ORNL/TM-2016/312

Powertrain Test Procedure Development for EPA GHG Certification of Medium- and Heavy-Duty Engines and Vehicles

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July 2016

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2016/312

Energy & Transportation Science Division

POWERTRAIN TEST PROCEDURE DEVELOPMENT FOR EPA GHG CERTIFICATION OF MEDIUM- AND HEAVY-DUTY ENGINES AND VEHICLES

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Date Published: July 2016

Prepared by
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Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACRONYMS

AMT	automated manual transmission
ARB	Air Resources Board
BSFC	brake-specific fuel consumption
CAN	controller area network
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CILCC	combined international local and commuter cycle
COV	coefficient of variation
DOE	U.S. Department of Energy
ECM	engine controller module
ECU	electronic control unit
EPA	US Environmental Protection Agency
GEM	Greenhouse Gas Emissions Model
GHG	greenhouse gas
GVW	gross vehicle weight
HD	heavy duty
HIL	hardware-in-the-loop
HTUF6	Hybrid Truck Users Forum Class 6
N/V	engine speed over vehicle speed ratio
NMHC	non-methane hydrocarbon
NREL	National Renewable Energy Laboratory
NTRC	National Transportation Research Center
ORNL	Oak Ridge National Laboratory
QAPP	Quality Assurance Project Plan
SwRI	Southwest Research Institute
TCM	transmission controller model
THC	total hydrocarbon emissions
USP	Ultra Shift Plus (Eaton Transmission commercial name)
VSI	Vehicle System Integration
WHVC	World Harmonized Vehicle Cycle

ABSTRACT

The goal of this project is to develop and evaluate powertrain test procedures that can accurately simulate real-world operating conditions, and to determine greenhouse gas (GHG) emissions of advanced medium- and heavy-duty engine and vehicle technologies.

ORNL used their Vehicle System Integration Laboratory to evaluate test procedures on a stand-alone engine as well as two powertrains. Those components where subjected to various drive cycles and vehicle conditions to evaluate the validity of the results over a broad range of test conditions. Overall, more than 1000 tests were performed. The data are compiled and analyzed in this report.

1. STATEMENT OF OBJECTIVES

1.1 TASK 1: REFINE POTENTIAL POWERTRAIN CERTIFICATION TEST PROCEDURES USING ORNL HEAVY-DUTY POWERTRAIN ANALYTICAL PHASE

1.1.1 Select Specific Engine/Transmission Hardware and Configure Using Powertrain Test System

At the direction of the US Environmental Protection Agency (EPA), the sponsor of this research, Oak Ridge National Laboratory (ORNL) will determine the best vehicle powertrain system(s) to evaluate during this project. ORNL will use a Class 8 heavy-duty (HD) truck equipped with a Cummins ISX series 450 hp–rated engine and an Eaton automated manual transmission (AMT) for extensive analysis based upon current data obtained through well-controlled chassis dynamometer tests and a real-world driving route test. ORNL will use this bank of data provided by the EPA as a benchmarking tool to produce direct comparisons of engine and transmission hardware and calibrations.

1.1.2 Refine and Validate Hardware-in-The-Loop Software to Simulate Vehicle Operation

ORNL will adapt the vehicle and driver model in order to simulate vehicle operation using the EPA's powertrain test system. As a baseline, the EPA will first provide its own vehicle and driver model to ORNL, derived certification tool – Greenhouse Gas Emissions Model (GEM), which has been implemented into other powertrain systems and validated against a medium-duty powertrain system without any known or identified issue. ORNL will modify the model in order to allow communication with the powertrain test system.

The vehicle model that will be implemented into the powertrain test cell will be validated using the transient Air Resources Board (ARB) cycle, ensuring that the powertrain system can follow the speed trace in compliance with the requirements of 40 CFR 1066.430(e).

1.1.3 Test Specific HD Class 8 Vehicle Configurations

Previous tests resulted in vehicle parameters of the specific HD class 8 vehicle (described in Subtask 1.1.1) that has been chassis-tested as well as the variations of vehicle parameters that will be used to simulate operation of multiple vehicles over a number of drive cycles. This will allow for the direct comparison of powertrain-in-the-loop results with chassis dynamometer results.

1.1.4 Evaluate Potential Test Procedures for Advanced HD Powertrain Technologies

Utilizing the same drive cycles described in Subtask 1.1.3, procedures for testing advanced powertrain systems for HD applications will be evaluated. The attention must be focused on measurement of greenhouse gas (GHG) emissions and criteria emissions. The proposed powertrain test procedures (determined jointly by ORNL and EPA) will be evaluated to determine if they are comprehensive enough to simulate real-world operation of advanced HD powertrain systems. Tests will also be done simulating multiple vehicle configurations and drive cycles to generate performance data on several simulated vehicles and duty cycles.

1.1.4.1 Automatic transmission with Cummins ISX 450

Using twelve vehicle configurations as defined by EPA, a powertrain with a Cummins ISX and Allison TC10 will be tested throughout cycles: ARB transient at 55 mph and at 65 mph with road grade. Each pair of cycle and vehicle configurations will be repeated at least three times. If the output of coefficient of variation (COV) for carbon dioxide (CO_2) emissions per mile is greater than 0.5%, the test configuration will be repeated a total of five times.

1.1.4.2 Automatic transmission with Cummins ISX 400

The ISX engine controller will be replaced with a new unit programmed with a 400 hp calibration (referred to as ISX 400). ORNL will test a Cummins ISX 400 engine and Allison TC10 transmission.

Using twelve vehicle configurations as defined by EPA, the powertrain will be tested on the following cycles: ARB transient, at 55 mph and at 65 mph with road grade. Each pair of cycle and vehicle configurations will be repeated at least three times. If the COV for CO_2 emissions per mile is greater than 0.5%, the test configuration will be repeated a total of five times.

1.1.5 Evaluate Potential Test Procedures for Advanced HD Engines

1.1.5.1 Engine-Mapping Procedure

Procedures for testing advanced engine systems for HD applications will be evaluated. The tests will include evaluating engine-mapping procedures, engine-in-the-loop, and cold/hot start transient cycles. The repeats of the two engine-mapping tests should bookend the engine-only testing.

1.1.5.2 Alternate engine-mapping procedure

Following 40 CFR 1065, testing will be conducted on the Cummins ISX engine to evaluate an alternate engine-mapping procedure. The test procedure will use cycle average results instead of a steady-state fuel map to represent the engine in simulation. Cycles will be as follows: GEM engine cycles for ARB transient, 55 mph, and 65 mph with grade. For each drive cycle, a total of twelve vehicle configurations will be simulated. Each drive cycle and vehicle combination will be repeated three times unless the COV CO_2 emissions per mile is greater than 0.5%, in which case it will be repeated a total of five times.

1.1.5.3 Alternate engine-mapping procedure (ISX 400 engine)

In support of the HD GHG rule development, EPA would like to evaluate an alternate engine-mapping test procedure. The test procedure leverages cycle-average results instead of a steady-state fuel map to represent engine fuel consumption in computer simulations. ORNL will test the Cummins ISX engine to evaluate this procedure. The testing will consist of testing the engine at different ratings and with different simulated transmissions. The testing will comport with EPA's test engine certification test procedures in 40 CFR Part 1065.

Cycles will be generated using GEM to create engine brake torque and engine shaft speed profiles that correspond to the following vehicle cycles: ARB transient, 55 mph, and 65 mph with road grade. For each drive cycle, the engine will be tested with a total of twelve different GEM-simulated vehicle configurations. Each drive cycle and vehicle combination will be repeated three times unless the COV for CO_2 emissions per mile is greater than 0.5 percent, in which case it will be repeated a total of five times.

For this task, the ISX engine controller will be replaced with a new unit flashed with a 400 hp calibration.

1.1.6 Evaluate Advanced HD Engine and Powertrain Technologies

Contingent upon available funds and performance on previous tasks, this task will be activated to evaluate advanced HD engines and powertrain technologies, and the test procedures required to quantify their performance. These advanced technologies may include but are not limited to natural gas or other alternative fuel engines, hybrid powertrains, and waste-heat recovery systems. These technologies will be evaluated with respect to their GHG (e.g., CO_2, N_2O, and CH_4) and criteria (e.g., NO_x and particulate matter) emission rates. The details of this task will be specified by the EPA.

1.1.7 Road Grade Cycles

In the development of the next phase of the HD GHG rule, tests for up to eight road grade cycles will be applied to cruise cycles using three different powertrains and three different vehicle configurations. Test configurations will be repeated a minimum of three times each. If the output of COV for CO_2 emissions per mile is greater than 0.5%, the test configuration will be repeated a total of five times.

1.2 TASK 2: TEST PROCEDURE AND DATA ANALYSIS OF ENGINE, POWERTRAIN AND CHASSIS DYNAMOMETER TESTING

1.2.1 Data Analysis for Alternate Engine-Mapping Procedure

In support of the HD GHG rule development, EPA would like to evaluate an alternate engine-mapping test procedure, which utilizes cycle-average values as map points, rather than steady-state engine operation points. ORNL will analyze data collected in Subtasks 1.1.5.2 and 1.1.5.3 in order to specify the exact configurations of the 12 different GEM-simulated vehicles to minimize interpolation error between the 12 configurations.

ORNL will also investigate numerical schemes that minimize interpolation and extrapolation error and will compare alternative numerical schemes to the numerical scheme EPA describes in the HD Phase 2 Notice of Proposed Rulemaking.

1.2.2 Data Analysis for Powertrain Test Procedure

In support of the HD GHG rule development, EPA would like to assess the proposed powertrain test procedure definitions of the different generic vehicles. ORNL will analyze how effectively the proposed vehicle definitions represent a large number of other vehicle configurations in which the same powertrain could be installed. ORNL will investigate numerical schemes that minimize the interpolation and extrapolation error of the powertrain test procedure.

1.2.3 Data Analysis for Combined Steady-State Map and Alternate Engine-Mapping Procedure (i.e., "Hybrid Approach")

In support of the HD GHG rule development, EPA would like to evaluate a "hybrid approach" to engine fuel mapping that would include the alternate (i.e., cycle average) engine-mapping test procedure for the ARB transient cycle and a more sparsely populated steady-state fuel map with less than 143 points for the 55 mph and 65 mph vehicle cycles. ORNL will investigate what would be the minimum number of steady-state fuel mapping points that would be needed for simulating vehicles on the proposed 55 mph and 65 mph cycles with road grade.

ORNL will use GEM to simulate a minimum of 10 vehicles to investigate how grams of CO_2 per mile changes when the 143-point fuel map generated according to 40 CFR1036.535 is used vs. a more sparsely populated test point fuel map. The study will look into using fewer points (80 to 100), and it will characterize points that are most needed for CO_2 evaluation and the ones that can be eliminated without significant loss in model fidelity.

ORNL will consult EPA to determine which vehicles that will be simulated in GEM.

2. TECHNICAL DISCUSSION

2.1 TASK 1: REFINE POTENTIAL POWERTRAIN CERTIFICATION TEST PROCEDURES USING ORNL HD POWERTRAIN

2.1.1 Select Specific Engine/Transmission Hardware and Configure Using Powertrain Test System

2.1.1.1 Southwest Research Institute chassis rolls results

EPA contracted the Southwest Research Institute (SwRI) to test a Kenworth T700 equipped with a Cummins ISX series 450 hp (referred to as ISX450)rated engine and an Eaton AMT on its chassis rolls facilities.

Test data for five drive cycles were made available to compare with powertrain-in-the-loop results:

- World Harmonized Vehicle Cycle (WHVC),
- Combined International Local and Commuter Cycle (CILCC),
- California Air Resources Board (CARB) Transient,
- 55 mph cruise and
- 65 mph cruise).

Fuel consumption was calculated from carbon balance of dilution tunnel emissions measurements as well as modal data from a fuel flowmeter (as well as J1939 fuel estimation). Results are shown in Figure 1.

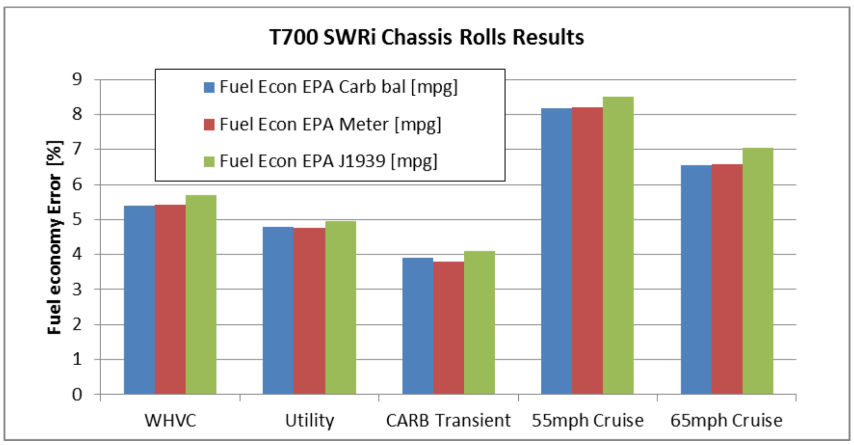


Figure 1. Southwest Research Institute chassis rolls fuel economy results of Kenworth T700.

2.1.1.2 Chassis rolls vs. powertrain-in-the-loop comparison

Chassis rolls results were compared with available powertrain-in-the-loop results conducted on the Vehicle System Integration (VSI) Laboratory test cell in 2013. The Kenworth T700 vehicle model was run on a real-time hardware in the loop computer while the T700 powertrain (Cummins ISX15 450 hp engine and an Eaton UltraShift AMT) was running on the ORNL test cell. The vehicle model was based on an unnumbered version of GEM provided on June 19, 2013, and used the following vehicle parameters:

- axle ratio: 3.36:1;
- tire_radius: 0.5 m;

- axle_eff: 1;
- veh_mass: 33130 kg
- rolling_coeff: 0.00584
- Discharge coefficient: 0.7149
- Frontal area: 9.6m^2

Because these powertrain-in-the-loop tests were conducted prior to the start of the project and the implementation of the Quality Assurance Project Plan , each cycle was only conducted once, and no repeatability data are available. However, the available results show a good correlation between chassis rolls results and powertrain-in-the-loop results, as shown in Figure 2. The ARB cycle exhibits a larger discrepancy (almost 5%), which is explained by the light load of this cycle causing the engine to not consistently exceed the 100°C oil temperature threshold above which all warm-up strategies are disabled and it operates at peak efficiency.

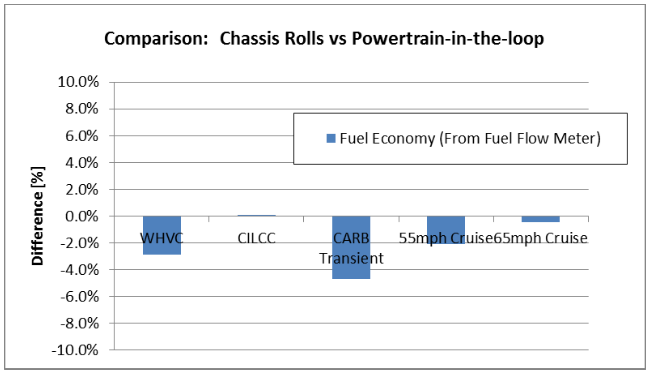


Figure 2. Comparison of chassis rolls fuel economy vs. Powertrain-in-the-loop fuel economy.

2.1.2 Refine and Validate Hardware-In-The-Loop Software to Simulate Vehicle Operation

2.1.2.1 Vehicle System Integration Laboratory

In 2013, ORNL commissioned its Vehicle Systems Integration (VSI) Laboratory, located at the National Transportation Research Center (NTRC), in Knoxville, Tennessee. The research facility was designed to investigate the complex interactions of advanced powertrain technologies by performing prototype component-level research and characterization, as well as complete powertrain integration research and development, targeting system efficiency optimization and emissions reductions. The VSI Laboratory can accommodate engines, electric motors, transmissions, and complete conventional or hybrid powertrains for most application sizes up to class 8 trucks.

The VSI Laboratory consists of two test cells: the Powertrain Test Cell, capable of testing light-duty to full heavy-duty Class 8 powertrains, and the Component Test Cell, capable of testing engines, electric machines, and energy storage systems (Figure 3).

This project will be using the Powertrain Test Cell. It is equipped with

- two 500kW AC transient dynamometers and a combining gearbox capable of up to 20000 Nm of torque;
- one 400kW, 800V, 600A battery emulator, which enables hybrid powertrain testing with fewer constraints than with real batteries;

- one hardware-in-the-loop system running real-time models of virtual vehicles; and
- two five-gas analyzers for full engine-out and tailpipe emissions characterization.

Figure 3. The Powertrain test cell and component test cell in ORNL's Vehicle System Integration Laboratory.

2.1.2.2 Hardware-in-the-loop environment

The VSI powertrain test cell is capable of emulating a virtual vehicle environment in order to assess the behavior the powertrain from a vehicle perspective. This is achieved thanks to a hardware-in-the-loop (HIL) platform that runs real time models of the components that are not physically present inside the test cell. In the case of a powertrain, the engine and transmission are installed in the test cell and are connected to the dynamometers; the HIL system emulates the driveline, axle, wheels, vehicle, trailer, driver and road environment. These modeled components calculate the load and speed that the engine and transmission would experience in the vehicle, and the dynamometers apply those conditions. This way, the powertrain can be subjected to real-world conditions that can easily be changed by modifying the vehicle model, and the conditions can be easily be repeated thanks to the controlled test cell environment. The HIL principle is shown in Figure 4.

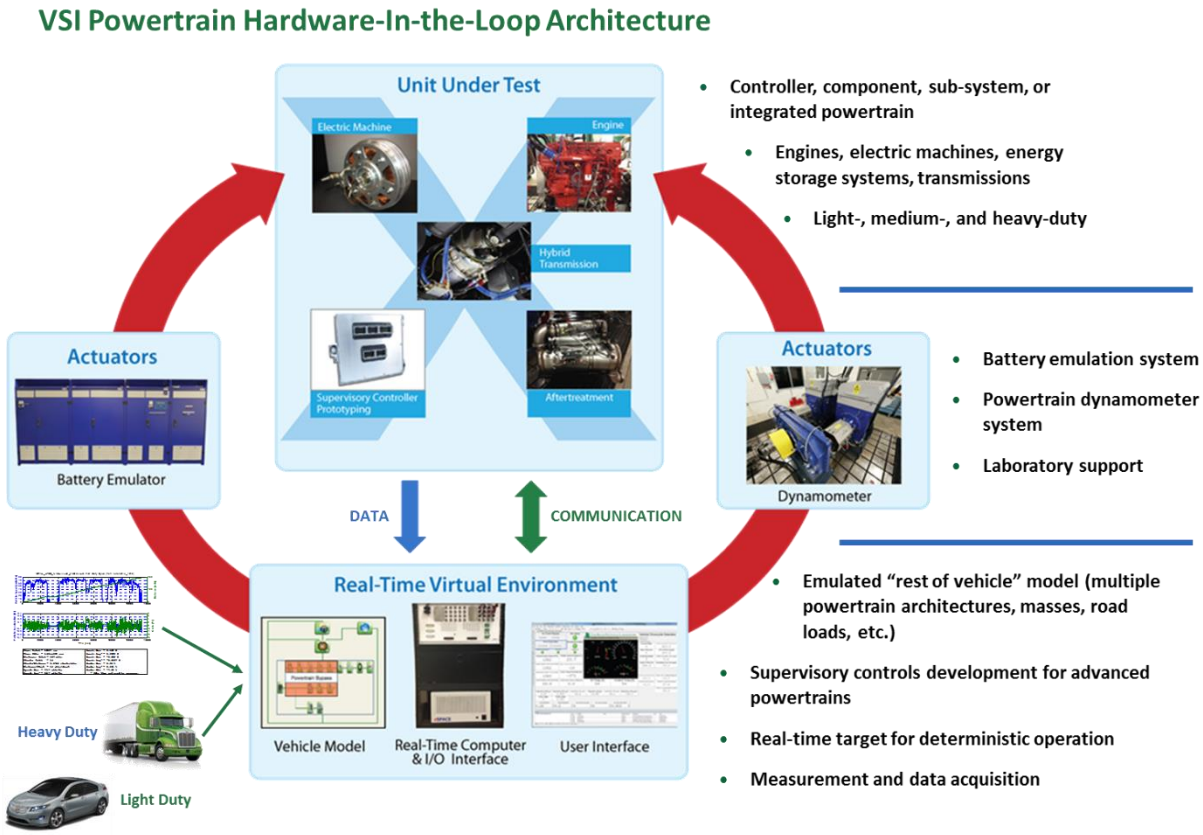


Figure 4. Representation of the hardware-in-the-loop concept implemented in ORNL's Vehicle System Integration Laboratory to test powertrains in real-world conditions without a vehicle.

2.1.2.3 Vehicle model selection

2.1.2.3.1 Vehicle equations

EPA provided an early version of GEM (release 2.0.5) as well as the vehicle model equations released in 40 CFR 1037.550 (referred to as "1037.550").

1037.550 equations were implemented in Simulink and were validated against the GEM model on several cycles [ARB, 55 mph and 65 mph cruise, Hybrid Truck Users Forum Class 6 (HTUF6), CILCC, and WHVC]. The main difference between the two models is the accounting of the powertrain inertia, which is lumped into one constant parameter in the 1037.550 equations whereas the GEM model continuously calculates engine and transmission inertias, which will vary based on transmission ratios.

Overall, the two models generate vary similar results. Figure 5 demonstrates the match between the two models on an ARB cycle. For all powertrain tests, the hardware in the loop system will be running the 1037.550 equation model.

