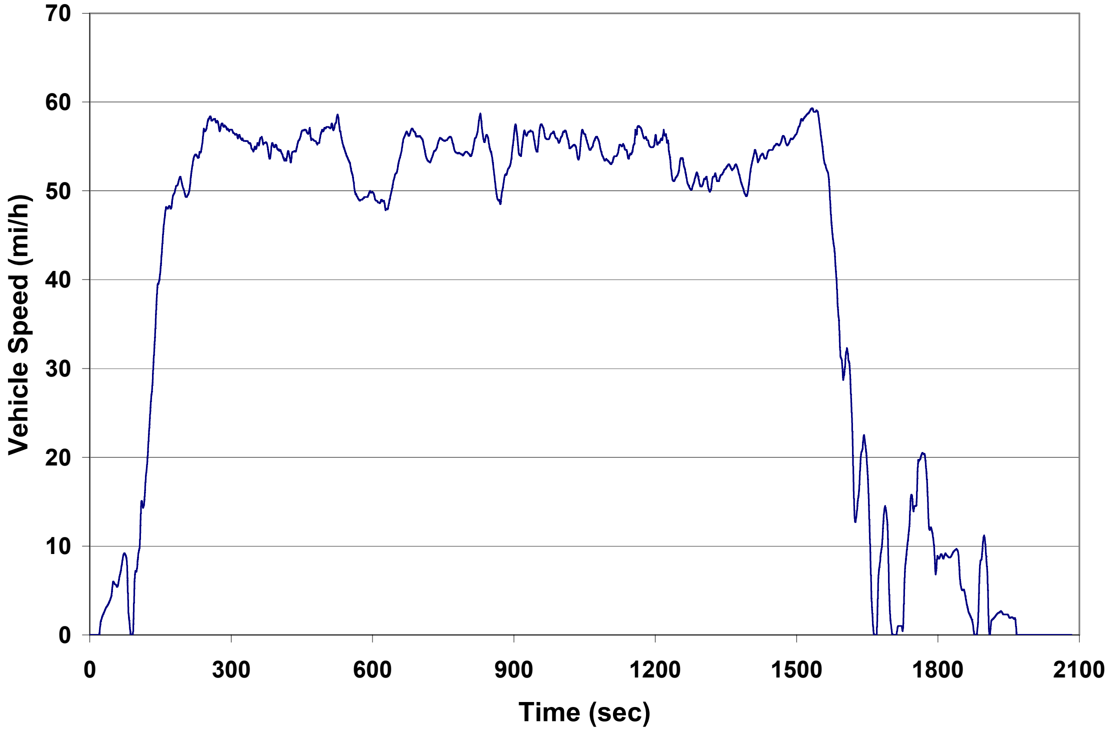

Figure 3: Cruise Mode Target Speed Trace

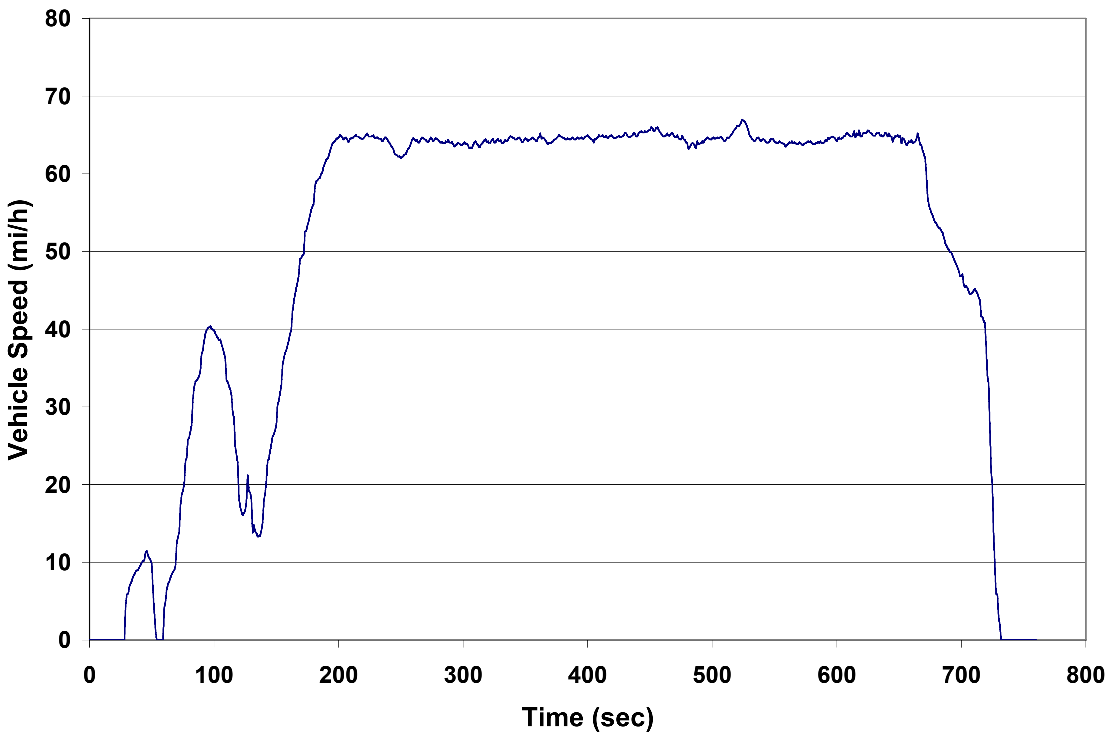

Figure 4: HHDDT_S Mode Target Speed Trace

Approach

The methodology for mode creation presented below was applied to all four active modes of the HHDDT. The methodology is described below primarily in terms of the Transient mode, which was completed first.

Step 1: Data Catalog and Verification

First, all Transient vehicle test runs (chassis dynamometer) and engine control unit (ECU) data were selected. The ECU data were aligned in time with the vehicle test data by aligning the vehicle speed signal, which was recorded in both data sets. Data completeness and regularity were verified by quality inspection for each test run. In some cases, certain runs had to be eliminated from the database if required parameters were not logged or if incorrect data were recorded. Table 2 in step 4 below was generated for the Transient mode to show the quality status of all existing engine data. The discarded engine data were associated with an explanation of why they could not be used.

Step 2: Torque and Engine Speed Translation and Unification

All mode development was performed in the domain of ‘%speed’ and ‘%torque’. The parameters %speed and %torque were widely discussed in the definition of the not-to-exceed (NTE) zone in diesel engine emissions regulation. These values were derived from the broadcast engine parameters of engine speed (in rpm) and %load. First, the speed was converted to %speed using the method of CFR40, based on idle speed as %speed = 0 and rated speed as %speed = 100%. Rated speed was acquired from the engine manufacturer for each engine equipped in the test truck.

Generally, the broadcast parameter %load was computed by the ECU using inferred fueling rates and engine speed. There was no flawless way to convert %load to %torque. For the creation of an engine test mode, it was considered satisfactory to cause the minimum and maximum values of %load and %torque to be related reasonably, and to assume correspondence over the range of operation.

In some cases, the %load corresponded closely to %torque, and there was no need for translation. In almost all cases %load = 100% implied %torque = 100% at each particular speed. However, in some cases, %load corresponded more closely to a fraction of the maximum fueling than a fraction of the maximum torque at values below 100%. Thus %load might have a finite value when %torque was zero (engine idling). In other words, the %load might have no correction (or even an improper correction) for friction and accessories horsepower.

The best approach involved scaling %torque from 0 to 100% as %load ranged from the finite idle value to 100%. This technique must be applied across the whole speed range, because no idle (zero torque) data were reliably available over the whole engine speed range. The implied error in microtrip energy of this correction would be small.

Engine lug curves were also requested from the engine manufacturers to assist the %load investigation and %torque conversion. The generation of Excel data files (%speed vs. time and %torque vs. time) for each test run provided convenience for future computer program calculations (performed using Matlab, see below). For simplicity, each Excel file had the same format and sampling frequency.

Step 3: Microtrip Definition and Name Code
Each engine mode must have the same time duration as the original chassis mode. The engine mode was viewed as representing the behavior of an engine as a truck is driven through the chassis mode, except that the "engine" and "truck" must represent a fleet composite of engines, gearing and operating weights.

In the case of the Transient mode, a microtrip was defined as an operational period from a stop (engine idling or truck fully stopped) to another stop in the vehicle speed-time trace. A stop must have at least a five-second duration. For example, the target Transient mode (chassis mode), shown in Figure 5, was divided into four microtrips. The time durations of microtrips one through four were 155 seconds, 90 seconds, 265 seconds, and 178 seconds, respectively.

In practice, the engine mode had as many microtrips as the chassis mode and each engine microtrip had the same duration as the corresponding chassis microtrip. The portions of idle were equal in the engine and chassis modes as well. The Cruise and HHDDT_S modes had different microtrip lengths and break points that did not necessarily correspond to portions of idle. In this case, a method of averaging the two microtrips was used, as described later in this report.

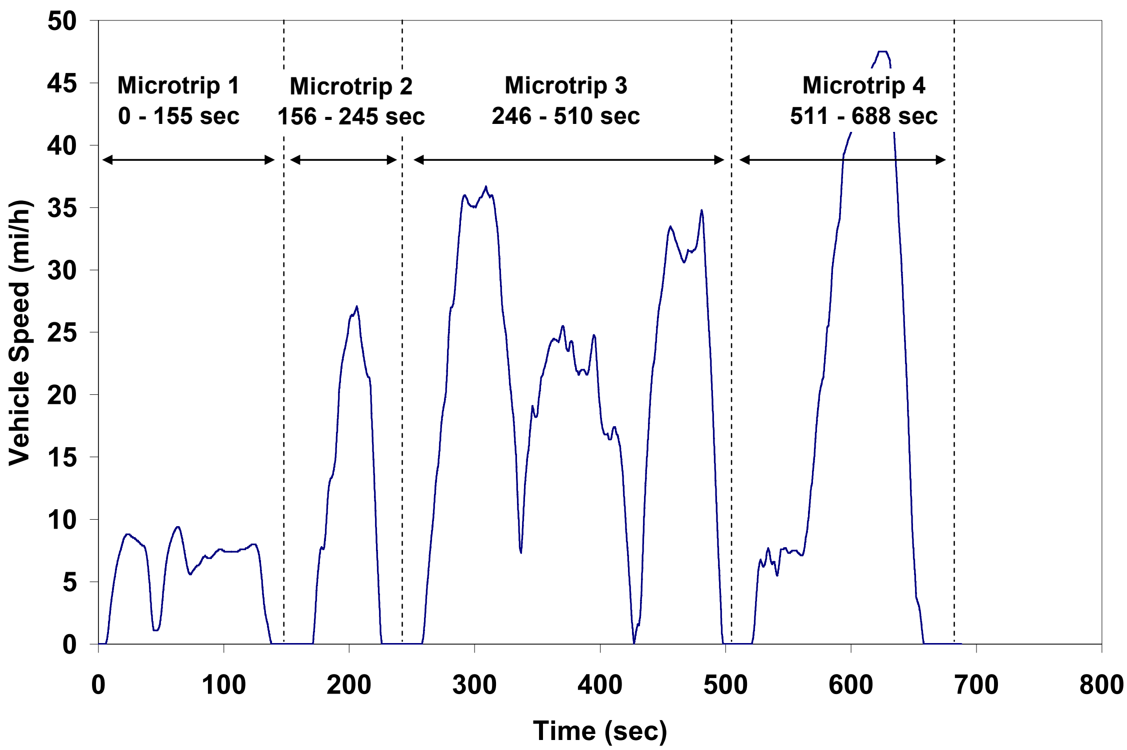

Figure 5: Transient Mode Microtrip Lengths

In order to manage the microtrip statistics, an eight-digit code was assigned to individual microtrip from each truck, test run, and test weight. The method used to generate the code is described in the following Table 1.

For example, 3126131000 should be decoded as 3-1-26-1-3-1-000. A single digit of 3 indicated that this was a Transient mode. Next, the number 1 denoted which microtrip (1-4) it was. A two-digit number represented that the data were obtained from the CRC26 truck, where the truck number corresponded to the E-55/59 truck number. The engine type, test weight, and repeat number were all represented next using a single digit for each. The example truck was equipped with a Caterpillar engine and the test weight was 30,000 lb. The final three zeros were reserved digits. Table 1 below summarizes the decoding procedure.

Table 1: Microtrip Number Decoding

Test Mode (one digit)	**Creep**		**Transient**		**Cruise**		**High-Speed Cruise**
	2		3		4		5
Microtrip number (one digit)	**Microtrip #1**		**Microtrip #2**		**Microtrip #3**		**Microtrip #4**
	1		2		3		4
Test Truck (two digits)	**CRC26**	**CRC27**	**CRC28**	**CRC29**	**CRC30**	**CRC34**	**CRC35**	
	26	27	28	29	30	34	35	
Engine Type (one digit)	**Caterpillar C-10**		**Detroit Diesel Series**		**Cummins**		**-**
	1		2		3		-
Test Weight (one digit)	**30,000 lb**		**56,000 lb**		**66,000 lb**		**-**
	3		5		6		-
Repeat Run (one digit)	**Initial Run**		**Second Run repeat)**		**Repeat Run Two**		**-**
	1		2		3		-
Reserve Digits (three digits)	-		-		-		-

Step 4: Microtrip Matrix Creation

The description of mode creation below was based on the Transient mode. From the database of chassis microtrips, numbered one through four, corresponding engine microtrips were selected to represent different trucks, engines and test weights. This was achieved by assembling a number of candidate engine modes (of four microtrips each) and comparing the statistics of these candidate modes to the statistics of the database of all tests available for the Transient mode.

A microtrip matrix was generated for all available Transient modes. The microtrip matrix described all Transient mode microtrips and their properties determined by a quality audit (acceptable, correctable, unavailable, and unclear). The correctable microtrips included two situations: one was small-scale noise, possibly repairable by interpolation, and the other was a consistent percent offset (higher or lower). The unavailable runs included runs with un-repairable incompleteness or excessive noise. The unclear runs included incompleteness and noise that was substantial but possibly repairable. The last reserved digit of the microtrip name code was used to represent these properties.

- Microtrip Acceptable (1)
- Microtrip Correctable (2)
- Microtrip Unavailable (3)
- Microtrip Unclear (4)

Based on initial investigation of the Transient mode, a microtrip matrix was created and is shown in Table 2. Here, the run numbers are either bold, in parenthesis, double strikethrough, or underlined. Each of these formats was associated with the reserve digit (1, 2, 3, or 4), described above. A formal table was only created for the Transient mode showing the eliminated and acceptable runs in terms of the individual coded microtrip numbers. Another table can be found later in the report describing which runs were eliminated in terms of the truck, engine technology, and test weight.

Table 2: Transient Mode Microtrip Table

Microtrip #1	Microtrip #2	Microtrip #3	Microtrip #4
3126131004	**3226131001**	**3326131001**	**3426131001**
3126151004	**3226151001**	**3326151001**	(3426151002)
3126161004	~~3226161003~~	~~3326161003~~	~~3426161003~~
(3127231002)	**3227231001**	**3327231001**	**3427231001**
(3127251002)	3227251004	3327251004	3427251004
3127261004	3227261004	3327261004	3427261004
3128231004	3228231004	3328231004	3428231004
3128251004	**3228251001**	(3328251002)	3428251004
3128261004	3228261004	3328261004	3428261004
3129331004	~~3229331003~~	~~3329331003~~	~~3429331003~~
3129351004	3229351004	3329351004	3429351004
3129361004	3229361004	3329361004	3429361004
3130231004	~~3230231003~~	~~3330231003~~	~~3430231003~~
3130251004	**3230251001**	**3330251001**	(3430251002)
3130261004	3230261004	3330261004	3430261004
3134231004	~~3234231003~~	~~3334231003~~	~~3434231003~~
3134251004	~~3234251003~~	~~3334251003~~	~~3434251003~~
3134261004	~~3234261003~~	~~3334261003~~	~~3434261003~~
3135231004	~~3235231003~~	~~3335231003~~	~~3435231003~~
3135251004	~~3235251003~~	~~3335251003~~	~~3435251003~~
3135261004	**3235261001**	**3335261001**	**3435261001**

Step 5: Candidate Modes Creation

As a result of exercising quality control and correction procedures on microtrips listed in the table, there were a different number of runs available for mode creation in the first, second, third, and fourth microtrips. Therefore weighting of microtrips was necessary so that the proportion of original activity in the mode was preserved in the calculation of database statistics. The following explanation used the creation of the Transient mode as an example to address the methodology and formulas.

If there were *m* candidates for the first microtrip, *n* candidates for the second microtrip, *p* candidates for the third microtrip and *q* candidates for the fourth microtrip, then the fleet (database) average statistics for the Transient mode were found in the following way.

Database Statistics

Database statistics included average %speed, average %torque, average %speed squared, and average %torque squared. The use of %speed and %speed squared was equivalent to considering average %speed and standard deviation of %speed as separate metrics.

Database average %speed:

$$\overline{\%speed}_{database} = \frac{1}{t_1 + t_2 + t_3 + t_4}\left(\begin{array}{l} \frac{t_1}{m}\sum_i^m \overline{\%speed}_{microtrip\ 1} + \frac{t_2}{n}\sum_i^n \overline{\%speed}_{microtrip\ 2} + \\ \frac{t_3}{p}\sum_i^p \overline{\%speed}_{microtrip\ 3} + \frac{t_4}{q}\sum_i^q \overline{\%speed}_{microtrip\ 4} \end{array} \right)$$

t_1 is the time duration of microtrip 1.
t_2 is the time duration of microtrip 2.
t_3 is the time duration of microtrip 3.
t_4 is the time duration of microtrip 4.

$\overline{\%speed}_{microtrip\ 1}$ is the average %speed for each candidate of the first microtrips.
$\overline{\%speed}_{microtrip\ 2}$ is the average %speed for each candidate of the second microtrips.
$\overline{\%speed}_{microtrip\ 3}$ is the average %speed for each candidate of the third microtrips.
$\overline{\%speed}_{microtrip\ 4}$ is the average %speed for each candidate of the fourth microtrips.

m is the number of candidates for microtrip 1.
n is the number of candidates for microtrip 2.
p is the number of candidates for microtrip 3.
q is the number of candidates for microtrip 4.

Similar equations were applied to average %speed squared, average %torque and average %torque squared.

$$\overline{(\%speed)^2}_{database} = \frac{1}{t_1 + t_2 + t_3 + t_4}\left(\begin{array}{l} \frac{t_1}{m}\sum_i^m \overline{(\%speed)^2}_{microtrip\ 1} + \frac{t_2}{n}\sum_i^n \overline{(\%speed)^2}_{microtrip\ 2} + \\ \frac{t_3}{p}\sum_i^p \overline{(\%speed)^2}_{microtrip\ 3} + \frac{t_4}{q}\sum_i^q \overline{(\%speed)^2}_{microtrip\ 4} \end{array} \right)$$

$$\overline{\%torque}_{database} = \frac{1}{t_1 + t_2 + t_3 + t_4}\left(\begin{array}{l} \frac{t_1}{m}\sum_i^m \overline{\%torque}_{microtrip\ 1} + \frac{t_2}{n}\sum_i^n \overline{\%torque}_{microtrip\ 2} + \\ \frac{t_3}{p}\sum_i^p \overline{\%torque}_{microtrip\ 3} + \frac{t_4}{q}\sum_i^q \overline{\%torque}_{microtrip\ 4} \end{array} \right)$$

$$\overline{(\%torque)^2}_{database} = \frac{1}{t_1+t_2+t_3+t_4}\left(\begin{array}{l} \frac{t_1}{m}\sum_i^m \overline{(\%torque)^2}_{microtrip\ 1} + \frac{t_2}{n}\sum_i^n \overline{(\%torque)^2}_{microtrip\ 2} + \\ \frac{t_3}{p}\sum_i^p \overline{(\%torque)^2}_{microtrip\ 3} + \frac{t_4}{q}\sum_i^q \overline{(\%torque)^2}_{microtrip\ 4} \end{array}\right)$$

Candidate Mode Statistics

A Matlab program was composed to create candidate modes from the combination of all available microtrips. A basic program template was created for the Transient mode, then adapted to the other modes by simply changing the input data and microtrip durations. Each newly created Transient engine mode was labeled with all information of the selected microtrips. The program also performed the pre-selection by following the criteria below to confine the total number of candidate modes.

1. A sample mode could not have more than one microtrip from the same test run, nor from the same truck at the same test weight.
2. A sample mode could not have only one test weight or one test weight for more than two microtrips.
3. A sample mode could not have all microtrips from one engine technology (i.e. at least two different engine manufacturers or two different engine types from one engine manufacturer will be selected)

The rest of the candidate Transient modes were considered statistically to locate the best candidate mode. Each candidate mode has its own four average statistics calculated in the following way:

$$\overline{\%speed}_{candidate} = \frac{1}{t_1+t_2+t_3+t_4}\left(\begin{array}{l} t_1 \times \overline{\%speed}_{microtrip\ 1} + t_2 \times \overline{\%speed}_{microtrip\ 2} + \\ t_3 \times \overline{\%speed}_{microtrip\ 3} + t_4 \times \overline{\%speed}_{microtrip\ 4} \end{array}\right)$$

t_1 is the time duration of microtrip 1.
t_2 is the time duration of microtrip 2.
t_3 is the time duration of microtrip 3.
t_4 is the time duration of microtrip 4.

$\overline{\%speed}_{microtrip\ 1}$ is the average %speed for the chosen first microtrips.
$\overline{\%speed}_{microtrip\ 2}$ is the average %speed for the chosen second microtrips.
$\overline{\%speed}_{microtrip\ 3}$ is the average %speed for the chosen third microtrips.
$\overline{\%speed}_{microtrip\ 4}$ is the average %speed for the chosen fourth microtrips.

$$\overline{(\%speed)^2}_{candidate} = \frac{1}{t_1 + t_2 + t_3 + t_4}\begin{pmatrix} t_1 \times \overline{(\%speed)^2}_{microtrip\ 1} + t_2 \times \overline{(\%speed)^2}_{microtrip\ 2} + \\ t_3 \times \overline{(\%speed)^2}_{microtrip\ 3} + t_4 \times \overline{(\%speed)^2}_{microtrip\ 4} \end{pmatrix}$$

$$\overline{\%torque}_{candidate} = \frac{1}{t_1 + t_2 + t_3 + t_4}\begin{pmatrix} t_1 \times \overline{\%torque}_{microtrip\ 1} + t_2 \times \overline{\%storque}_{microtrip\ 2} + \\ t_3 \times \overline{\%torque}_{microtrip\ 3} + t_4 \times \overline{\%torque}_{microtrip\ 4} \end{pmatrix}$$

$$\overline{(\%torque)^2}_{candidate} = \frac{1}{t_1 + t_2 + t_3 + t_4}\begin{pmatrix} t_1 \times \overline{(\%torque)^2}_{microtrip\ 1} + t_2 \times \overline{(\%torque)^2}_{microtrip\ 2} + \\ t_3 \times \overline{(\%torque)^2}_{microtrip\ 3} + t_4 \times \overline{(\%torque)^2}_{microtrip\ 4} \end{pmatrix}$$

Microtrip Statistics

The average statistics of a single microtrip were calculated in the following way:

$$\overline{\%speed}_{microtrip} = \frac{1}{t}(\int_0^t \%speed)$$

t is the time duration of the microtrip.

$$\overline{(\%speed)^2}_{microtrip} = \frac{1}{t}(\int_0^t (\%speed)^2)$$

$$\overline{\%torque}_{microtrip} = \frac{1}{t}(\int_0^t \%torque)$$

$$\overline{(\%torque)^2}_{microtrip} = \frac{1}{t}(\int_0^t (\%torque)^2)$$

Final Mode Determination

Least squares theory was used to identify the candidate modes, which best represent the center and spread properties (%speed, %torque) of the database. For each candidate mode, the least squares values, S, of average %speed, average %torque, average of (%speed squared), and average of (%torque squared) were calculated. The least squares values, S, was calculated in the following way:

$$S = \sqrt{\begin{aligned} &\left(\frac{\overline{\%speed}_{candidate} - \overline{\%speed}_{database}}{\overline{\%speed}_{database}}\right)^2 + \left(\frac{\overline{(\%speed)^2}_{candidate} - \overline{(\%speed)^2}_{database}}{\overline{(\%speed)^2}_{database}}\right)^2 + \\ &\left(\frac{\overline{\%torque}_{candidate} - \overline{\%torque}_{database}}{\overline{\%torque}_{database}}\right)^2 + \left(\frac{\overline{(\%torque)^2}_{candidate} - \overline{(\%torque)^2}_{database}}{\overline{(\%torque)^2}_{database}}\right)^2 \end{aligned}}$$

Based on values of S, the five best modes were chosen for inspection by the investigators. These modes were inspected to see that no parameter match was disadvantaged. For example (shown in the following chart), candidate mode 1 may have had a very small value of *S* as the result of being very closing to three average statistics. Candidate mode 2 may have shown a more homogeneous distribution and would be considered to have superior representation of database engine behavior, although it may have had slightly larger *S*. By careful inspection and using engineering judgment, one final candidate mode was chosen as the final mode.

Figure 6 shows a graphical comparison of the two modes and database statistics. Figure 7 shows an overall flow chart of best candidate cycle approach.

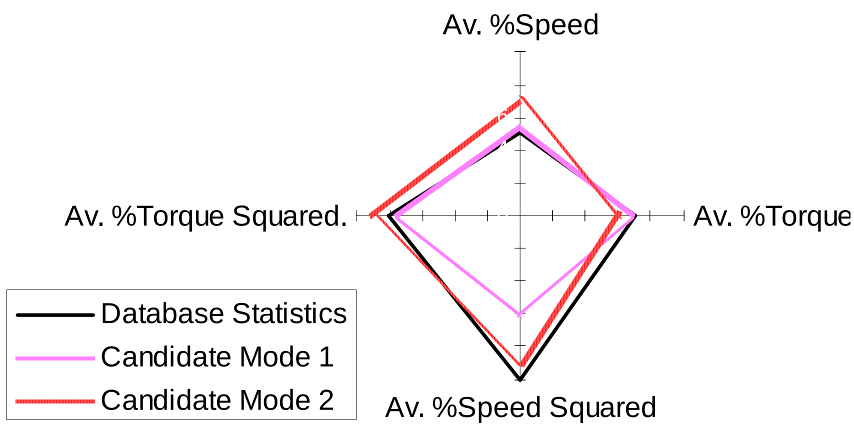

Figure 6: Candidate Mode Comparison

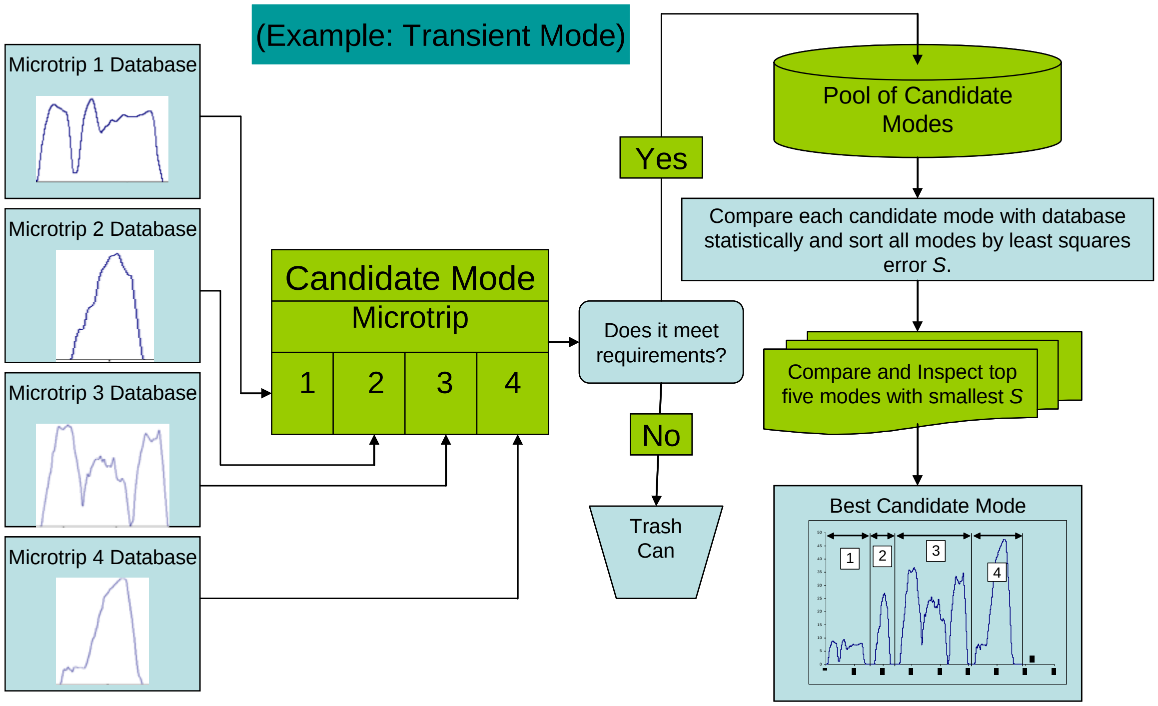

Figure 7: Flow Chart of Best Candidate Mode Approach

A creation procedure similar to that used for the Transient mode was applied to Creep mode development. However, Cruise and High-Speed Cruise modes required extra investigation. Neither mode included intermittent idle sections, making microtrip length determination difficult.

For example, the High-Speed Cruise mode is shown in Figure 8. To remain consistent and ensure that the cycle selection program could easily be adapted to the other modes, all modes were made to have four microtrips. The first and last segments were chosen as the transient parts of the mode. They could be roughly separated as the 0 to 250th second and 651st second to the end. The remaining two segments shared equal time duration from the 251st to 450th second and the 451st to the 650th second.