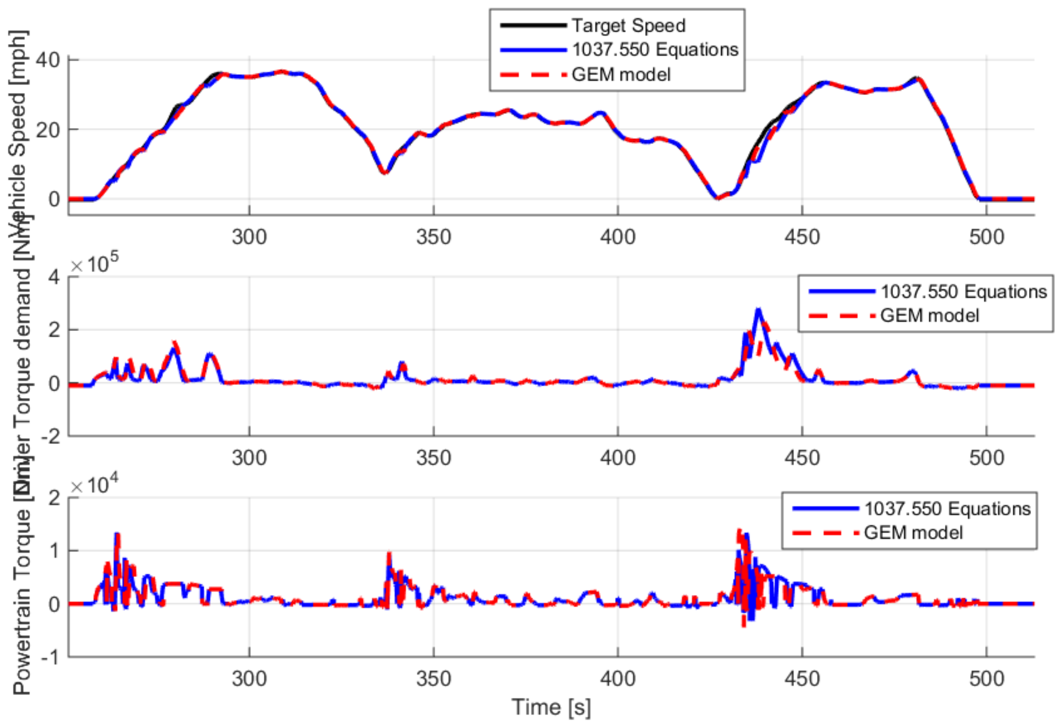


Figure 5. Comparison of GEM model simulation results with 1037.550 equations results on the ARB cycle.

Figure 6 quantifies the average error between transmission output speed and torque estimated by the GEM model or the 1037.550 equation model for various cycles.

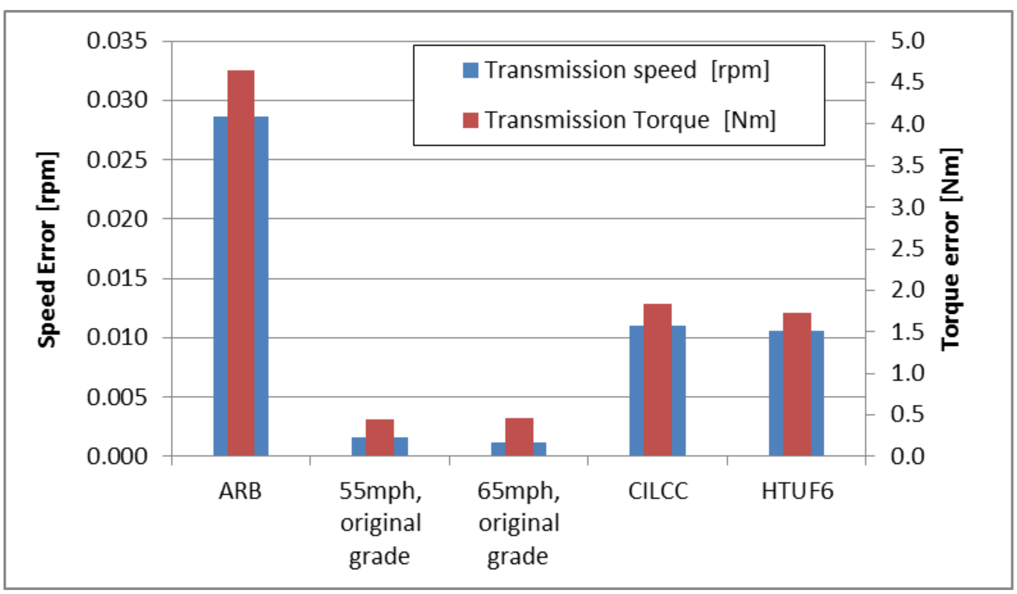


Figure 6. Average error between GEM and 1037.550 model for transmission speed and torque.

2.1.2.3.2 Driver model

The 1037.550 model uses a variant of the GEM driver model. It has been modified to add a gain-scheduling feature on the proportional gain. This renders the driver less active when vehicle speed is within half a mile per hour of the set point. This was implemented to remove some excessive activity by the driver during the cruise section of the WHVC as shown on Figure 7, which causes fast transients on the engine and unnecessary gear shifts on the transmission. Figure 8 and Figure 9, respectively, show the original GEM driver implementation and its variant with gain scheduling.

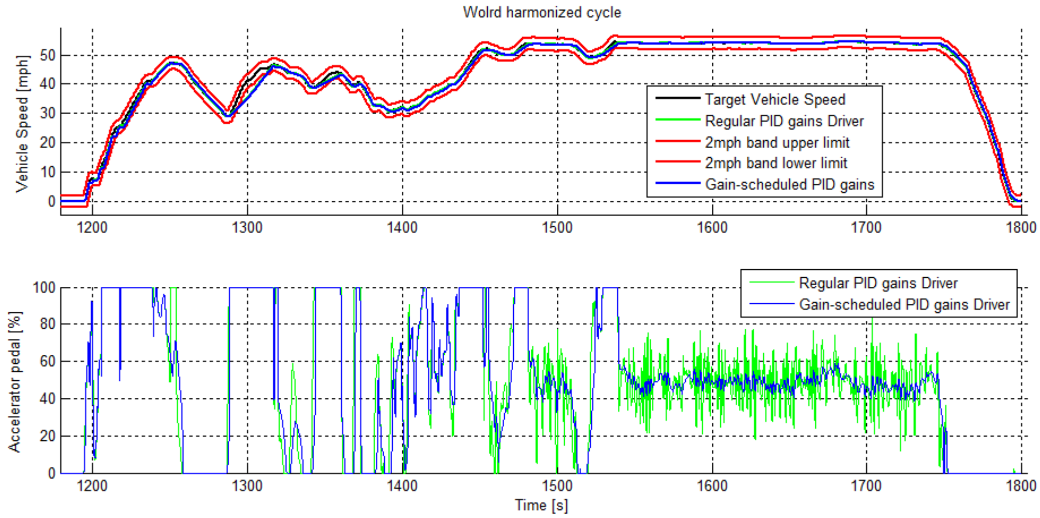


Figure 7. Effect of gain scheduling to reduce driver over activity during cruise conditions on the WHVC.

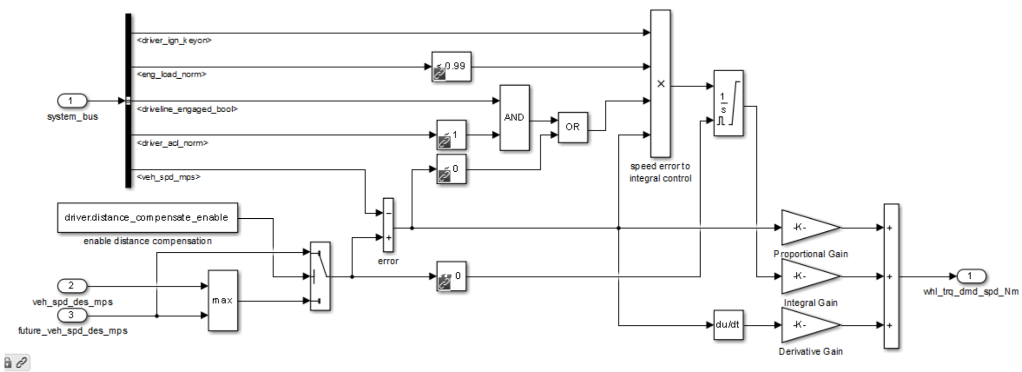


Figure 8. Original GEM driver (release 2.0.5).

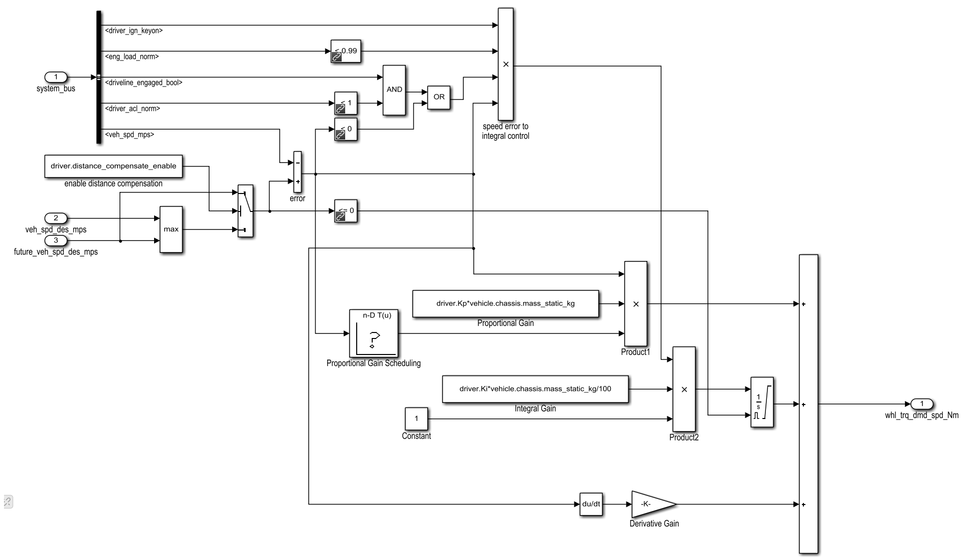


Figure 9. Modified GEM driver with gain scheduler on proportional term.

2.1.2.3.3 Hardware-in-the-loop implementation

The vehicle model was modified to provide an interface between the virtual vehicle model and the powertrain (or engine) under test on the test cell. This allows the model to use test cell measurements to update its status and calculate new set points for the powertrain (or engine) to operate next.

The overall GEM structure is unchanged, as shown in Figure 10.

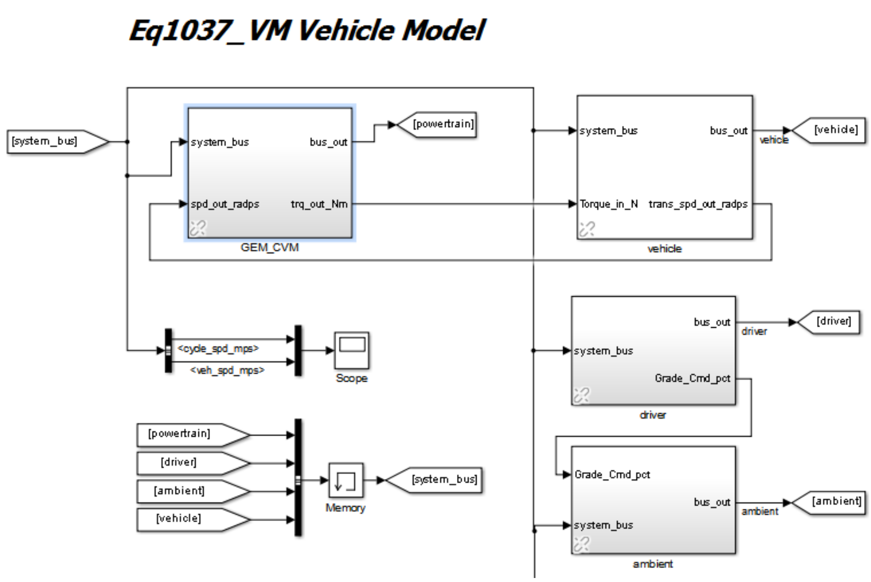


Figure 10. Overall Gem model structure.

The GEM "Powertrain" block is replaced. Instead of containing a model of the engine and transmission, it contains communication blocks to interface with the test cell and powertrain (Figure 11).

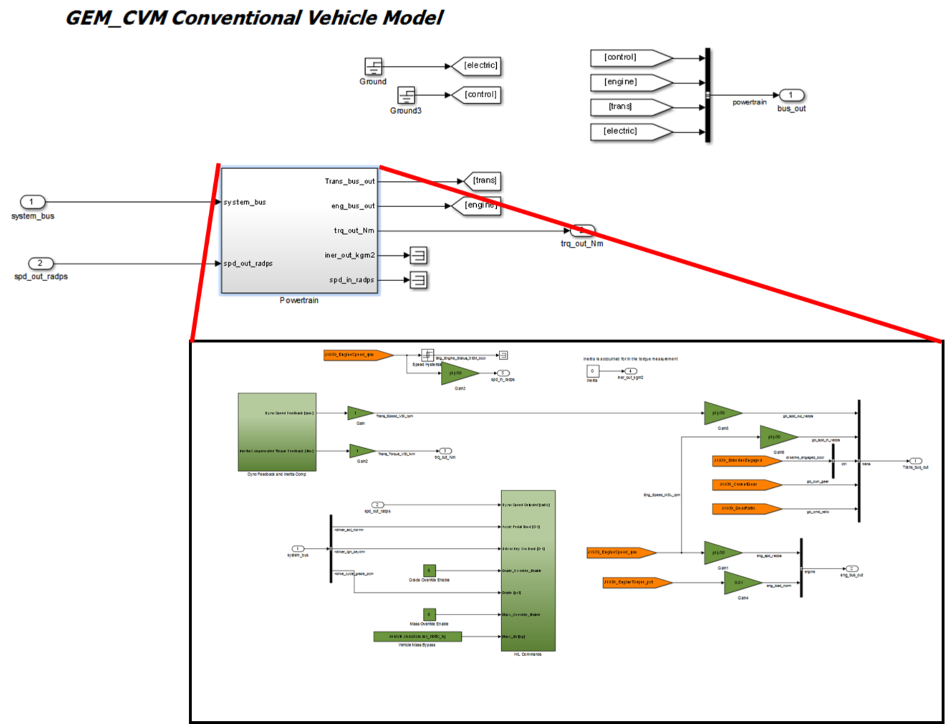


Figure 11. Powertrain interface block.

The interface to the test cell and dynamometers was handled over a controller area network (CAN). The torque command is communicated to the engine by emulating the pedal position sensor. For that purpose, the engine pedal command had to be characterized. It replaces a linear conversion between pedal position and torque command that is assumed by the base model. Figure 12 shows the conversion table for the ISX 450 engine.

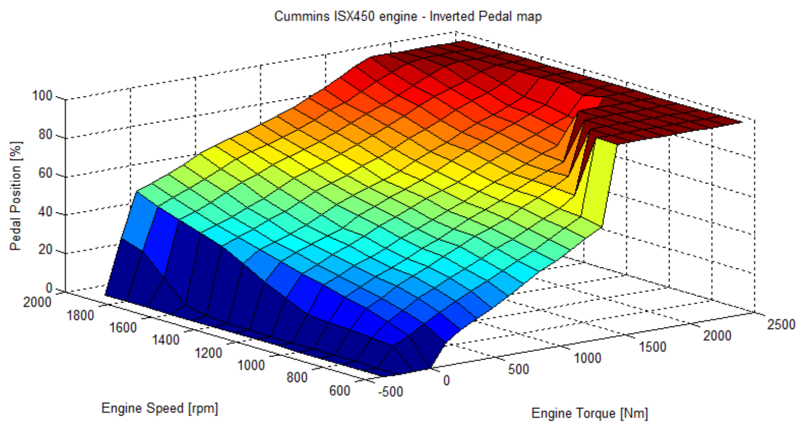


Figure 12. ISX 450 pedal conversion table.

2.1.3 Test Specific HD Class 8 Vehicle Configurations: Cummins ISX 450 and Eaton UltraShift Automated Manual Transmission

2.1.3.1 Powertrain commissioning in VSI Laboratory

As explained in section 2.1.1, the first powertrain to be tested is a 15l Cummins ISX 450 and an Eaton Ultra Shift Plus AMT.

- Engine Specifications:
  - Model: ISX15 450
  - Date of manufacture: 3/12
  - Number: 79567263
  - Engine Controller Module (ECM):
    - Name: CM2250
    - Part number:4993120
    - Serial number: 77792
    - Code: CL10135.30
- Transmission Specifications:
  - Name: Eaton UltraShift Plus 10-speed Automated Manual Transmission
  - Model: FO-16E310C-LAS
  - Part Number: TA-J06-12X
  - Serial Number: K0975129
  - transmission controller module (TCM):
    - Serial Number: ETE0076863
    - Hardware version: 4306473
    - Software version: 5569906
    - Code: 13029

The engine is using a "dyno cal," meaning that some parameters are modified compared to a production calibration to disable some vehicle-level features or sensors such as the water in fuel sensor and the coolant level sensor, such that the engine operates normally (as if it were in a vehicle) when coupled to a dynamometer in a test cell. (Modifications were performed by a Cummins Crosspoint engineer.)

The transmission controller module (TCM) calibration and code had to be slightly modified from their production versions to offer two bypasses:

- One bypass is for the grade sensor measurement. The TCM has a built-in accelerometer that is used to infer grade. When installed in the VSI Laboratory, the TCM is stationary, and therefore grades are not reliable, hence the need to bypass them.
- Vehicle mass estimation is also bypassed to prevent any transient effect as the TCM tries to evaluate the vehicle at each key cycle.

(Modifications were performed by an Eaton engineer.)

The effect of those two bypasses is small when looking at transmission work (0.14% for grade and 0.37% for mass) (see Figure 13), but they do cause the transmission to shift differently in some conditions. (See Figure 14 and Figure 15).

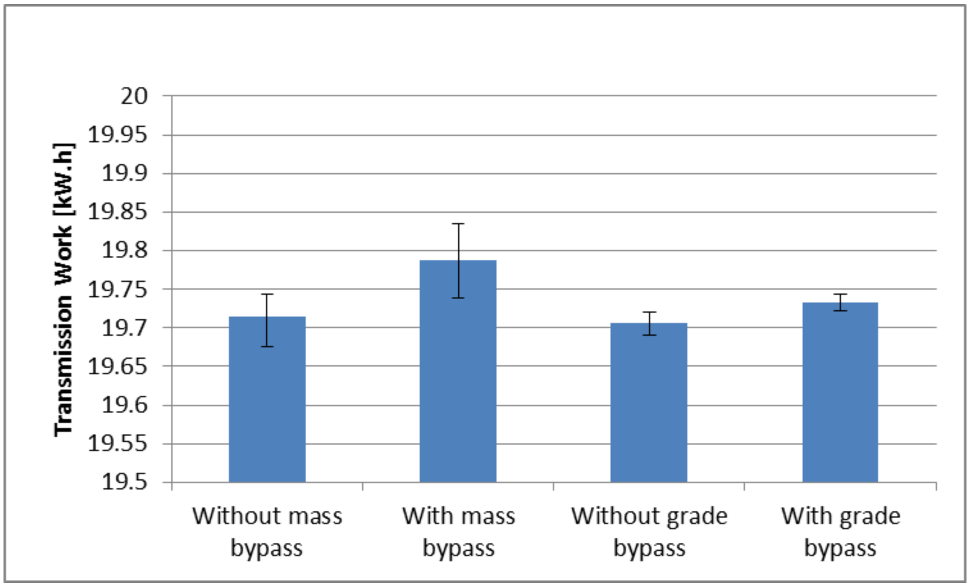


Figure 13. Effect of grade and mass bypass on transmission work.

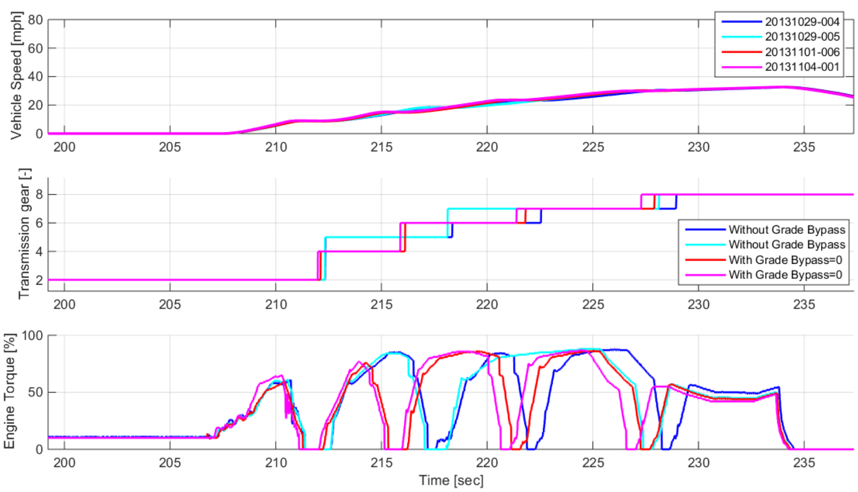


Figure 14. Effect of grade bypass on AMT shift strategies during ARB cycle.

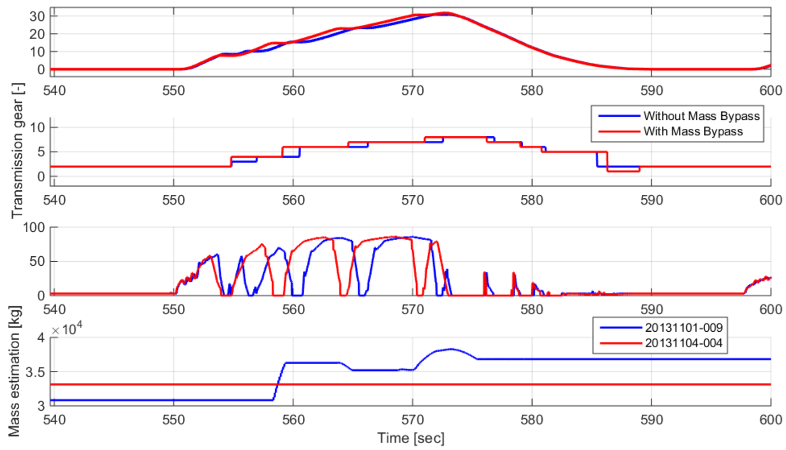


Figure 15. Effect of mass bypass on AMT shift strategies during ARB cycle.

With the help of Cummins and Eaton, the powertrain was successfully commissioned in the VSI Laboratory (Figure 16).

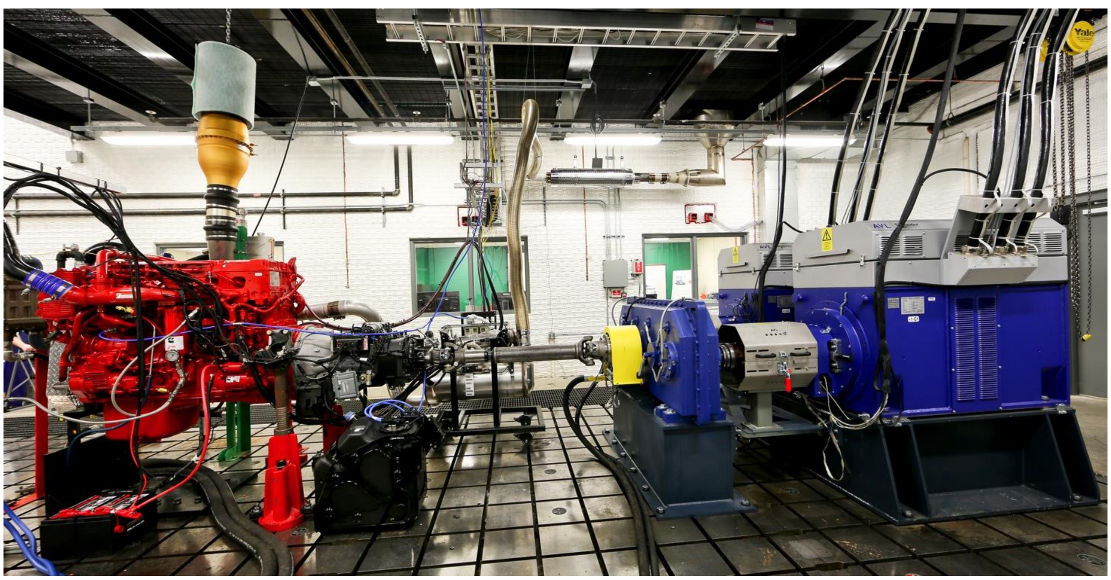


Figure 16. ISX450 engine and UltraShift Plus AMT under test in the Powertrain test cell of ORNL's VSI Laboratory.

For these tests, the VSI Laboratory was operated in powertrain-in-the-loop mode with the "1037.550-equation" model, where the driver model tries to keep up with the vehicle speed profile specified in the drive cycle. The driver model generates accelerator pedal and brake pedal commands. The accelerator command is converted into a pedal signal that the ECM ECU understands. The engine generates torque according to that demand, and the transmission selects the best gear for the current conditions. The resulting powertrain torque is absorbed and measured by the dynamometer and is fed to the real-time vehicle model to calculate the corresponding vehicle speed. The driver model will react to this new vehicle speed with a new accelerator pedal command and will reiterate this process every 10 ms.

The process is represented in the diagram shown in Figure 17. It helps visualizing how the powertrain under test and model are interconnected and interdependent. They react to each other's behavior, hence the "powertrain in the loop "denomination.

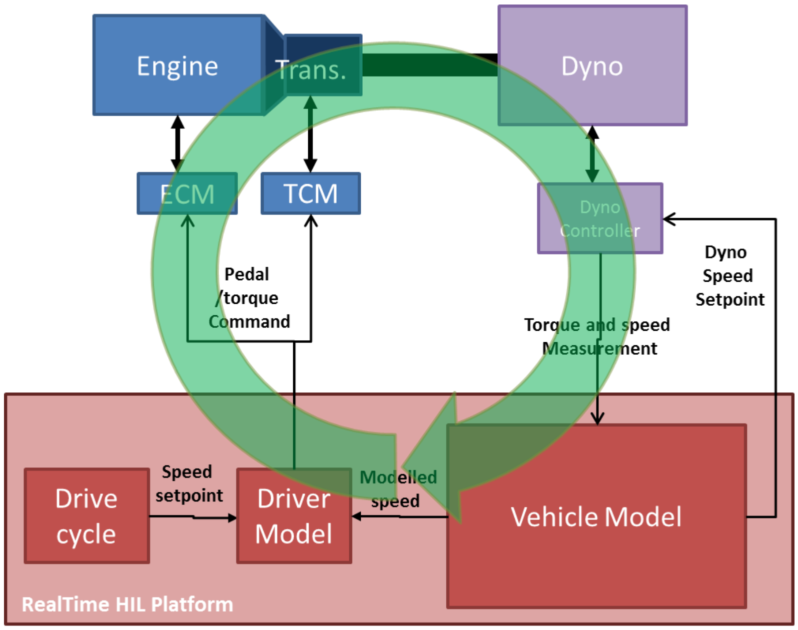


Figure 17. Powertrain-in-the-loop diagram.

2.1.3.2 Powertrain test plan

The tests summarized in Table 1were conducted using the ISX15 450 + Ultra Shift Plus (USP) 10-speed AMT powertrain .

Table 1. Powertrain tests

Simulated Vehicles	Cycle
T700 and Veh 13 to 30	ARB Transient 55 mph - grade profile D 65 mph - grade profile D NREL Vocational Cycle
T700	HTUF6 CILCC
T700 and T700 generic	cold WHVC w/load hot WHVC w/load
Veh 13, 17, 28	All Grade Cycles and original grade profile
Veh 13, 17, 21, 14, 19, 23	WHVC

The vehicles are described in Table 2.

Table 2. Powertrain vehicles descriptions

	M (kg)	C_DA	*Crr* (g/kg)	$M_{rotating}$ (kg)	*r* (m)	Rear Axle Ratio	Axle Eff. (%)
T700	33,130	7.04	5.84	1,134			95.5
T700 generic		Rated power		811	0.493		95.0
Veh 13	31,978	5.4		1,134		3.36	
Veh 14	22,679	4.7		907			
Veh 15	19,051	4		680			
Veh 16	40,895	6.1		1,134			
Veh 17	31,978	5.4		1,134		2.81	
Veh 18	22,679	4.7		907			
Veh 19	19,051	4		680			
Veh 20	40,895	6.1		1,134			
Veh 21	31,978	5.4		1,134			
Veh 22	22,679	4.7	6.9	907	0.5	3.82	95.5
Veh 23	19,051	4		680			
Veh 24	31,978	5.4		1,134			
Veh 25	22,679	4.7		907		4.32	
Veh 26	19,051	4		680			
Veh 27	40,895	6.1		1,134			
Veh 28	31,978	5.4		1,134		4.65	
Veh 29	22,679	4.7		907			
Veh 30	19,051	4		680			

Additional powertrain tests were conducted with a 400 hp calibration in the engine controller (Table 3).

Table 3. Additional Powertrain Tests

Simulated Vehicles	Cycle
Veh 13 & 23	WHVC
	ARB
Veh 13, 17, 28, 14, 19, 30	55 mph - grade profile D
	65 mph - grade profile D

All tests procedures were specified in the *Quality Assurance Project Plan* (EPA_GHG2_QAPP_draft10.docx).

2.1.3.3 Powertrain test results

CO, CO_2, NO_x, total hydrocarbon emission (THC), nonmethane hydrocarbon (NMHC) and CH_4 emission in grams per mile and in grams per kilowatt-hour were calculated according to 40 CFR 1066 and 1065, respectively. Fuel consumption from carbon emission and direct fuel measurement in miles per gallon were calculated according to 40 CFR 1066.

Results for the 450 hp ISX450 engine and Eaton USP transmission were compiled in a summary Excel document docketed with this report:
ORNL PIL Summary_USP_ISX 450_V4_10Hz_Master_DD.xlsx.

Results for the 400 hp ISX15 engine and Eaton UltraShift transmission were compiled in a summary Excel document docketed with this report:

ORNL PIL Summary_USP_ISX 400_V3_10Hz_Master_DD.xlsx.

2.1.4 Evaluate Potential Test Procedures for Advanced HD Powertrain Technologies

2.1.4.1 Automatic transmission with Cummins ISX 450

2.1.4.1.1 Automatic transmission with Cummins ISX 450 Commissioning in VSI Laboratory

The same Cummins ISX15 450 engine was commissioned in the VSI lab. For this new series of tests, it is now coupled with a 10-speed automatic transmission from Allison Transmission: the TC10 model (see Figure 18).

- Engine Specifications:
  - Model: ISX15 450
  - Date of manufacture: 3/12
  - Number: 79567263
  - ECM:
    - Name: CM2250
    - Part number:4993120
    - Serial number: 77792
    - Code: CL10135.30
- Transmission Specifications:
  - Name: Allison TC10 10-speed Automatic Transmission
  - Model: TC10
  - Part Number: 29554787
  - Serial Number: 0001305
  - TCM:
    - Part number: 29550693
    - Serial Number: BK0693A540420042
    - Software version: T15BCD_PC_5J69

No modification was made to the TCM code and calibration. The VSI Laboratory was operated in powertrain-in-the-loop mode with the 1037-equation model.

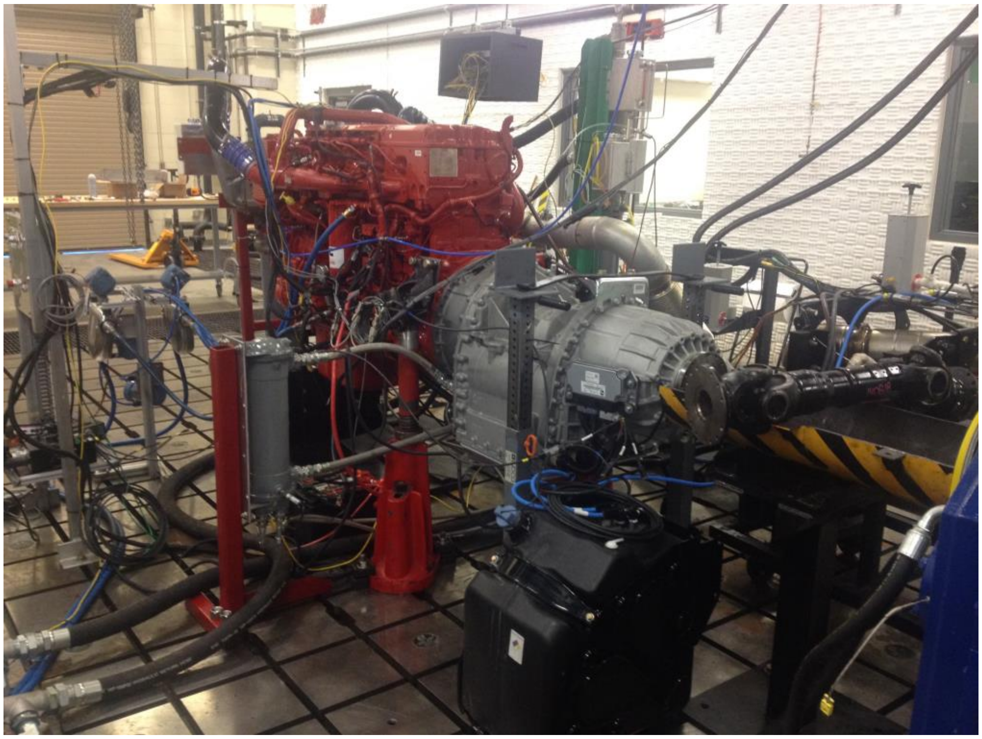


Figure 18. ISX15 450 engine and TC automatic transmission installed in ORNL's VSI Laboratory.

2.1.4.1.2 Automatic transmission with Cummins ISX 450 test plan

The tests conducted on the Cummins ISX450 engine connected to the Allison TC10 automatic transmission are summarized in Table 4.

Table 4. Automatic transmission with Cummins ISX 450 tests

Simulated Vehicles	Cycle
T700 and Veh 1 to 15	ARB Transient WHVC 55 mph w/grade 65 mph w/grade NREL Vocational Cycle
T700	HTUF6 CILCC 55 mph 65 mph
T700 and T700 generic	cold WHVC w/load hot WHVC w/load

All tests procedures were specified in the *Quality Assurance Project Plan* (EPA_GHG2_QAPP_draft10.docx).

Cycles are shown in Appendix A.

The vehicles are described in Table 5.

Table 5. Automatic transmissions with Cummins ISX 450 vehicles

	M (kg)	CDA	Crr (g/kg)	Mrotating (kg)	r (m)	Rear Axle Ratio	Axle Eff. (%)	Calibration Mode: Econo (2), Default (1)
T700	33,130	7.04	5.84	1,134	0.4925	2.47	95.5	
T700 generic		Rated power		811	0.4925	2.47	95.0	
Veh 1	40,895	6.1		1,134				2
Veh 2	31,978	5.4		1,134		2.4		
Veh 3	22,679	4.7		907				
Veh 4	19,051	4		680				1
Veh 5	40,895	6.1		1,134				
Veh 6	31,978	5.4		1,134		2.64		2
Veh 7	22,679	4.7		907				
Veh 8	19,051	4	6.9	680	0.5		95.5	1
Veh 9	31,978	5.4		1,134				2
Veh 10	22,679	4.7		907		3		
Veh 11	19,051	4		680				1
Veh 12	40,895	6.1		1,134				
Veh 13	31,978	5.4		1,134		3.36		2
Veh 14	22,679	4.7		907				
Veh 15	19,051	4		680				1

2.1.4.1.3 Automatic transmission with Cummins ISX 450 test results

CO, CO_2, NO_x, THC, NMHC, and CH_4 emission in grams per mile and in grams per kilowatt-hour were calculated according to 40 CFR 1066 and 1065, respectively. Fuel consumption from carbon emission and direct fuel measurement in miles per gallon, were also calculated according to 40 CFR 1066.

These results were compiled in a summary Excel document docketed with this report:

ORNL PIL Summary_TC10_V5_10Hz_Master_DD.xlsx.

2.1.4.2 Automatic transmission with Cummins ISX 400

2.1.4.2.1 Automatic transmission with Cummins ISX 400 test plan

The ISX engine controller (with a default 450 hp calibration) was replaced with a new controller flashed with a 400 hp calibration (referred to as ISX 400). The hardware was identical: same engine, same Allison TC10 transmission.

All tests procedures were specified in the *Quality Assurance Project Plan* (EPA_GHG2_QAPP_draft10.docx).

Cycles are shown in Appendix A.

The tests that were conducted are described in Table 6.

Table 6. Automatic Transmission with Cummins ISX 400 Tests

Simulated Vehicles	Cycles					
Veh 2	ARB	55 mph grade	65 mph grade	WHVC	55 mph - grade profile D	65 mph - grade profile D
Veh 4	ARB	55 mph grade	65 mph grade			
Veh 6					55 mph - grade profile D	65 mph - grade profile D
Veh 7	ARB	55 mph grade	65 mph grade			
Veh 13	ARB	55 mph grade	65 mph grade	WHVC	55 mph - grade profile D	65 mph - grade profile D
Veh 15	ARB	55 mph grade	65 mph grade			

2.1.4.2.2 Automatic transmission with Cummins ISX 400 test results

CO, CO_2, NO_x, THC, NMHC and CH_4 emission in grams per mile and grams per kilowatt-hour were calculated according to 40 CFR 1066 and 1065, respectively. Fuel consumption from carbon emission and direct fuel measurement in miles per gallon were also calculated according to 40 CFR 1066.

Those results were compiled in a summary Excel document docketed with this report:

ORNL PIL Summary_TC10_V5_10Hz_Master_DD.xlsx.

2.1.5 Evaluate Potential Test Procedures for Advanced HD Engines

2.1.5.1 Engine-mapping procedure

2.1.5.1.1 Cummins ISX 450 commissioning in the VSI Laboratory

The Cummins ISX 450 was installed in the VSI Laboratory (Figure 19). The test cell was configured in “engine-only” mode, where the engine is coupled directly to one dynamometer only. This configuration is suitable to handle the speed and torque envelope of the engine and is better suited than the powertrain dynamometer configuration (made of two dynamometers and one gearbox) because it results in a lower inertia, which allows for faster transients such as the one experienced during gear shifts.

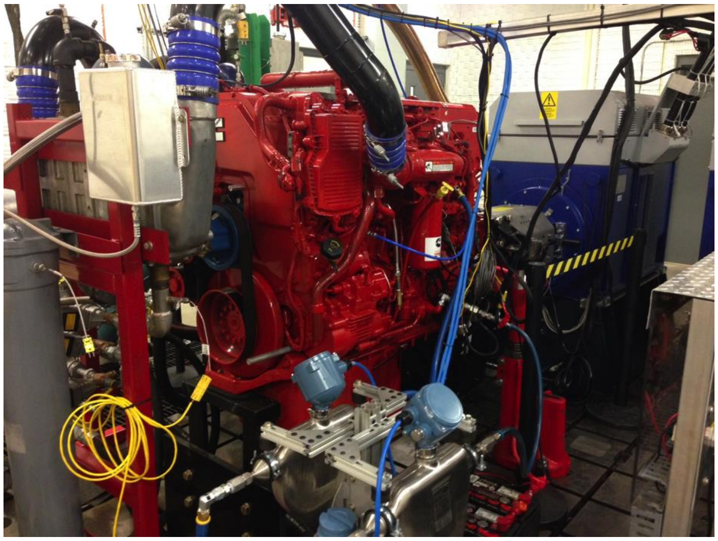


Figure 19. ISX450 engine installed in ORNL’s VSI Laboratory.

2.1.5.1.2 Cummins ISX 450 mapping test plan

First a torque curve is performed to characterize the engine operating envelope.

Two steady-state mapping procedures were conducted.

The first mapping procedure was performed according to 40 CFR1036.535 specifications. After warm-up, it starts from the maximum speed and maximum torque conditions, discretely reducing torque while maintaining speed. After recording the zero torque condition at that speed, speed is lowered to the next lower set point and torque is set to its maximum value at that speed before repeating the decreasing-step torque sweep. Each point is held for 90 s, and measurements only use the last 30 s at each set point.

The speed range is divided in 13 equally spaced points between idle speed and the maximum speed ("fntest") defined by powertrain torque curve. The torque range is divided in 11 equally spaced, normalized values ranging from zero torque to maximum torque at each speed.

The second mapping procedure covers the same test points but changes the sequence and duration of each point. Test point order is based on increasing power, meaning that both speed and torque are likely to change between two consecutive points. Also, each point is maintained for 5 min, while measurements are averaged over the last 30 s of that interval.

On top of the two maps, some transient engine cycles were recorded. Some cycles were performed in "playback" mode, where the drive cycle specifies a speed and torque profile and the test cell controller controls the dynamometer to achieve the speed set point and controls the engine to achieve the torque set point. The process is represented in Figure 20.

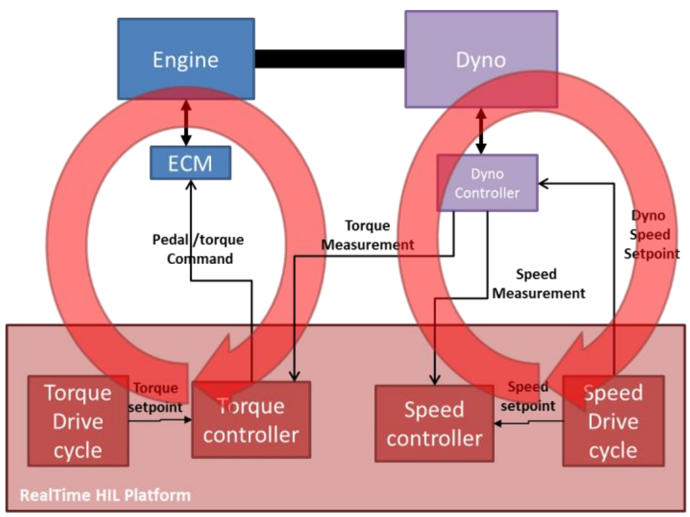


Figure 20. Engine Playback diagram.

The following cycles were performed in "playback" mode. They are shown in Appendix B:

- Cold FTP
- Hot FTP
- SET
- Cold WHTC
- Hot WHTC
- 55 mph
- 65 mph
- ARB

Some other cycles were performed in engine-in-the-loop mode, where a real-time model of the vehicle interacts with the engine in the test cell to follow a vehicle speed profile. The principle is similar to the powertrain-in-the-loop principle described in section 2.1.3.1, except that, in engine-in-the-loop mode, the transmission is not installed in the test cell. Instead, it is modeled with the rest of the virtual vehicle (Figure 21).

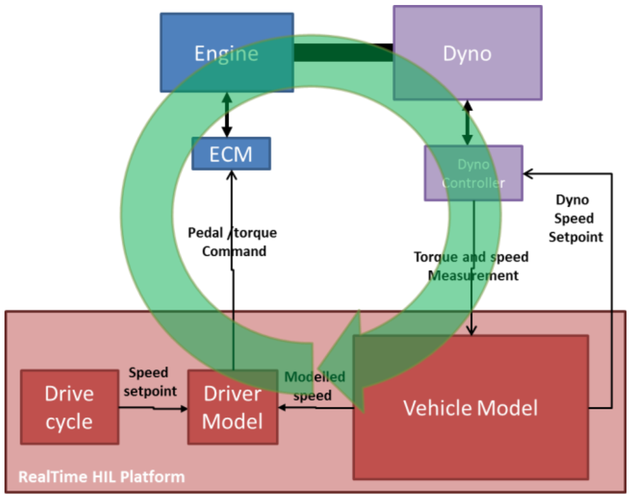


Figure 21. Engine-in-the-loop diagram.