If the mode was assembled from four chosen microtrips, there was a concern that the %torque and %speed would not match at the junctions between the microtrips, because these junctions would not occur during idle operation. This mismatch was smoothed by blending the data from the two source files on each side of the junction between microtrips. The blending occurred over a time range of approximately 20 seconds such that the rate of speed change did not exceed 8 rpm per second, even for an engine rated at 3,000 rpm. The mapping of engines for the FTP occurs at 8 rpm per second, so this was considered to be quasi-steady operation. This %speed and %torque blending at the interface affected standard deviation of %torque and %speed only slightly. It was applied only to the final mode that was selected.

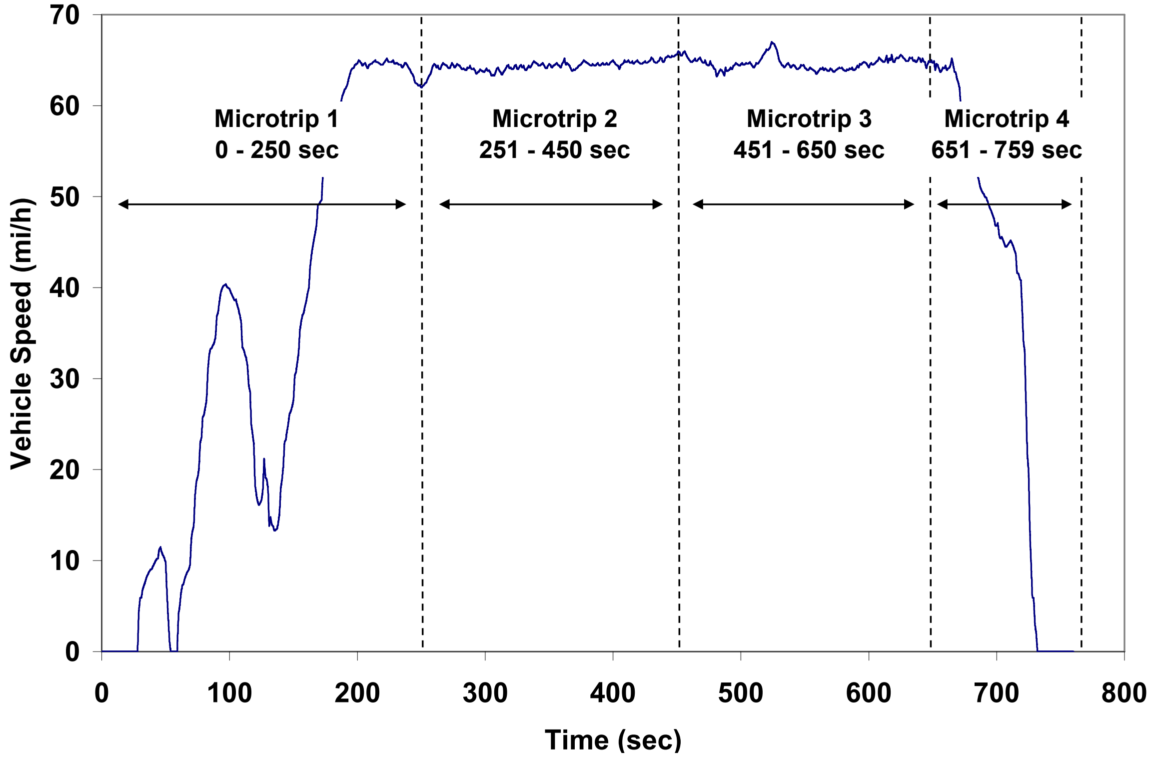

Figure 8: High Speed Cruise Microtrip Lengths

Available Data

For each test mode, the ECU and chassis emissions data were aligned by vehicle speed. As each run was aligned, the data were checked to ensure that they were credible and that all required parameters were broadcast from the ECU. In some cases when vehicle speed was missing from the ECU file, it was taken from the chassis emissions file. In addition, the starting point was checked to ensure that data logging did not start late, missing data in the first few seconds. Usually these files were simply eliminated, unless the quantity of missing data was very small and occurred during vehicle idle, in which case it could be recreated.

Figure 9 shows an example of data alignment using vehicle speed for a Detroit Diesel powered, 30,000lb test weight vehicle operating on the Transient mode on the chassis dynamometer during E-55/59 testing. This case also shows how the data for microtrip 1 were preserved even when shifted back in time to align them with the emissions (chassis) data. Some cases required a forward shift or had missing data.

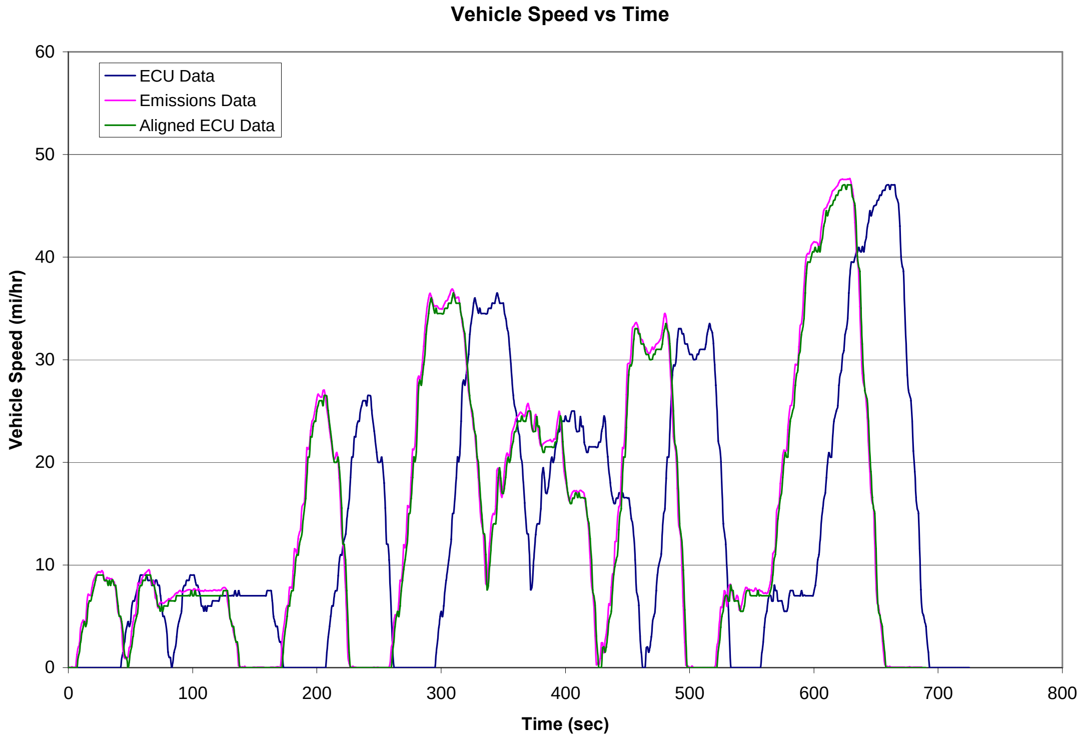

Figure 9: Transient Mode Vehicle Speed Alignment

Table 3 shows all originally available runs as well as those that were eliminated. In the table, shaded rows indicate that the run was eliminated. A run was eliminated if matching ECU and emissions files (i.e. E-55/59 files) could not be found, if the data had excessive noise or other interference, if the required parameters were not logged, or if a large portion of the data was missing at the beginning of the run. For those runs that had only a small amount of missing data in the beginning, similar data from later in the same run were used to fill in the missing data. This was done only for idle portions or smooth, brief periods of acceleration. If a run had missing data over a very transient part, the run was eliminated because the data could not be recreated reliably.

Table 3: Available and Eliminated Data for all Modes

Truck Info	Truck Number	Test Weight			Test Mode			
		30K	56K	66K	Creep	Transient	Cruise	HHDDT_S
1998 Caterpillar C-10 350hp	CRC26 2435		x		x			
			x			x		
			x					x
	CRC26 2445			x	x			
				x		x		
				x				x
				x			x	
	CRC26 2465		x		x			
			x			x		
			x				x	
	CRC26 2466	x			x			
		x					x	
	CRC26 2470		x		x			
1999 Detroit Diesel Series 60 500hp	CRC27 2450			x	x			
				x			x	
				x				x
	CRC27 2455		x		x			
			x			x		
	CRC27 2457	x			x			
		x				x		
		x					x	
		x						x
1998 Detroit Diesel Series 60 500hp	CRC28 2476		x		x			
			x			x		
			x				x	
			x					x
	CRC28 2477	x			x			
		x				x		
		x					x	
		x						x
	CRC28 2480			x	x			
				x		x		
				x			x	
				x				x
	CRC28 2563		x			x		
			x				x	
Cummins ISX475ST2 450hp	CRC29 2485		x		x			
			x			x		
			x					x
	CRC29 2486			x		x		
				x	x			
				x			x	
				x				x
1998 Detroit Diesel Series 60 500hp	CRC30 2526		x		x			
			x			x		
			x				x	
			x					x
	CRC30 2583			x	x			
				x		x		
				x			x	
				x				x
	CRC30 2586		x			x		
			x		x			
			x				x	
			x					x
2003 Detroit Diesel Series 60 500hp	CRC34 2603			x	x			
				x			x	
				x				x
	CRC34 2608		x					x
2000 Detroit Diesel Series 60 470hp	CRC35 2617		x					x
	CRC35 2621			x	x			
				x		x		

Example plots of vehicle speed, percent engine speed, and percent engine torque are shown in Figure 10 to Figure 12 for a 56,000 lb Detroit Diesel powered vehicle operating on the Transient mode and in Figure 13 to Figure 15 for a 30,000 lb Detroit Diesel vehicle operating on the Cruise mode.

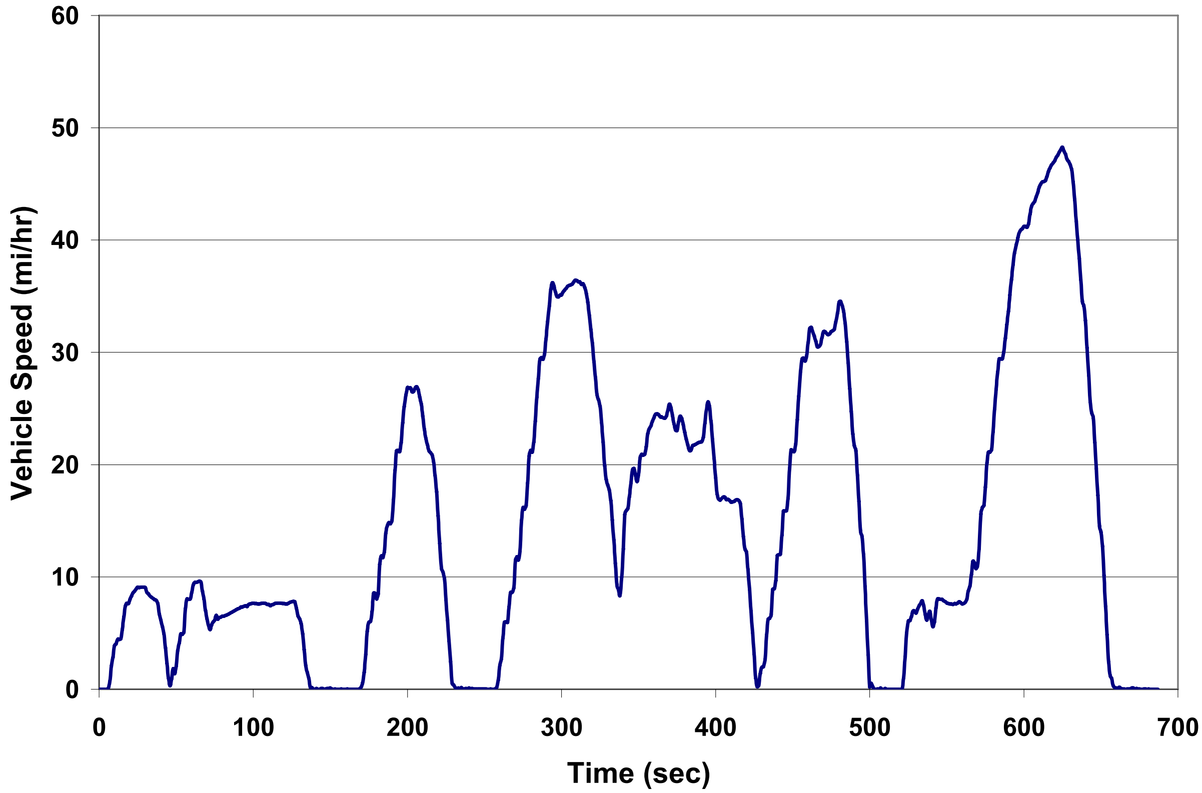

Figure 10: Transient Mode Vehicle Speed

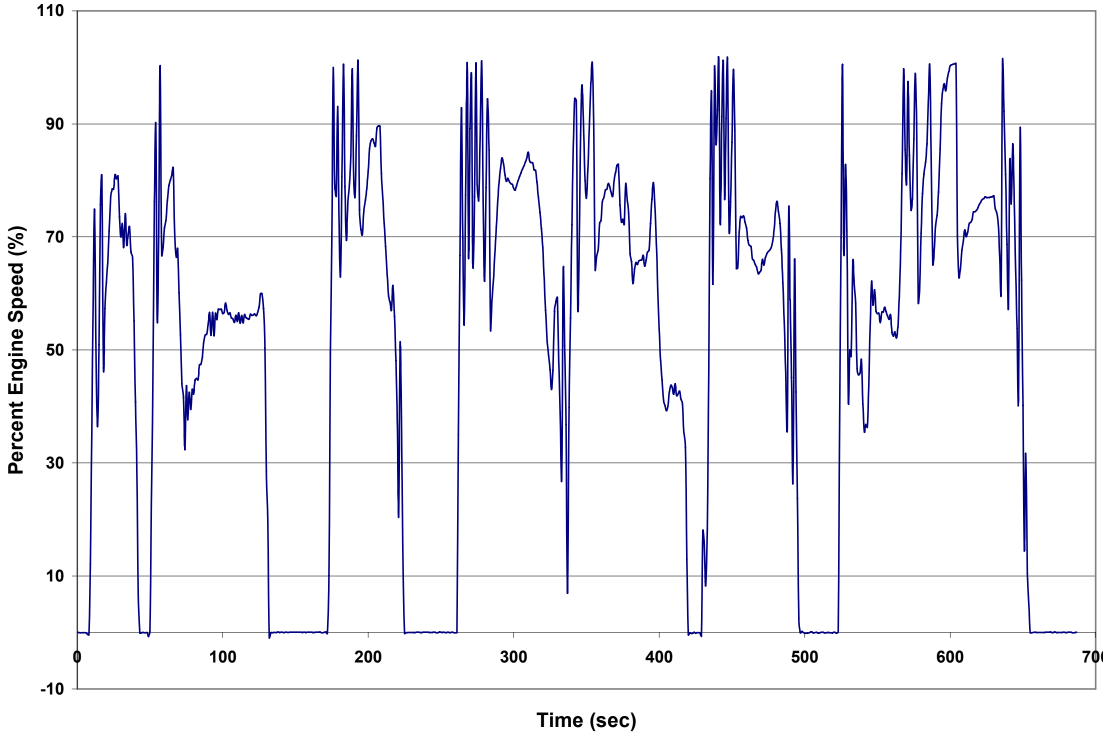

Figure 11: Transient Mode Percent Engine Speed

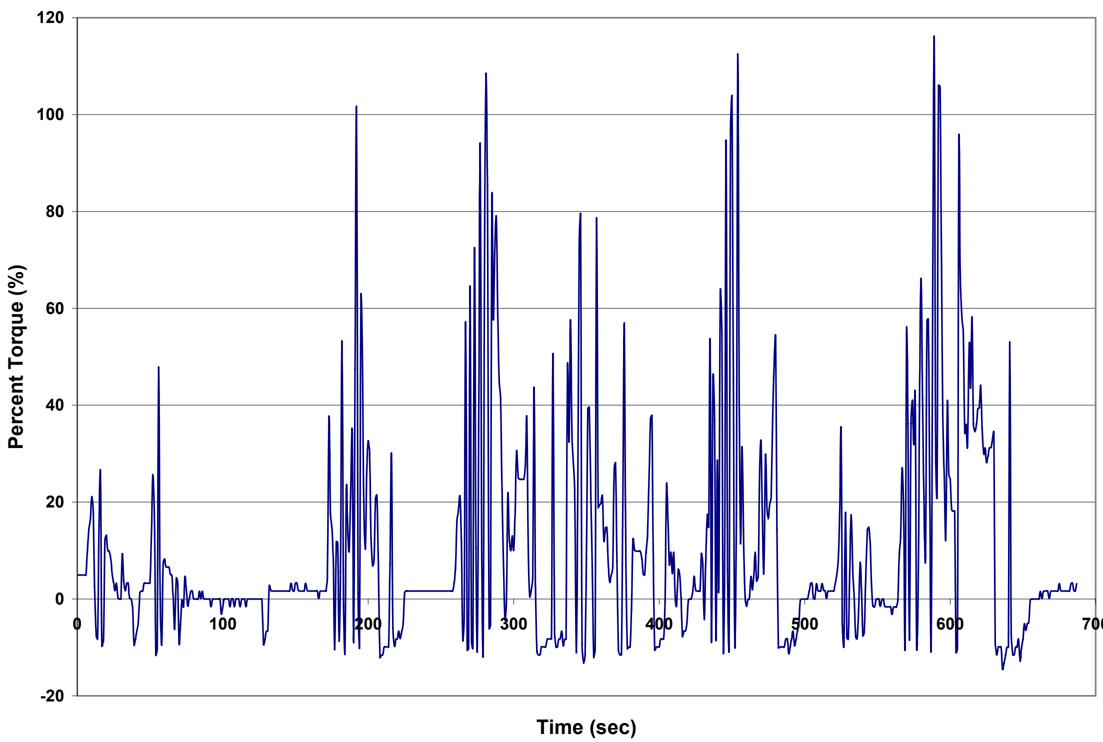

Figure 12: Transient Mode Percent Torque

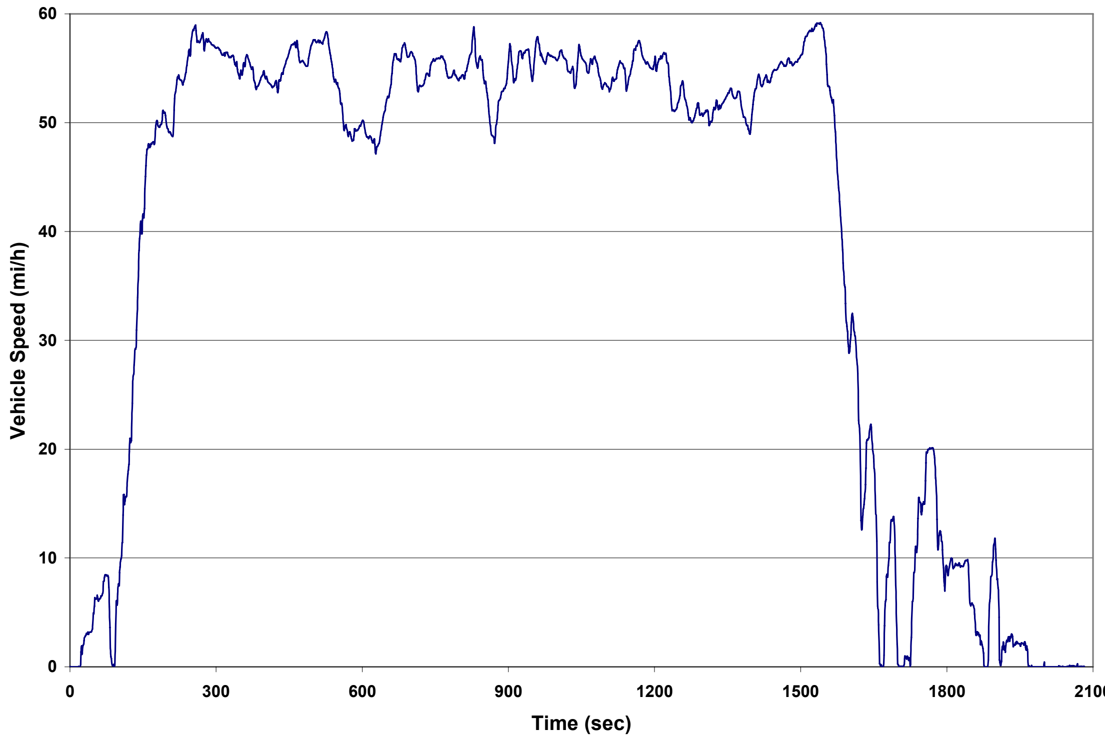

Figure 13: Cruise Mode Vehicle Speed

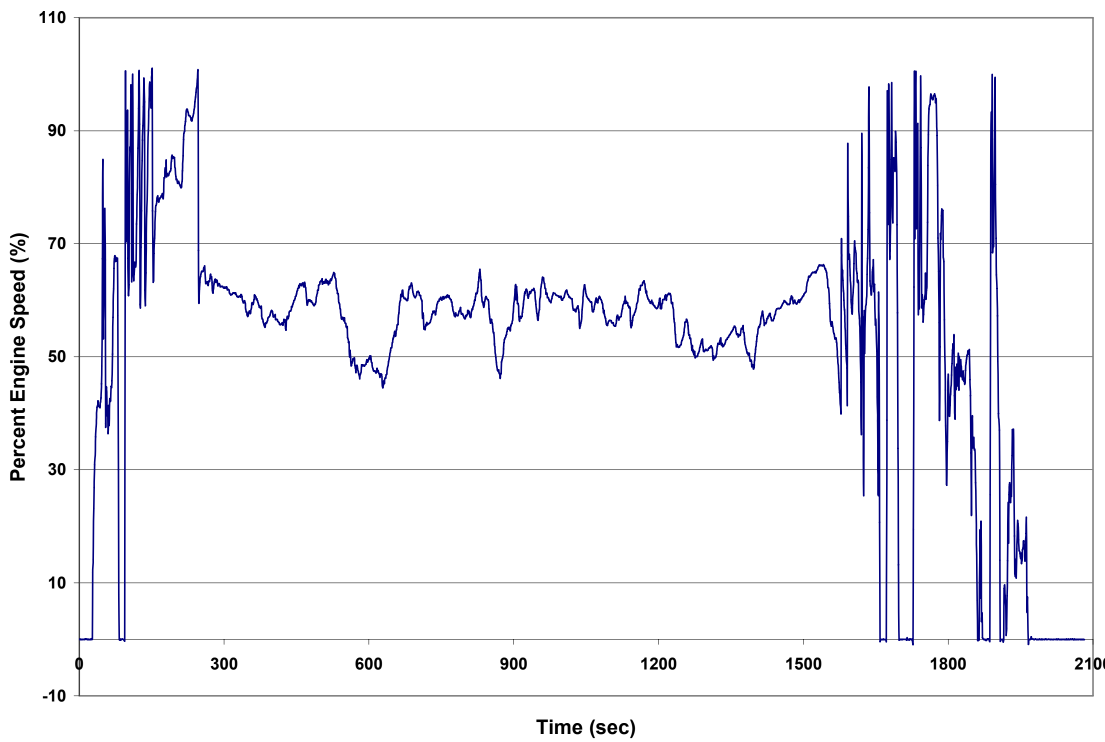

Figure 14: Cruise Mode Percent Engine Speed

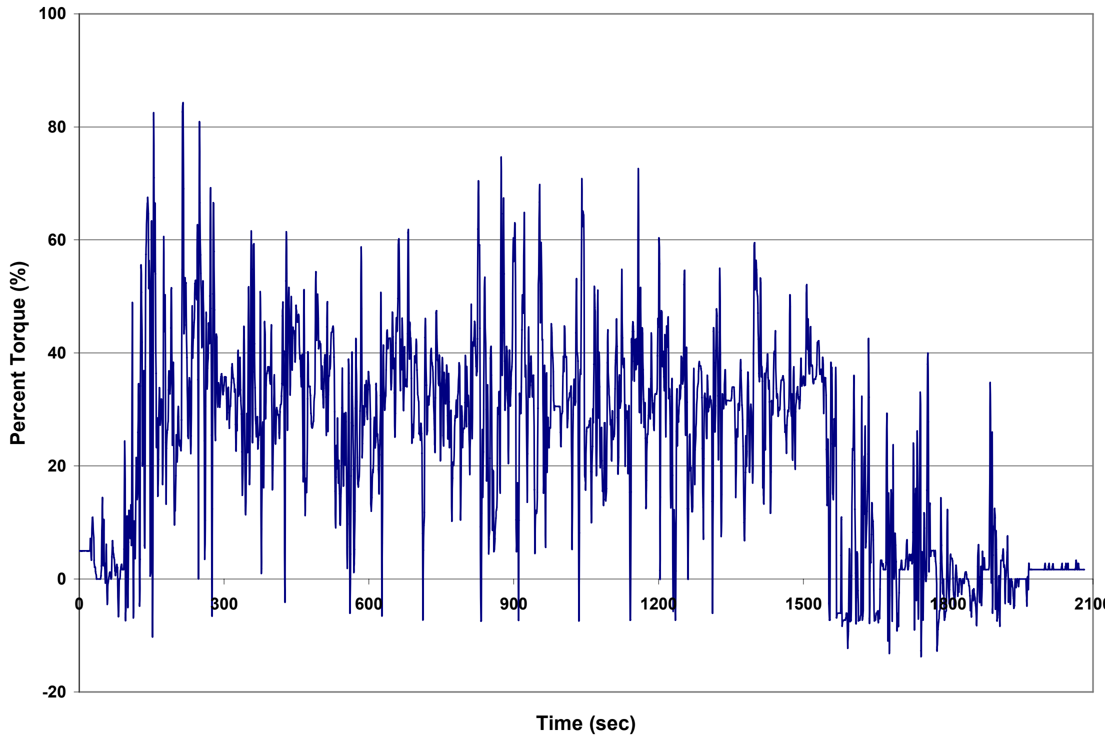

Figure 15: Cruise Mode Percent Torque

Construction of Engine Modes

The data for each mode were converted from actual engine speed (in rpm) and percent load to percent speed and percent torque. In all cases, translating engine speed was straightforward. The rated and idle engine speeds were given by each engine manufacturer and corresponded to 0% and 100% engine speed, respectively. This definition of percent speed was consistent with the definition in the Code of Federal Regulations.

Translation of percent load was different for the three different engine manufacturers. For Caterpillar engines, the percent load broadcast was equivalent to percent torque. Additionally, these engines reported negative torque, and this information was needed for the cycle development. Detroit Diesel engines broadcast a percent load parameter (defined as the currently available torque to maximum available torque ratio) and an actual torque parameter (in Nm, torque available at flywheel), which included negative torque. Since the actual percent torque available at any time was desired, the actual torque parameter was converted to a percent torque. To accomplish this, engine maps were obtained for each Detroit Diesel engine, but these maps reported torque only at engine speeds representing a typical in-use operating range under power, and this range did not extend to low idle speed. These engine torque curves were extended all the way to idle speed by drawing a straight line from the torque at idle speed to the next available full load point. To extend the torque curve to rated speed, the torque at 2,225 RPM was assumed to be zero. A spline interpolation was used to create a smooth curve. A Matlab program was written to import each Detroit Diesel engine actual torque and engine speed, find the maximum torque at that engine speed, and divide the actual engine torque by it. This then created an actual percent engine torque, which included negative motoring torque. This use of actual torque, as the source for %torque, deviated from the original methodology, which was to use %load as the source.

The Cummins engines correctly reported percent torque, but they did not broadcast negative values. Instead, zero torque was reported for these values. Because only a small amount of negative torque was typically seen and since there were a small number of Cummins engines in the database, this was ignored during candidate cycle creation. Only after the final cycle was chosen for each mode, were the negative torque values added for any Cummins engines. To accomplish this, a Detroit Diesel motoring torque curve was used to ensure for a given engine speed, the motoring torque was within an acceptable range. Each selected microtrip required individual engineering attention for the addition of motoring torque. These corrections typically did not last longer than 5-10 seconds or go below -10% torque because diesel engine motoring torque is usually small in magnitude relative to rated torque.

With the available percent torque and speed, a Matlab program created all combinations of microtrips, evaluated the statistics, and selected the best candidate mode. Table 4 presents the statistics of the databases and final candidates for the four modes. The least squares value was also calculated and presented. The next sections address the detailed construction information for each mode.

Table 4: Database and Modes Statistics

	Creep		Transient		Cruise		HHDDT_S	
	Database	Candidate Mode	Database	Candidate Mode	Database	Candidate Mode	Database	Candidate Mode
Average Speed (%speed)	9.99	9.96	47.22	48.04	56.88	57.28	57.66	56.50
Average Speed Squared $(\%speed)^2$	419.47	421.36	3461.92	3424.81	3897.93	3954.25	3796.77	3629.21
Average Torque (%torque)	3.75	3.71	14.87	14.77	33.52	33.52	43.01	42.93
Average Torque Squared $(\%torque)^2$	73.89	73.66	961.54	972.85	1993.31	1995.26	2956.26	2936.19
Least Squares Value (S)	---	0.0120	---	0.0244	---	0.0161	---	0.0490

Transient Mode

The final Transient mode was constructed using data from the engine types, vehicles, and test weights shown in Table 5. The final mode included Detroit Diesel Series 60 engines for the first three microtrips and the final microtrip was from a Caterpillar C-10. The final mode had two 56,000 lb microtrips, one 30,000 lb microtrip and one 66,000 lb microtrip. By implementing the pre-selection criteria, the final mode included two different engine technologies and all three possible test weights, making it representative of the whole database.