In the engine-in-the-loop configuration, the vehicle model will emulate a T700 vehicle equipped with a 10-speed automated manual transmission modelled using EPA's GEM.

The following cycles will be performed:

- 55 mph w/grade
- 65 mph w/grade
- ARB transient
- WHVC

All operations procedures were also summarized in the *Quality Assurance Project Plan* (EPA_GHG2_QAPP_draft10.docx).

2.1.5.1.3 Cummins ISX 450 test results

Torque curve: Torque curve was performed as described in 40 CFR 1065.510. It ramped up speed at a rate of 5 rpm/s from 570 rpm to 2150 rpm. Figure 22 shows the traction and motoring torque curves for ISX15 450 engine.

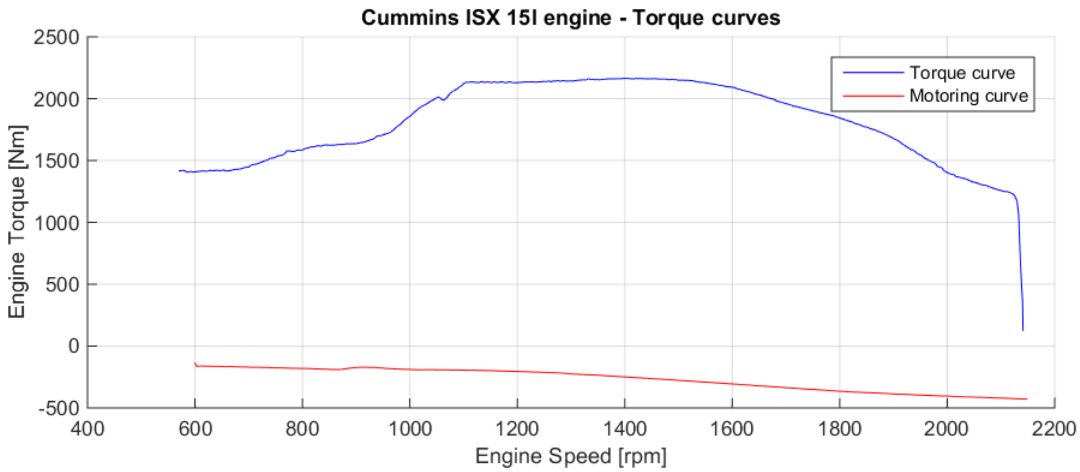


Figure 22. ISX15 450 engine torque curves.

The raw data were fed into the EPA provided postprocessing file Torque_Curve_and_Emissions_Cycle_Analysis_Rev_2_2014-05-13 Tin2.xlsm, to calculate key speed parameters for FTP, SET, WHTC and other cycles. Table 7 shows the "EPA report New" tab of that spreadsheet.

Table 7. "EPA report New" tab of torque curve postprocessing file Torque_Curve_and_Emissions_Cycle_Analysis_Rev_2_2014-05-13 Tin2.xlsm

	Speed	Torque[1]		Power[1]		
Intermediate Speed	(rpm)	(lbf-ft)	(N-m)	(hp)	(kW)	Reference
Manufacturer Declared:		NA	#VALUE!	NA	#VALUE!	40CFR1065.510(f)(3)(ii)
Measured:	1329.70	1589.03	2154.44	402.30	300.00	40CFR1065.610(c)(3)
Final Selected Speed:	1329.70	1589.03	2154.44	402.30	300.00	40CFR1065.510(f)(3)(ii)
Maximum Test Speed	(rpm)	(lbf-ft)	(N-m)	(hp)	(kW)	Reference
Manufacturer Declared:		NA	#VALUE!	NA	#VALUE!	40CFR1065.510(f)(3)(i)
Measured:	1981.97	1071.79	1453.16	404.46	301.61	40CFR1065.610(a)(1)-(2
Final Selected Speed:	1981.97	1071.79	1453.16	404.46	301.61	40CFR1065.510(f)(3)(i)
A, B, and C Speeds	(rpm)	(lbf-ft)	(N-m)	(hp)	(kW)	Reference
Mfr Declared A Speed:	NA	NA	#VALUE!	NA	#VALUE!	40CFR1065.510(f)(3)(ii)
Measured A Speed:	1257.50	1580.47	2142.82	378.41	282.18	40CFR1065.610(c)(2)
Final Selected A Speed:	1257.50	1580.47	2142.82	378.41	282.18	40CFR1065.510(f)(3)(ii)
Mfr Declared B Speed:	NA	NA	#VALUE!	NA	#VALUE!	40CFR1065.510(f)(3)(ii)
Measured B Speed:	1548.95	1570.57	2129.40	463.19	345.40	40CFR1065.610(c)(2)
Final Selected B Speed:	1548.95	1570.57	2129.40	463.19	345.40	40CFR1065.510(f)(3)(ii)
Mfr Declared C Speed:	NA	NA	#VALUE!	NA	#VALUE!	40CFR1065.510(f)(3)(ii)
Measured C Speed:	1840.41	1315.00	1782.89	460.79	343.61	40CFR1065.610(c)(2)
Final Selected C Speed:	1840.41	1315.00	1782.89	460.79	343.61	40CFR1065.510(f)(3)(ii)
Supplemental Reference Speeds	(rpm)	(lbf-ft)	(N-m)	(hp)	(kW)	Reference
n-lo:	966.04	1280.23	1735.75	235.48	175.59	40CFR1065.610(c)(2)
Measured E Speed:	1140.91	1572.44	2131.94	341.58	254.72	40CFR86.1360-2007(c)
fn @ Pmax	1604.37	1541.75	2090.33	470.96	351.19	NA
fnPmax	1689.19	1455.65	1973.60	468.17	349.11	40CFR1065.610(a)(1)
fn @ Tmax	1398.20	1596.25	2164.22	424.95	316.88	NA
fnTmax	1329.70	1589.03	2154.44	402.30	300.00	40CFR1065.610(c)(3)
n-high:	2131.87	812.21	1101.21	329.68	245.84	40CFR1065.610(c)(2)

[1] On the maximum torque vs. speed map, a.k.a wide-open throttle torque curve.

Engine mapping: Mapping results were compiled in four summary Excel documents docketed with this report:

- 1st_EPA_1036_Mapping_Summary_V2.xlsx contains the first mapping performed according to 1036
- 2nd_EPA_1036_Mapping_Summary_V2.xlsx contains the second mapping performed according to 1036
- 1st_RisingPower_Mapping_Summary_V2.xlsx contains the first mapping based on the new "rising power" procedure
- 2nd_RisingPower_Mapping_Summary.xlsx contains the second mapping based on the new "rising power" procedure

Playback engine transient cycles: Playback engine transient cycle results were compiled in a summary Excel document docketed with this report: ORNL Engine Playback Summary_V6.xlsx.

Engine-in-the-loop transient cycles: Engine-in-the-loop transient cycle results were compiled in a summary Excel document docketed with this report: ORNL EIL Summary_V5.xlsx.

2.1.5.2 Alternate engine-mapping procedure

2.1.5.2.1 Alternate ISX 450 engine-mapping test plan

The alternate engine-mapping procedure, also referred to as "cycle average" consists of subjecting a stand-alone engine to speed and torque profiles generated by GEM and calculating the resulting engine positive work, engine speed over vehicle speed ratio (N/V), and fuel consumption to populate a table that can later on be used to interpolate the fuel consumption of other vehicles fitted with the same engine.

Test cycles are generated using GEM release RC17b. Nine test vehicles are specified in Table 2 of 40 CFR 1036.540. The torque curve described in 2.1.5.1.3 is used to establish the minimum and maximum engine speeds in this table. Combined, they allow specifying the vehicle parameters fed to GEM to generate the speed and torque profiles. (See Table 8.)

Table 8. Alternate ISX 450 engine-mapping test

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
M (kg)	31,978	25,515	19,051	31,978	25,515	19,051	31,978	25,515	19,051	29,529	20,529	29,500
C_DA	5.4	4.7	4	5.4	4.7	4	5.4	4.7	4	4.7	4.7	5.4
$M_{rotating}$ (kg)	1,134	907	680	1,134	907	680	1,134	907	680	907	680	1,134
engine speed (description)	Minimum NTE exclusion speed	Minimum NTE exclusion speed	Minimum NTE exclusion speed	B	B	B	Maximum test speed	Maximum test speed	Maximum test speed	Less than 1100rpm	interpolation point	interpolation point
engine speed (rpm)	1230	1230	1230	1549	1549	1549	1982	1982	1982	1186	1384	1750
Speed (m/s) (65mph)	29.05	29.05	29.05	29.05	29.05	29.05	29.05	29.05	29.05	29.05	29.05	29.05
tire size(rev/m) $\frac{f_{ntire}}{v_{vehicle}}$	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318	0.318
ktopgear ( )	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
ka (final drive ratio)	3.039	3.039	3.039	3.827	3.827	3.827	4.896	4.896	4.896	2.930	3.419	4.323

For vehicle 1, 2, 3,(and 10, the torque minimum speed was not used (1140 rpm increased to 1230 rpm) because it resulted in the engine operating in ninth gear during the 55 mph cruise cycle, which in turn, causes the N/V ratio for those tests to overlap with tests 4, 5, and 6. Therefore, engine speed was increased for those test points, which allowed for tenth-gear operation at 55 mph, resulting in a better coverage of the work and N/V space, as shown in Figure 23. The left-hand side graph shows the cycle average points using 1146 rpm for tests 1, 2, and 3 (blue crosses). The right-hand plot shows the results of using 1230 rpm for the same tests. This is what was used for our cycle average tests.

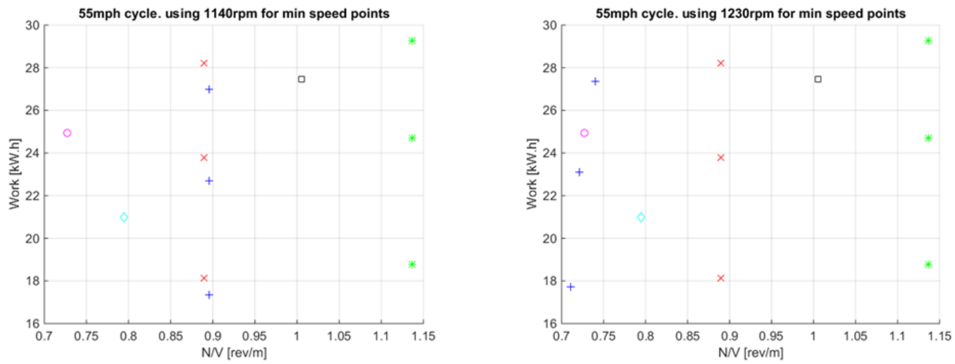


Figure 23. Cycle average test points for 55 mph cycle. Effect of minimum engine speed selection.

Different transmissions were defined for cruise and transient cycles. the ARB transient cycle profiles were generated with GEM where the transmission is an automatic transmission whereas the 55 mph and 65 mph cruise cycles were generated with GEM where the transmission is an AMT.

In addition to the standard nine points listed in Table 2 of § 40 CFR1036.540, three additional points are created to test interpolation and extrapolation routines on the resulting table. Those points were therefore selected to be located either on the edge or middle of the nine default points, as shown in Figure 24.

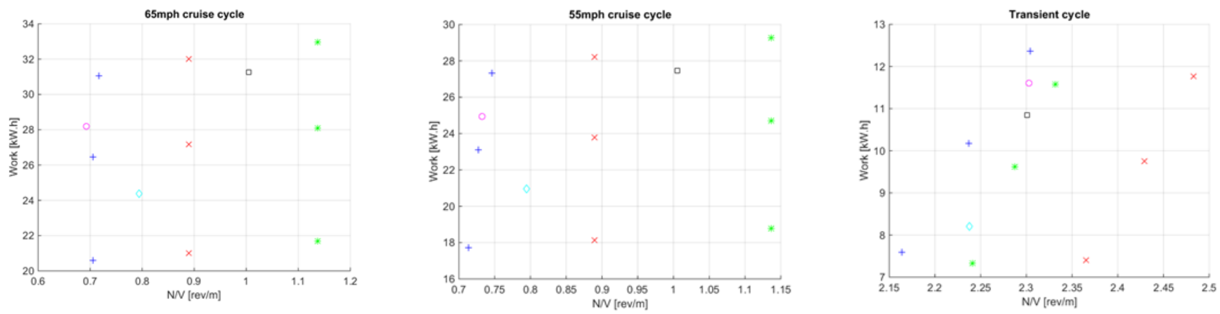


Figure 24. Cycle average test points for 55 mph and 65 mph cruise cycles as well as transient cycles. test1, 2, and 3 are blue crosses; test 4, 5, and 6 are red x's; test 8, 9, and 10 are green stars; test 10 is a pink circle; test 11 is a cyan diamond; and test 12 is square.

Table 9 shows the GEM input file that specifies vehicle parameters for speed and torque profile generation.

Table 9. GEM input file specifying vehicle parameters for speed and torque profile generation

Regulatory Category	Tractor													
Manufacturer Name	EPA													
Model Year	2018-2024													
GEM Version	P2v1.10	Engine	Transmission	Drive A:	Drive A:	Drive A:	Aerodyn	Steer Ax	Drive Ax	Drive Axl	Drive Axle	Technolog	Technolo	Technc
Run ID	Regulatory Subca	Data	Data	Configu	Ratio	Data	Aerodyn	Rolling F	Rolling F	Rolling Re	Loaded Tir	Vehicle Sp	Weight A	Neutra
Unique Identifier	(e.g. C8_SC_HR)	File Name	File Name	(e.g. 6x	#	File Nar	m^2	kg/t	kg/t	kg/t	rev/mi	MPH or N/	lbs	Y/N
2018_Engine455_6spdAT_cycle01	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.382	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_6spdAT_cycle02	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.382	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine455_6spdAT_cycle03	C7_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	4x2	3.382	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine455_6spdAT_cycle04	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	4.259	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_6spdAT_cycle05	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	4.259	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine455_6spdAT_cycle06	C7_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	4x2	4.259	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine455_6spdAT_cycle07	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	5.45	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_6spdAT_cycle08	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	5.45	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine455_6spdAT_cycle09	C7_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	4x2	5.45	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine455_6spdAT_cycle10	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.261	NA	4.7	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_6spdAT_cycle11	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.805	NA	4.7	6.9	6.9	6.9	500	NA	29762	Y
2018_Engine455_6spdAT_cycle12	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	4.812	NA	5.4	6.9	6.9	6.9	500	NA	8194	Y
2018_Engine455_10spdAMT_cycle01	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.111	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_10spdAMT_cycle02	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.111	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine455_10spdAMT_cycle03	C7_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	4x2	3.111	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine455_10spdAMT_cycle04	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.918	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_10spdAMT_cycle05	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.918	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine455_10spdAMT_cycle06	C7_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	4x2	3.918	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine455_10spdAMT_cycle07	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	5.014	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_10spdAMT_cycle08	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	5.014	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine455_10spdAMT_cycle09	C7_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	4x2	5.014	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine455_10spdAMT_cycle10	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3	NA	4.7	6.9	6.9	6.9	500	NA	0	Y
2018_Engine455_10spdAMT_cycle11	C8_DC_MR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.501	NA	4.7	6.9	6.9	6.9	500	NA	29762	Y
2018_Engine455_10spdAMT_cycle12	C8_SC_HR	ISX_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	4.427	NA	5.4	6.9	6.9	6.9	500	NA	8194	Y

All operations procedures were also summarized in the *Quality Assurance Project Plan* (EPA_GHG2_QAPP_draft10.docx).

2.1.5.2.2 Alternate ISX 450 engine mapping test results

CO, CO_2, NO_x, THC, NMHC and CH_4 emission in grams per mile and grams per kilowatt-hour, were calculated according to 40 CFR 1066 and 1065, respectively. Fuel consumption from carbon emission and direct fuel measurement in miles per gallon were also calculated according to 40 CFR 1066.

Those results were compiled in a summary Excel document docketed with this report (ORNL Engine GEM Cycle Avg Summary_ISX 450_V3_DD.xlsx)

The data were post processed to plot brake-specific fuel consumption (BSFC) as a function of N/V ratio and work. It is shown in Figure 25 and Figure 26.

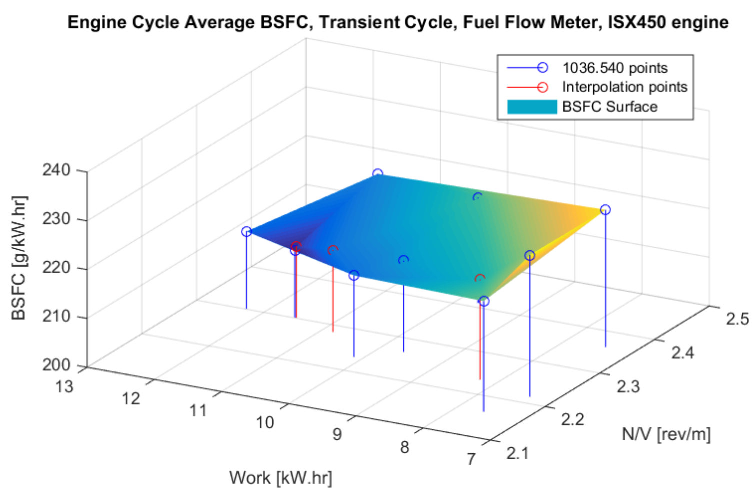


Figure 25. Cycle average results obtained for ISX 450 engine on transient cycle using fuel flowmeter measurements.

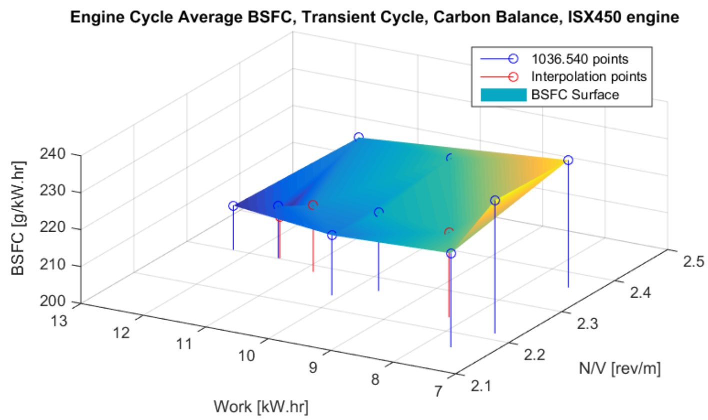


Figure 26. Cycle average results obtained for ISX 450 engine on transient cycle using carbon balance measurements.

2.1.5.3 Alternate engine-mapping procedure (ISX 400 engine)

2.1.5.3.1 Alternate ISX 400 engine-mapping test plan

The same procedure that was described in section 2.1.3.2.1 for the baseline ISX 450 engine was used to generate speed and torque profiles for the ISX 400 engine.

The only difference is that the test description input file lists the ISX 400 engine component input file as the engine. That file was generated starting from the ISX 450 engine input file; its torque curve was adjusted but the fuel map was not.

Figure 27 shows the ISX 400 and ISX 450 torque curves.

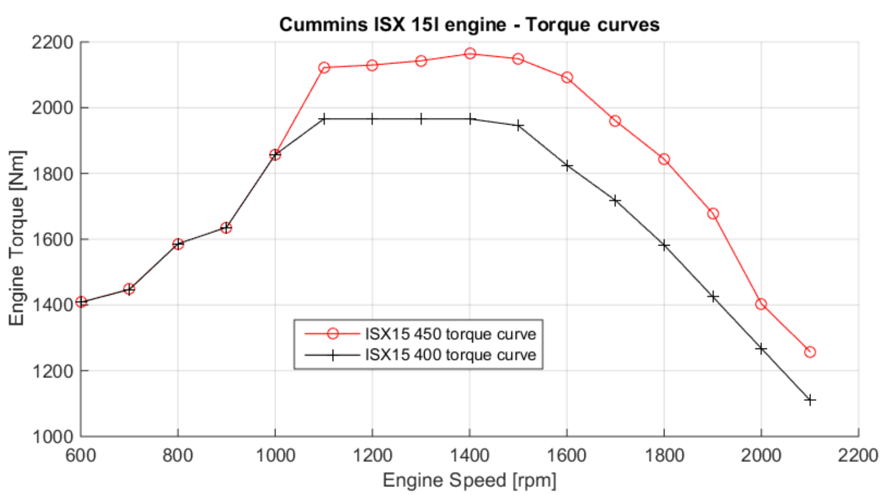


Figure 27. ISX15 Engine torque curve for 450 hp cal and 400 hp cal.

Table 10 shows the GEM input file that specifies vehicle parameters for speed and torque profile generation for the ISX400 cycle average case.

Table 10. GEM input file specifying vehicle parameters for speed and torque profile generation

Regulatory Category	Tractor													
Manufacturer Name	EPA													
Model Year	2018-2024													
GEM Version	P2v1.10	Engine	Transmission	Drive Axle	Drive Axle	Drive Axle	Aerodynar	Steer Axle	Drive Axle	Drive Axle	Drive Axle	Technolog	Technolog	Technolog
Run ID	Regulatory Subcategory	Data	Data	Configurat	Ratio	Data	Aerodynar	Rolling Res	Rolling Res	Rolling Res	Loaded Tir	Vehicle Sp	Weight Ad	Neutral-Id
Unique Identifier	(e.g. C8_SC_HR)	File Name	File Name	(e.g. 6x4)	#	File Name	m^2	kg/t	kg/t	kg/t	rev/mi	MPH or N/	lbs	Y/N
2018_Engine400_6spdAT_cycle01	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.382	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_6spdAT_cycle02	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.382	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine400_6spdAT_cycle03	C7_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	4x2	3.382	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine400_6spdAT_cycle04	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	4.259	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_6spdAT_cycle05	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	4.259	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine400_6spdAT_cycle06	C7_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	4x2	4.259	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine400_6spdAT_cycle07	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	5.45	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_6spdAT_cycle08	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	5.45	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine400_6spdAT_cycle09	C7_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	4x2	5.45	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine400_6spdAT_cycle10	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.261	NA	4.7	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_6spdAT_cycle11	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	3.805	NA	4.7	6.9	6.9	6.9	500	NA	29762	Y
2018_Engine400_6spdAT_cycle12	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AT_6_HHD_lockup_in_3rd.csv	6x4	4.812	NA	5.4	6.9	6.9	6.9	500	NA	8194	Y
2018_Engine400_10spdAMT_cycle01	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.111	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_10spdAMT_cycle02	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.111	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine400_10spdAMT_cycle03	C7_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	4x2	3.111	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine400_10spdAMT_cycle04	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.918	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_10spdAMT_cycle05	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.918	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine400_10spdAMT_cycle06	C7_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	4x2	3.918	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine400_10spdAMT_cycle07	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	5.014	NA	5.4	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_10spdAMT_cycle08	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	5.014	NA	4.7	6.9	6.9	6.9	500	NA	13275	Y
2018_Engine400_10spdAMT_cycle09	C7_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	4x2	5.014	NA	4	6.9	6.9	NA	500	NA	6147	Y
2018_Engine400_10spdAMT_cycle10	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3	NA	4.7	6.9	6.9	6.9	500	NA	0	Y
2018_Engine400_10spdAMT_cycle11	C8_DC_MR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	3.501	NA	4.7	6.9	6.9	6.9	500	NA	29762	Y
2018_Engine400_10spdAMT_cycle12	C8_SC_HR	ISX400_ORNL_DEF_C_Bal_Exp_T_Curve.csv	Transmissions\EPA_AMT_10_C78_4490_hires.csv	6x4	4.427	NA	5.4	6.9	6.9	6.9	500	NA	8194	Y

2.1.5.3.2 Alternate ISX 400 engine-mapping test results

CO, CO_2, NO_x, THC, NMHC and CH_4 emission in grams per mile and grams per kilowatt-hour, were calculated according to 40 CFR 1066 and 1065, respectively. Fuel consumption from carbon emission and direct fuel measurement in miles per gallon were also calculated according to 40 CFR 1066.

These results were compiled in a summary Excel document docketed with this report (ORNL Engine GEM Cycle Avg Summary_ISX 400_V2_DD.xlsx)

The data were post processed to plot BSFC as a function of N/V ratio and work. It is shown in Figure 28 and Figure 29.

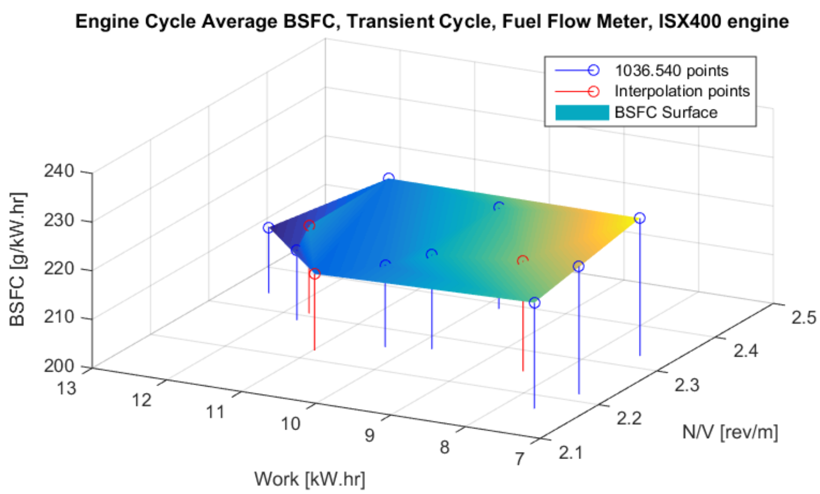


Figure 28. Cycle average results obtained for ISX 400 engine on transient cycle using fuel flowmeter measurements.

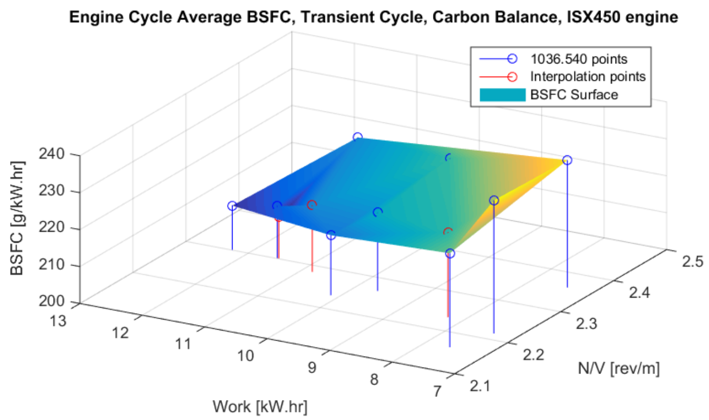


Figure 29. Cycle average results obtained for ISX 400 engine on transient cycle using carbon balance measurements.

2.1.6 Evaluate Advanced HD Engine and Powertrain Technologies

This task was contingent upon available funds and performance on previous tasks. It was intended to evaluate advanced HD engines and powertrain technologies and the test procedures required to quantify their performance.

The details of this task have not been specified by the EPA yet, and no work has been performed.

2.1.7 Road Grade Cycles

2.1.7.1.1 Road grade cycle (ISX 450 engine) mapping test plan

EPA provided four grade profiles to be run in both forward and reverse directions at 55 mph and 65 mph for a total of 10 different drive cycles (the grade profiles are shown in Appendix A):

- Grade Profile A, Test Speed: 55 mph, Trace Direction: forward
- Grade Profile A, Test Speed: 55 mph, Trace Direction: reverse
- Grade Profile A, Test Speed: 65 mph, Trace Direction: forward
- Grade Profile A, Test Speed: 65 mph, Trace Direction: reverse
- Grade Profile B, Test Speed: 55 mph, Trace Direction: forward
- Grade Profile B, Test Speed: 55 mph, Trace Direction: reverse
- Grade Profile C, Test Speed: 65 mph, Trace Direction: forward
- Grade Profile C, Test Speed: 65 mph, Trace Direction: reverse
- Grade Profile D, Test Speed: 55 mph, (symmetrical)
- Grade Profile D, Test Speed: 65 mph, (symmetrical)

These drive cycles are applied to two powertrains:

- Cummins ISX15 (450 hp cal) engine coupled to Allison TC10 automatic transmission
- Cummins ISX15 (450 hp cal) engine coupled to Eaton UltraShift Plus AMT

The VSI Laboratory was operated in powertrain-in-the-loop mode with the “1037-equation” model.

The vehicle configurations performed with the TC10 transmission are listed in Table 11.

Table 11. Vehicle configurations performed with the TC10 transmission

	M (kg)	C_DA	*Crr* (g/kg)	$M_{rotating}$ (kg)	*r* (m)	Rear Axle Ratio	Axle Eff. (%)	Calibration Mode: Econo (2), Default (1)
Veh 2						2.4		
Veh 6	31,978	5.4	6.9	1,134	0.5	2.64	95.5	2
Veh 13						3.36		

The vehicle configurations performed with the UltraShift transmission are listed in Table 12.

Table 12. Vehicle configurations performed with the UltraShift transmission

	M (kg)	C_DA	*Crr* (g/kg)	$M_{rotating}$ (kg)	*r* (m)	Rear Axle Ratio	Axle Eff. (%)
Veh 13						3.36	
Veh 17	31,978	5.4	6.9	1,134	0.5	2.81	95.5
Veh 28						4.65	

Because the TC10 automatic transmission has two modes (economy and performance), this transmission was tested on two more vehicles (#2 and #13) with a subset of four cycles:

- Grade Profile B , 55 mph, forward
- Grade Profile C, 65 mph, forward
- Grade Profile D, 55 mph
- Grade Profile D, 65 mph

All operations procedures were also summarized in the *Quality Assurance Project Plan* (EPA_GHG2_QAPP_draft10.docx).

2.1.7.1.2 Road grade cycle (ISX 450 engine) mapping test results

Table 13 and Table 14 show respectively the TC10 and UltraShift test matrixes; dates are those on which tests were performed.

Table 13. TC10 powertrain test tracker of grade cycle test matrix

	55mph Profile B Fwd	55mph Profile B Rvrs	55mph Profile A Fwd	55mph Profile A Rvrs	65mph Profile A Fwd	65mph Profile A Rvrs	65mph Profile C Fwd	65mph Profile C Rvrs	55mph Profile D	65mph Profile D
Veh 2	7/29/2015	8/4/2015	8/4/2015	8/5/2015	8/5/2015	8/5/2015	8/7/2015	8/7/2015	8/7/2015	8/7/2015
Veh 6	7/30/2015	7/30/2015	7/30/2015	7/30/2015	7/30/2015	7/31/2015	7/31/2015	7/31/2015	7/31/2015	7/31/2015
Veh 13	7/29/2015	8/7/2015	8/7/2015	8/10/2015	8/10/2015	8/10/2015	8/10/2015	8/10/2015	8/11/2015	8/11/2015

Performance Mode Switch

	55mph Profile B Fwd	65mph Profile C Fwd	55mph Profile D	65mph Profile D
Veh 2	8/13/2015	8/13/2015	8/13/2015	8/13/2015
Veh 13	8/11/2015	8/11/2015	8/13/2015	8/13/2015

Table 14. USP powertrain test tracker of grade cycle test matrix

	55mph Profile B Fwd	55mph Profile B Rvrs	55mph Profile A Fwd	55mph Profile A Rvrs	65mph Profile A Fwd	65mph Profile A Rvrs	65mph Profile C Fwd	65mph Profile C Rvrs	55mph Profile D	65mph Profile D
Veh 13	11/2/2015	11/2/2015	11/2/2015	11/2/2015	11/2/2015	10/30/2015	10/30/2015	10/30/2015	10/30/2015	10/30/2015
Veh 17	11/20/2015	11/20/2015	11/18/2015	11/18/2015	11/18/2015	11/16/2015	11/13/2015	11/13/2015	11/13/2015	11/13/2015
Veh 28	1/27/2016	1/27/2016	1/27/2016	1/27/2016	1/27/2016	1/20/2016	1/20/2016	1/20/2016	1/15/2016*	1/15/2016*

requires single dyno config to handle transmission output speed

Requires a rerun do to the test being outside the standard COV limits

Vehicle 28, which utilizes the Eaton UltraShift transmission and whose final drive ratio is 4.65:1, had to be tested with a different test cell configuration. The powertrain configuration in the VSI Laboratory has a transmission output speed limit of 1850 rpm, which is exceeded on the 55 mph and 65 mph cruise cycles (55 mph corresponds to 2183 rpm, and 65 mph corresponds to 2580 rpm). Therefore the powertrain was coupled a single dynamometer that can handle up to 5000 rpm and 3750 Nm (Figure 30). During these cruise cycles where the transmission operates in eighth to tenth gear, the powertrain cannot over-torque the dynamometer. Therefore, this configuration is acceptable.

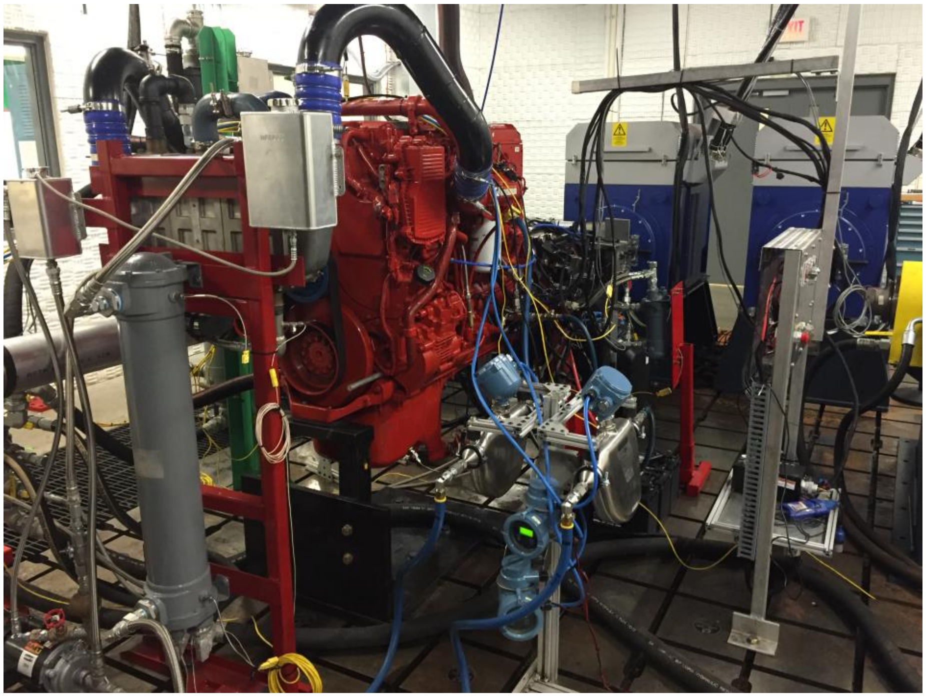


Figure 30. ISX15+USP powertrain installed in VSI Laboratory in a single dynamometer configuration.

CO, CO_2, NO_x, THC, NMHC and CH_4 emission in grams per mile and grams per kilowatt-hour, were calculated according to 40 CFR 1066 and 1065, respectively. Fuel consumption was also calculated from carbon emission and direct fuel measurement in miles per gallon, according to 40 CFR 1066.

Grade cycle results for the 450 hp ISX15 engine and Eaton UltraShift transmission were compiled in a summary Excel document docketed with this report (ORNL PIL Summary_USP_ISX 450_V4_10Hz_Master_DD.xlsx). They are listed in the same tab as the non-grade cycles for a given vehicle.

Grade cycle results for the 450 hp ISX15 engine and Allison TC10 transmission were compiled in a summary Excel document docketed with this report (ORNL PIL Summary_TC10_V5_10Hz_Master_DD.xlsx. They are listed in the same tab as the non-grade cycles for a given vehicle.

2.2 TASK 2: TEST PROCEDURE AND DATA ANALYSIS OF ENGINE, POWERTRAIN AND CHASSIS DYNAMOMETER TESTING

2.2.1 Data Analysis for Alternate Engine-Mapping Procedure

Cycle average tests were performed as reported in sections 2.1.5.2 and 2.1.5.3. For each engine calibration (400 and 450 hp), 12 different vehicles were tested (see table 8 for exact vehicle configurations). Vehicles 1 through 9 are specified according to 40 CFR1036.540 and were used to generate the cycle average map specific to this engine. The three additional vehicles (10, 11, and 12) were used to evaluate the interpolation methods by comparing the actual fuel mass measured during cycle average testing on that engine against the output of the cycle average table fed with the work and N/V ratios specific to these tests. Figure 31 shows the surface generated by the vehicle configuration mapping points as well as the interpolation test points, in this instance, all of these points were collected on the transient cycle.

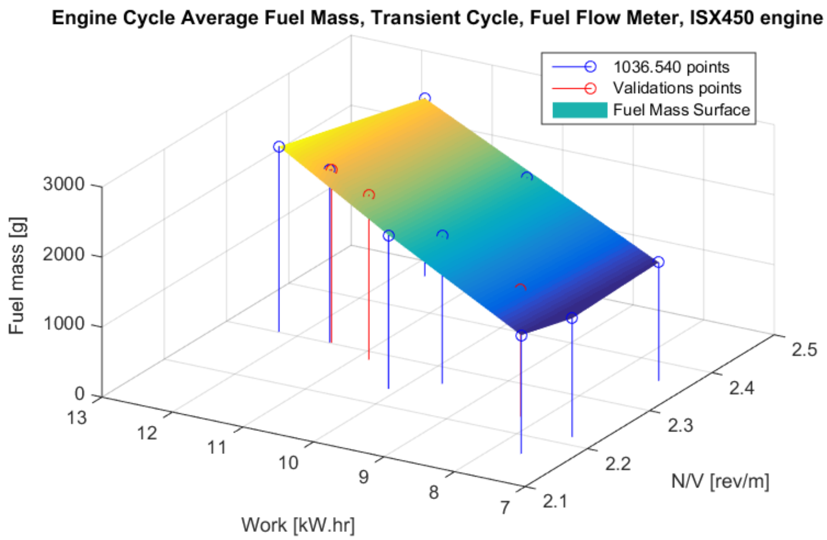


Figure 31. Cycle average results obtained for ISX 450 engine on transient cycle using fuel flowmeter measurements.

The four total interpolation routines that evaluated in this study are listed in Table 15, where:

- NV is the ratio of average engine speed over vehicle speed,
- W is the positive engine work
- T is ratio of positive engine work over average engine speed
- N is the average engine speed

Table 15. Interpolation routines definition

Method number	Description
5	1 + NV + W + NV * W
6	1 + N + T + N * T
7	1 + NV + W
8	1 + N + T

2.2.1.1 Engine cycle average interpolation results for ISX 450 engine

The interpolation method does not seem to make a significant difference with the worse error between two methods being 0.34%. Results are shown in Figure 32 and Figure 33 for fuel meter measurements and carbon balance calculation, respectively.

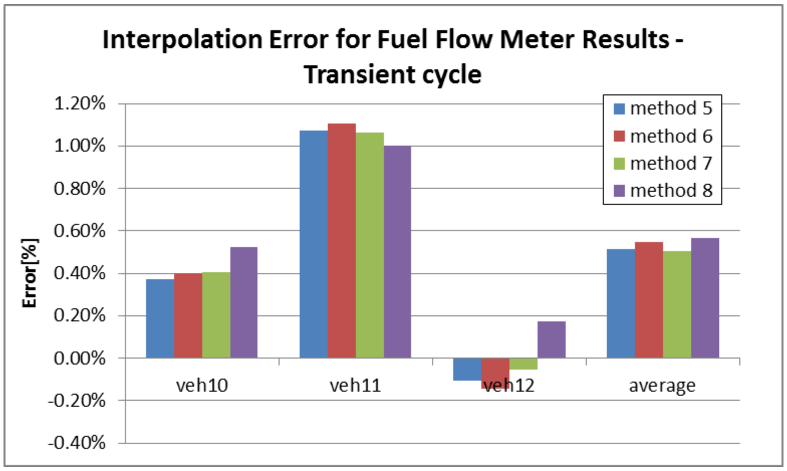


Figure 32. Interpolation error results for fuel flowmeter measurements on transient cycle.

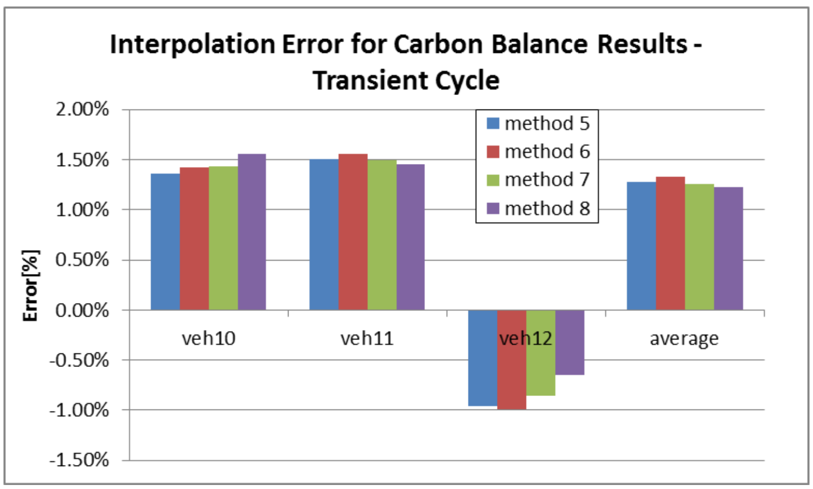


Figure 33. Interpolation error results for carbon balance measurements on transient cycle.

The interpolation study was conducted on all three tests cycles: transient cycle, 55 mph cruise cycle, and 65 mph cruise cycle.

Differences between interpolation methods tend to be larger on cruise cycles: up to 5% (see Figure 34 and Figure 35). Some of that is due to the larger spread of vehicle work and N/V ratio causing interpolations over larger intervals.

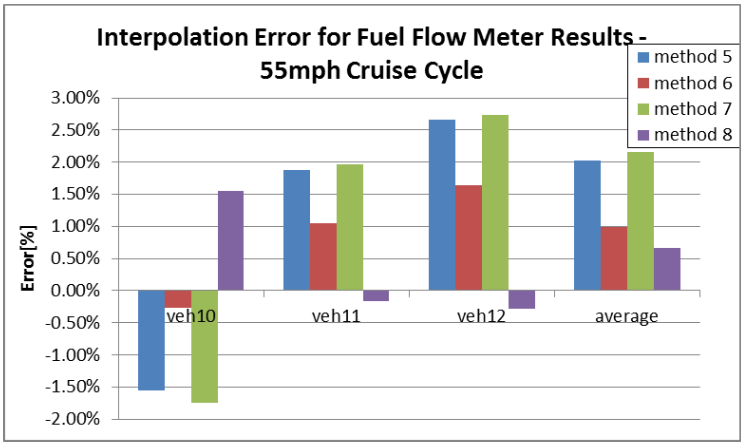


Figure 34. Interpolation error results for fuel flow measurements on 55 mph cruise cycle.