Table 5: Transient Data Availability

Vehicle	**Test Weights**			**Engine MY**	**Engine Type**	**Engine hp**
	30k	56k	66k			
CRC26		x1	x1	1998	Caterpillar C-10	350
CRC27	x1	x1		1999	Detroit Diesel Series 60	500
CRC28	x1	x1		1998	Detroit Diesel Series 60	500
CRC29		x1	x1	1999	Cummins ISX475ST2	450
CRC30			x1	1998	Detroit Diesel Series 60	500
CRC35			x1	2000	Detroit Diesel Series 60	470

Figure 16 to Figure 18 show the final Transient mode vehicle speed, percent engine speed, and percent torque plotted against time. These are the final candidate modes which were slightly modified later to simulate actual on-road truck performance on the engine dynamometer. These modifications are discussed later in this report.

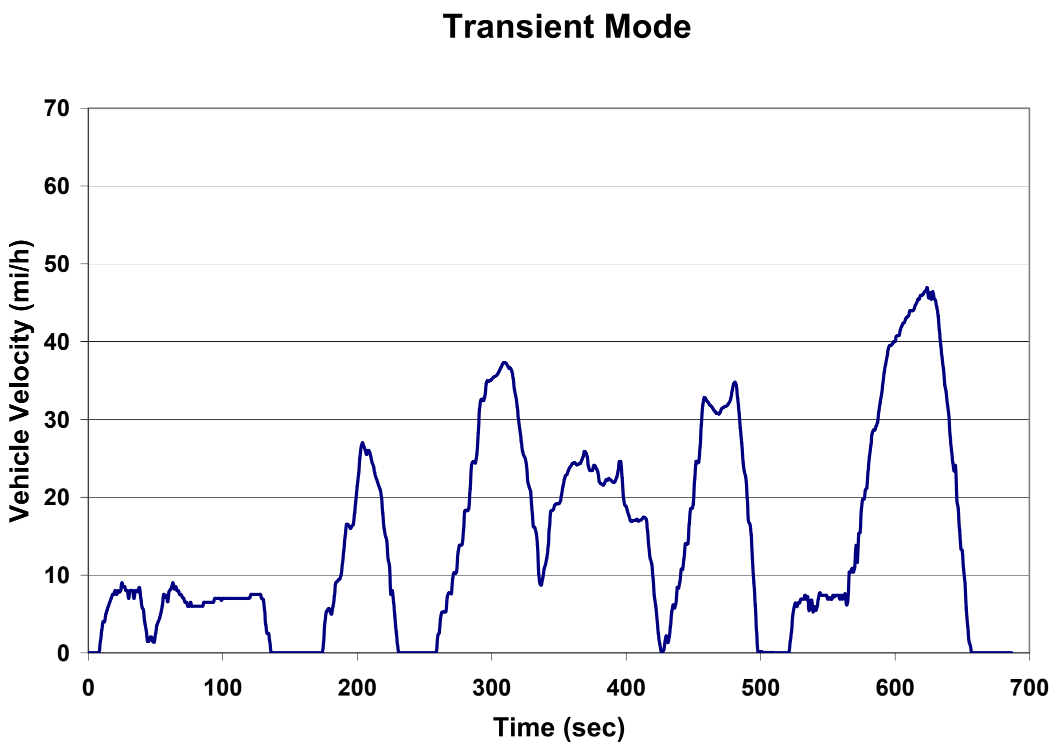

Figure 16: Transient Mode Vehicle Speed

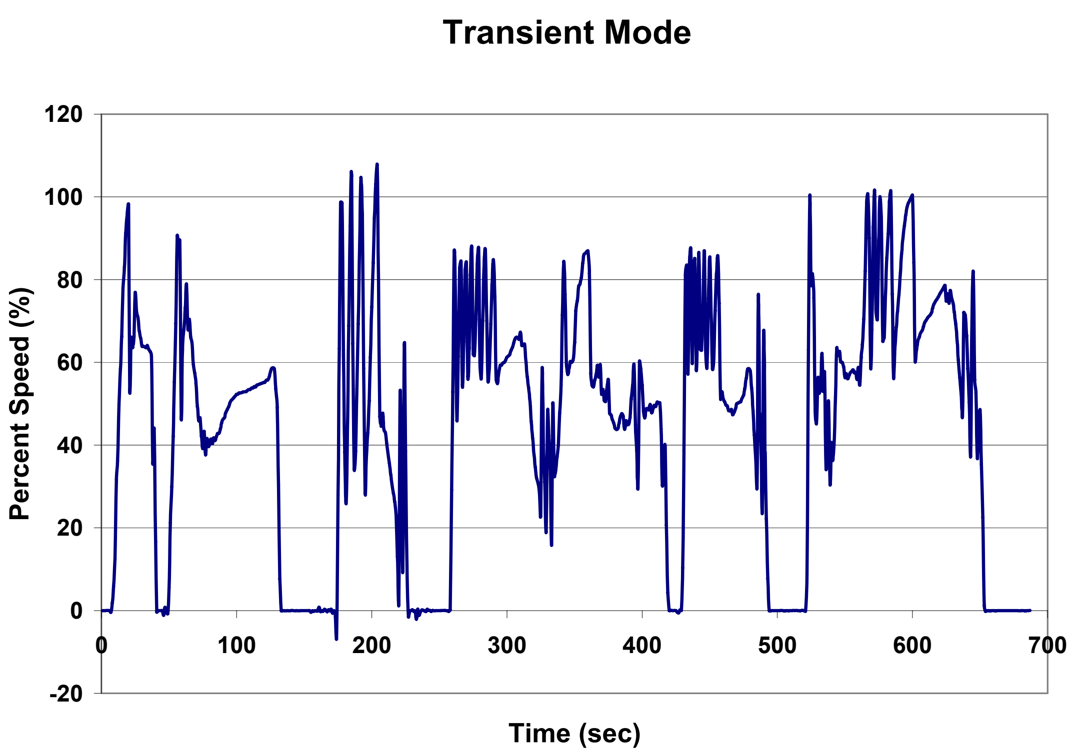

Figure 17: Transient Mode Percent Speed

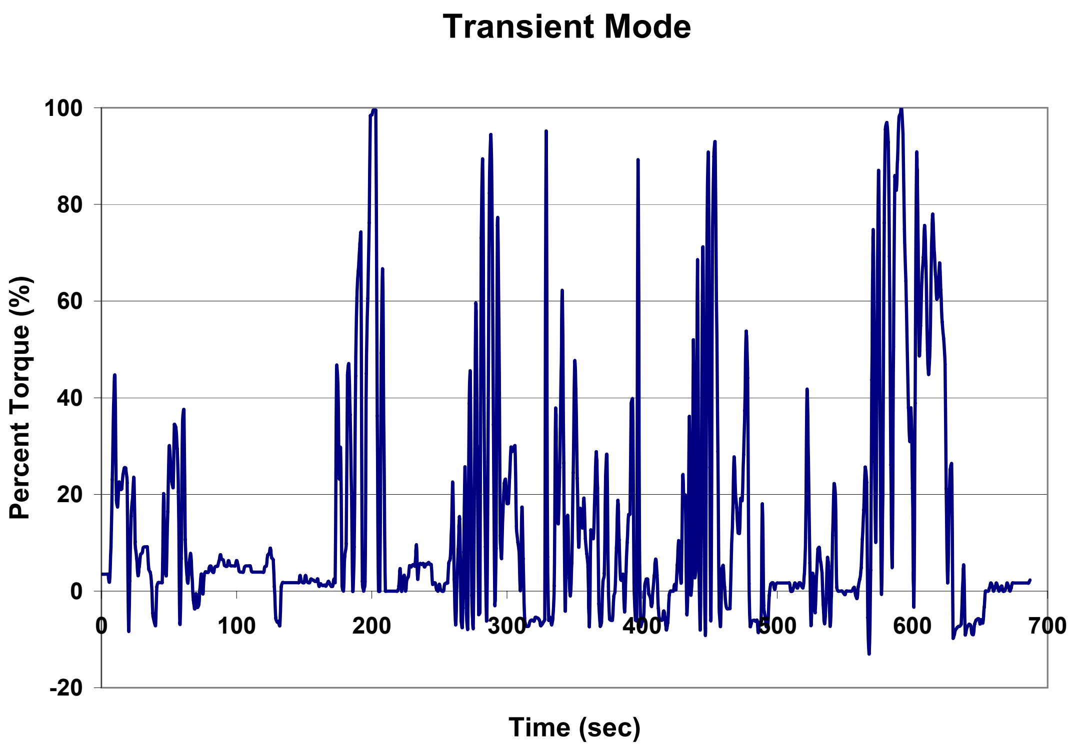

Figure 18: Transient Mode Percent Torque

Creep Mode

The final Creep modes were constructed using the available data shown in Table 6. The final mode included three microtrips with a Detroit Diesel Series 60 engine and one with a Caterpillar C-10. Two 56,000 lb and two 66,000 lb test weights were represented in the final mode.

Table 6: Creep Data Availability

Vehicle	Test Weights			Engine MY	Engine Type	Engine hp
	30k	56k	66k			
CRC26	x1	x2	x1	1998	Caterpillar C-10	350
CRC27	x1	x1		1999	Detroit Diesel Series 60	500
CRC29			x1	1999	Cummins ISX475ST2	450
CRC30		x1	x1	1998	Detroit Diesel Series 60	500
CRC34			x1	2003	Detroit Diesel Series 60	500

Figure 19 to Figure 21 show the vehicle speed, percent engine speed, and percent torque plots for the final creep mode before modification for engine dynamometer testing.

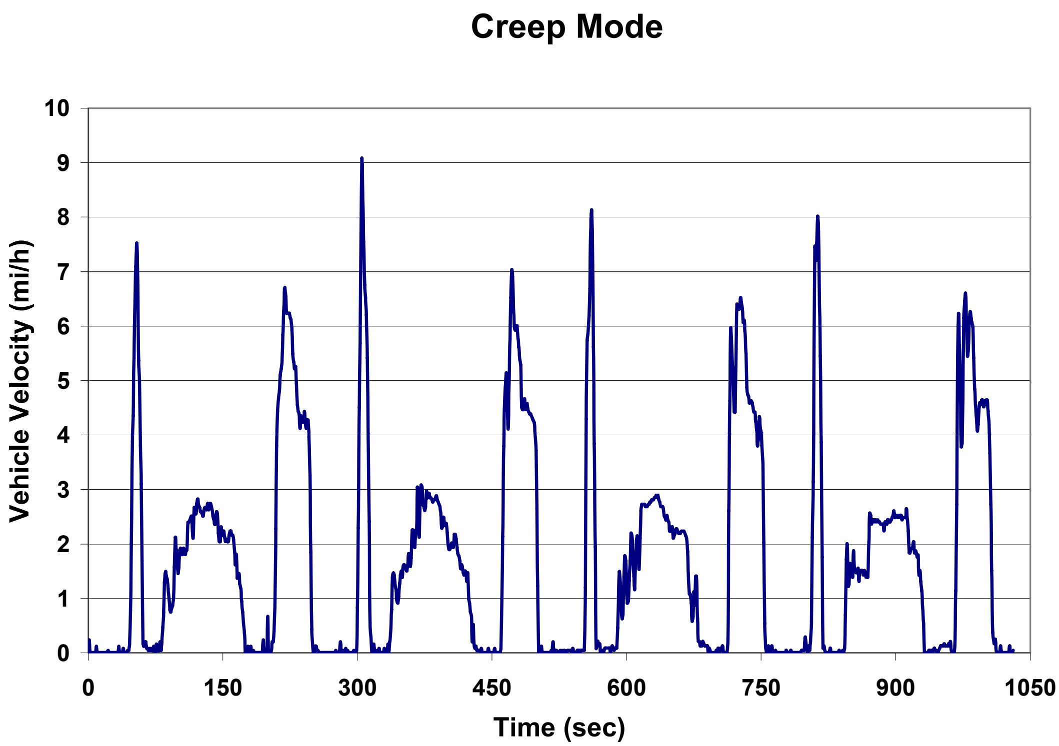

Figure 19: Creep Mode Vehicle Speed

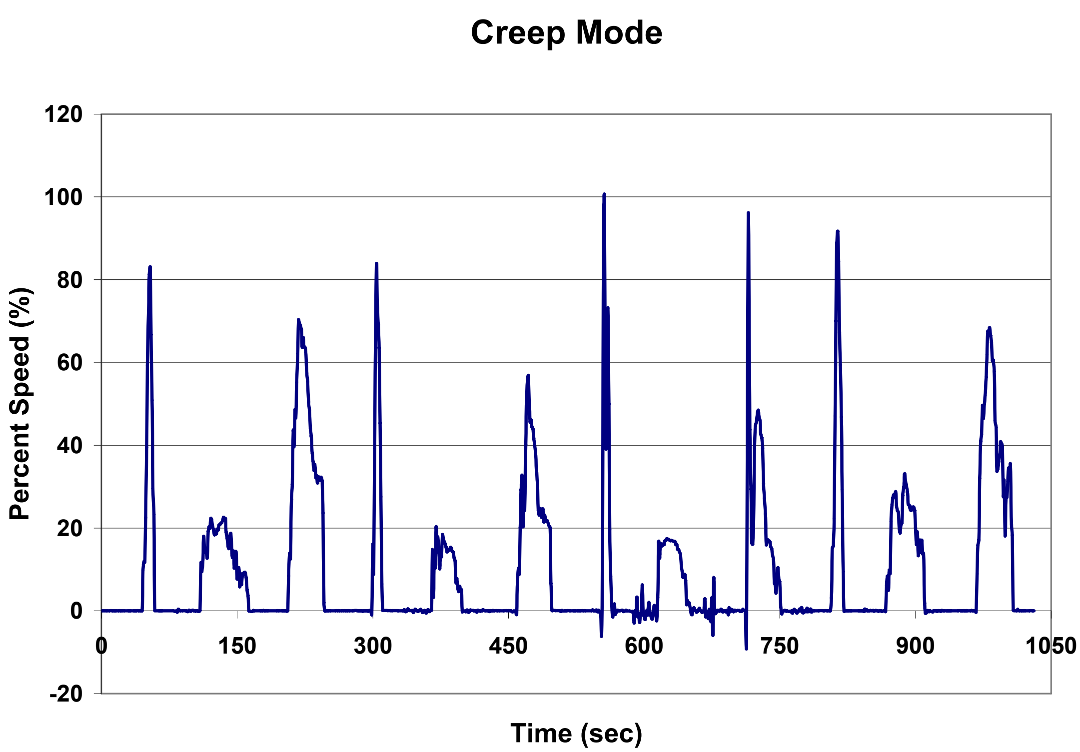

Figure 20: Creep Mode Percent Speed

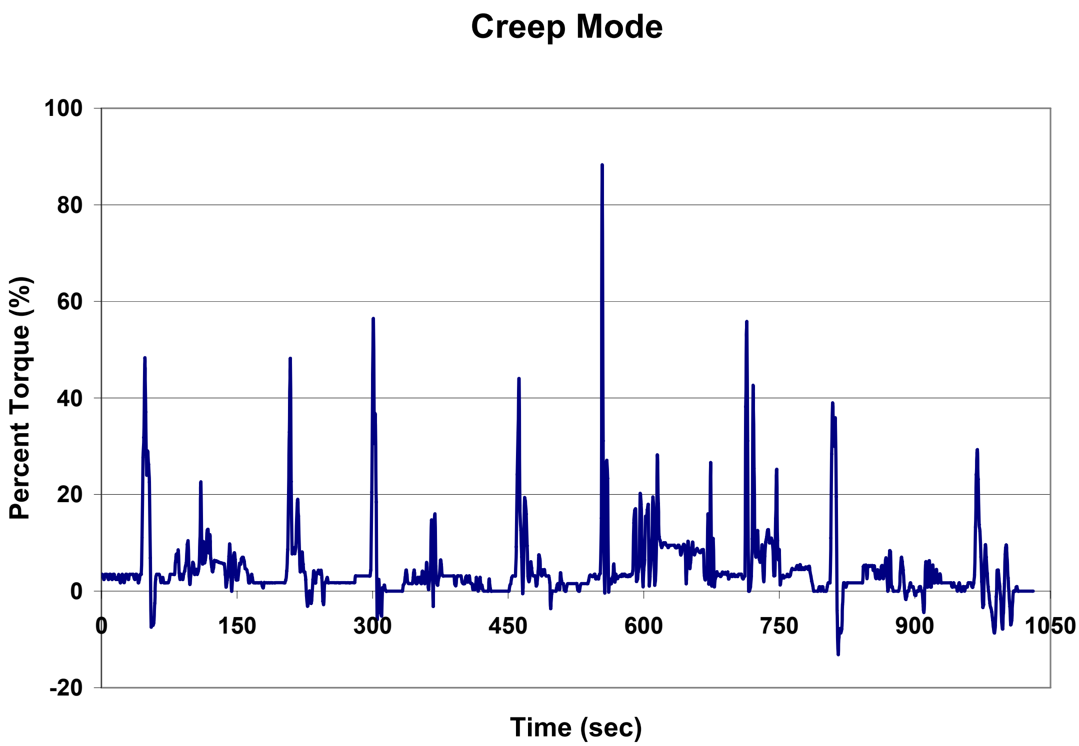

Figure 21: Creep Mode Percent Torque

Cruise Mode

The final Cruise mode was assembled from the available data shown in Table 7. The cruise database was smaller than the databases for the other modes, mainly because matching ECU and emissions files were not available and some runs had to be eliminated due to missing or incomplete data. This mode was created from one vehicle with a Cummins ISX engine and three vehicles with Detroit Diesel Series 60 engines. The final mode included two microtrips with 66,000 lb test weights and two with 30,000 lb test weights.

Table 7: Cruise Data Availability

Vehicle	Test Weights			Engine MY	Engine Type	Engine hp
	30k	56k	66k			
CRC27	x1			1999	Detroit Diesel Series 60	500
CRC28			x1	1998	Detroit Diesel Series 60	500
CRC29			x1	1999	Cummins ISX475ST2	450
CRC30			x1	1998	Detroit Diesel Series 60	500

The final cruise mode vehicle speed, percent engine speed, and percent torque plots can be seen in Figure 22 to Figure 24. The HHDDT_S ("high speed cruise") mode (presented after the Cruise mode) and Cruise modes differed in basic appearance from one another with respect to %torque. The HHDDT_S represented fairly smooth vehicle speed. The engine speed was therefore also quite smooth, and the torque did not vary rapidly or excessively, although the driver did vary the load request (pedal) during the E-55/59 chassis testing to maintain target speed. The Cruise mode contained variations in vehicle speed during the "cruise" section. These small speed variations, because of the heavy vehicle weight and high vehicle speed, implied substantial power swings in engine operation.

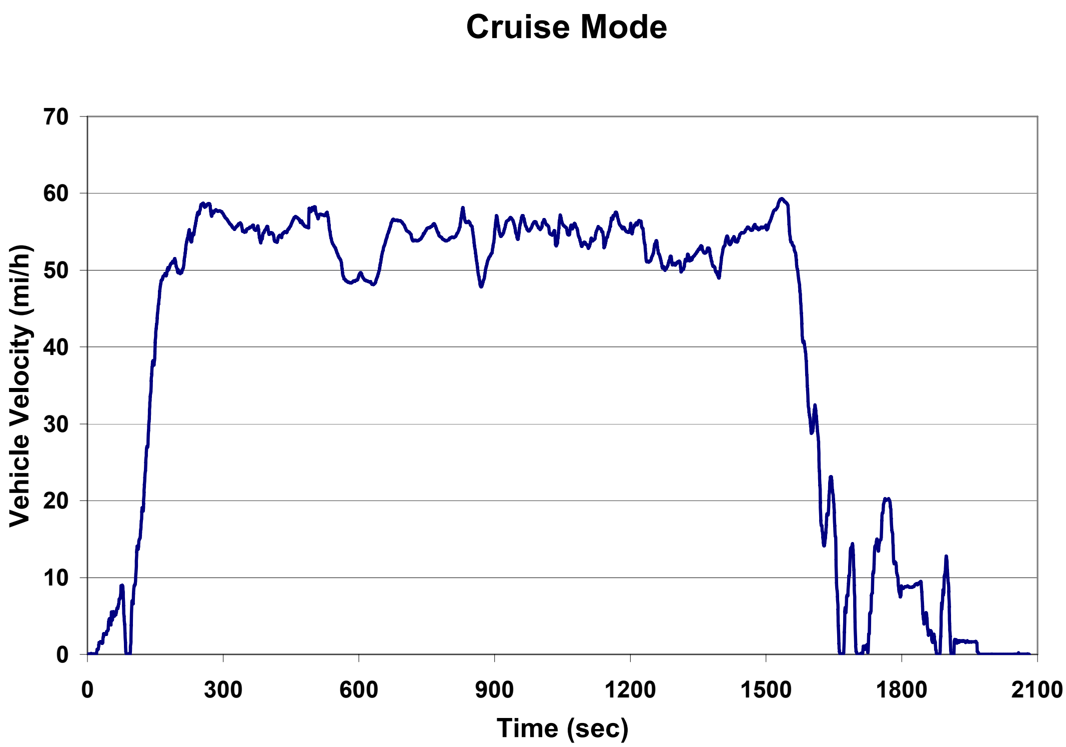

Figure 22: Cruise Mode Vehicle Speed

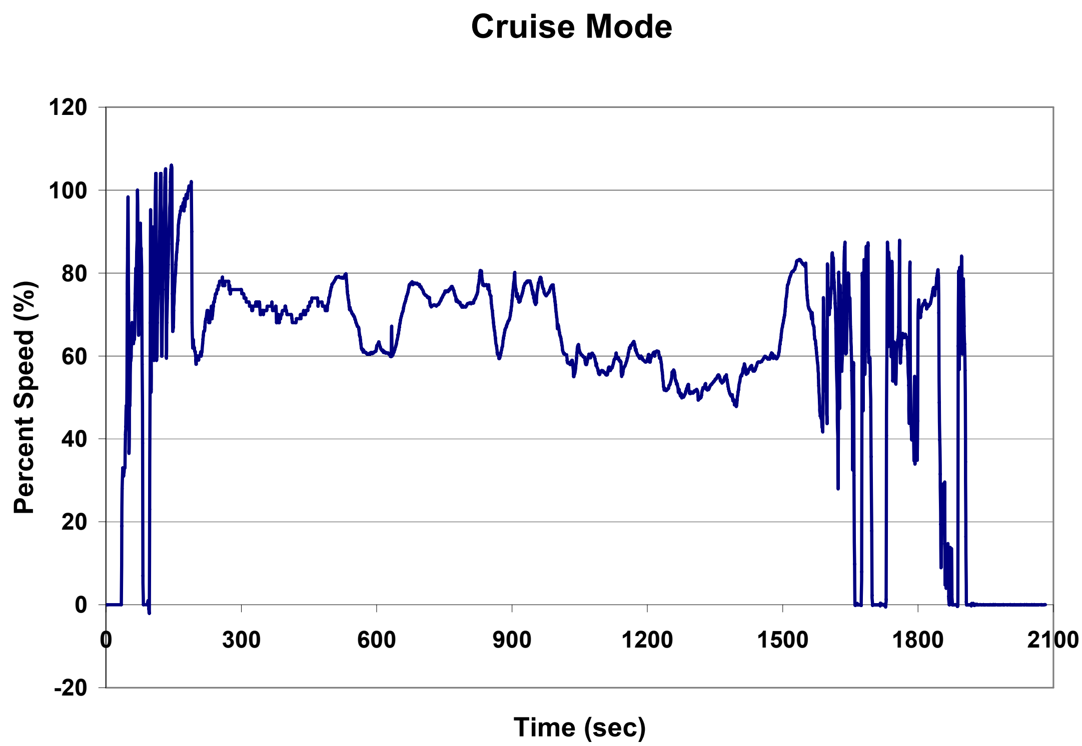

Figure 23: Cruise Mode Percent Speed

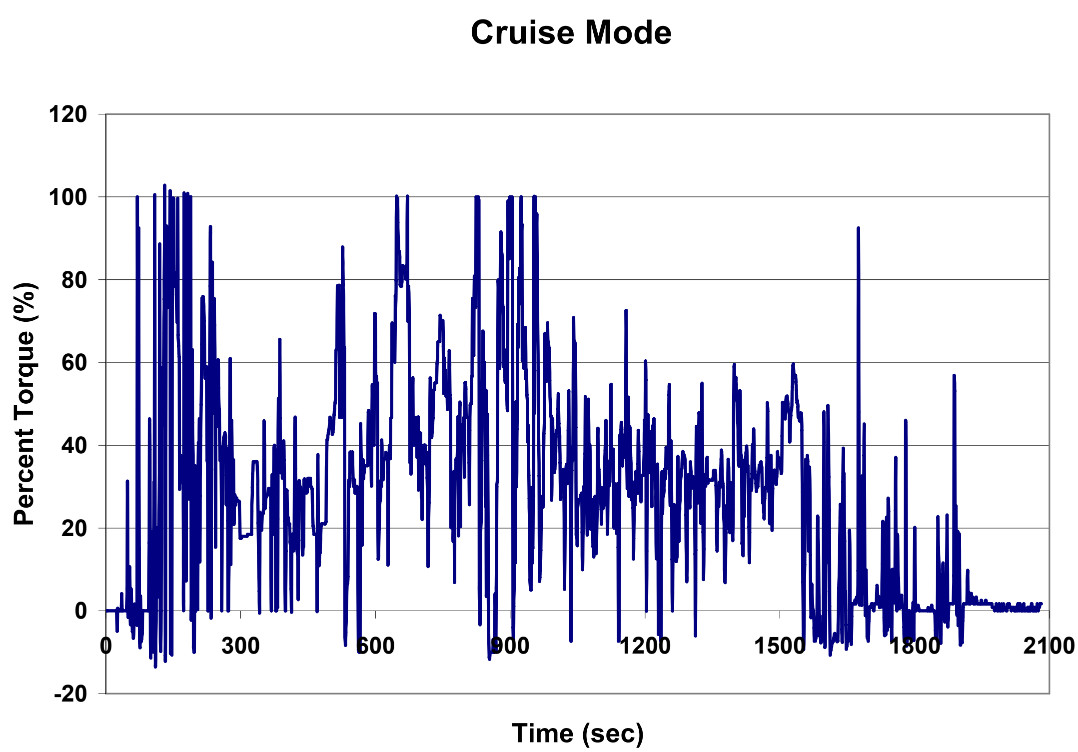

Figure 24: Cruise Mode Percent Torque

High-Speed Cruise (HHDDT_S) Mode

The final mode developed was the high-speed cruise, or HHDDT_S mode. The available data used to construct the mode can be seen in Table 8. The final mode included three Detroit Diesel engine microtrips and one Cummins ISX microtrip. This represented the database well, while still having two different engine technologies in the final mode. All three test weights were represented in the final mode. Two microtrips had a 66,000 lb test weight, one had a 56,000 lb test weight, and one had a 30,000 lb test weight.

Table 8: HHDDT_S Data Availability

Vehicle	Test Weights			Engine MY	Engine Type	Engine hp
	30k	56k	66k			
CRC27	x1			1999	Detroit Diesel Series 60	500
CRC28	x1		x1	1998	Detroit Diesel Series 60	500
CRC29		x1		1999	Cummins ISX475ST2	450
CRC30			x1	1998	Detroit Diesel Series 60	500
CRC34			x1	2003	Detroit Diesel Series 60	500

The final HHDDT_S mode vehicle speed, percent engine speed, and percent torque plots can be seen in Figure 25 to Figure 27. In particular, the smoothing between microtrips can be observed in the percent engine speed plot. As stated, the smoothing was achieved in such a way that the engine speed did not change by more than 8 rpm/sec. This slow rate of change prevented addition of transients not included in the original data.