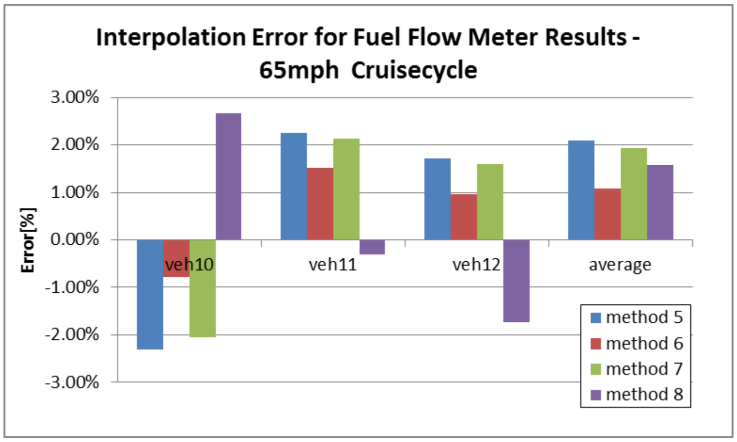


Figure 35. Interpolation error results for fuel flow measurements on 65 mph cruise cycle.

Overall method #6 generates the smaller interpolation errors on the three test points averaged over all three cycles (see Figure 36). Yet the overall difference between interpolation methods is less than 0.7%

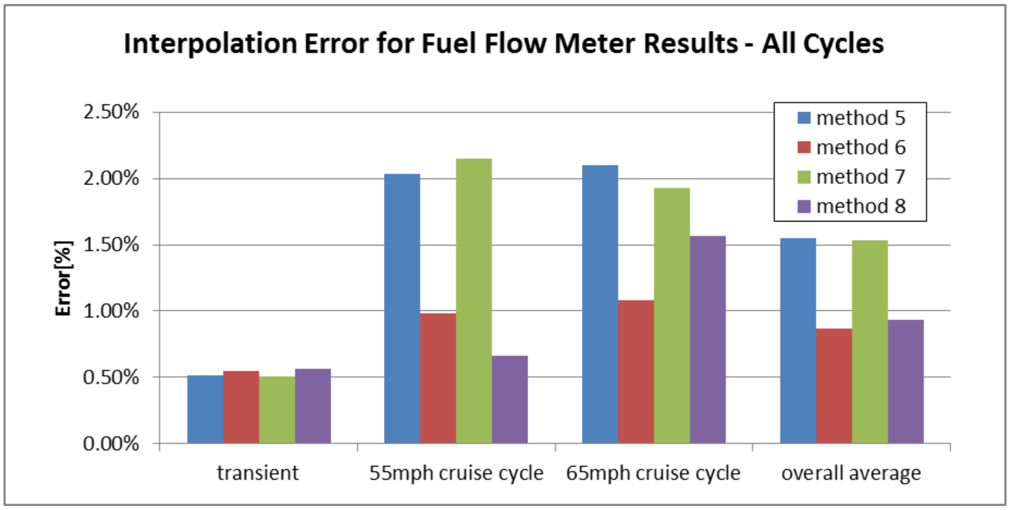


Figure 36. Interpolation error results for fuel flow measurements for all cycles.

2.2.1.2 Engine cycle average interpolation results for ISX 400 engine

The interpolation study was also conducted on ISX 400 data. (See Figure 37, Figure 38, and Figure 39.)

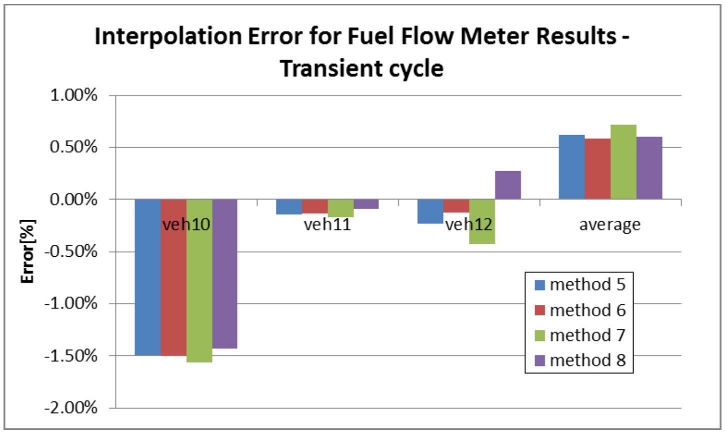


Figure 37. Interpolation error results for ISX 400 fuel flow measurements on transient cycle.

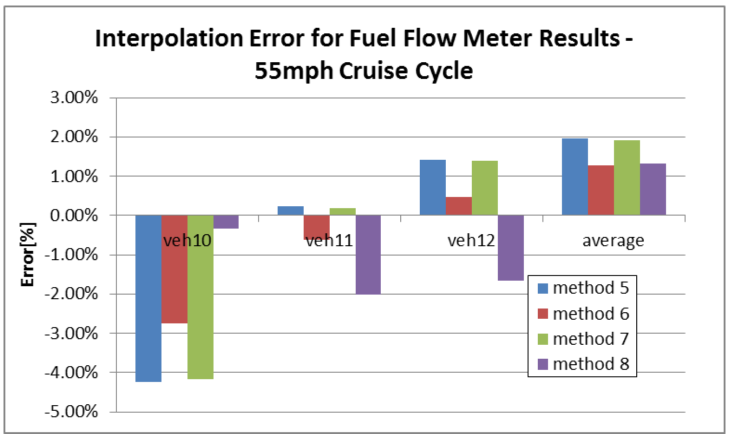


Figure 38. Interpolation error results for ISX 400 fuel flow measurements on 55 mph cruise cycle.

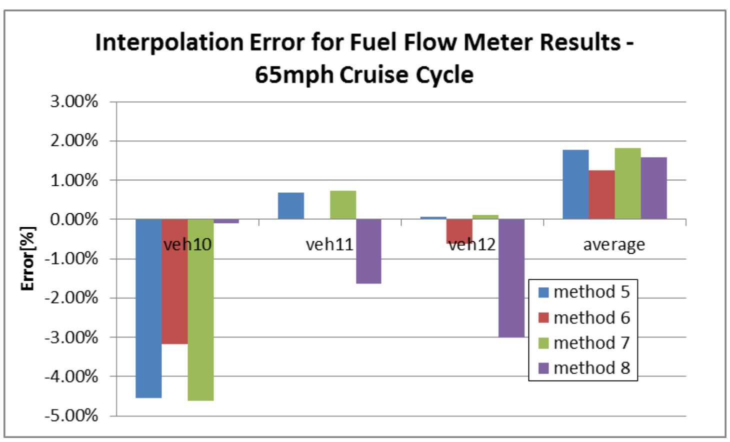


Figure 39. Interpolation error results for ISX 400 fuel flow measurements on 65 mph cruise cycle.

The same conclusions apply as on the ISX 450 table:

- Error is with 1.5% on transient cycle.
- Errors are larger on cruise cycles (up to 4% to 5%).
- Method #6, which relies on torque rather than work, performs best. (See Figure 40.)
- The overall difference between interpolation methods is less than 0.5%.

Also, errors tend to be larger on vehicle 10 which corresponds to an extrapolation point whereas other points are interpolation points.

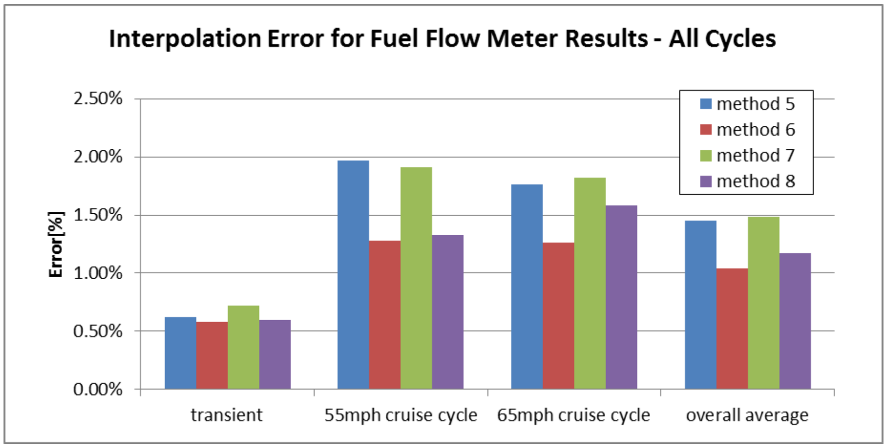


Figure 40. Interpolation error results for ISX 400 fuel flow measurements for all cycles.

2.2.2 Data Analysis of Powertrain Test Procedure

2.2.2.1 Interpolation method assessment

2.2.2.1.1 AMT powertrain mapping

Out of the 18 test vehicles defined in section 2.1.3.2, 9 are used to map the powertrain behavior and 9 are used to test the interpolation calculations. Table 16 offers a reminder of the vehicle configurations tested as powertrain-in-the-loop in the VSI Laboratory. Figure 41shows the surface generated by the vehicle configuration mapping points as well as the interpolation test points, in this instance, all of these points were collected on the transient cycle. Both on Table 16 and Figure 41, mapping points are in blue and validation points are in red.

Because the validations points were not specifically selected for this study, they do not represent all interpolation conditions: all validation points share either the same N/V ratio or cycle work with the map points and therefore only require interpolation in one dimension.

Table 16. AMT powertrain test matrix

	M (kg)	C_DA	Crr (g/kg)	$M_{rotating}$ (kg)	r (m)	Rear Axle Ratio	Axle Eff. (%)	N/V (rev/m)
T700 - AMT	33,130	7.04	5.84	1,134	0.493	3.36	95.5	1.08
Veh 13	31,978	5.4	6.9	1,134	0.5	3.36	95.5	1.07
Veh 14	22,679	4.7	6.9	907	0.5	3.36	95.5	1.07
Veh 15	19,051	4	6.9	680	0.5	3.36	95.5	1.07
Veh 16	40,895	6.1	6.9	1,134	0.5	2.81	95.5	0.89
Veh 17	31,978	5.4	6.9	1,134	0.5	2.81	95.5	0.89
Veh 18	22,679	4.7	6.9	907	0.5	2.81	95.5	0.89
Veh 19	19,051	4	6.9	680	0.5	2.81	95.5	0.89
Veh 20	40,895	6.1	6.9	1,134	0.5	3.82	95.5	1.22
Veh 21	31,978	5.4	6.9	1,134	0.5	3.82	95.5	1.22
Veh 22	22,679	4.7	6.9	907	0.5	3.82	95.5	1.22
Veh 23	19,051	4	6.9	680	0.5	3.82	95.5	1.22
Veh 24	31,978	5.4	6.9	1,134	0.5	4.32	95.5	1.38
Veh 25	22,679	4.7	6.9	907	0.5	4.32	95.5	1.38
Veh 26	19,051	4	6.9	680	0.5	4.32	95.5	1.38
Veh 27	40,895	6.1	6.9	1,134	0.5	4.65	95.5	1.48
Veh 28	31,978	5.4	6.9	1,134	0.5	4.65	95.5	1.48
Veh 29	22,679	4.7	6.9	907	0.5	4.65	95.5	1.48
Veh 30	19,051	4	6.9	680	0.5	4.65	95.5	1.48

(pink)	Validation Points
(blue)	Mapping points

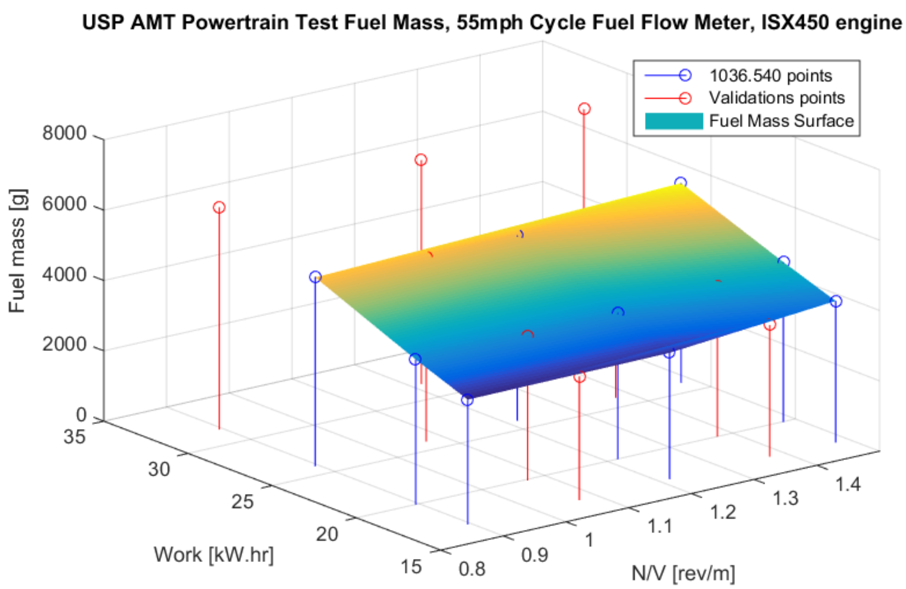


Figure 41. Fuel mass map for ISX 450+USP AMT powertrain using fuel flow measurements on 55 mph cruise cycle.

Only two methods were assessed for the powertrain configuration: method 5 and 7 as defined in Table 15. Both methods are on average equivalent. Interpolation errors vary with the type of drive cycles: errors are smaller on transient cycles (less than 1.5% and 0.5% on average), but larger on cruise cycles: up to 3% on 55 mph cruise and 4% on 65 mph cruise. (See Figure 42, Figure 43, and Figure 44).

The error on extrapolated points (veh# 16, 20, and 27) is comparable with error on interpolated points.

A potential explanation for larger errors on cruise cycles is the larger area covered by mapping surface resulting in larger interpolation intervals: the N/V ratio spread is identical for all cycles at 0.58 but positive work spread varies by a factor of 3: about 6 kWh for the transient cycle, and 15 and 16 kWh, respectively, for the 55 mph and 65 mph cruise cycles.

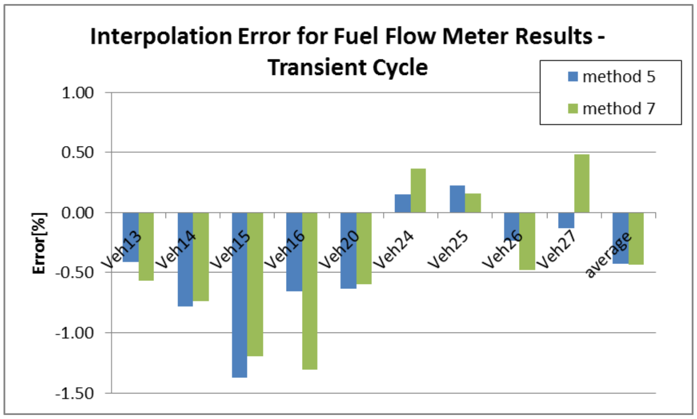


Figure 42. Interpolation errors on ISX 450+USP AMT powertrain map using fuel flow measurements on transient cycle.

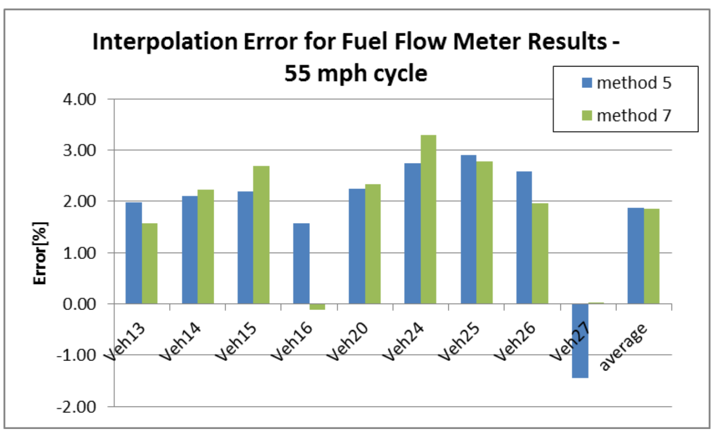


Figure 43. Interpolation errors on ISX 450+USP AMT powertrain map using fuel flow measurements on 55 mph cruise.

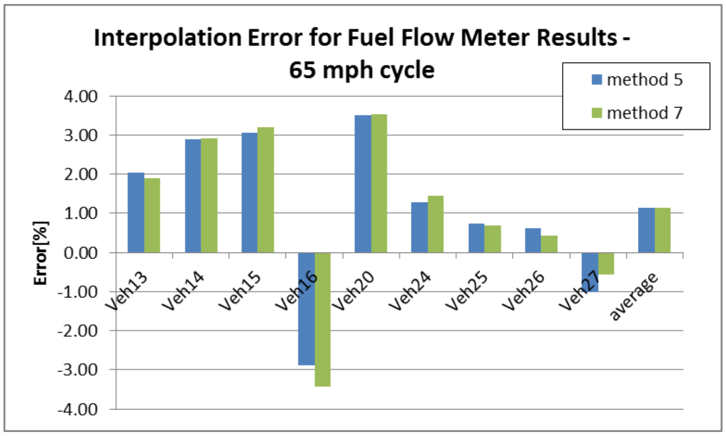


Figure 44. Interpolation errors on ISX 450+USP AMT powertrain map using fuel flow measurements on 65 mph cruise.

As an alternative to a global regression, an attempt was made to perform an interpolation between the two nearest points. For instance, in Figure 45, vehicle 15 (see Table 17) can be calculated using vehicle 19 and 23 using a simple linear interpolation. Interpolation errors can be reduced significantly, depending on the map location. In case of vehicle 15, error went down from 3% to 1.2%.

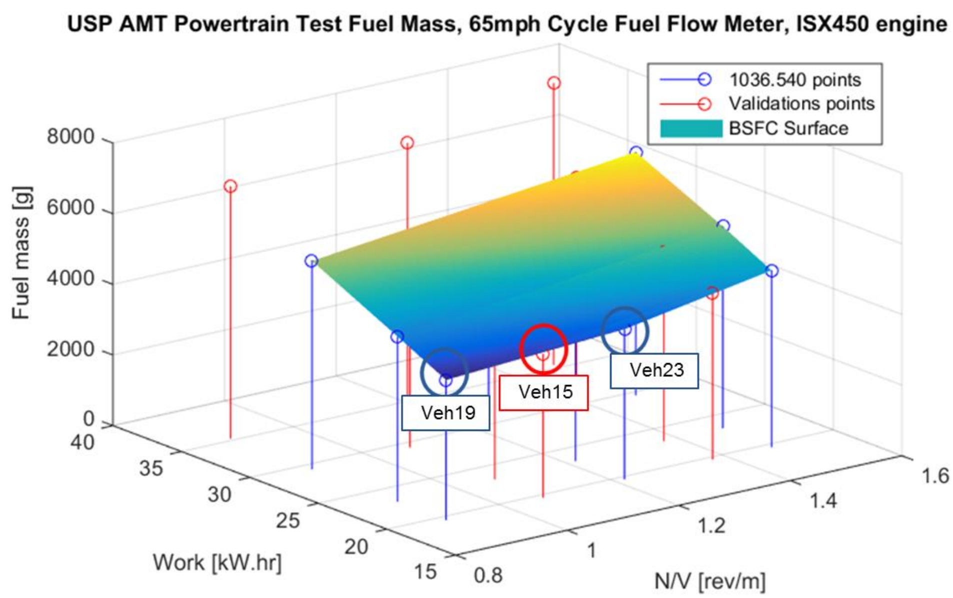


Figure 45. Local interpolation principle on ISX 450+USP AMT powertrain on 65 mph cruise cycle.

Table 17. Local interpolation results on ISX 450+USP AMT powertrain on 65 mph cruise cycle

65mph data									
PT map									
			Fuel Mass			Regress outputs			
vehicle	Powertrain	N/V	fuel flow	DEF C-Bal		fuel flow measurement			
	kWh	rev / mete	grams	grams		method #5	error	interpolated results	error
Veh13	29.32	1.07	5946.8	6001.0		6068.0	2.04%	6001.0	0.91%
Veh14	23.13	1.07	4740.0	4808.1		4877.4	2.90%	4802.4	1.32%
Veh15	19.60	1.07	4075.6	4201.0		4199.9	3.05%	4123.1	1.17%
Veh16	35.23	0.89	7142.7	7165.5		6936.8	-2.88%		
Veh17	29.30	0.89	5902.1	5941.0					
Veh18	23.05	0.89	4674.6	4787.4					
Veh19	19.52	0.89	3964.1	4088.2					
Veh20	35.44	1.22	7213.4	7065.6		7466.1	3.50%		
Veh21	29.52	1.22	6083.7	5963.2					
Veh22	23.18	1.22	4909.3	4856.5					
Veh23	19.61	1.22	4256.1	4205.5					
Veh24	29.59	1.38	6520.6	6412.1		6604.5	1.29%	6569.5	0.75%
Veh25	23.21	1.38	5360.2	5308.2		5399.2	0.73%	5396.4	0.67%
Veh26	19.65	1.38	4697.5	4608.0		4727.0	0.63%	4698.8	0.03%
Veh27	35.53	1.48	7966.1	7739.4		7884.9	-1.02%		
Veh28	29.53	1.48	6890.0	6745.8					
Veh29	23.18	1.48	5717.9	5673.8					
Veh30	19.63	1.48	4991.0	4935.8					

2.2.2.1.2 TC10 Powertrain mapping

Nine out of the 16 test vehicles defined in section 2.1.4.1.2 are used to map the powertrain behavior and 7 are used to test the interpolation calculations. Table 18 offers a reminder of the vehicle configurations tested as powertrain-in-the-loop in the VSI Laboratory. Figure 45 shows the surface generated by the vehicle configuration mapping points as well as the interpolation test points. In this instance, all of these points were collected on the transient cycle. Both on Table 18 and Figure 46, mapping points are in blue and validation points are in red.

Because validation points were not specifically selected for this study, they do not represent all interpolation conditions: all validation points except for T700 share either the same N/V ratio or cycle work with the map points and therefore only require interpolation in one dimension.