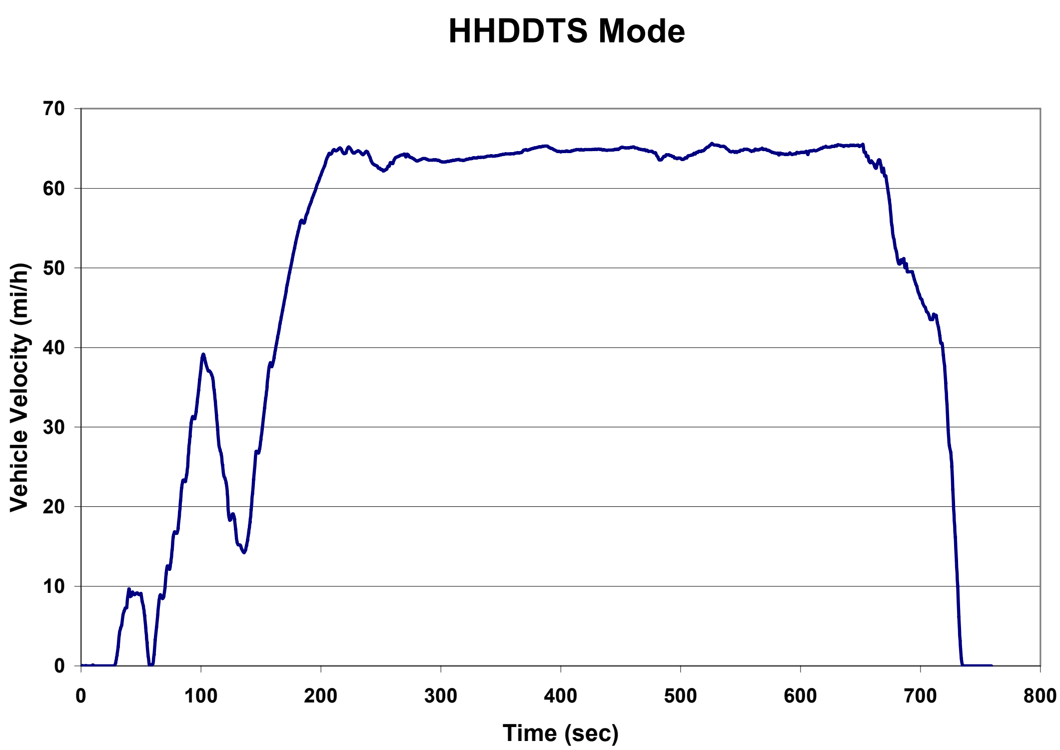

Figure 25: HHDDT_S Mode Vehicle Speed

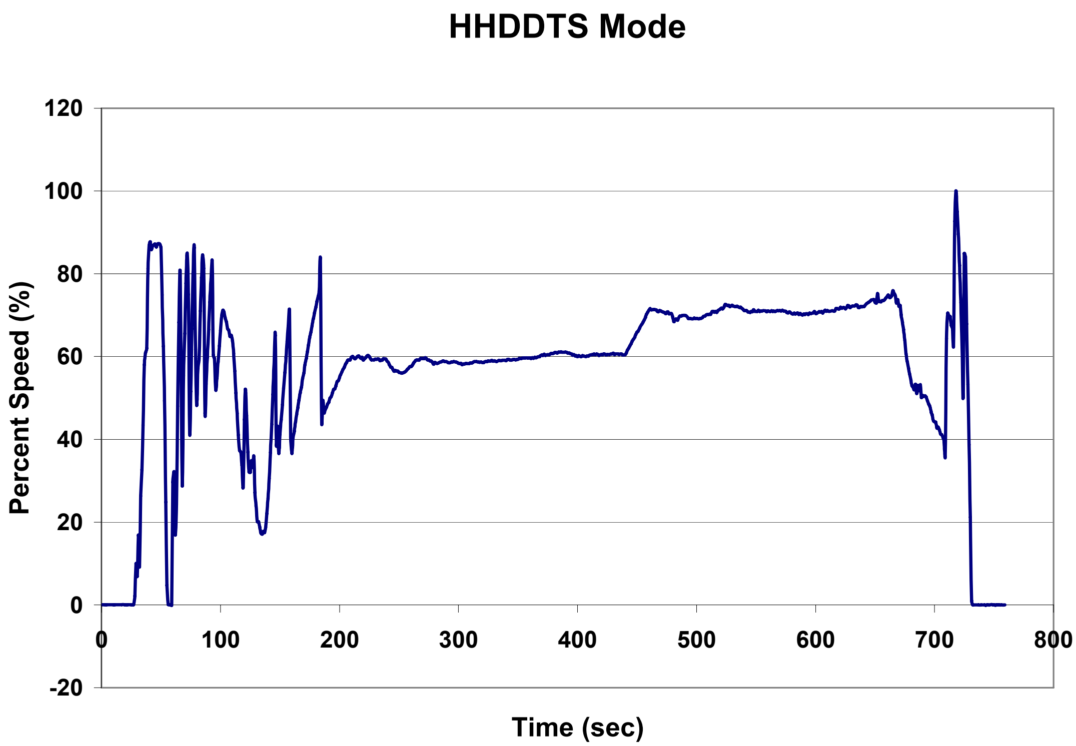

Figure 26: HHDDT_S Mode Percent Speed

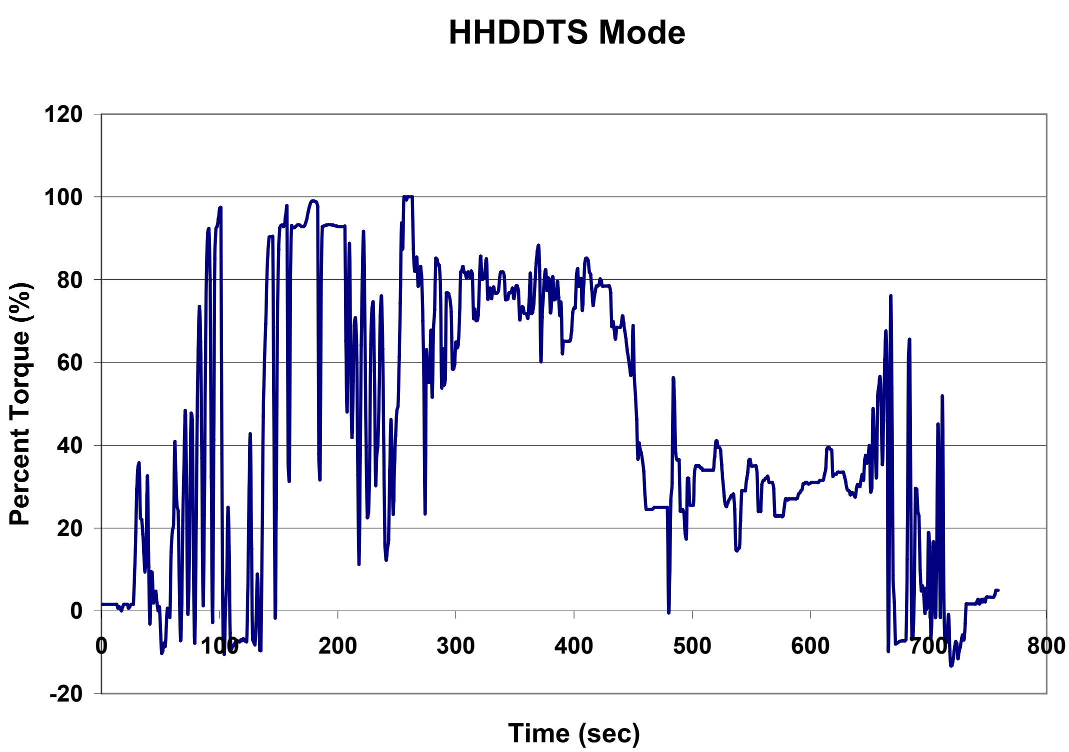

Figure 27: HHDDT_S Mode Percent Torque

Modes Demonstration

The ACES-1 modes underwent two testing periods. The first was a preliminary test using a 1992 Detroit Diesel heavy-duty diesel engine. For this preliminary testing, only the Transient mode was run (in Appendix A, the first three runs, E01565-03, E01566-01, and E01566-02, are the 1992 Detroit Diesel Engine runs). This engine was used simply to examine how the modes would behave on an engine dynamometer and if they would come close to meeting the current FTP regression parameters. For this test, the original modes (shown above) were run without any modification. The Transient mode was run in a WVU test cell using the typical throttle command code configured during prior WVU studies for stability in the steady-state regions of the CFR Heavy-Duty Diesel Engine test schedule (Federal Test Procedure). Next, the Transient mode was re-run with the throttle proportionality constant doubled to create more aggressive throttle input changes. Figure 28 to Figure 30 show the setpoint compliance of engine speed when the more aggressive throttle algorithm was used, and Figure 31 to Figure 33 present the compliance of torque.

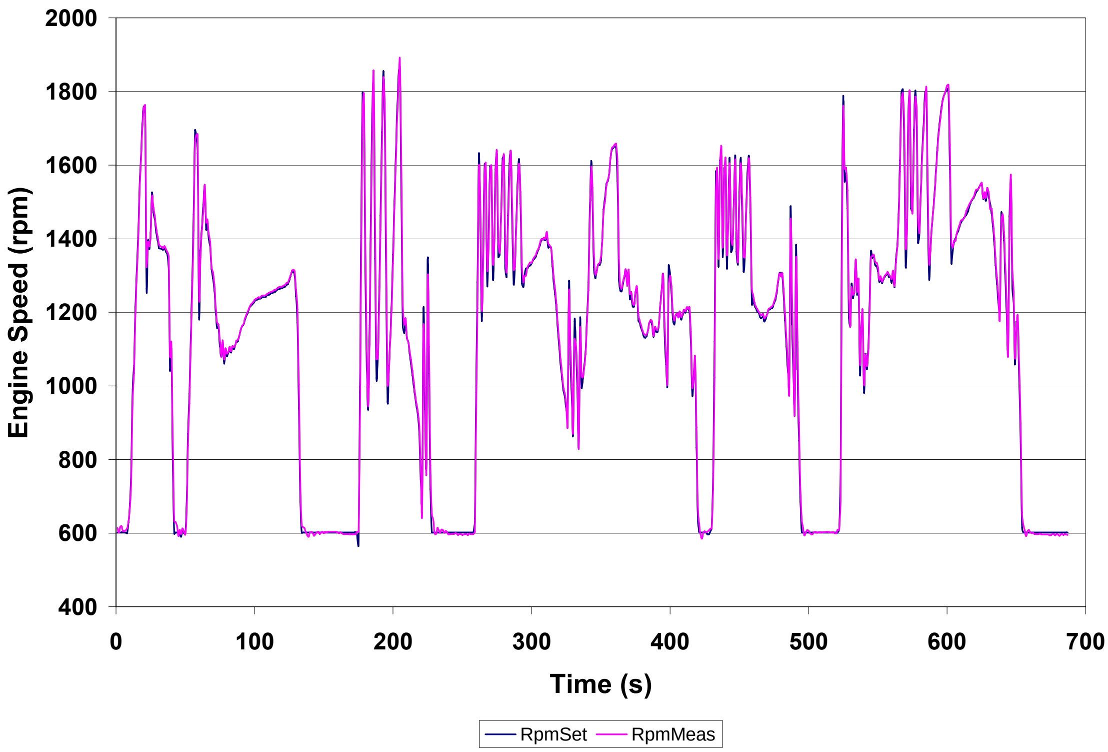

Figure 28: Transient Mode Engine Speed Setpoint Compliance

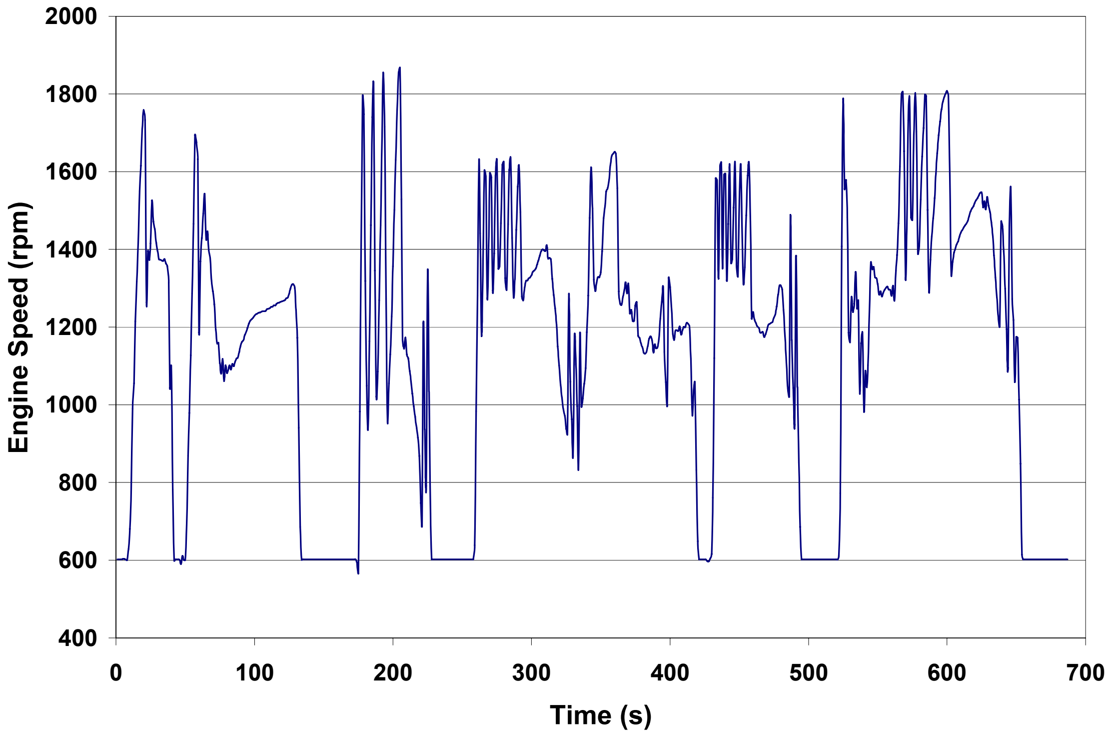

Figure 29: Transient Mode Engine Speed Setpoint

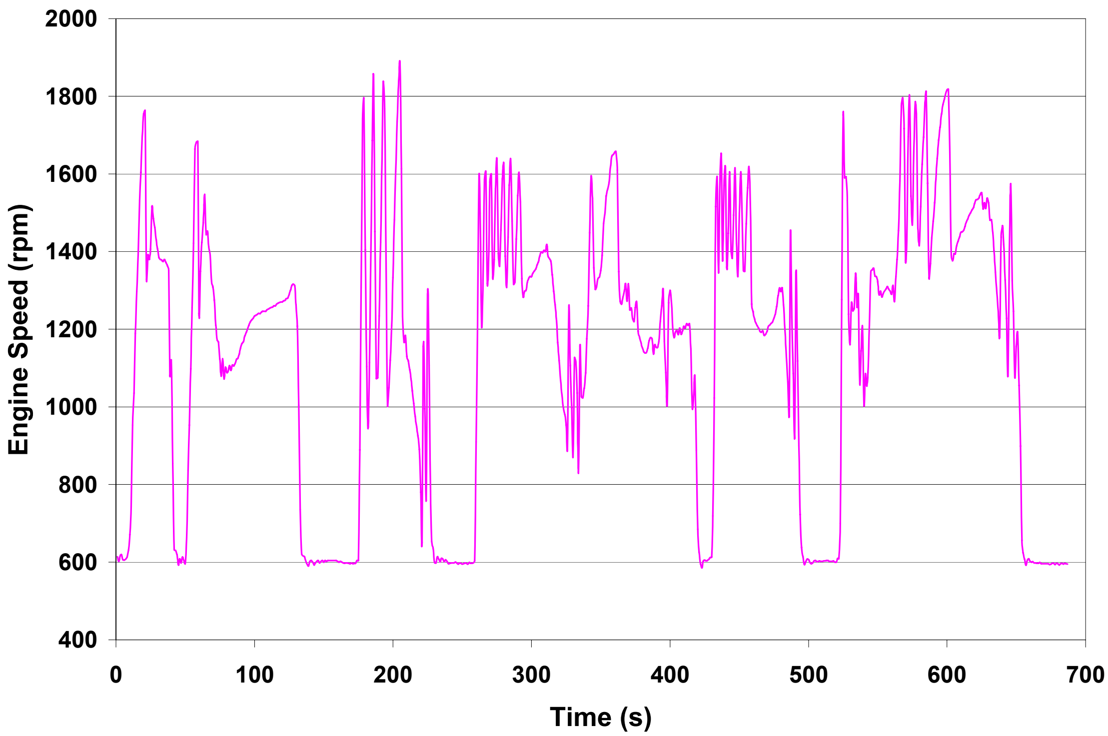

Figure 30: Transient Mode Engine Speed Measured

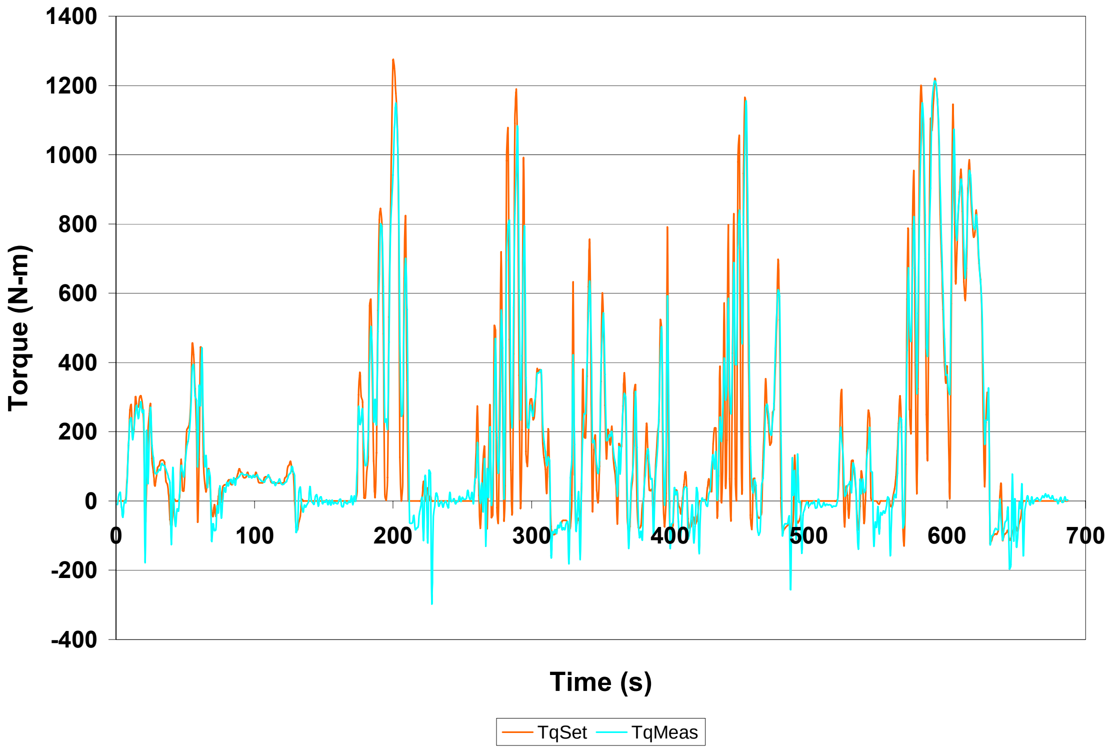

Figure 31: Transient Mode Torque Setpoint Compliance

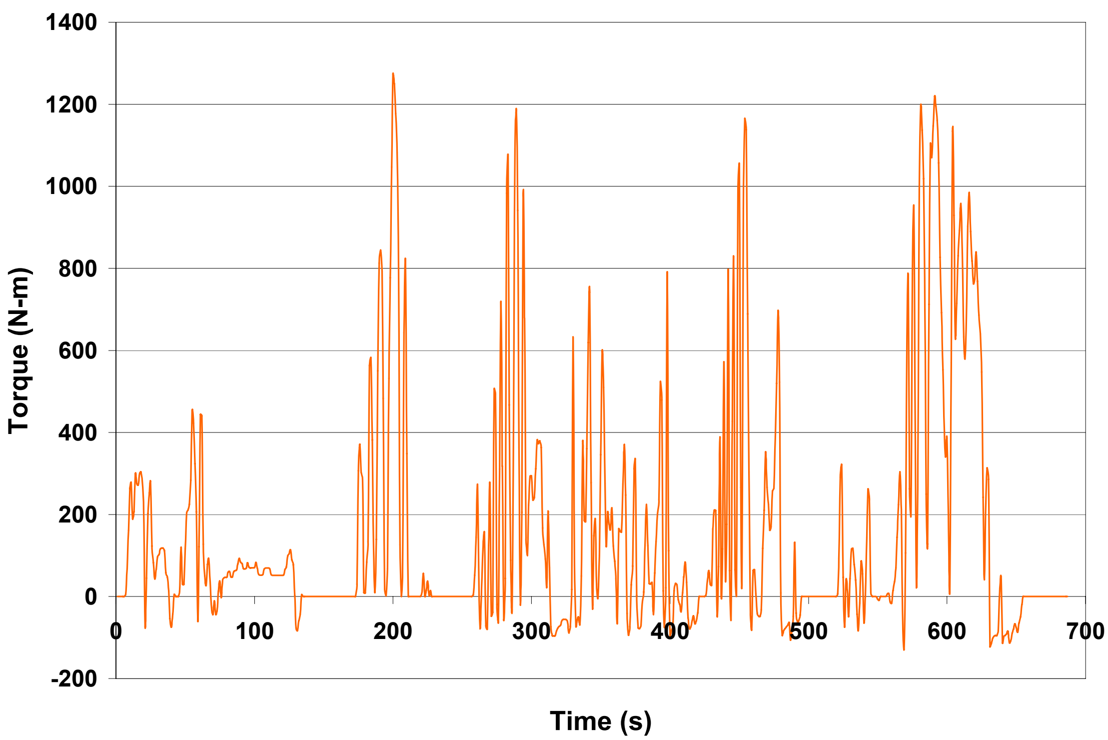

Figure 32: Transient Mode Torque Setpoint

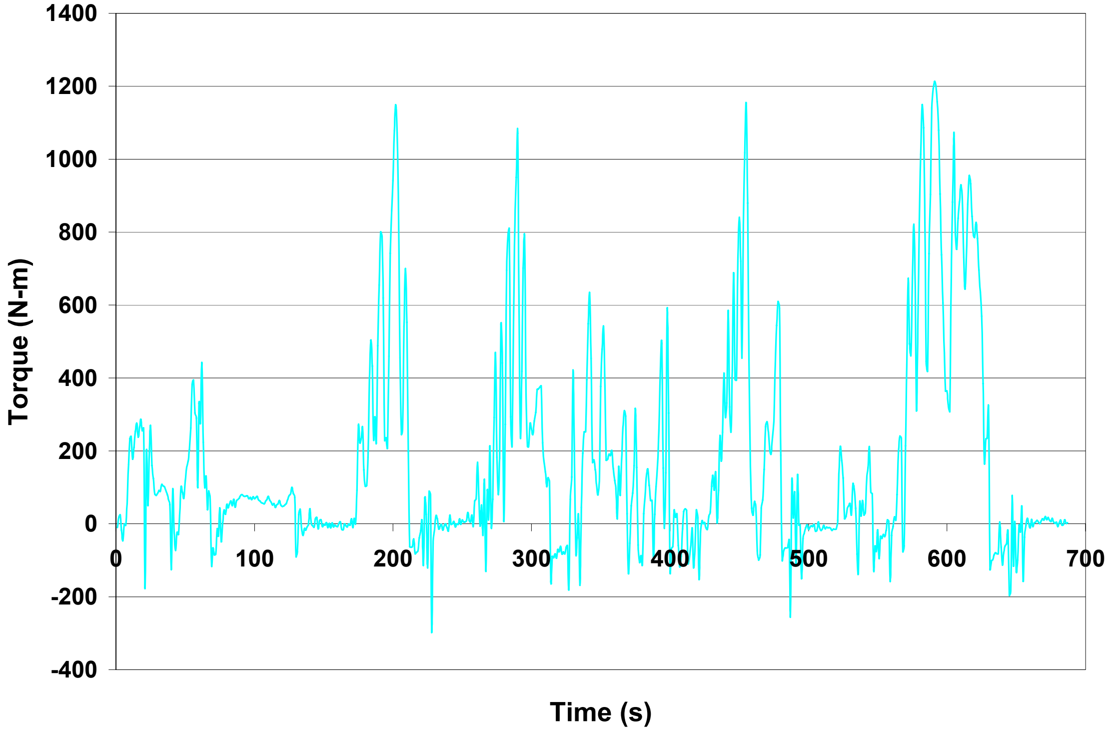

Figure 33: Transient Mode Torque Measured

The initial Transient mode testing did not meet current FTP regression criteria. The measured torque did not follow the setpoint torque during the simulated gearshifts and during periods of low torque. This behavior can be seen in Figure 34. However, the goal of ACES cycle development included creating new regression parameters and did not require any mode to meet current FTP regression criteria.

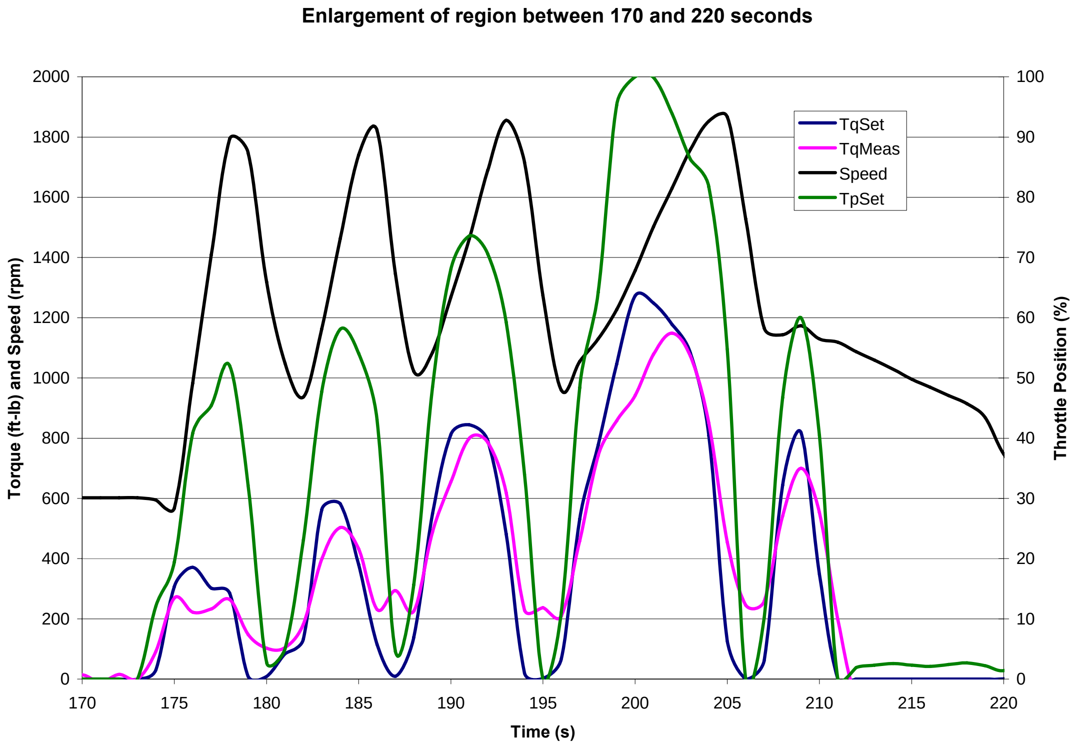

Figure 34: Transient Mode Torque Compliance (enlarged)

It can be observed from the transient torque plots that, during the simulated gearshift ramps, the total torque as seen by the engine cannot be made to follow the setpoint torque faithfully. The reason for the "poor" test performance can be observed in Figure 34. In the region between seconds 182 and 190, the scheduled torque rose from a low value to around 600 ft-lbs, and then dropped back down to nearly zero at second 187. However, the desired speed had risen from around 950 rpm at the onset of the torque demand, to near 1800 rpm at the next torque trough. Then the speed was required to drop back down to 1000 rpm over the following two seconds.

In-use applications have a clutch between the engine and the remaining inertial transmission components. The clutch disconnects these parts and removes them from inertial consideration during this period when the driver selects the next appropriate gear ratio. In the test cell, however, the engine was permanently coupled to a drive shaft and to the dynamometer, with a combined rotational inertia of 224 lb-ft^2/sec^2 in the case of the 500hp GE dynamometer used at the West Virginia University Engine Research Center. Since the speed was decreasing very quickly, there was clearly a very high system rotational inertia, which was translated to the engine. The dynamometer attempted to hold to the scheduled speed, so that during downturns in the speed setpoint trace, the dynamometer needed to exert torque to reduce the speed of the engine and dynamometer.

Prior to the final testing of all ACES modes, slight modifications were required to achieve better performance on the engine dynamometer. The goal was to follow all gearshift points more closely in torque and speed, to eliminate periods of sustained very low torque that the dynamometer could not reliably match, and to ensure that during all idle portions torque and speed are equal to zero.

Each mode was examined by inspection. First, the values were all rounded to integer values, as required by the throttle program. Next, each point where percent engine speed was zero was assigned a zero percent torque as well. This eliminated some very small torque values that may be associated with engine auxiliaries or friction. The contribution to the total integrated work was minimal so that no difference would be seen in the final mode statistics.

The next task was to determine “closed rack” points where the engine should be exerting maximum negative torque (at a given speed), particularly during decelerations. This allowed the engine to exert appropriate torque and allowed the setpoint torque during gearshift troughs to be matched. In order to maintain consistency with FTP protocol, all negative torque points were denoted as closed rack motoring. To indicate a closed rack point, a “[1]” was included in the setpoint file along with a footnote acknowledging that *[1] denotes closed rack motoring*, just as is done with the FTP. The WVU engine laboratory replaced these “[1]” points in the torque setpoint file with a large negative torque setpoint (-40%) prior to running the cycles. In this way, the dynamometer motored the engine, causing “closed rack” operation. These large negative torque values did not have any effect on regression because if the setpoint torques were much lower than the torque feedback, the fueling was reduced to a minimum and the point was eliminated as defined in the CFR § 86.1341-90 for FTP application.

By examining other engine data, the maximum engine speed deceleration that could be achieved without “closed rack” operation was found to be approximately 3%/sec for a typical over-the-road truck engine. So any point where the deceleration was larger than 3%/sec was also set to a closed rack operation command. The closed rack target points are shown as red dots on the horizontal axis to denote each point that is to be considered closed rack in plots below. The final as-tested percent engine speed and percent torque plots for each mode can be seen in Figure 35 to Figure 42.