Table 18. TC10 powertrain test matrix

	M (kg)	C_DA	Crr (g/kg)	$M_{rotating}$ (kg)	r (m)	Rear Axle Ratio	Axle Eff. (%)	Calibration Mode: Econo (2), Default (1)	N/V (rev/m)
T700	33,130	7.04	5.84	1,134	0.4925	2.47	95.5	2	0.80
Veh 1	40,895	6.1	6.9	1,134	0.5	2.4	95.5	2	0.76
Veh 2	31,978	5.4	6.9	1,134	0.5	2.4	95.5	2	0.76
Veh 3	22,679	4.7	6.9	907	0.5	2.4	95.5	2	0.76
Veh 4	19,051	4	6.9	680	0.5	2.4	95.5	1	0.76
Veh 5	40,895	6.1	6.9	1,134	0.5	2.64	95.5	2	0.84
Veh 6	31,978	5.4	6.9	1,134	0.5	2.64	95.5	2	0.84
Veh 7	22,679	4.7	6.9	907	0.5	2.64	95.5	2	0.84
Veh 8	19,051	4	6.9	680	0.5	2.64	95.5	1	0.84
Veh 9	31,978	5.4	6.9	1,134	0.5	3	95.5	2	0.95
Veh 10	22,679	4.7	6.9	907	0.5	3	95.5	2	0.95
Veh 11	19,051	4	6.9	680	0.5	3	95.5	1	0.95
Veh 12	40,895	6.1	6.9	1,134	0.5	3.36	95.5	2	1.07
Veh 13	31,978	5.4	6.9	1,134	0.5	3.36	95.5	2	1.07
Veh 14	22,679	4.7	6.9	907	0.5	3.36	95.5	2	1.07
Veh 15	19,051	4	6.9	680	0.5	3.36	95.5	1	1.07

(pink)	Validation Points
(blue)	Mapping points

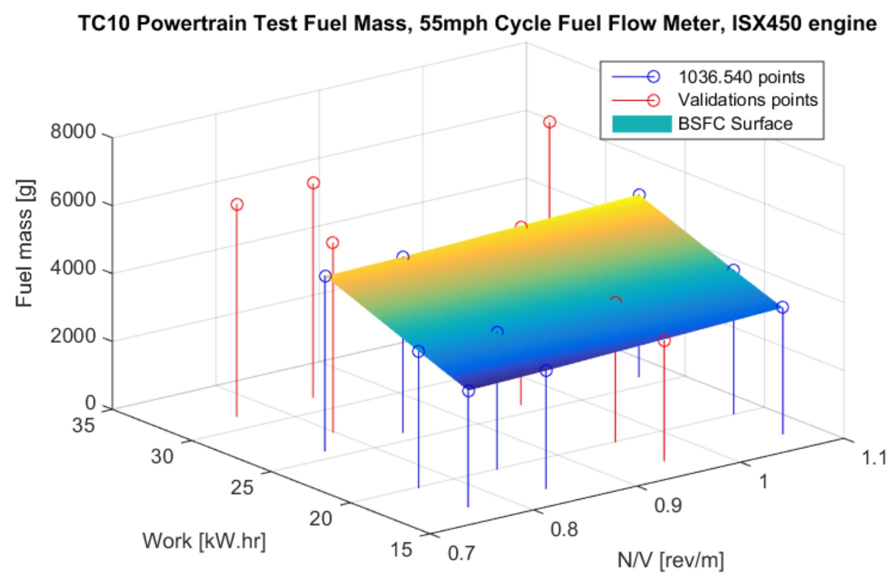


Figure 46. Fuel mass map for ISX 450+TC10 powertrain using fuel flow measurements on 55 mph cruise cycle.

Only two methods were assessed for the powertrain configuration: method 5 and 7 as defined in Table 15. Both methods are on average equivalent.

Interpolation errors vary with the type of drive cycles: errors are smaller on transient cycles (less than 1.5% and 0.5% on average), but larger on the 65 mph cruise cycles (3%). On this powertrain, the 55 mph cruise cycle interpolation errors are lower (1.5%) whereas they were up to 3% on the USP AMT. (See Figure 47, Figure 48, and Figure 49.

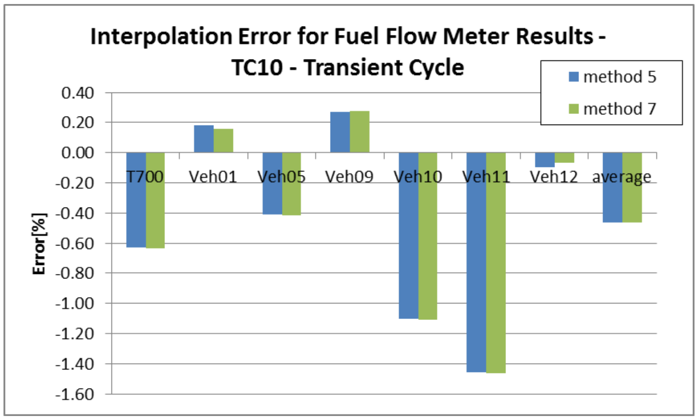


Figure 47. Interpolation errors on ISX 450+ TC10 powertrain map using fuel flow measurements on transient cycle.

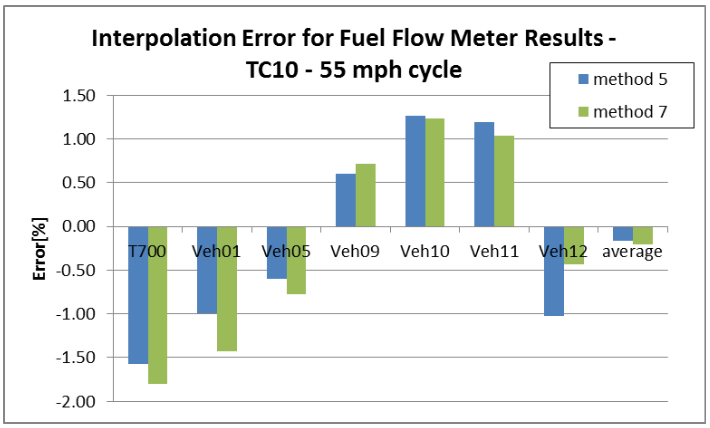


Figure 48. Interpolation errors on ISX 450+ TC10 powertrain map using fuel flow measurements on 55 mph cruise.

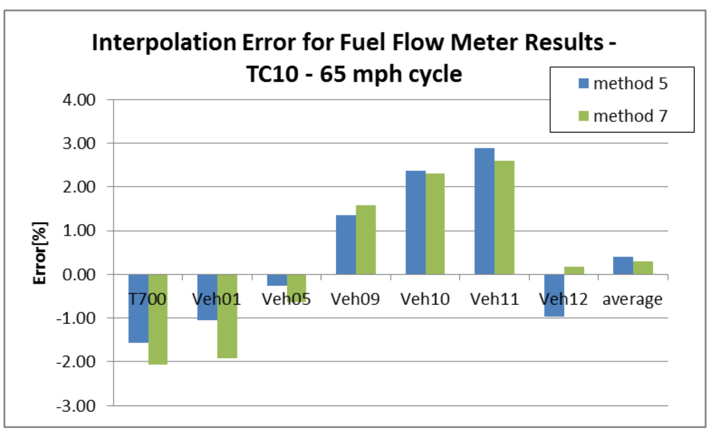


Figure 49. Interpolation errors on ISX 450+TC10 powertrain map using fuel flow measurements on 65 mph cruise.

As an alternative to a global regression, an attempt was made to perform an interpolation between the two nearest points. For instance in Figure 50, vehicle 9 (Table 19) can be calculated using vehicle 6 and 13 using a simple linear interpolation. Interpolation errors can be reduced depending on the map location. In case of vehicle 9, error went down from 1.4% to 1.0%.

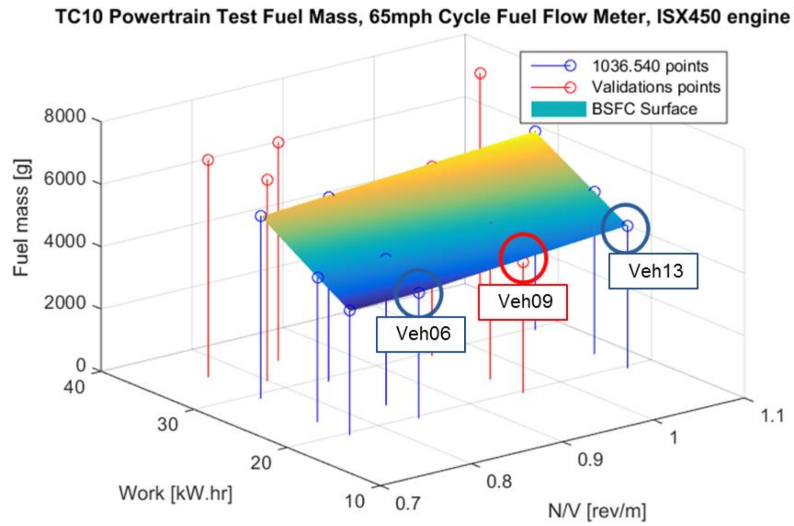


Figure 50. Local interpolation principle on ISX 450+TC10 powertrain on 65 mph cruise cycle.

Table 19. Local interpolation results on ISX 450+TC10 powertrain on 65 mph cruise cycle

65mph data								
PT map								
vehicle	Powertrain	N/V	fuel flow	DEF C-Bal	Regress outputs			
	kWh	rev / mete	grams	grams	fuel flow measurement			
T700	31.74	0.80	6469.6	6744.5	method #5	error	interpolated results	error
Veh01	34.74	0.76	6979.8	7119.0				
Veh02	29.12	0.76	5848.3	6075.2				
Veh03	23.02	0.76	4637.7	4814.0				
Veh04	19.56	0.76	3982.8	4158.8				
Veh05	34.67	0.84	7013.5	7237.1				
Veh06	29.25	0.84	5898.9	6041.3				
Veh07	23.08	0.84	4706.9	4893.8				
Veh08	19.58	0.84	4024.8	4224.6				
Veh09	29.39	0.95	6075.2	6161.6	6157.7	1.36%	6137.9	1.03%
Veh10	23.15	0.95	4868.8	5059.1	4984.2	2.37%	4962.8	1.93%
Veh11	19.61	0.95	4198.0	4371.6	4319.1	2.89%	4294.8	2.31%
Veh12	35.48	1.07	7522.3	7597.6				
Veh13	29.55	1.07	6376.8	6486.0				
Veh14	23.20	1.07	5218.7	5331.6				
Veh15	19.62	1.07	4564.8	4675.9				

2.2.2.2 Comparison of GEM results with ISX 450 powertrain experimental results

GEM 2.0RC17b was benchmarked against experimental data collected on the VSI Laboratory and described in section 2.1.3.2 and 2.1.4.1.2. These experiments were conducted the Cummins 15l ISX 450 engine and both the Eaton AMT as well as the Allison automatic transmission.

First the effect of some GEM settings was evaluated.

Engine accessories effect: GEM accounts for engine accessory loads whereas the engine tested in the VSI Laboratory was not fitted with any accessory: the alternator and air compressor was connected to the accessory belt but did not apply a load because tank air pressure was regulated externally and electrical loads are minimal on the powertrain.

Figure 51 shows how removing accessory loads from GEM help the match between GEM and experimental results when considering the powertrain map configuration. Match between the two methods is with 1% without loads whereas it was off by 3% with loads on the ARB cycle. The rest of the study will be performed with no accessory loads in GEM.

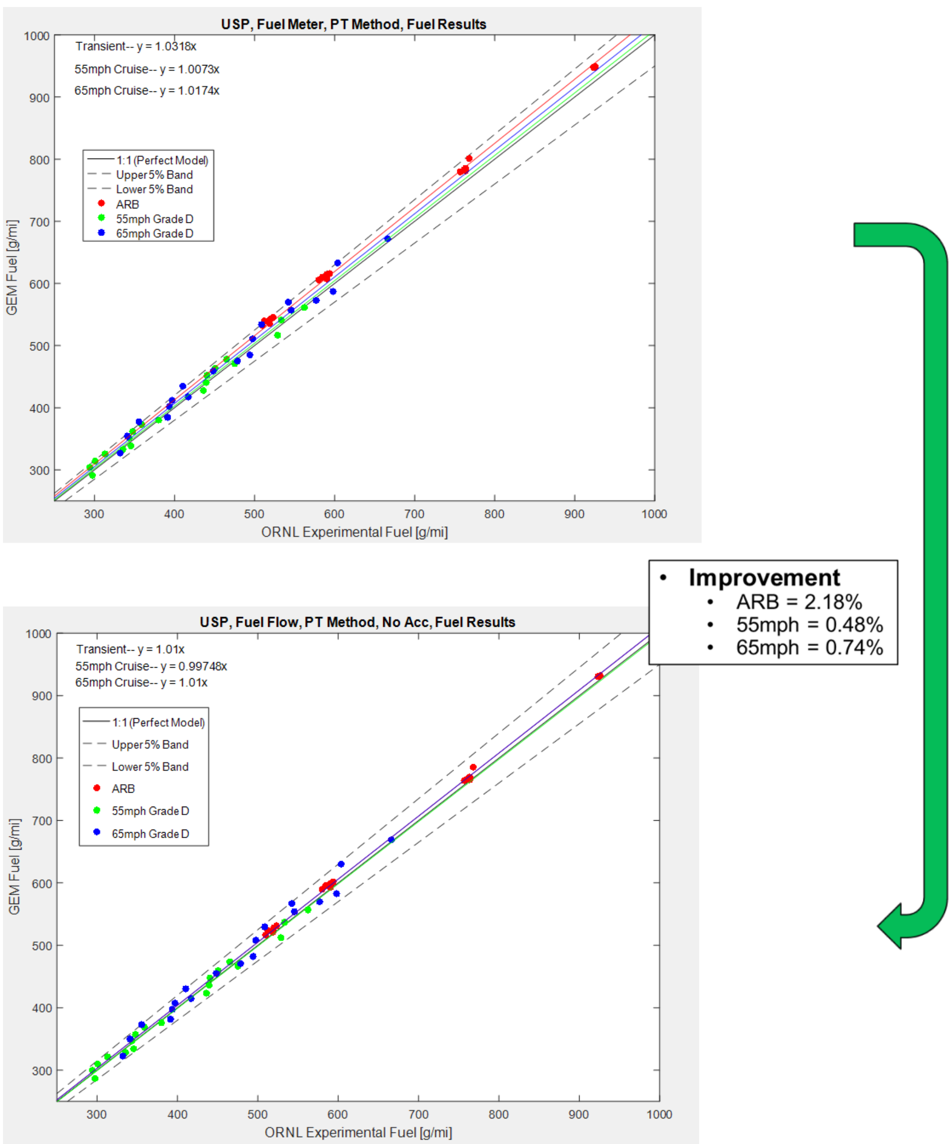


Figure 51. Effect of engine accessory load on match between GEM powertrain map results and experimental powertrain test results.

Fueling map, motoring torque behavior: The engine steady-state fuel map is only defined down to zero torque. GEM interpolates fueling between the zero torque point and full motoring torque for each speed on the map. The effect of one additional point between zero torque and full motoring torque was investigated.

The results are shown in Figure 52. It seems to help matching GEM with experimental data. The rest of the study will not use that option as this is a significant departure from the default GEM model.

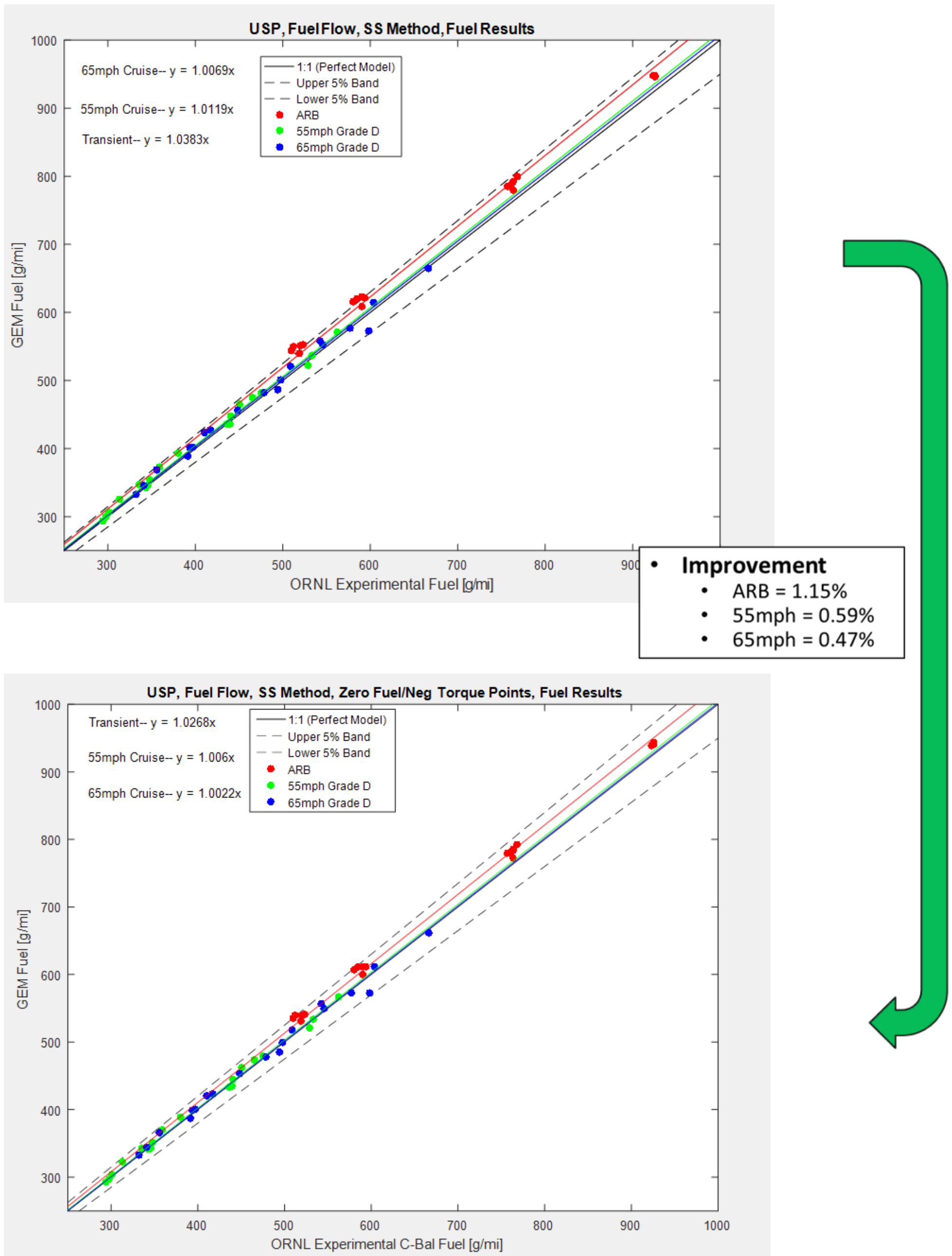


Figure 52. Effect of fueling map behavior during motoring operation on match between GEM steady-state engine map results and experimental powertrain test results.

Driver effect: VSI experimental tests were conducted with a variant of the GEM driver in order to quiet its activity during cruise cycle where the speed profile is not perfectly smooth like in the WHVC.

The effect of the driver was calculated and shown in Figure 53. The modified GEM driver effect, which is less than 1%, can help with the ARB but can be detrimental on cruise cycles. Therefore, the rest of the study will only consider the GEM model with its original driver, whereas experimental driver used the modified driver.

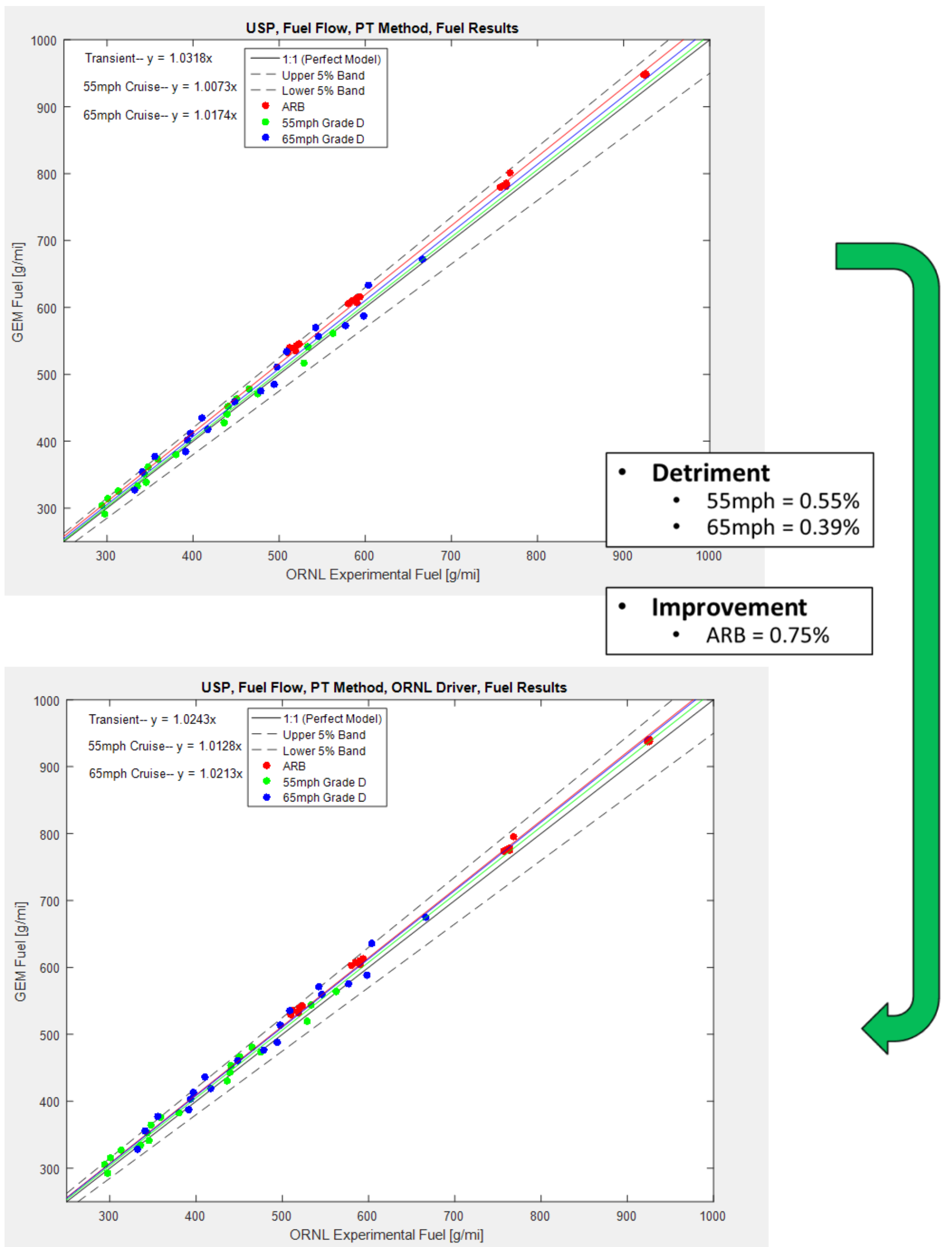


Figure 53. Effect of GEM driver on match between GEM powertrain map results and experimental powertrain test results.