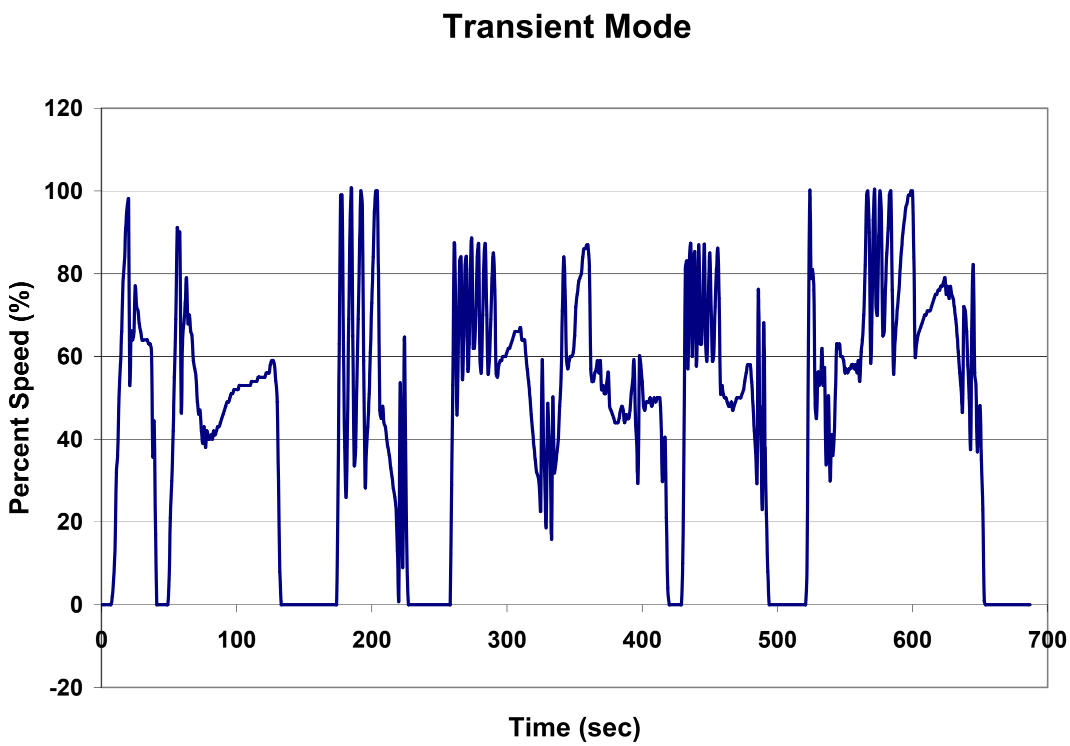

Figure 35: Transient Mode Final Percent Engine Speed

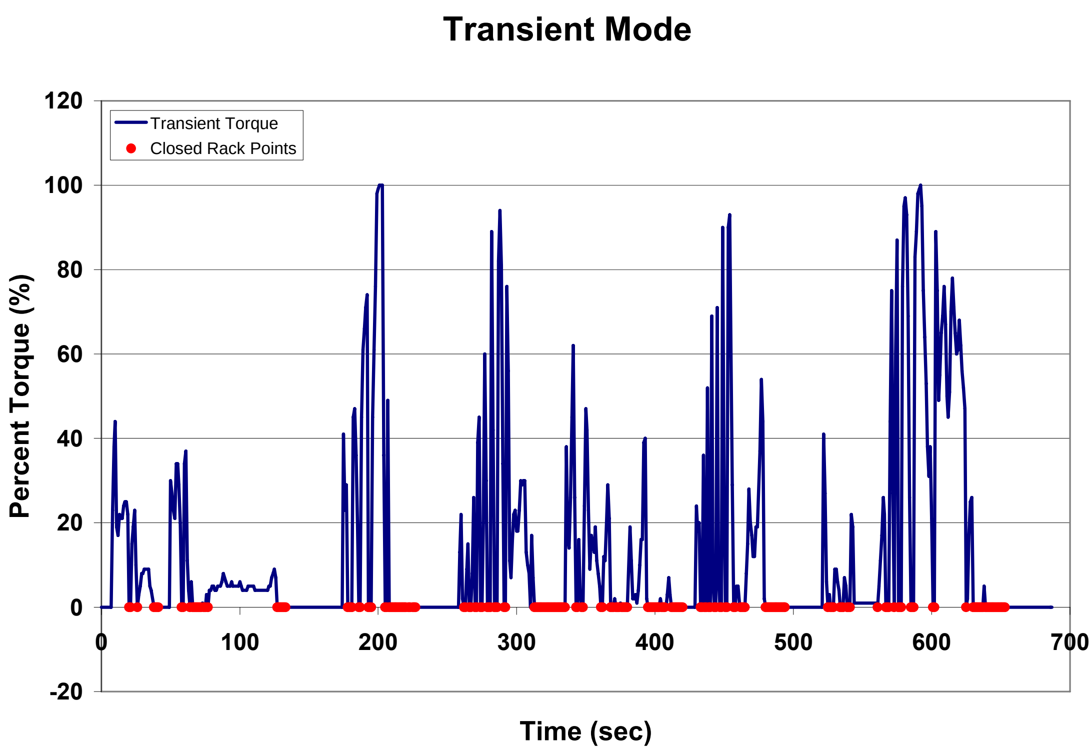

Figure 36: Transient Mode Final Percent Torque

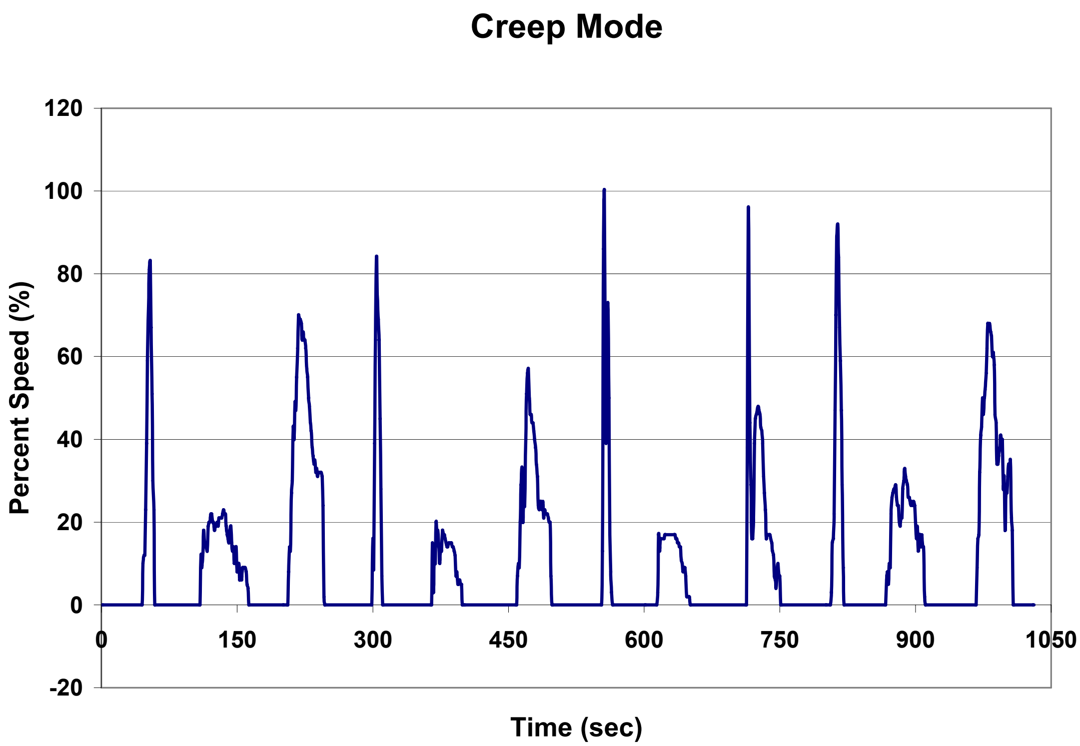

Figure 37: Creep Mode Final Percent Engine Speed

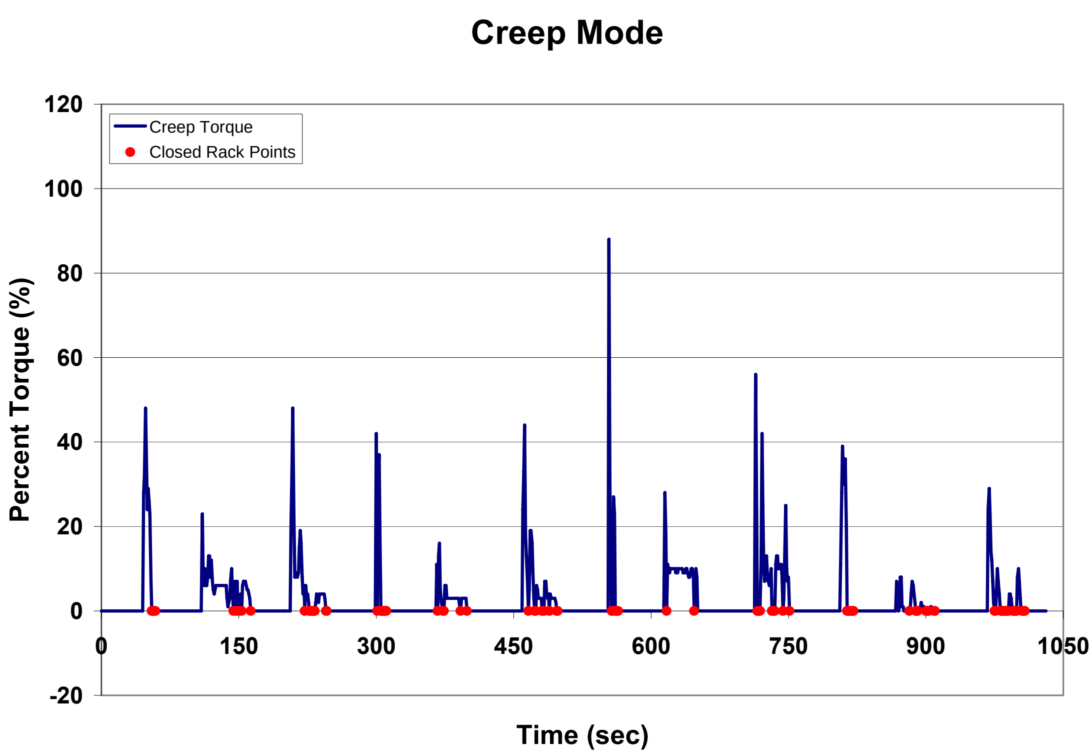

Figure 38: Creep Mode Final Percent Torque

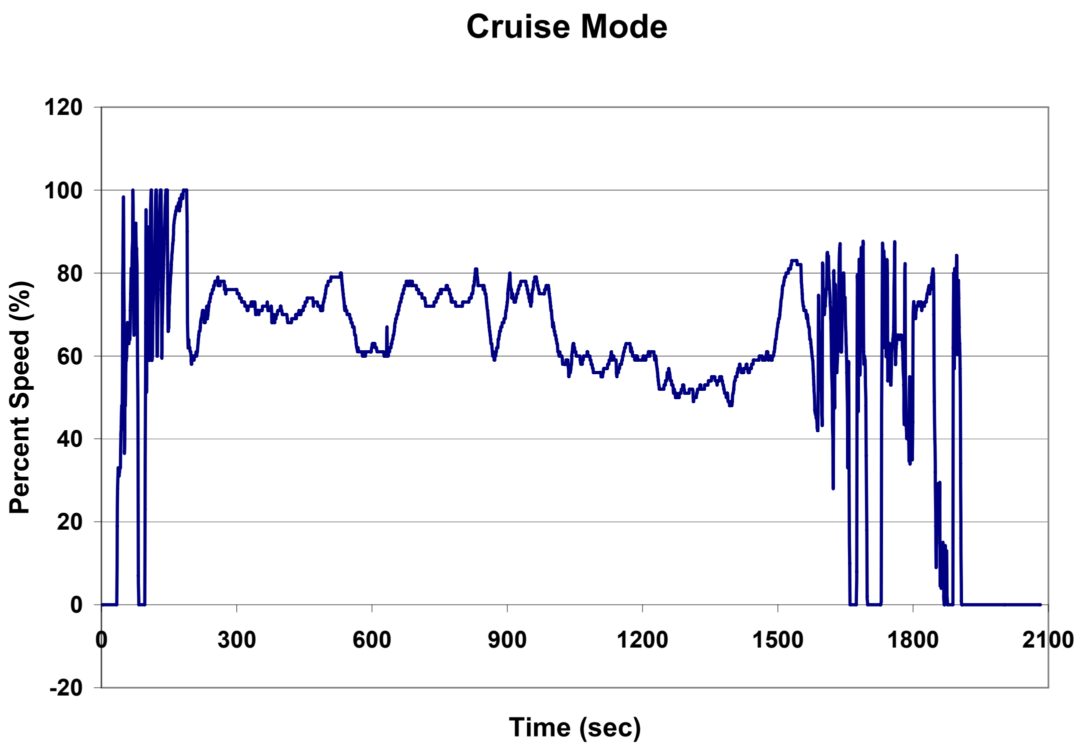

Figure 39: Cruise Mode Final Percent Engine Speed

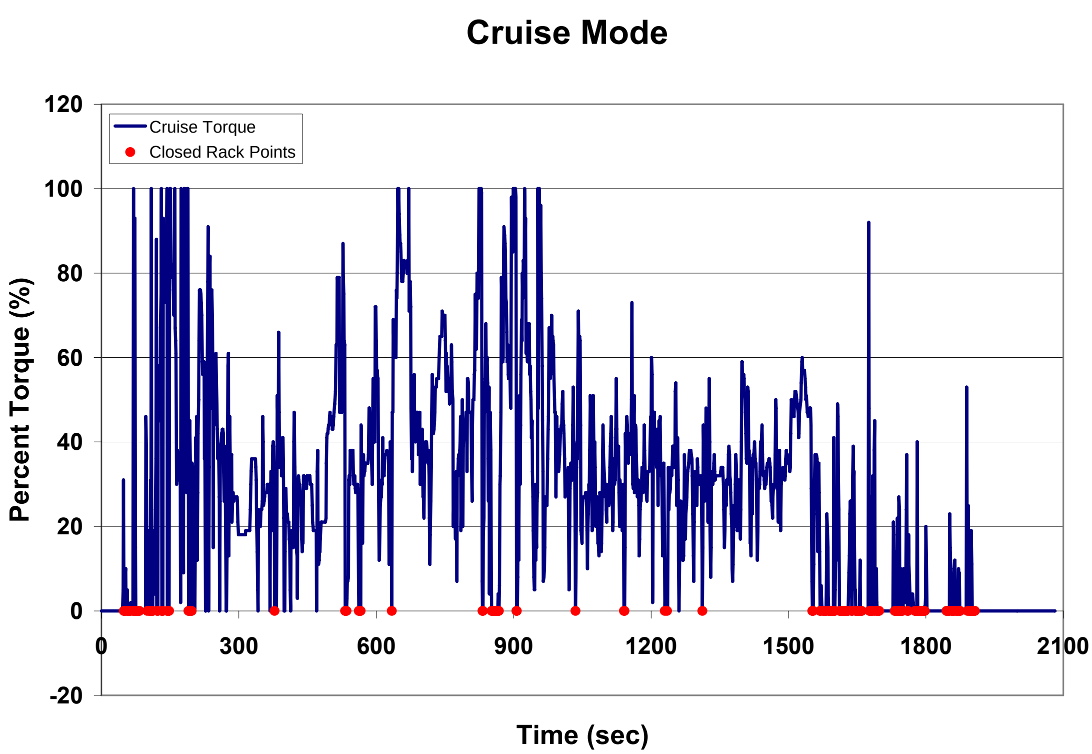

Figure 40: Cruise Mode Final Percent Torque

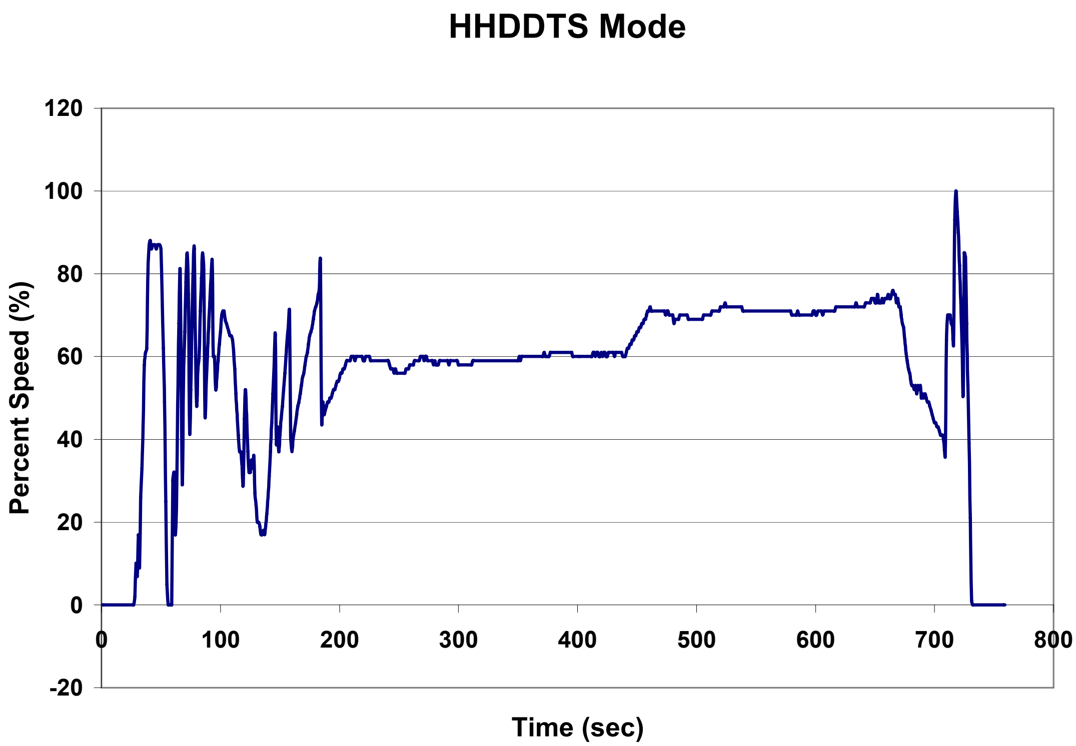

Figure 41: HHDDTS Mode Final Percent Engine Speed

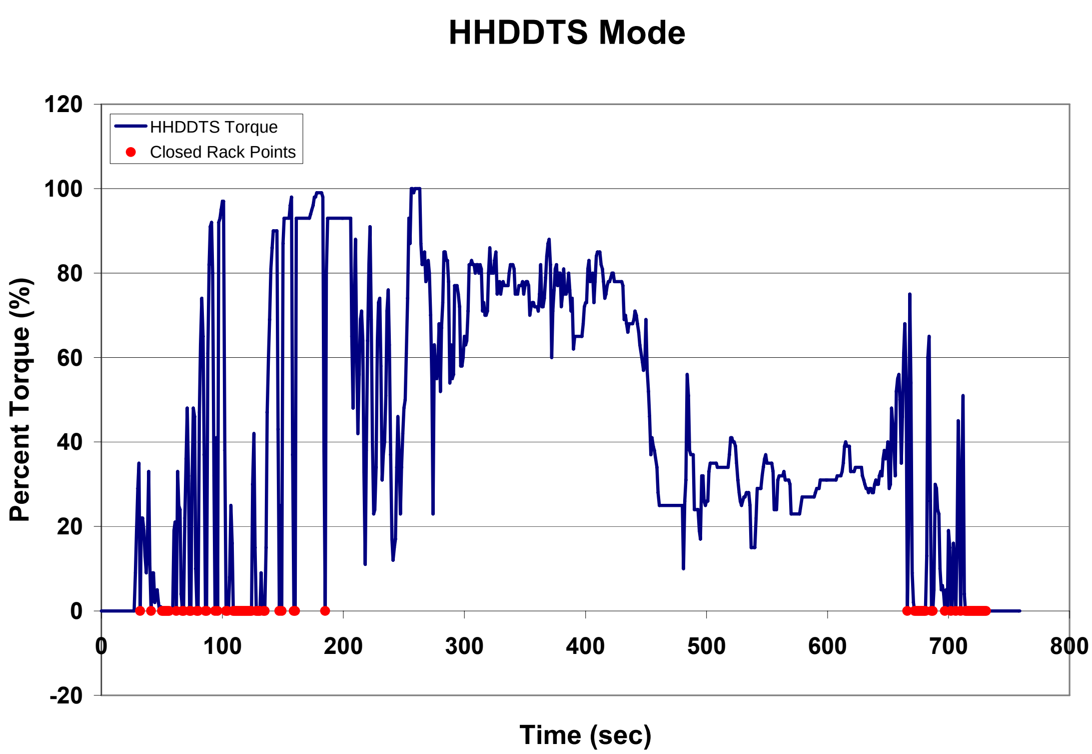

Figure 42: HHDDTS Mode Final Percent Torque

The final ACES cycle testing was performed at the West Virginia University Engine Research Center between February 29 and March 8, 2007. The testing was conduced using a 2004 Cummins ISM370 heavy-duty diesel engine connected to a 500-hp GE dynamometer via a driveshaft and Vulcan coupling. The engine was a modern, electronically controlled engine, with exhaust gas recirculation, so that the modes could be demonstrated using representative technology. In accordance with the original ACES-1 proposal, each mode was tested three times with 20-minute hot soaks in-between. Prior to the final testing, initial tests of each mode and the FTP were performed to ensure they would perform appropriately on the engine dynamometer. Two different throttle algorithms were implemented for several of these runs; however, the less aggressive throttle setting (standard setting) was chosen for the final ACES-1 cycle testing. This proved to come closer to meeting the current FTP regressions requirements, although meeting these requirements was not required for the ACES-1 cycle. The final modes were all hot starts and utilized the same fuel. The testing schedule included doing all three repeats of each mode in a row and can be seen in Table 9 below. Some results are presented later in this report from the alternate throttle settings and FTP runs.

Table 9: Final Modes Testing Schedule

Date	Time	Run Number	Mode
3/6/2007	11:35 AM	E01809-03	Transient
20 minute hot soak			
3/6/2007	12:07 PM	E01809-04	Transient
20 minute hot soak			
3/6/2007	12:39 PM	E01809-05	Transient
20 minute hot soak			
3/6/2007	1:11 PM	E01810-01	HHDDTS
20 minute hot soak			
3/6/2007	1:44 PM	E01810-02	HHDDTS
20 minute hot soak			
3/6/2007	2:17 PM	E01810-03	HHDDTS
20 minute hot soak			
3/6/2007	2:50 PM	E01811-01	Cruise
20 minute hot soak			
3/6/2007	3:46 PM	E01811-02	Cruise
20 minute hot soak			
3/6/2007	4:41 PM	E01811-03	Cruise
20 minute hot soak			
3/6/2007	5:36 PM	E01812-01	Creep
20 minute hot soak			
3/6/2007	6:14 PM	E01812-02	Creep
20 minute hot soak			
3/6/2007	6:52 PM	E01812-03	Creep

For all runs shown above, regulated emissions were measured (CO, NOx, THC, TPM), TEOM (instantaneous and cumulative particulate matter) and DMS500 data (particle size and distribution) were collected, and ECU data were logged. It was decided that an additional "cool down" creep mode was not required prior to the final three creep tests. The 20-min hot soak cooled the engine enough that there would be no discernable differences between the three creep runs as a result of further cooling.

Modes Demonstration Results

The results for the ACES-1 modes demonstration are separated into two sections below, dealing with regression performance and emissions results respectively. The regression performance adopted the methodology for FTP tests defined in the CFR. Measured torque, engine speed, and brake horsepower (BHP) were compared to the reference values and calculated results included the slope and intercept of the first order linear trend line. Comparisons between the results of the ACES modes and the FTP were used as reference to establish ACES regression criteria, which are addressed in the next section.

For one final run of each mode and the FTP, the speed and torque regressions were plotted and can be seen in Figure 43 through Figure 52 below. It should be noted that the regression lines on these plots were generated using all measured and target engine speed and torque points without discarding any points. As a result, Figures 43 through 52 show different slopes and y-intercepts than the regression criteria, based on the FTP, would suggest. The final regression statistics were determined by eliminating certain points according to the CFR (86.1341-90), and are shown in Table 11, which is presented later in this report.

Table 10: Permitted Point Deletions from Regression Analysis (from CFR (86.1341-90)

Condition	Points to be deleted
1. Wide Open Throttle and Torque Feedback < Torque Reference	Torque, and/or BHP.
2. Closed Throttle, Not an Idle Point, Torque Feedback >Torque Reference	Torque, and/or BHP.
3. Closed Throttle, Idle Point, and Torque Feedback = CITT (10 ft-lb)	Speed, and/or BHP.
For the purposes of this discussion: An Idle Point is defined as a point having a Normalized Reference Torque of 0 and a Normalized Reference Speed of 0. An engine tested as having a manual transmission has a curb idle transmission torque (CITT) of 0. Point deletion may be applied either to the whole or to any part of the cycle. EXPSTB='00'	

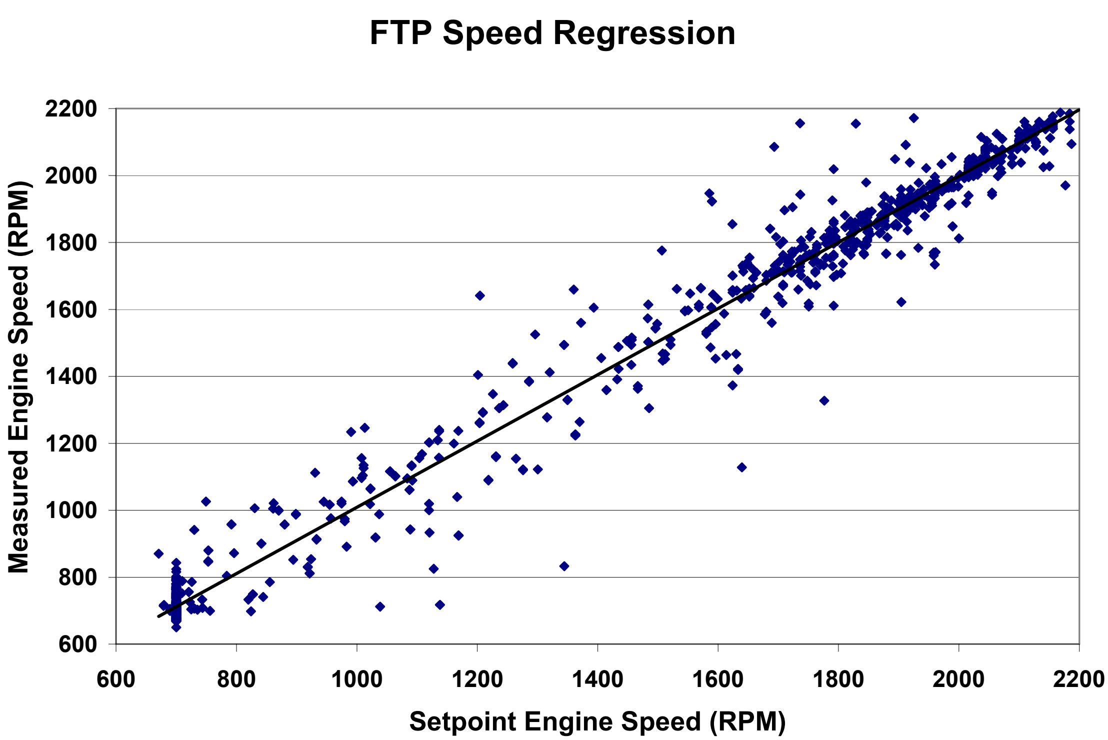

Figure 43: FTP Speed Regression, based on all measured and setpoint data with no point deletions. Statistics with point deletions appear in Table 11.

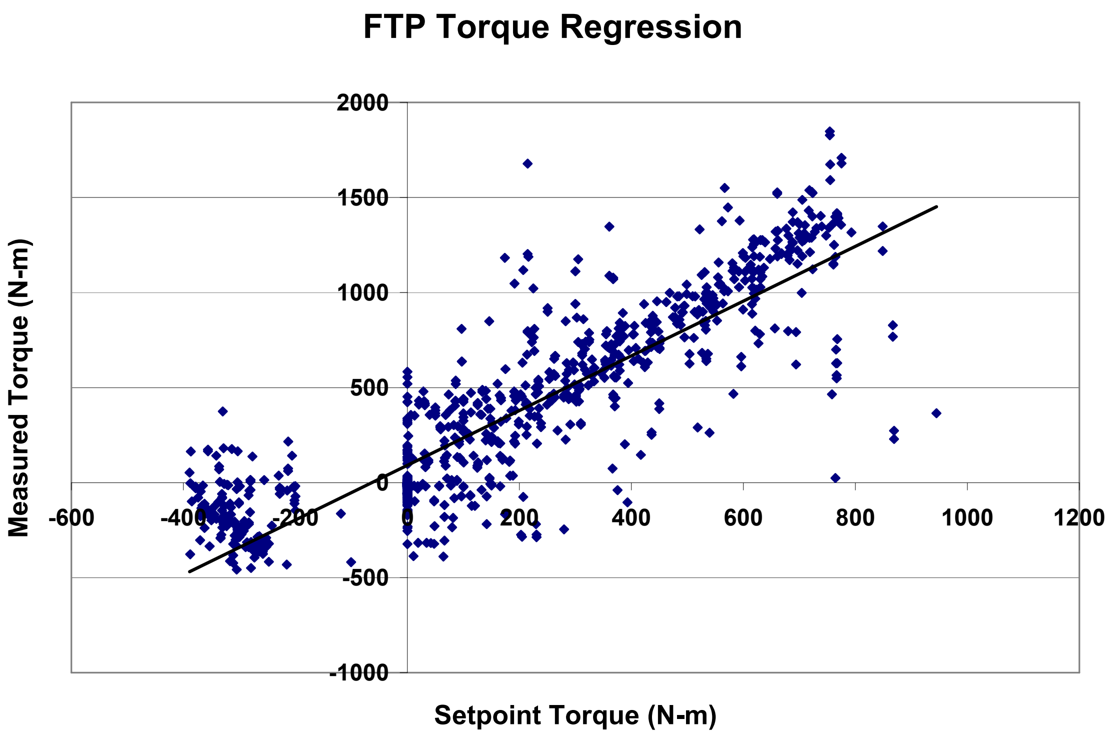

Figure 44: FTP Torque Regression (based on all measured and setpoint data with no point deletions)

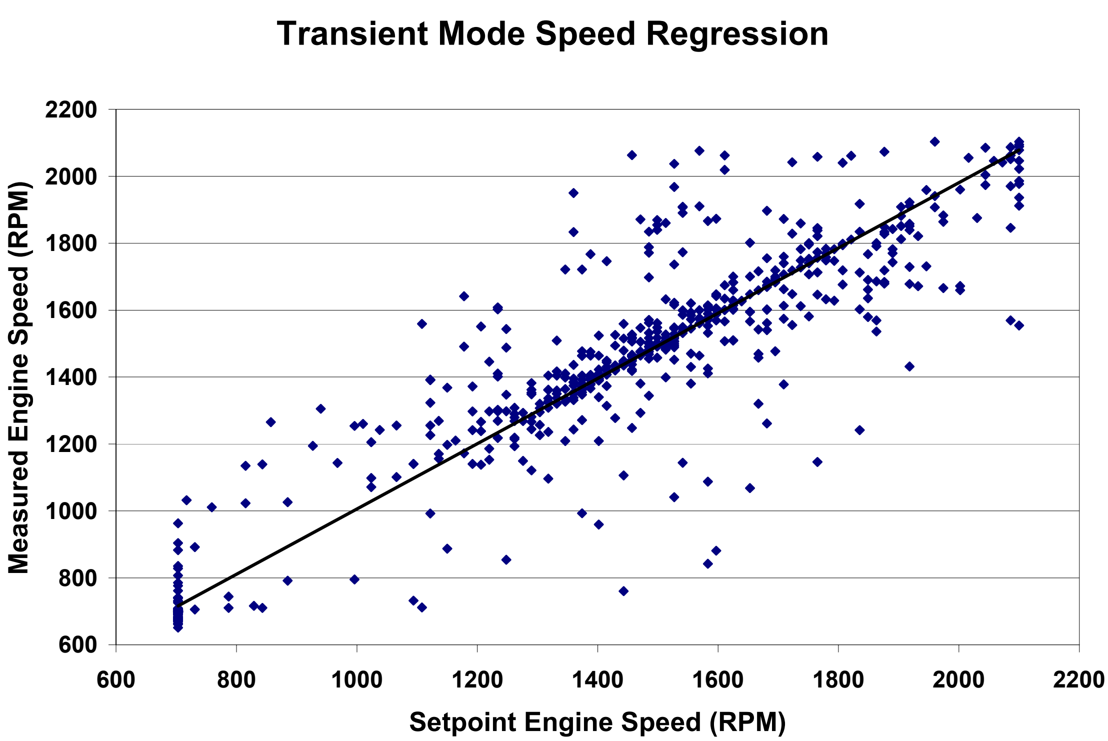

Figure 45: Transient Mode Speed Regression (based on all measured and setpoint data with no point deletions)

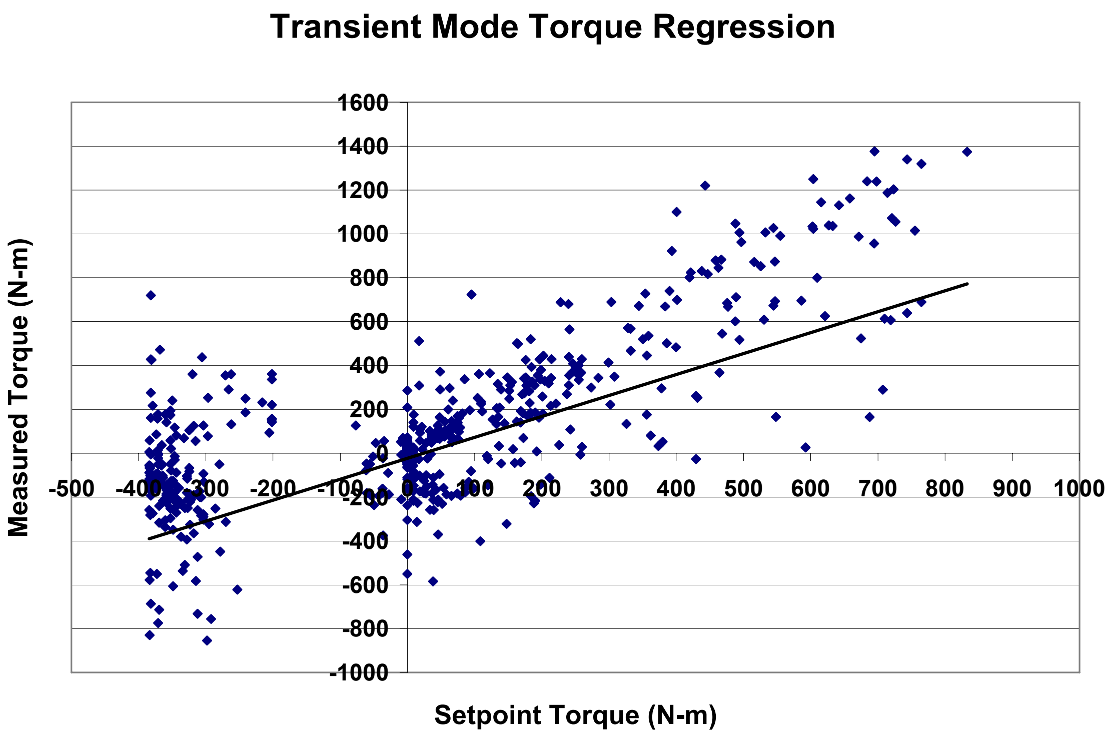

Figure 46: Transient Mode Torque Regression (based on all measured and setpoint data with no point deletions)

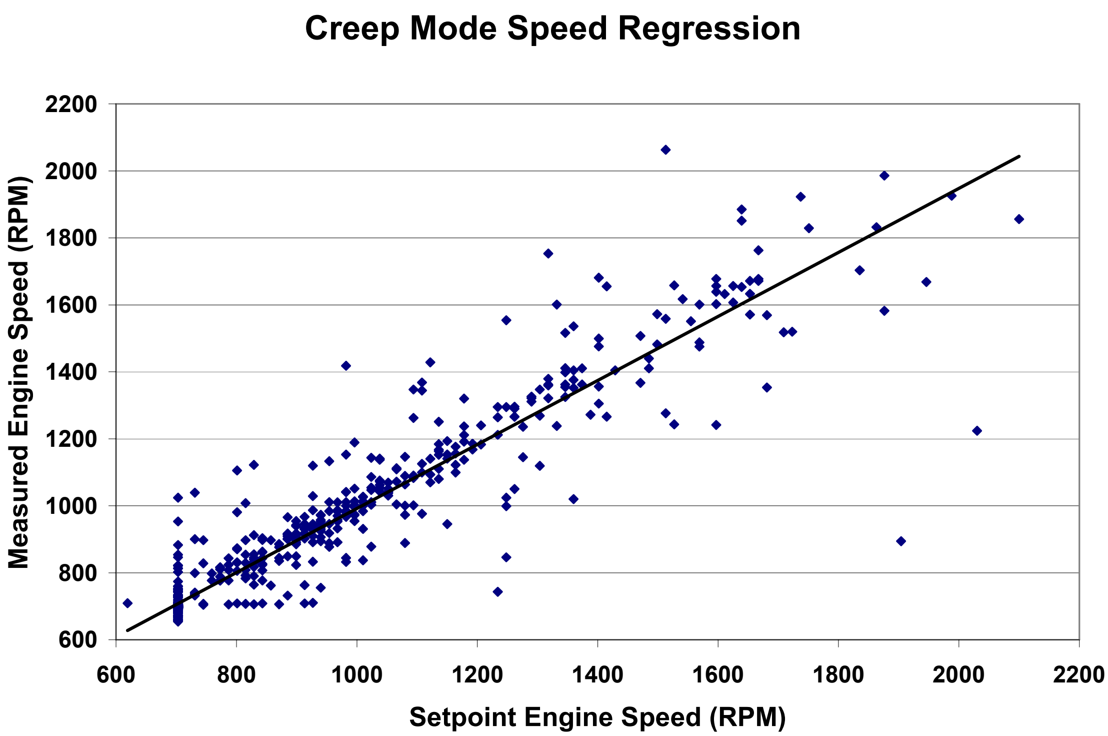

Figure 47: Creep Mode Speed Regression (based on all measured and setpoint data with no point deletions)

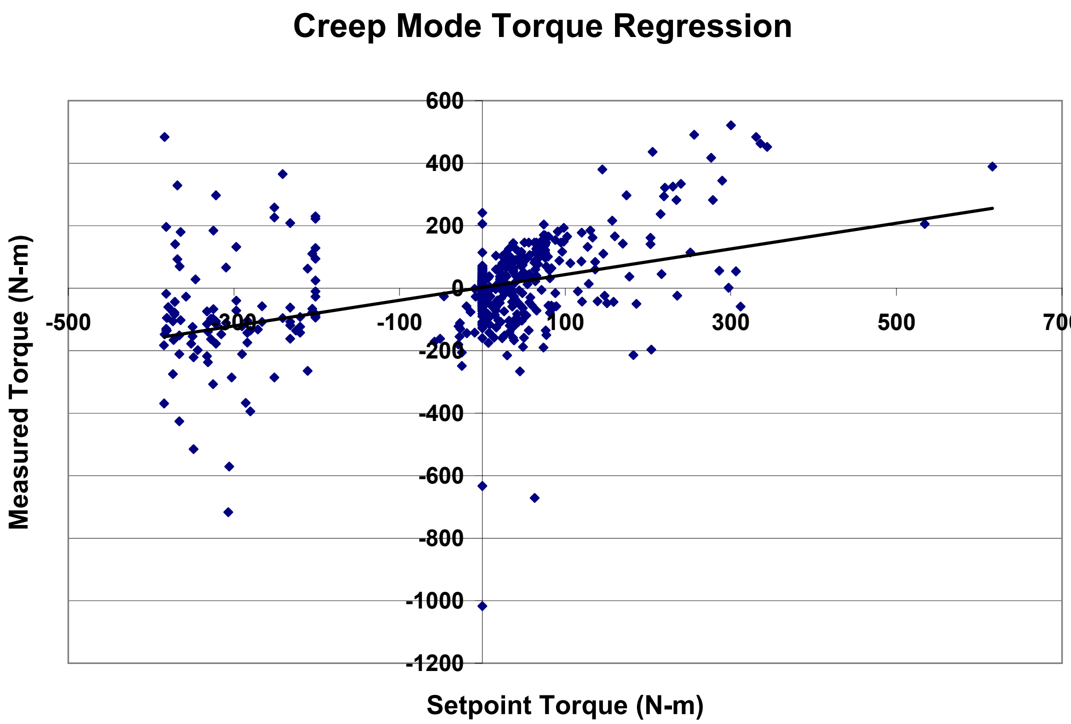

Figure 48: Creep Mode Torque Regression (based on all measured and setpoint data with no point deletions)

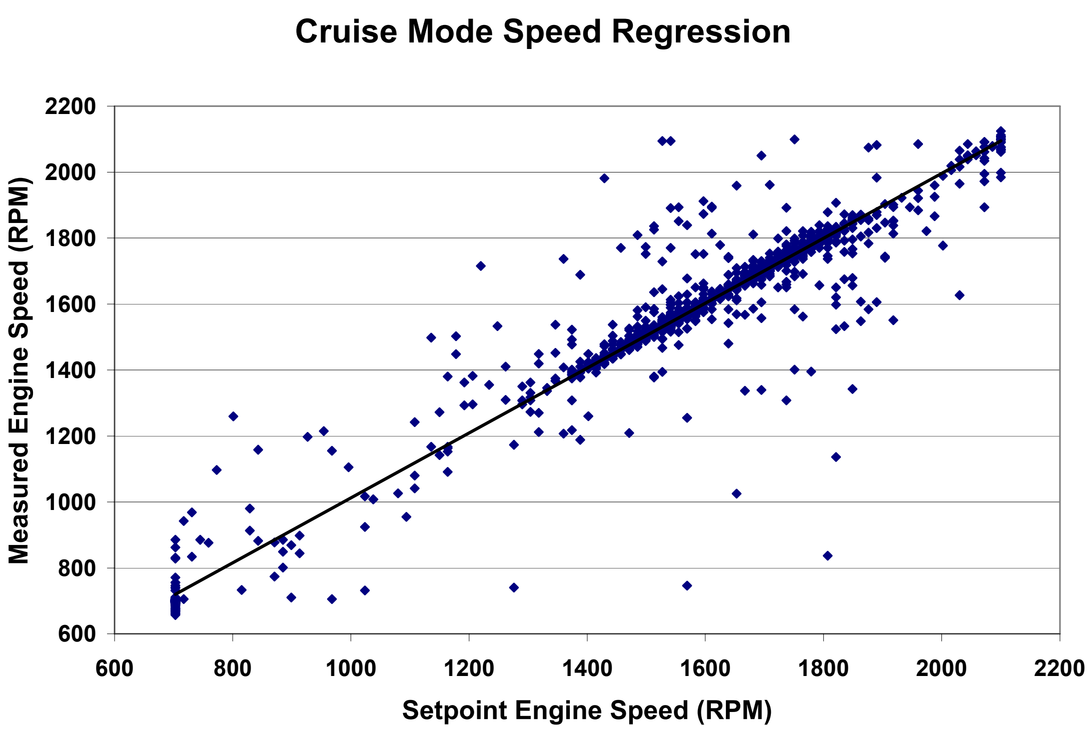

Figure 49: Cruise Mode Speed Regression (based on all measured and setpoint data with no point deletions)

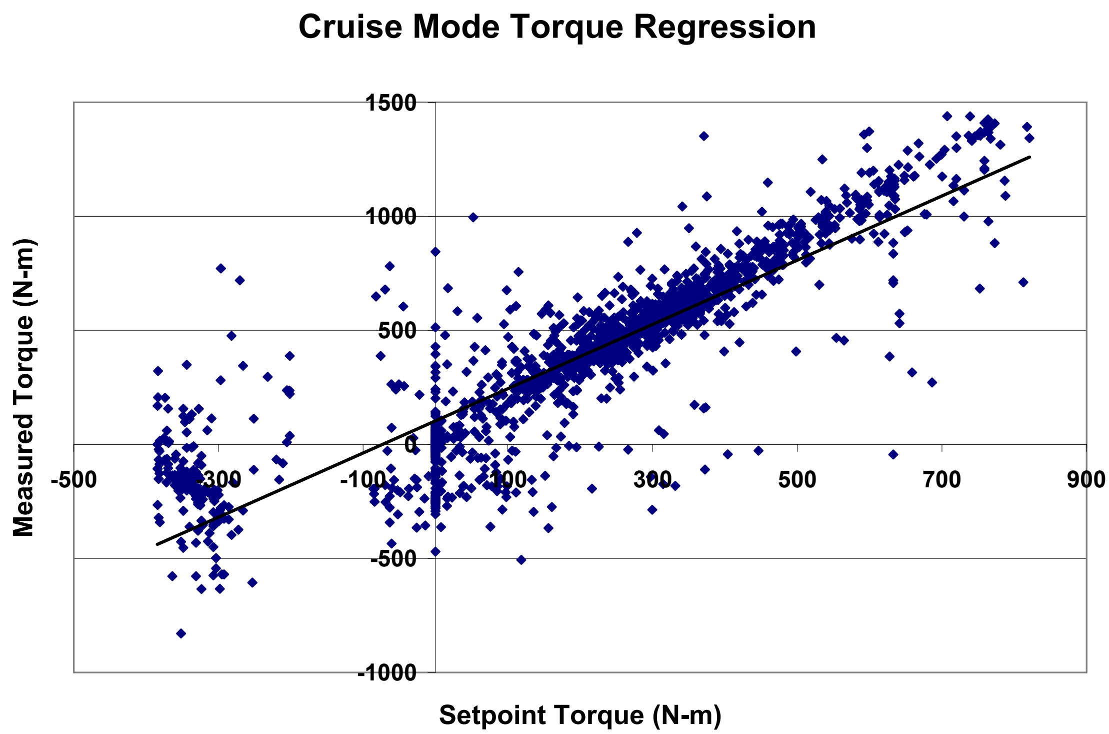

Figure 50: Cruise Mode Torque Regression (based on all measured and setpoint data with no point deletions)

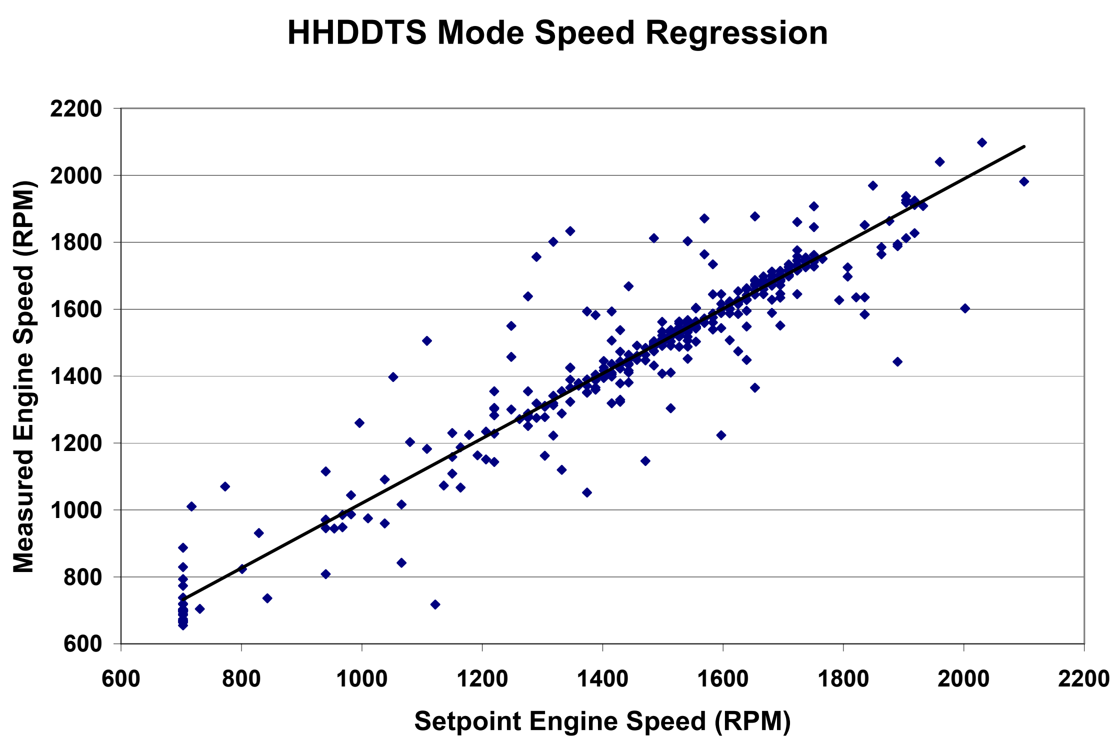

Figure 51: HHDDTS Mode Speed Regression (based on all measured and setpoint data with no point deletions)

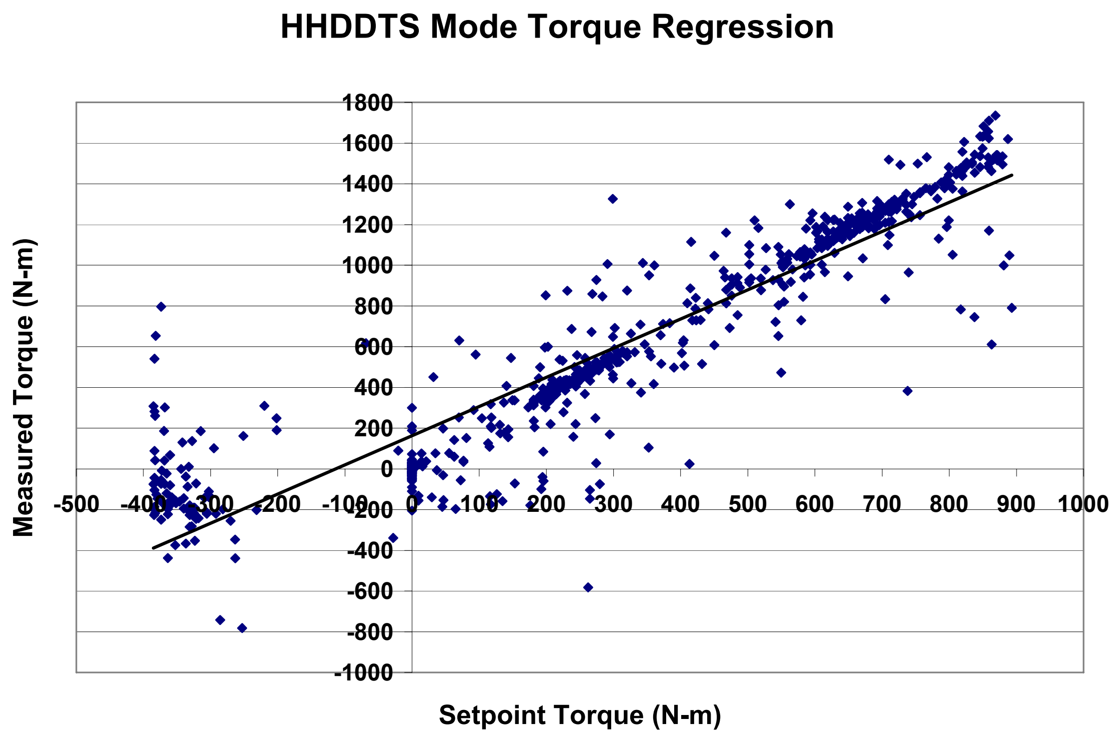

Figure 52: HHDDTS Mode Torque Regression (based on all measured and setpoint data with no point deletions)

The complete regression data for all runs can be found in Appendix A. In that appendix, throttle setting one corresponds to an "aggressive" throttle algorithm used in the test cell, while throttle setting three corresponds to a "normal" throttle setting. *EPA Criterion* corresponds to the passing range for FTP tests. Only hot start runs that were not missing any data were tabulated and presented. Other runs may have been performed for initial verification that the cycle runs without problems, to test other throttle settings, or for warm up purposes.

It was desired to determine any differences between the performance of an older engine and a newer engine on the ACES modes. Since these modes were created based on modern engine behavior, it was expected that the 2004 Cummins ISM engine might respond more closely to the target values than the 1992 Detroit Diesel. This comparison was performed for the Transient mode only, since it had the largest content of rapid acceleration and deceleration. Engine speed and engine torque were plotted for two different throttle settings for both of the engines. Results (frequency of 1 Hz) of the comparison for engine speed and torque can be seen in Figure 53 through Figure 58. The regression analysis in Appendix A shows that at normal throttle setting, the new ISM engine performed better on all statistical parameters for matching the setpoint speed. For the torque, the ISM engine was better on all parameters but one (y-intercept). At aggressive throttle setting, the old DDC engine was better on all parameters for matching the engine speed, and the Cummins engine was better on all parameters for matching the engine torque.

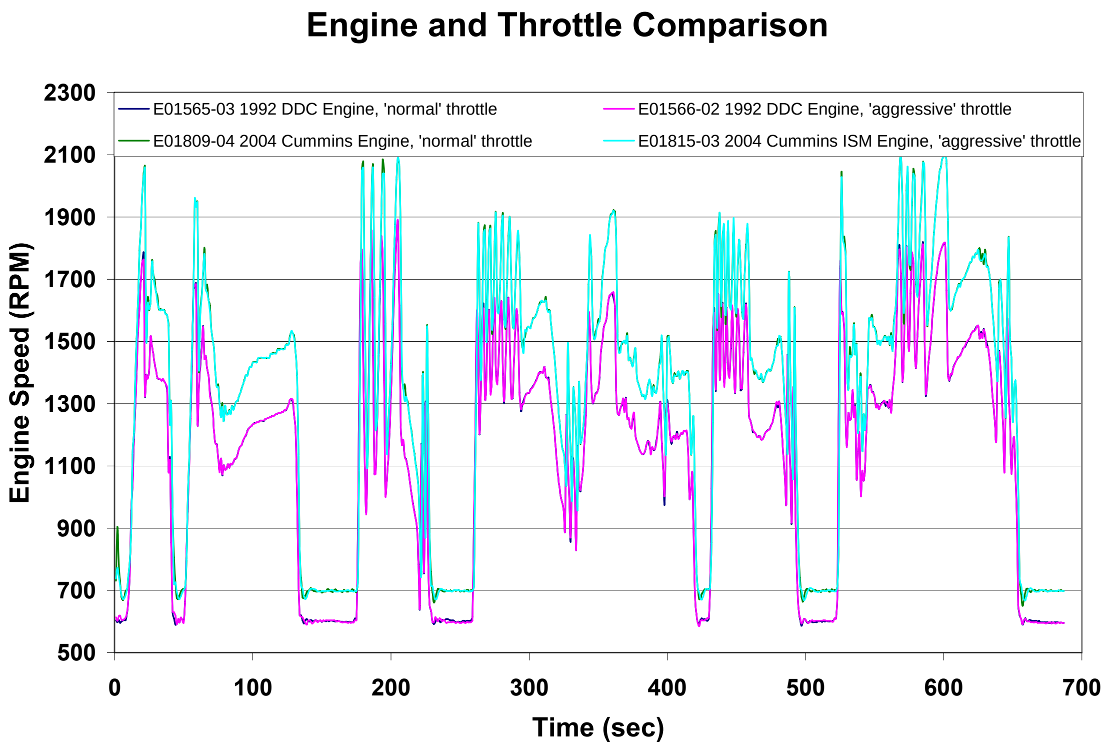

Figure 53: Two Engines and Two Throttle Settings Comparison, Engine Speed

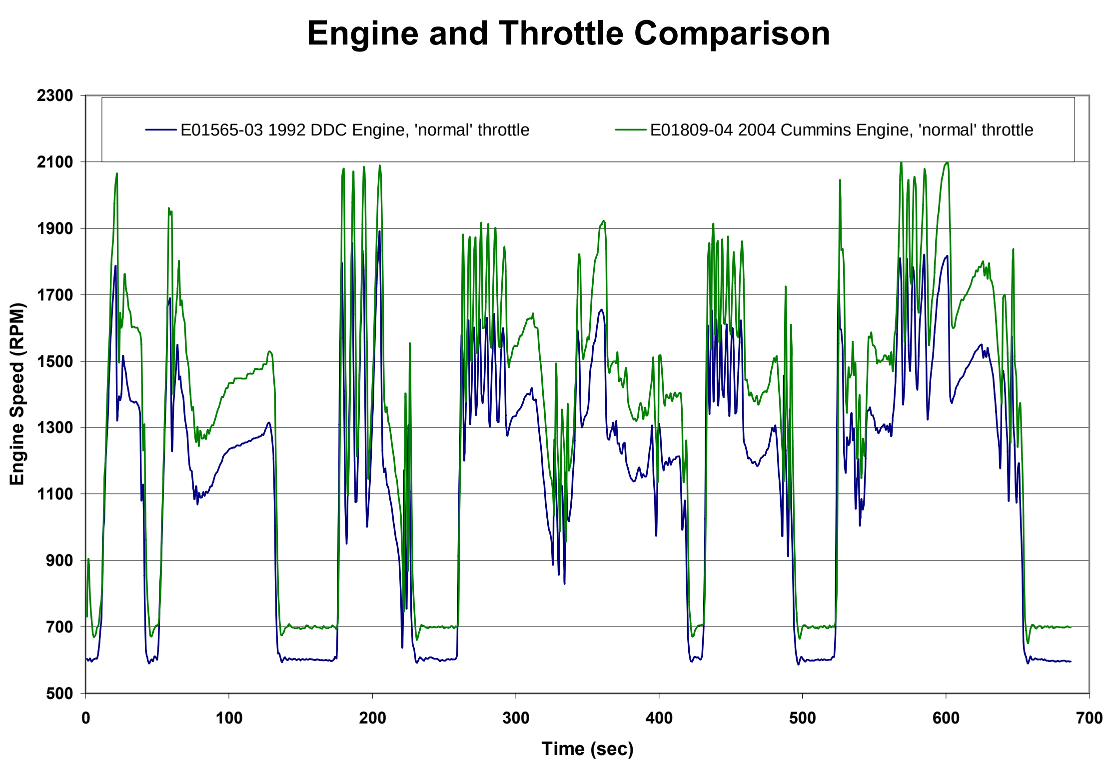

Figure 54: Two Engines on Normal Throttle Comparison, Engine Speed

Engine and Throttle Comparison

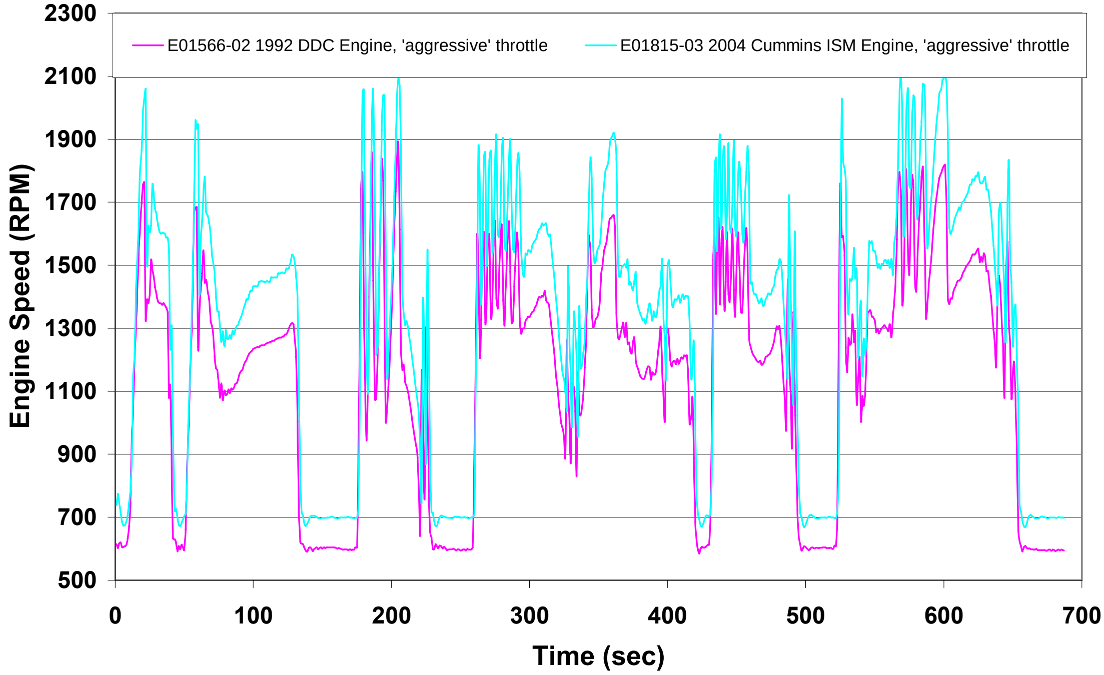

Figure 55: Two Engines on Aggressive Throttle Setting, Engine Speed

Engine and Throttle Comparison

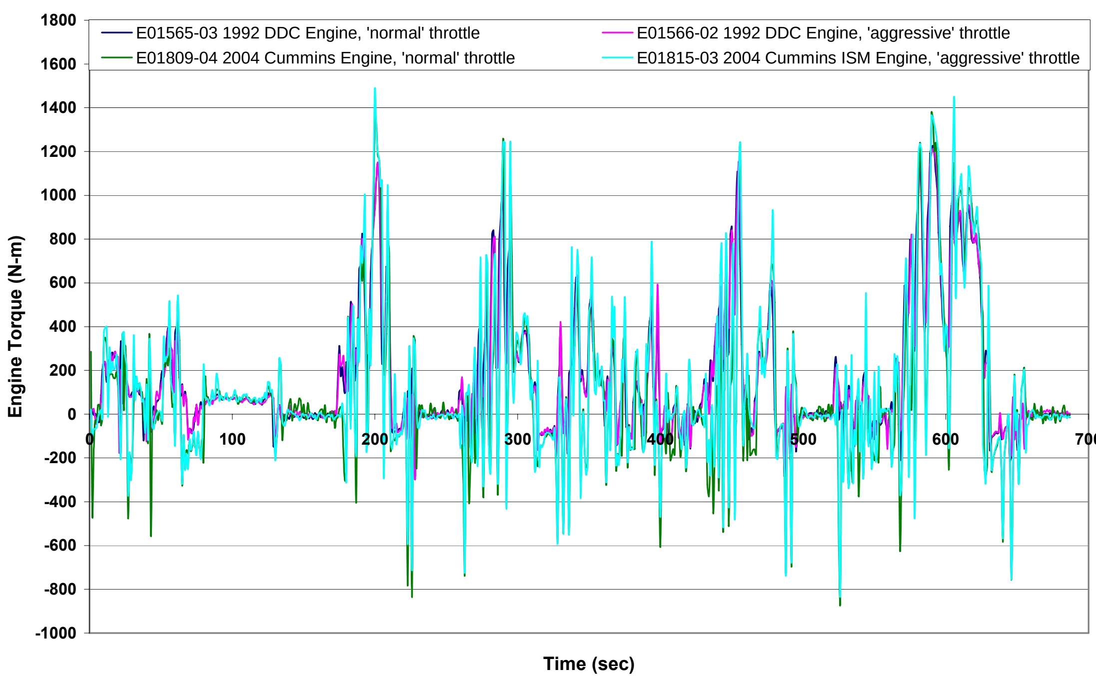

Figure 56: Two Engines and Two Throttle Settings Comparison, Torque

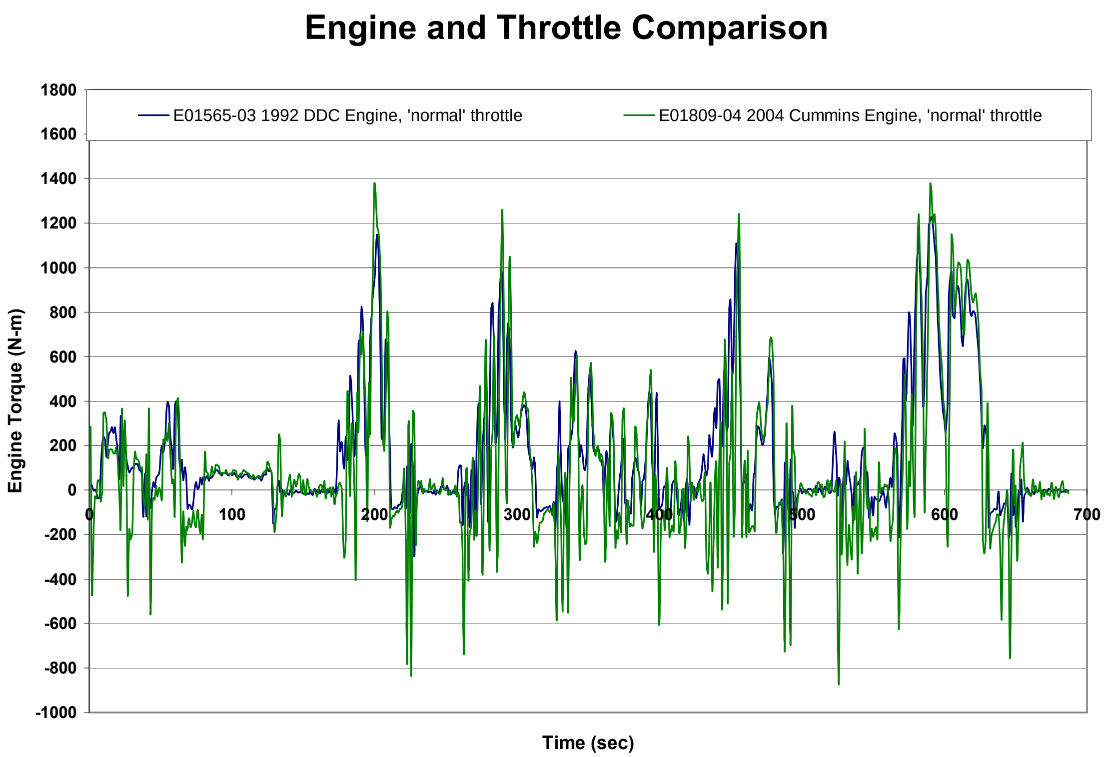

Figure 57: Two Engines on Normal Throttle Settings, Engine Torque

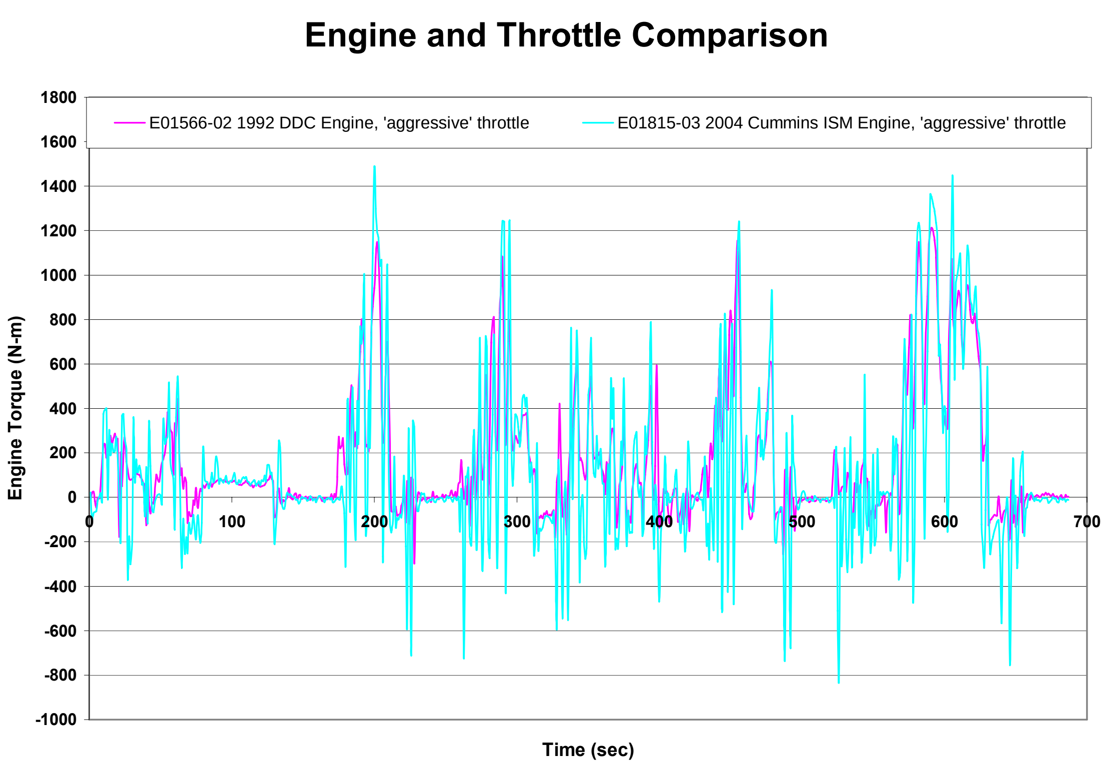

Figure 58: Two Engines on Aggressive Throttle Setting, Engine Torque

Emissions of NOx, PM, CO, HC, and CO_2 were measured for each run. The final emissions for each set of three runs for each mode were determined and plotted. The plots for each emission species are shown below in Figure 59 through Figure 63. The results were displayed for each run to show any variation between runs. It should be noted that the high emissions (g/bhp-hr) of the Creep Mode were because the mode required relatively low energy (bhp-hr) consumption. Chassis Creep mode data in the E-55/59 program were also high (in units of g/mile) for the same reason.

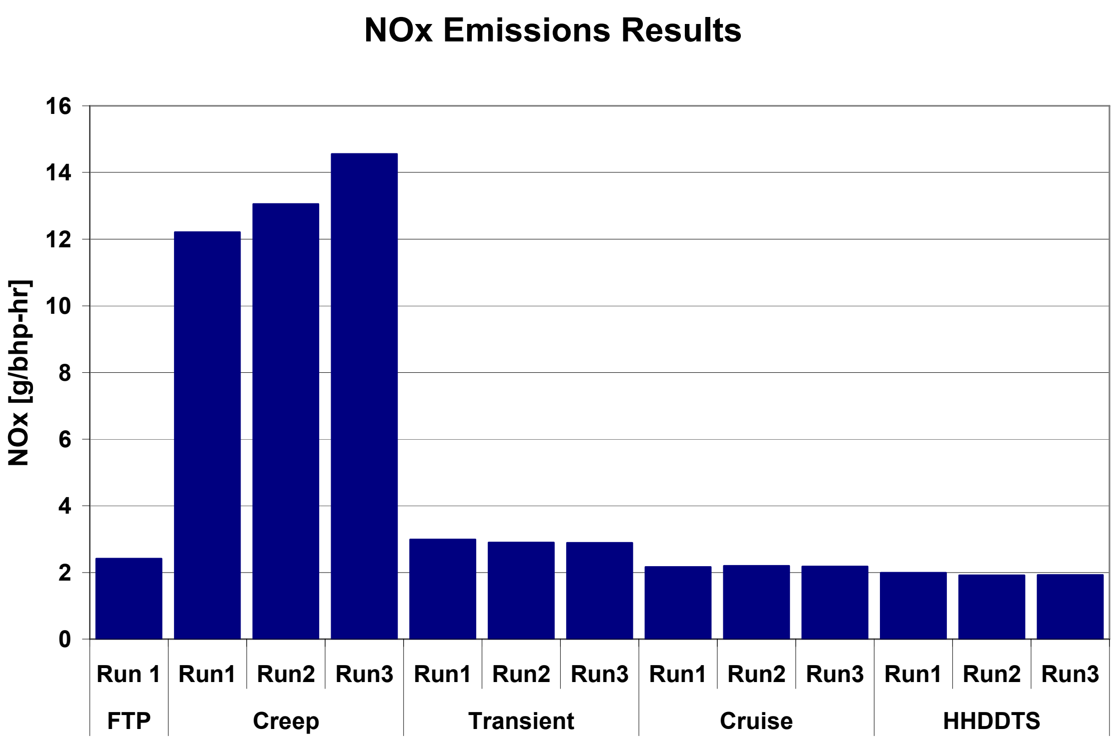

Figure 59: NOx Emissions

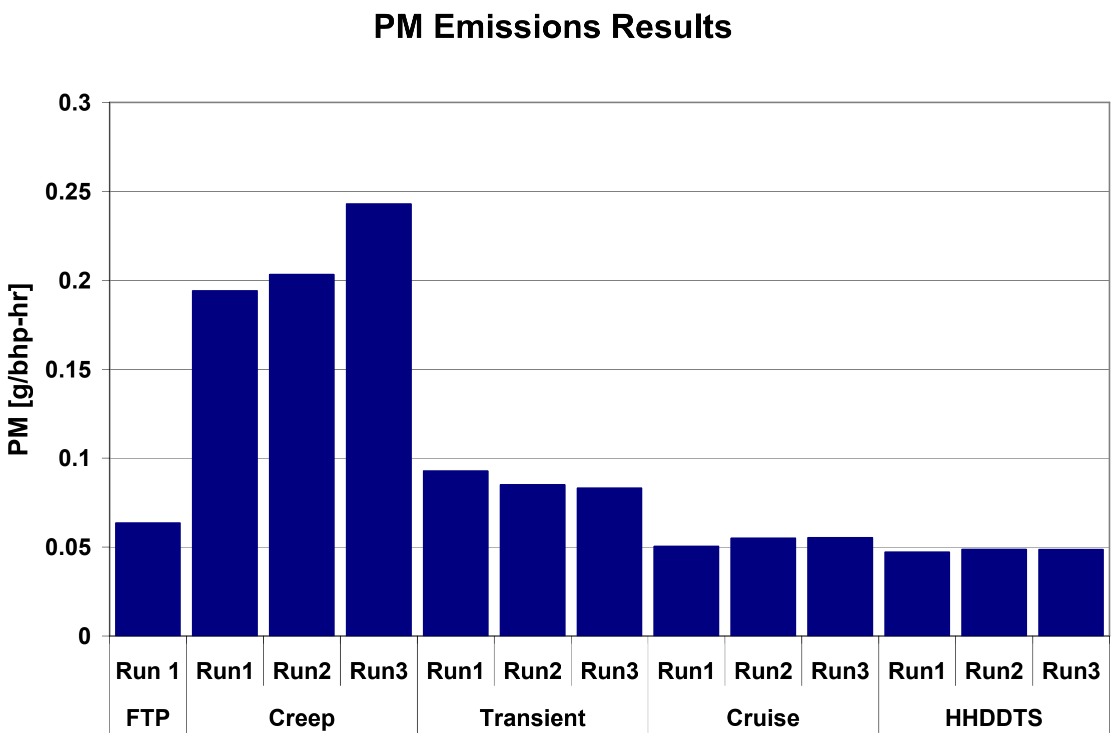

Figure 60: PM Emissions

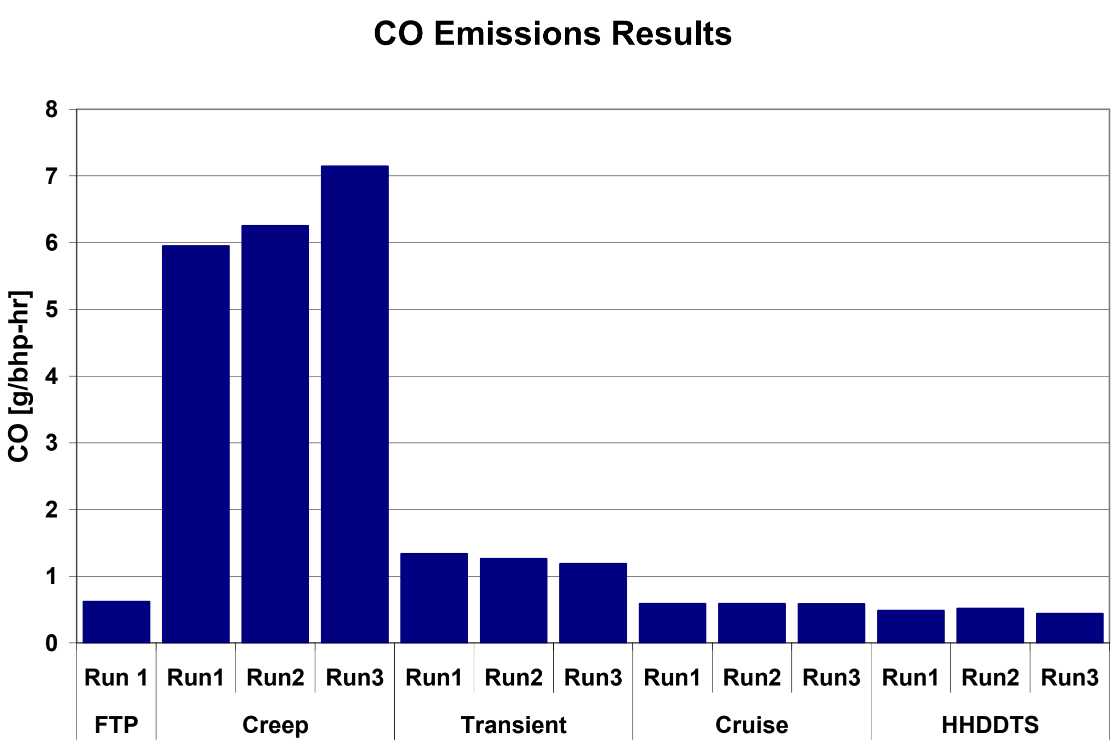

Figure 61: CO Emissions

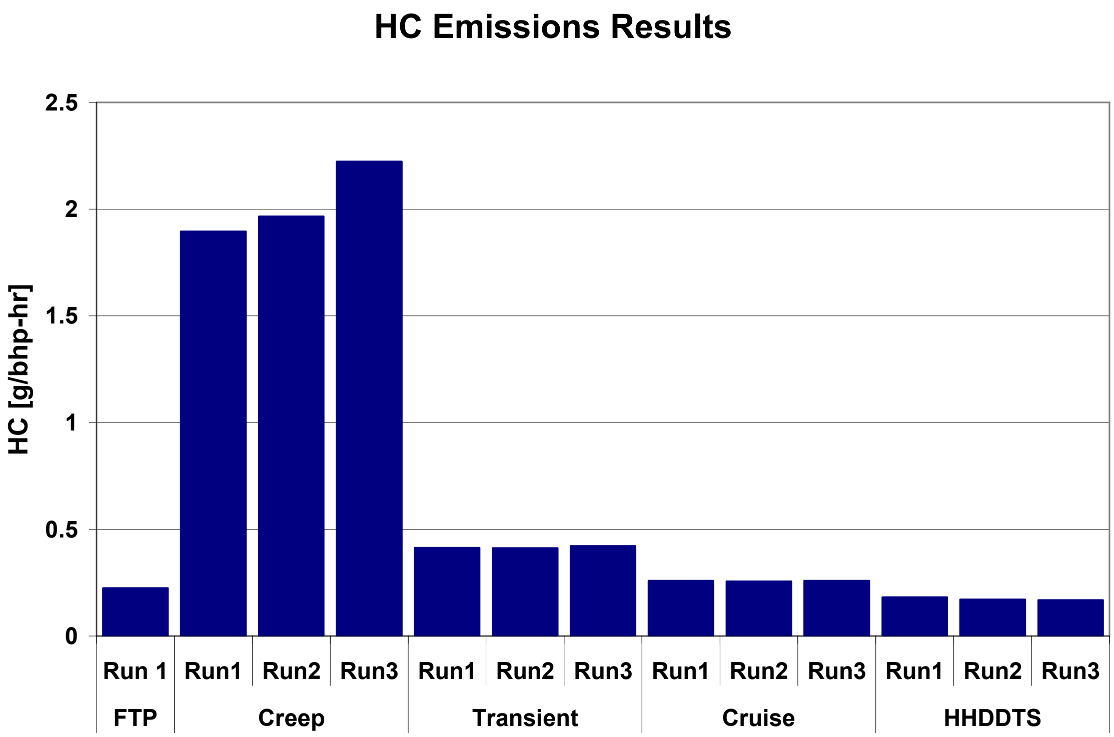

Figure 62: HC Emissions

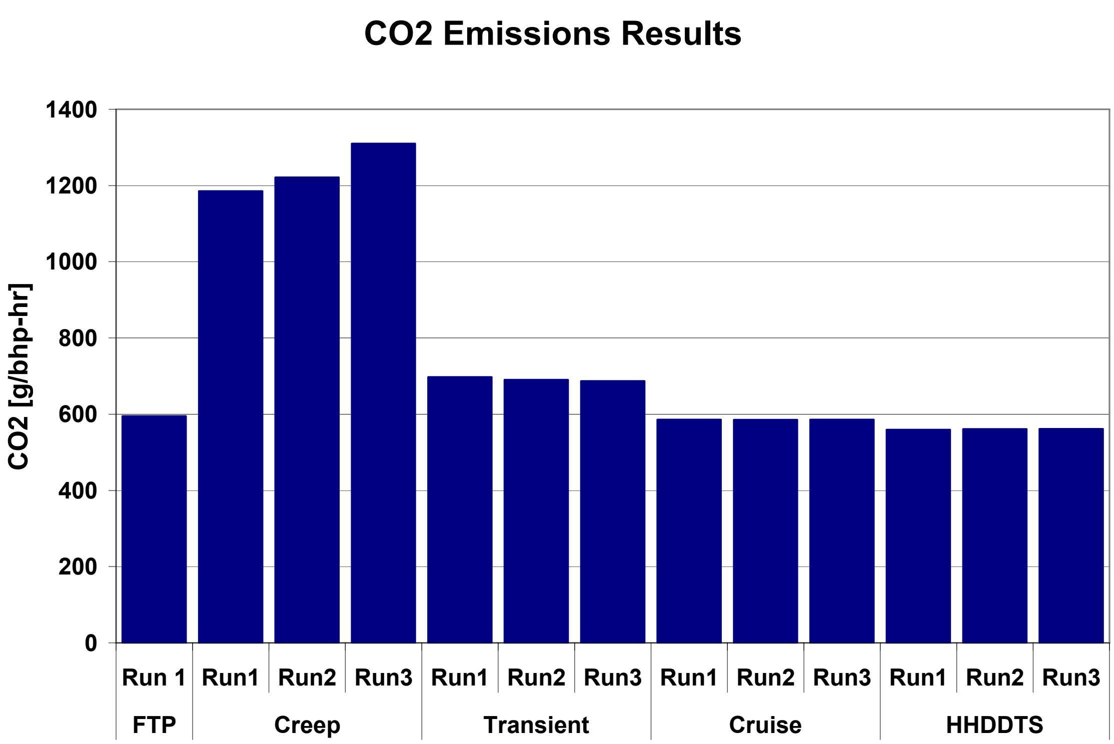

Figure 63: CO_2 Emissions

In addition to total emissions for each run, continuous NOx emissions were measured and recorded. The continuous NOx for each ACES mode and for the FTP can be seen in Figure 64 through Figure 68. The second run of each ACES mode was chosen to be plotted.

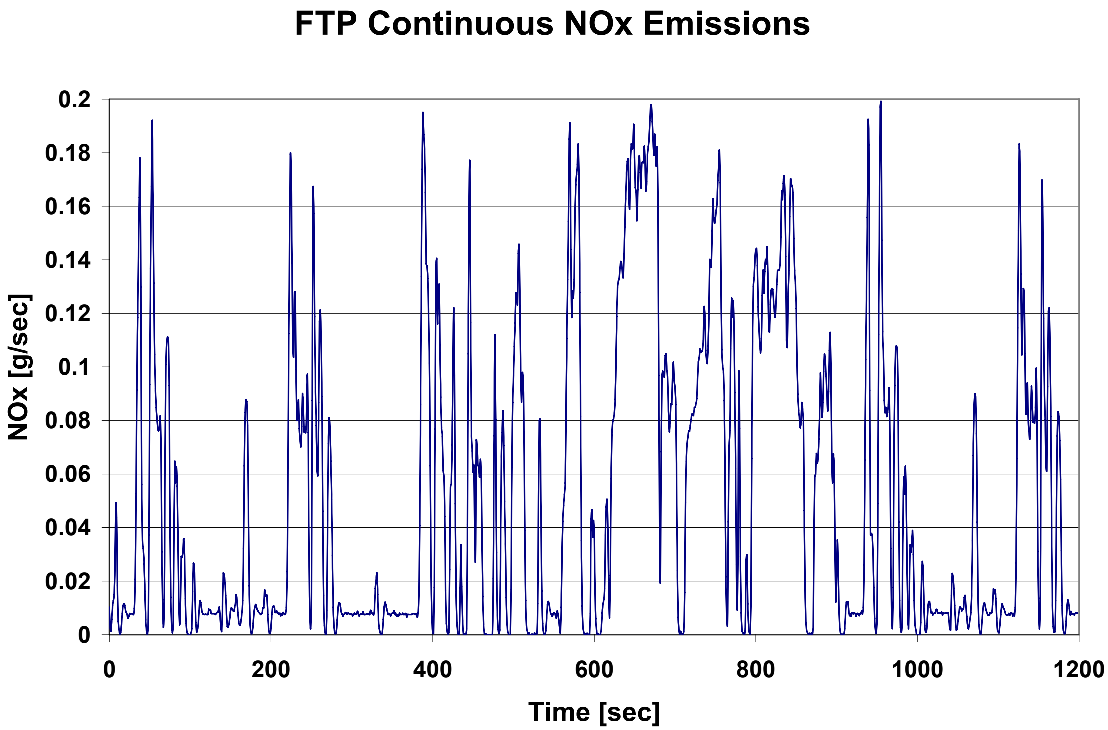

Figure 64: FTP Continuous NOx

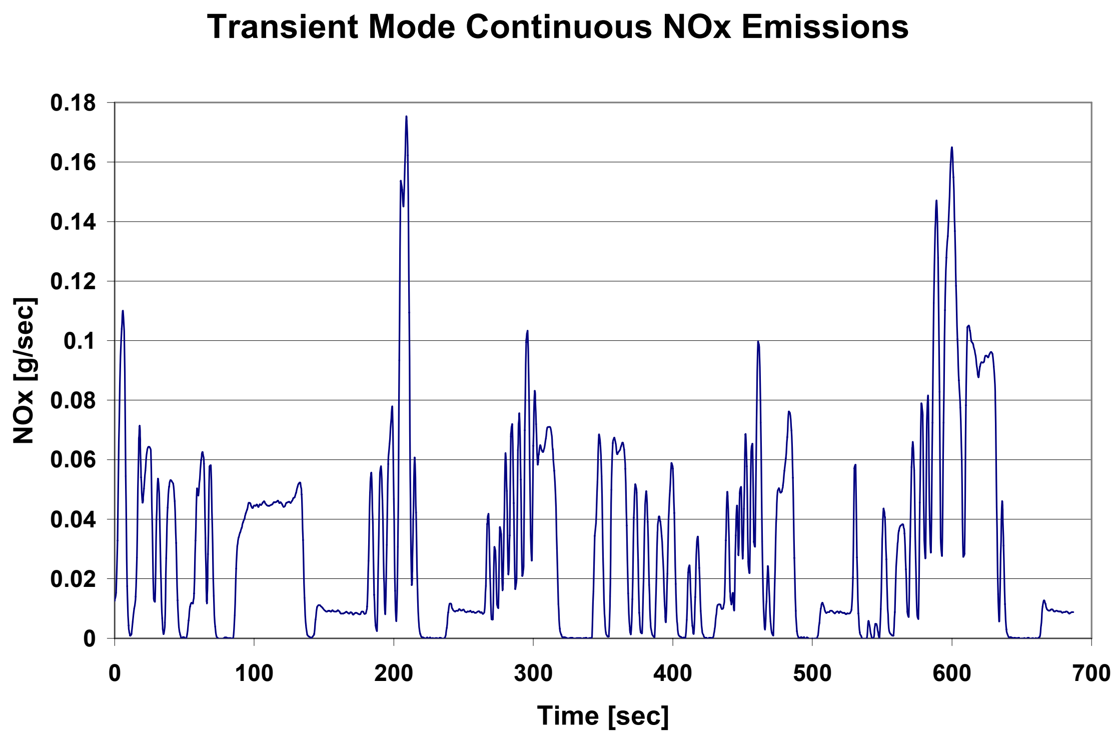

Figure 65: Transient Mode Continuous NOx

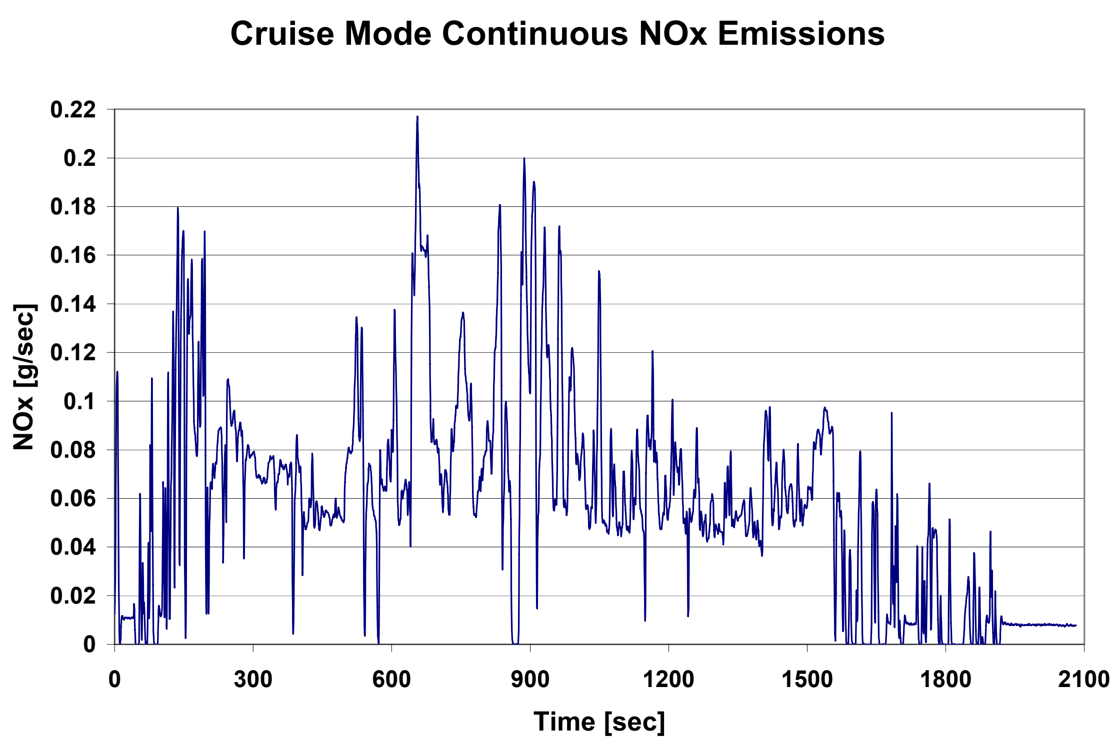

Figure 66: Cruise Mode Continuous NOx

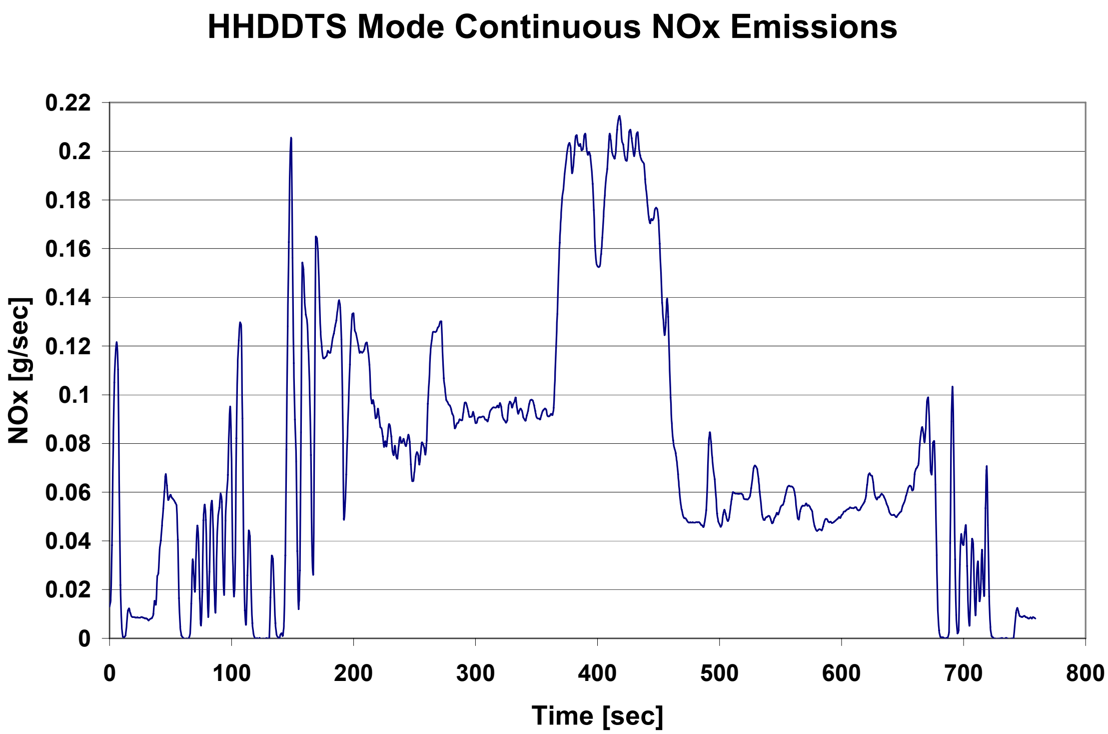

Figure 67: HHDDTS Mode Continuous NOx

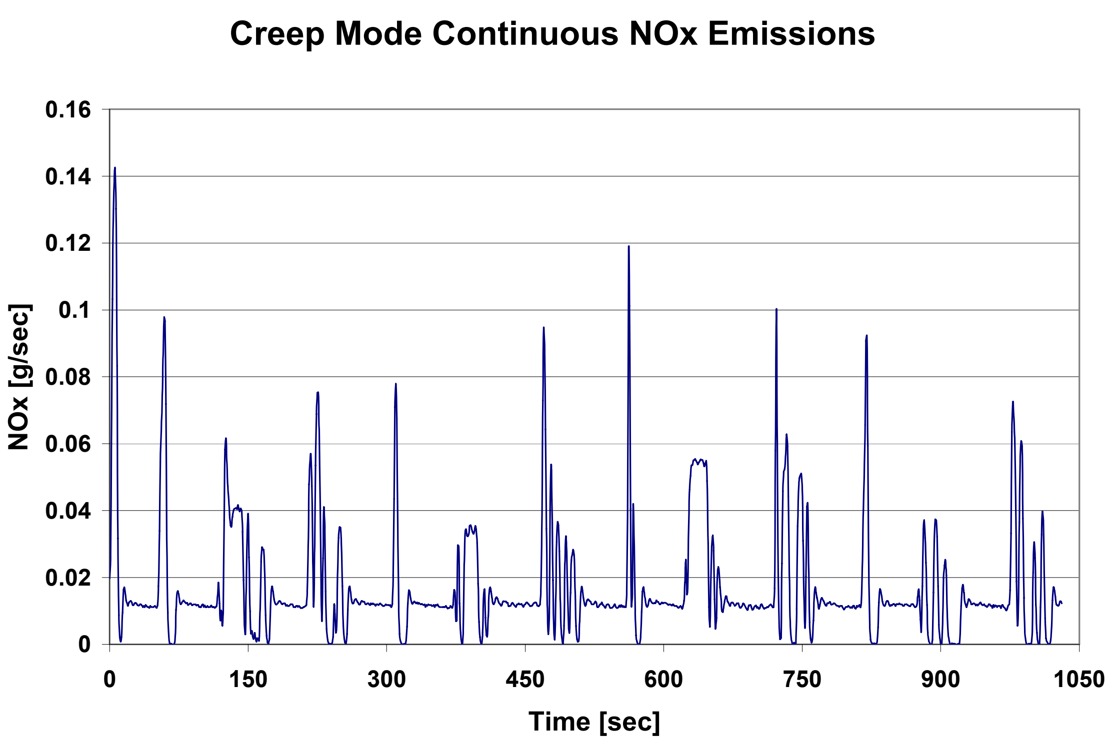

Figure 68: Creep Mode Continuous NOx

A fuel consumption comparison was performed as a quality control audit for each of the four ACES modes and for the FTP. For each, the measured fuel consumed, ECU broadcast fuel consumption, and carbon balance fuel consumption were determined. The carbon balance assumed a light diesel fuel ($C_{12.3}H_{22.2}$) with a molecular weight of 170. The results of the comparison can be seen in Figure 69 below. It should be noted that for the Creep mode, only two runs were averaged for the ECU broadcast fueling. This is because of incomplete ECU data for the final Creep mode run. It also should be noted that the fuel consumption was independent between the four modes because they each had a different time duration and energy consumption.

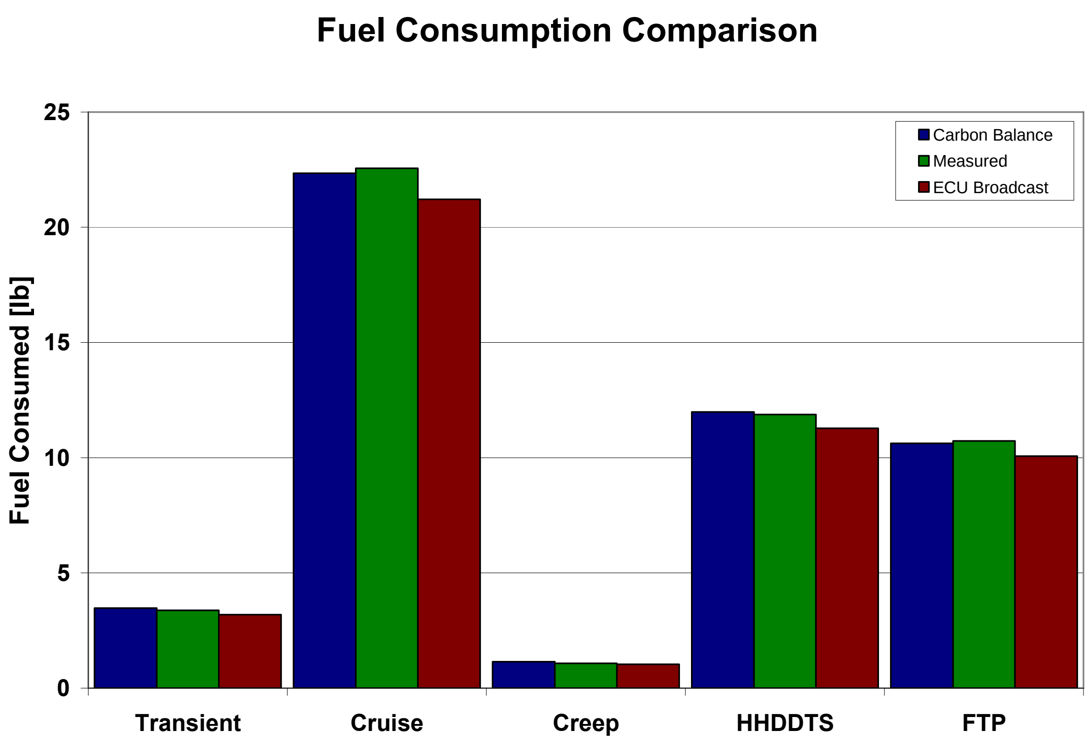

Figure 69: Fuel Consumption Comparison

Determination of Regression Parameters

The ACES modes were individually very different from the FTP. As a result, the modes did not necessarily meet current FTP regression standards. However, the goal of creating these modes was not to meet current FTP regression. Instead, new regression standards were introduced for the ACES modes based on the results of testing at West Virginia University and the existing FTP standards. It was decided that the FTP regression standards would be relaxed if a given mode did not meet the criteria, but not tightened if the criteria was met. Clearly, the regression standards offered in this report were predicated on the performance on a single engine in a single test cell, and they might be altered in the future if a body of data arises from various tests using the new schedule.

The method used to determine the new regression standards involved trying to match the acceptable range to the experimental results so that the results lay at the same point in the range as the FTP. For example, say the BHP y-intercept of some variable for the FTP was 2.5 and the acceptable range was ±5 (implying that the criterion was met by a factor of two, in absolute value), and the experimental results for the ACES mode produced a y-intercept of -13, then the acceptable range would be set to ±26.

Each of the regression statistics for each set of three final runs for each mode was averaged. Then the above method was applied to any point that did not meet the FTP regression. Only "normal" throttle setpoint strategy data were considered for all ACES modes and the FTP in implementing this approach.

The following formulas were applied to all regression criteria to determine the new upper and lower bounds for an acceptable run. These formulas were applied to speed, torque, and BHP data. However, the integrated BHP criterion (which appears in the CFR for the FTP) required some extra investigation, as discussed below. In the formulas, EPA_{upper} and EPA_{lower} are the FTP upper and lower EPA requirements, FTP_{actual} are the actual regression results from a representative FTP run, and actual is the actual mode result for the particular regression criteria.

$$X_{upper} = \left(\frac{EPA_{upper} - FTP_{actual}}{FTP_{actual}} \right) \cdot actual + actual$$

$$X_{lower} = -\left(\frac{FTP_{actual} - EPA_{lower}}{FTP_{actual}} \right) \cdot actual + actual$$

The new regression standards for speed, torque, and BHP (except integrated BHP, which is discussed next) are summarized in Table 11, Table 12, and Table 13 below.

Table 11: New Speed Regression Statistics

	Speed							
	Standard Error		Slope of Regression		Y-Intercept		Coefficient of Regression	
FTP	0.00	100.00	0.97	1.03	-50.00	50.00	0.97	1.00
Transient	0.00	100.00	0.96	1.03	-69.52	69.52	0.97	1.00
Cruise	0.00	100.00	0.97	1.03	-61.62	61.62	0.97	1.00
HHDDTS	0.00	100.00	0.97	1.03	-50.00	50.00	0.97	1.00
Creep	0.00	100.00	0.96	1.03	-62.22	62.22	0.97	1.00

Table 12: New Torque Regression Statistics

	Torque							
	Standard Error		Slope of Regression		Y-Intercept		Coefficient of Regression	
FTP	0.00	171.02	0.83	1.03	-15.00	15.00	0.88	1.00
Transient	0.00	171.02	0.77	1.03	-15.00	15.00	0.85	1.00
Cruise	0.00	171.02	0.81	1.03	-15.00	15.00	0.88	1.00
HHDDTS	0.00	171.02	0.81	1.03	-15.00	15.00	0.88	1.00
Creep	0.00	171.02	0.59	1.03	-15.00	15.00	0.60	1.00

Table 13: New BHP Regression Statistics

	BHP							
	Standard Error		Slope of Regression		Y-Intercept		Coefficient of Regression	
FTP	0.00	28.33	0.89	1.03	-5.00	5.00	0.91	1.00
Transient	0.00	31.32	0.85	1.03	-5.00	5.00	0.87	1.00
Cruise	0.00	28.33	0.89	1.03	-5.00	5.00	0.89	1.00
HHDDTS	0.00	28.33	0.88	1.03	-5.00	5.00	0.91	1.00
Creep	0.00	28.33	0.62	1.03	-5.00	5.00	0.52	1.00

The integrated BHP criteria employed the same formula. However, each mode and the FTP had its own separate set of EPA requirements. The EPA requirements specified that the integrated BHP be between +5% and -15% of the calculated value based on the input engine speed and torque. It was desired to produce a new range in terms of a percentage above or below the reference BHP so that the standards were independent of engine power. First, the same formulas were applied to the integrated BHP, where EPA_{upper} and EPA_{lower} were the upper and lower EPA requirements for the FTP. Then the new calculated range was compared to the EPA range for the particular mode. For all of the modes, the actual value fell within the EPA range of +5% and -15% of the reference work. Because of this, the current EPA standard of +5% and -15% of reference work was retained for all of the ACES modes. Figure 70 illustrates the ranges and points examined for the creep mode as an example and Table 14 shows a summary of the integrated BHP regression standards.

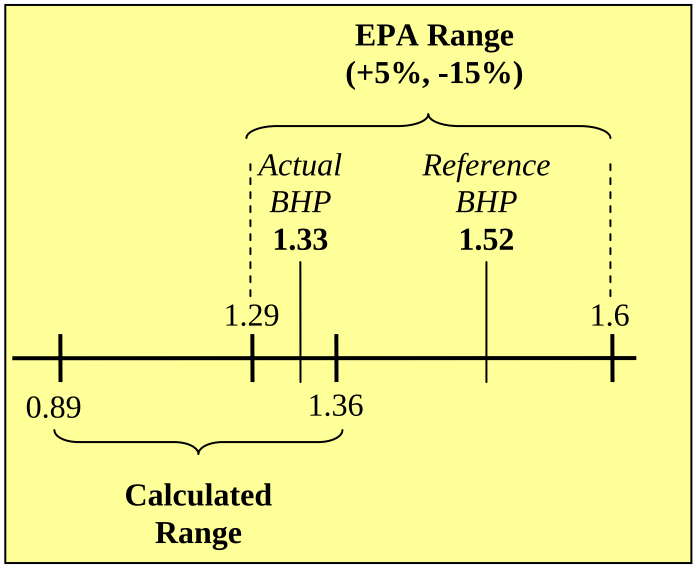

Figure 70: Creep Mode Integrated BHP Range Determination

Table 14: Integrated BHP Regression Statistics

	Integrated BHP [BHP-hr]					
	Actual	Calculated Range		EPA Mode Range (-15%, +5%)		Reference Work
FTP	25.75	---	---	21.33	26.35	25.10
Transient	7.23	5.99	7.40	6.69	8.27	7.88
Cruise	54.86	45.44	56.13	46.30	57.19	54.47
HHDDTS	30.01	24.86	30.71	25.69	31.74	30.23
Creep	1.33	1.10	1.36	1.29	1.60	1.52

Conclusions

The ACES engine test schedule, consisting of the Transient, Cruise, Creep and High-Speed Cruise (HHDDT_S) modes was developed based on ECU data taken from trucks driven on a chassis dynamometer during the E-55/59 program. A 2004 model year engine was exercised through these modes in a transient test cell. The results showed that the ACES test modes were readily implemented on an engine dynamometer. Minor adjustment of ECU data was required to define closed rack (zero fuel) periods of engine operation in the final modes. New regression criteria were determined for the ACES modes to account for individual differences between the new modes and the established FTP. This report is accompanied by an electronic file defining percent torque and percent speed for each mode, and provides sufficient information for the execution of the modes in transient test cells.

Appendix A: Comprehensive Regression Data

Speed										
Run Number	Throttle Setting	Mode Tested	Standard Error		Slope of Regression		Y Intercept		Coefficient of Regression	
			Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion
E01565-03	#3	Transient	38.54	0 -- 100	0.9714	0.97 -- 1.03	40.96	±50.00	0.9791	0.97 -- 1
E01566-02	#1	Transient	19.48	0 -- 100	0.9769	0.97 -- 1.03	34.43	±50.00	0.9944	0.97 -- 1
E01566-01	#3	FTP	13.4	0 -- 100	0.9962	0.97 -- 1.03	11.29	±50.00	0.999	0.97 -- 1
E01806-02	#1	Transient	115.75	0 -- 100	0.8643	0.97 -- 1.03	205.97	±50.00	0.8226	0.97 -- 1
E01806-03	#3	FTP	55.96	0 -- 100	0.9893	0.97 -- 1.03	21.65	±50.00	0.9871	0.97 -- 1
E01806-04	#3	Cruise	49.84	0 -- 100	0.9493	0.97 -- 1.03	86.75	±50.00	0.9348	0.97 -- 1
E01806-06	#3	Creep	50.04	0 -- 100	0.954	0.97 -- 1.03	50.71	±50.00	0.9668	0.97 -- 1
E01809-03	#3	Transient	32.37	0 -- 100	0.9835	0.97 -- 1.03	29.1	±50.00	0.9879	0.97 -- 1
E01809-04	#3	Transient	32.42	0 -- 100	0.9825	0.97 -- 1.03	30.73	±50.00	0.9878	0.97 -- 1
E01809-05	#3	Transient	32.41	0 -- 100	0.9826	0.97 -- 1.03	30.47	±50.00	0.9878	0.97 -- 1
E01810-01	#3	HHDDTS	11.6	0 -- 100	0.9898	0.97 -- 1.03	20.77	±50.00	0.9965	0.97 -- 1
E01810-02	#3	HHDDTS	11.6	0 -- 100	0.9905	0.97 -- 1.03	19.62	±50.00	0.9965	0.97 -- 1
E01810-03	#3	HHDDTS	11.58	0 -- 100	0.9909	0.97 -- 1.03	18.94	±50.00	0.9965	0.97 -- 1
E01811-01	#3	Cruise	20.99	0 -- 100	0.9868	0.97 -- 1.03	26.51	±50.00	0.989	0.97 -- 1
E01811-02	#3	Cruise	20.98	0 -- 100	0.9868	0.97 -- 1.03	26.5	±50.00	0.989	0.97 -- 1
E01811-03	#3	Cruise	20.97	0 -- 100	0.9865	0.97 -- 1.03	27.04	±50.00	0.9891	0.97 -- 1
E01812-01	#3	Creep	36.36	0 -- 100	0.9786	0.97 -- 1.03	26.69	±50.00	0.9833	0.97 -- 1
E01812-02	#3	Creep	36.41	0 -- 100	0.978	0.97 -- 1.03	27.34	±50.00	0.9832	0.97 -- 1
E01812-03	#3	Creep	36.45	0 -- 100	0.9786	0.97 -- 1.03	26.79	±50.00	0.9832	0.97 -- 1
E01815-02	#1	Transient	84.92	0 -- 100	0.9055	0.97 -- 1.03	145.99	±50.00	0.9033	0.97 -- 1
E01815-03	#1	Transient	71.57	0 -- 100	0.917	0.97 -- 1.03	129.08	±50.00	0.9309	0.97 -- 1
E01815-04	#1	Transient	75.57	0 -- 100	0.9067	0.97 -- 1.03	144.21	±50.00	0.922	0.97 -- 1
E01816-01	#1	FTP	37.34	0 -- 100	0.9922	0.97 -- 1.03	17.3	±50.00	0.994	0.97 -- 1
E01816-02	#1	FTP	43.32	0 -- 100	0.9922	0.97 -- 1.03	17.21	±50.00	0.9919	0.97 -- 1
E01816-03	#1	FTP	43.3	0 -- 100	0.9923	0.97 -- 1.03	17.21	±50.00	0.9919	0.97 -- 1

Note: These regression analyses excluded the points permitted in CFR 86.1341-90.

Torque										
Run Number	Throttle Setting	Mode Tested	Standard Error		Slope of Regression		Y Intercept		Coefficient of Regression	
			Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion
E01565-03	#3	Transient	91.96	0 -- 171.02	0.9118	0.83 -- 1.03	15.76	±15.00	0.9001	0.88 -- 1
E01566-02	#1	Transient	88.24	0 -- 171.02	0.92	0.83 -- 1.03	18.71	±15.00	0.9067	0.88 -- 1
E01566-01	#3	FTP	56.48	0 -- 171.02	0.9911	0.83 -- 1.03	-0.81	±15.00	0.978	0.88 -- 1
E01806-02	#1	Transient	77.98	0 -- 171.02	1.0091	0.83 -- 1.03	0.2	±15.00	0.9201	0.88 -- 1
E01806-03	#3	FTP	80.44	0 -- 171.02	1.016	0.83 -- 1.03	2.47	±15.00	0.9444	0.88 -- 1
E01806-04	#3	Cruise	58.83	0 -- 171.02	1.019	0.83 -- 1.03	-1.34	±15.00	0.9495	0.88 -- 1
E01806-06	#3	Creep	37.13	0 -- 171.02	0.9242	0.83 -- 1.03	-4.47	±15.00	0.7815	0.88 -- 1
E01809-03	#3	Transient	77.68	0 -- 171.02	0.9375	0.83 -- 1.03	-23.07	±15.00	0.9146	0.88 -- 1
E01809-04	#3	Transient	77.55	0 -- 171.02	0.9372	0.83 -- 1.03	-23.18	±15.00	0.9148	0.88 -- 1
E01809-05	#3	Transient	77.44	0 -- 171.02	0.9389	0.83 -- 1.03	-23.46	±15.00	0.9154	0.88 -- 1
E01810-01	#3	HHDDTS	57.6	0 -- 171.02	0.9862	0.83 -- 1.03	-7.86	±15.00	0.974	0.88 -- 1
E01810-02	#3	HHDDTS	58.18	0 -- 171.02	0.9843	0.83 -- 1.03	-6.81	±15.00	0.9734	0.88 -- 1
E01810-03	#3	HHDDTS	57.37	0 -- 171.02	0.9864	0.83 -- 1.03	-8.42	±15.00	0.9742	0.88 -- 1
E01811-01	#3	Cruise	61.61	0 -- 171.02	0.9943	0.83 -- 1.03	-10.68	±15.00	0.9422	0.88 -- 1
E01811-02	#3	Cruise	61.55	0 -- 171.02	0.995	0.83 -- 1.03	-11.09	±15.00	0.9424	0.88 -- 1
E01811-03	#3	Cruise	61.42	0 -- 171.02	0.9971	0.83 -- 1.03	-11.62	±15.00	0.9428	0.88 -- 1
E01812-01	#3	Creep	36.76	0 -- 171.02	0.7479	0.83 -- 1.03	-6.94	±15.00	0.7012	0.88 -- 1
E01812-02	#3	Creep	37.39	0 -- 171.02	0.7436	0.83 -- 1.03	-6.6	±15.00	0.6916	0.88 -- 1
E01812-03	#3	Creep	43.52	0 -- 171.02	0.6569	0.83 -- 1.03	-6.04	±15.00	0.5356	0.88 -- 1
E01815-02	#1	Transient	57.27	0 -- 171.02	0.9845	0.83 -- 1.03	-5.23	±15.00	0.9537	0.88 -- 1
E01815-03	#1	Transient	148.08	0 -- 171.02	0.8245	0.83 -- 1.03	-17.89	±15.00	0.6819	0.88 -- 1
E01815-04	#1	Transient	54.51	0 -- 171.02	0.9709	0.83 -- 1.03	-6.5	±15.00	0.9566	0.88 -- 1
E01816-01	#1	FTP	58.29	0 -- 171.02	1.008	0.83 -- 1.03	-3.73	±15.00	0.9698	0.88 -- 1
E01816-02	#1	FTP	59.67	0 -- 171.02	1.0125	0.83 -- 1.03	-3.34	±15.00	0.9685	0.88 -- 1
E01816-03	#1	FTP	59.13	0 -- 171.02	1.0132	0.83 -- 1.03	-3.81	±15.00	0.9693	0.88 -- 1

Note: These regression analyses excluded the points permitted in CFR 86.1341-90.

BHP

Run Number	Throttle Setting	Mode Tested	Standard Error		Slope of Regression		Y Intercept		Coefficient of Regression		Integrated BHP	
			Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion	Actual	EPA Criterion
E01565-03	#3	Transient	28.57	0 -- 28.33	0.8901	0.89 -- 1.03	8.04	±5.00	0.8909	0.91 -- 1	9.13	7.452 -- 9.205
E01566-02	#1	Transient	27.6	0 -- 28.33	0.9159	0.89 -- 1.03	8.7	±5.00	0.9004	0.91 -- 1	9.37	7.452 -- 9.205
E01566-01	#3	FTP	19.23	0 -- 28.33	0.9906	0.89 -- 1.03	1.66	±5.00	0.973	0.91 -- 1	25.006	21.33 -- 26.35
E01806-02	#1	Transient	27.68	0 -- 28.33	0.9703	0.89 -- 1.03	3.55	±5.00	0.9091	0.91 -- 1	9.82	7.55 -- 9.33
E01806-03	#3	FTP	26.39	0 -- 28.33	0.9995	0.89 -- 1.03	2.36	±5.00	0.9461	0.91 -- 1	25.75	21.33 -- 26.35
E01806-04	#3	Cruise	21.08	0 -- 28.33	1	0.89 -- 1.03	2.37	±5.00	0.9285	0.91 -- 1	57.88	46.96 -- 58.01
E01806-06	#3	Creep	14.26	0 -- 28.33	0.7476	0.89 -- 1.03	3.64	±5.00	0.6253	0.91 -- 1	1.95	1.51 -- 1.87
E01809-03	#3	Transient	29.24	0 -- 28.33	0.9593	0.89 -- 1.03	-13.02	±5.00	0.9062	0.91 -- 1	7.24	6.69 -- 8.27
E01809-04	#3	Transient	29.05	0 -- 28.33	0.9564	0.89 -- 1.03	-12.78	±5.00	0.9068	0.91 -- 1	7.24	6.69 -- 8.27
E01809-05	#3	Transient	29.23	0 -- 28.33	0.9576	0.89 -- 1.03	-12.9	±5.00	0.906	0.91 -- 1	7.22	6.69 -- 8.27
E01810-01	#3	HHDDTS	17.3	0 -- 28.33	0.9856	0.89 -- 1.03	-1.74	±5.00	0.9657	0.91 -- 1	30.01	25.69 -- 31.74
E01810-02	#3	HHDDTS	17.38	0 -- 28.33	0.9852	0.89 -- 1.03	-1.66	±5.00	0.9654	0.91 -- 1	30	25.69 -- 31.74
E01810-03	#3	HHDDTS	17.15	0 -- 28.33	0.9868	0.89 -- 1.03	-2.1	±5.00	0.9664	0.91 -- 1	30.01	25.69 -- 31.74
E01811-01	#3	Cruise	21.71	0 -- 28.33	0.9966	0.89 -- 1.03	-3.84	±5.00	0.9224	0.91 -- 1	54.86	46.30 -- 57.19
E01811-02	#3	Cruise	21.71	0 -- 28.33	0.9984	0.89 -- 1.03	-4.15	±5.00	0.9228	0.91 -- 1	54.85	46.30 -- 57.19
E01811-03	#3	Cruise	21.67	0 -- 28.33	0.9999	0.89 -- 1.03	-4.25	±5.00	0.9232	0.91 -- 1	54.86	46.30 -- 57.19
E01812-01	#3	Creep	15.14	0 -- 28.33	0.747	0.89 -- 1.03	-4.9	±5.00	0.6233	0.91 -- 1	1.139	1.29 -- 1.60
E01812-02	#3	Creep	15.37	0 -- 28.33	0.7474	0.89 -- 1.03	-5.12	±5.00	0.6165	0.91 -- 1	1.139	1.29 -- 1.60
E01812-03	#3	Creep	19.83	0 -- 28.33	0.6028	0.89 -- 1.03	-3.99	±5.00	0.3672	0.91 -- 1	1.005	1.29 -- 1.60
E01815-02	#1	Transient	21.37	0 -- 28.33	0.9589	0.89 -- 1.03	-0.39	±5.00	0.9453	0.91 -- 1	7.99	6.69 -- 8.27
E01815-03	#1	Transient	59.44	0 -- 28.33	0.823	0.89 -- 1.03	-8.58	±5.00	0.6206	0.91 -- 1	7.98	6.69 -- 8.27
E01815-04	#1	Transient	20.85	0 -- 28.33	0.9488	0.89 -- 1.03	-1.31	±5.00	0.9467	0.91 -- 1	7.97	6.69 -- 8.27
E01816-01	#1	FTP	19.98	0 -- 28.33	0.993	0.89 -- 1.03	0.91	±5.00	0.9677	0.91 -- 1	25.44	21.48 -- 26.54
E01816-02	#1	FTP	19.24	0 -- 28.33	0.9957	0.89 -- 1.03	1.43	±5.00	0.9701	0.91 -- 1	25.43	21.48 -- 26.54
E01816-03	#1	FTP	19.05	0 -- 28.33	0.9962	0.89 -- 1.03	1.33	±5.00	0.9707	0.91 -- 1	25.44	21.48 -- 26.54

Note: These regression analyses excluded the points permitted in CFR 86.1341-90.