Effect of cycle average map size: Cycle average maps are typically based on 9 points. Since 18 different vehicle configurations were tested during powertrain testing in the VSI Laboratory, the use of all 18 points to define the map was evaluated and compared to a 9-point map.

The outcome is inconclusive: the difference between the two approaches is less than 0.5%, it helps a little bit (0.3% and 0.5%) on cruise cycles and makes it a bit worse (0.25%) on the transient cycle (see Figure 54).

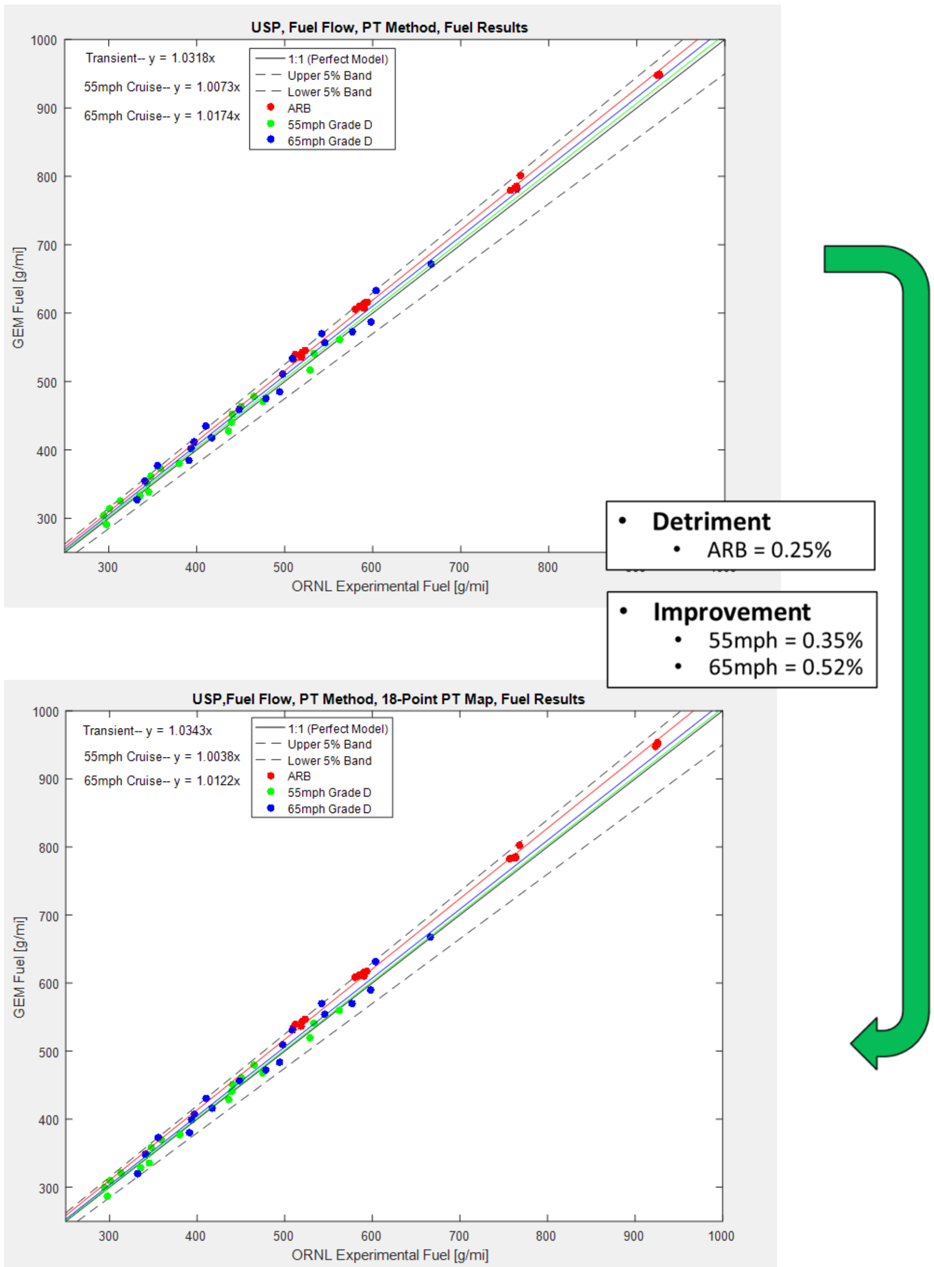


Figure 54. Effect of powertrain cycle average map size on match between GEM powertrain map results and experimental powertrain test results.

2.2.2.2.1 Comparison of powertrain cycle average GEM results with experimental powertrain results

First, GEM was run with the powertrain cycle average option: GEM runs a generic powertrain model to calculate the transmission positive work and the N/V ratio for the current drive cycle and vehicle configuration. It then feeds these two values into an experimentally derived cycle average map of the fuel mass consumed by that powertrain for each drive cycle.

This output of GEM is compared with results obtained while testing the same powertrain inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Thanks to the same distance compensation feature implemented in GEM and the powertrain testing in the VSI Laboratory, we get a perfect match between GEM and experimental results. (See Figure 55.)

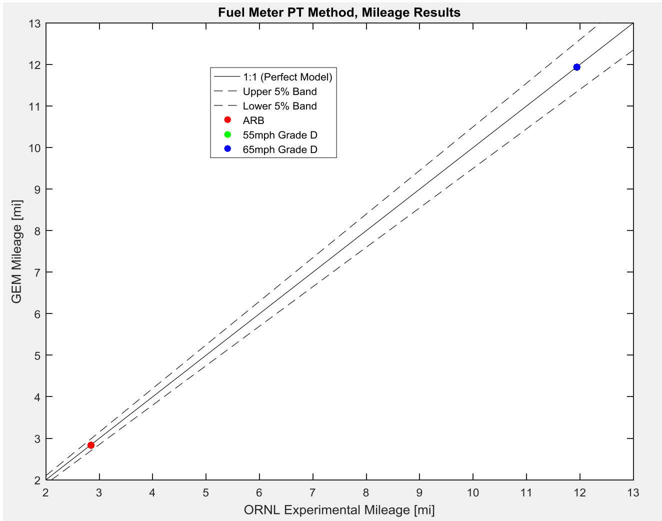


Figure 55. Comparison of mileage results obtained with GEM powertrain cycle average option, against powertrain experimental results.

Even though distance matches perfectly between GEM and experimental results, transmission output work does not exhibit such a good match on cruise cycles where the difference is 2% to 3%, whereas the transient cycle match is much better (a difference of less than 1%), as shown in Figure 56. This could be due to the use of a generic powertrain in GEM instead of the engine and transmission that correspond to the exact powertrain under test. Yet the work error remains small and when used as an input in the powertrain cycle average map method, it has a minimal effect on the fuel mass estimation, as shown in Figure 57.

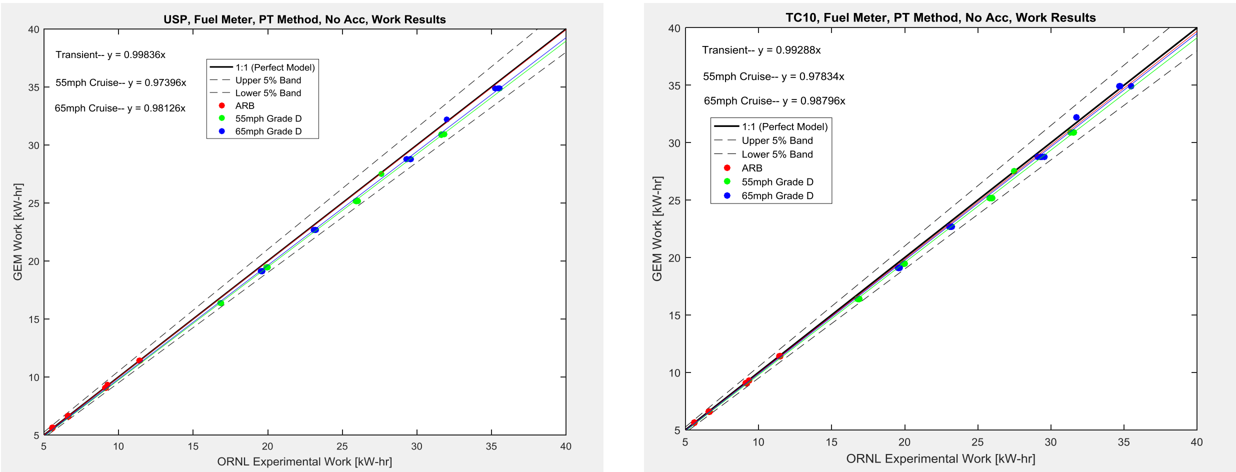


Figure 56. Comparison of transmission output work results obtained with GEM powertrain cycle average option, against powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

Fuel mass results derived from fuel flowmeter measurements matched very well: the difference is less than 1% on all cycles for the USP transmission and about 2% for the TC10 transmission. (See Figure 57.)

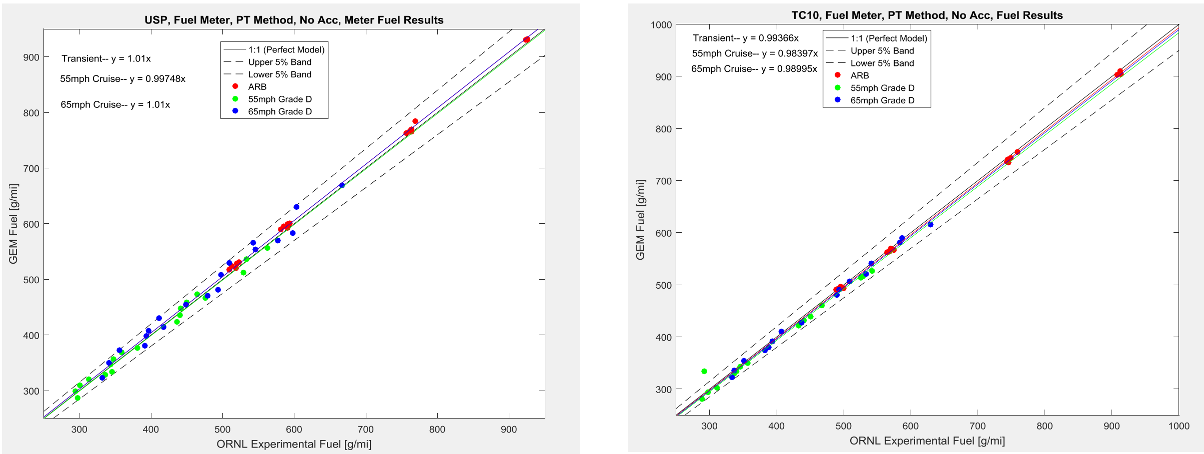


Figure 57. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM powertrain cycle average option, against powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

Fuel mass results derived from the carbon balance calculation matched very well: the difference is about 1% on all cycles for the USP transmission and less than 2% for the TC10 transmission. (See Figure 58.)

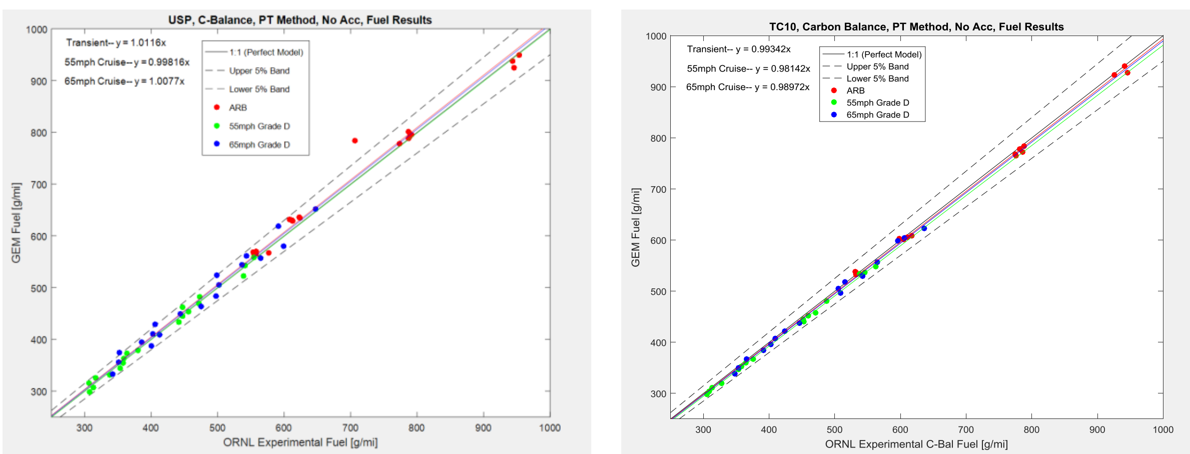


Figure 58. Comparison of carbon balance based fuel mass estimation results obtained with GEM powertrain cycle average option, against powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.2.2 Comparison of steady-state engine map GEM results with experimental powertrain results

GEM was also run with the steady-state engine map option: the engine steady-state operation is characterized by a traditional speed and load steady-state fuel map, and is passed into GEM using the engine input file. The GEM model also runs a complex model of the transmission and its controls as well as the rest of the vehicle to estimate overall fuel consumption.

This output of GEM is compared with results obtained while testing the same powertrain inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Transmission output work exhibits a 2% to 3% mismatch on cruise cycles and less than 1% on transient cycle, as experienced on the powertrain cycle average map method. See Figure 59.

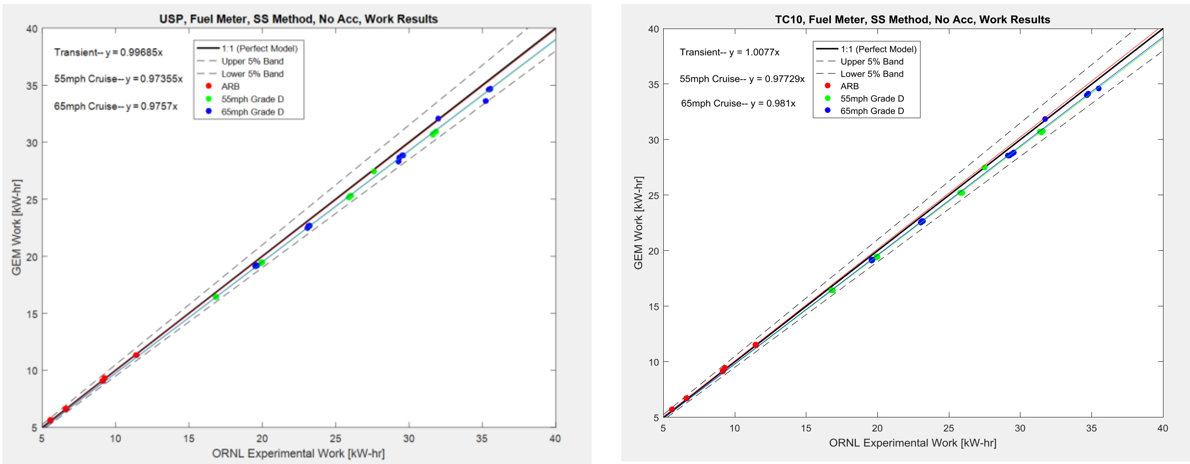


Figure 59. Comparison of transmission output work results obtained with GEM steady-state engine map option, against powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

Fuel mass results derived from fuel flowmeter measurements matched very well for the USP transmission: the difference is less than 0.5% on cruise cycles and 2% on transient cycle but the match is not as good for the TC10 transmission: around 2% for cruise cycles and almost 10% on the transient cycle. (See Figure 60.)

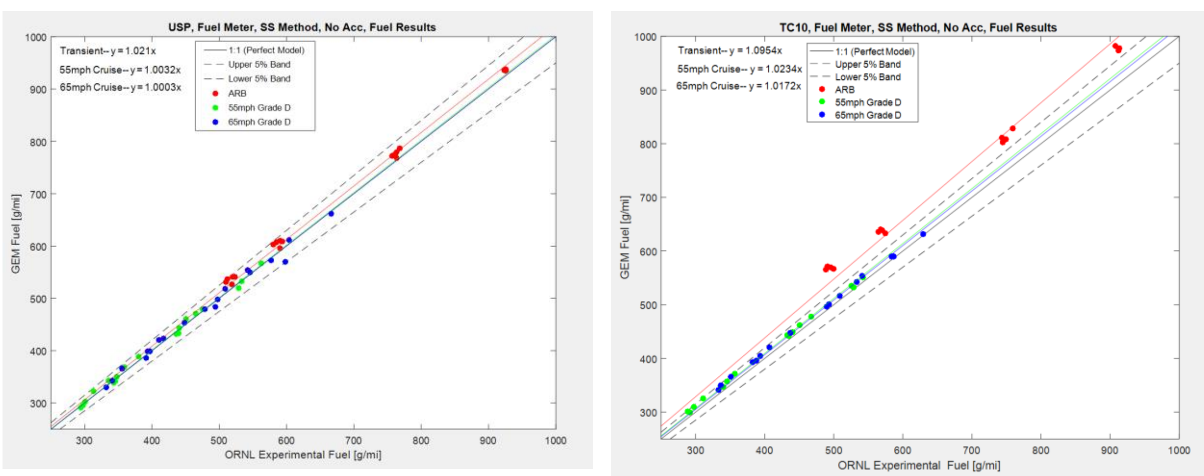


Figure 60. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM steady-state engine map option, against powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.2.3 Comparison of engine cycle average GEM results with experimental powertrain results

GEM was run with the engine cycle average map option: GEM runs the steady-state engine map to calculate engine work and N/V ratio (average engine speed over average vehicle speed), and these two values are fed to an experimentally derived cycle average map of the fuel mass consumed by this engine for each drive cycle.

This output of GEM is compared with results obtained while testing the same powertrain inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Cycle-average map and steady-state map used the same work, so the work comparison study is not duplicated in this section (see section 2.2.2.2.2 for work comparison).

Fuel mass results derived from fuel flowmeter measurements matched very well with for the USP transmission: the difference is less than 1.5% for all cycles. For the TC10 transmission: cruise cycles results are very good (within 0.6% of experiment) but the transient behavior is more than 12% off. (See Figure 61.)

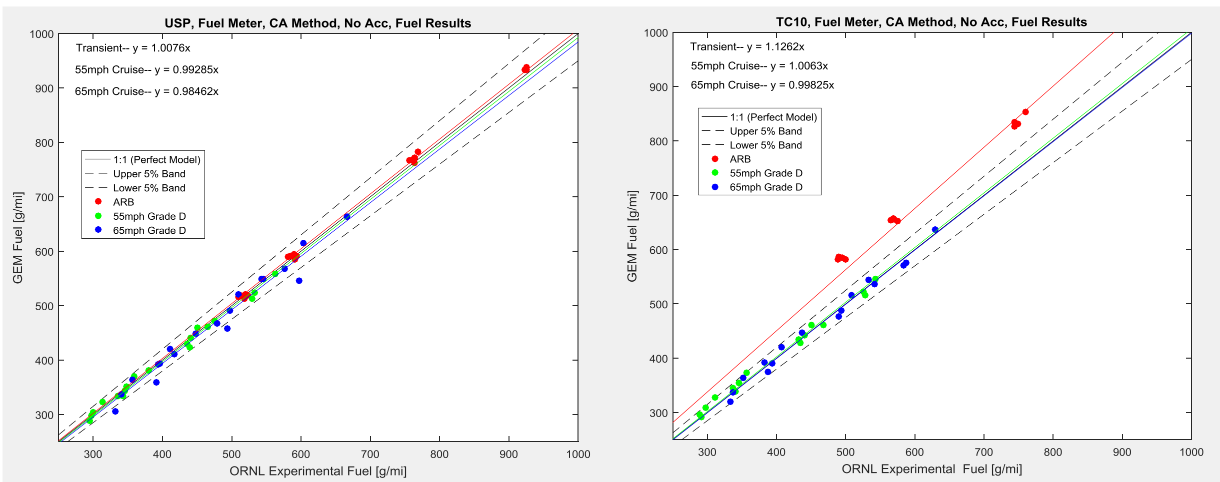


Figure 61. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM engine cycle average option, against powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.2.4 Summary of comparison of GEM results with experimental powertrain results

GEM results for each method were summarized based on the linear regression coefficient that fits through all vehicle configurations tested in this study (between 15 and 18, depending on the transmission). This way it facilitates the comparison between methods, although it might not capture the fact that one vehicle configuration (or more) might be an outlier and might not be well represented by the methods even though, overall, the match is satisfactory.

Using experimental powertrain results as the reference, the difference with GEM results for several key variables (work, fuel mass, and CO_2 mass) was calculated to compare methods with each other.

Work estimation is pretty consistent between methods, but it seems to consistently underestimate cruise cycle work by about 2%, as shown in Figure 62. The average listed in the graph is an absolute value.

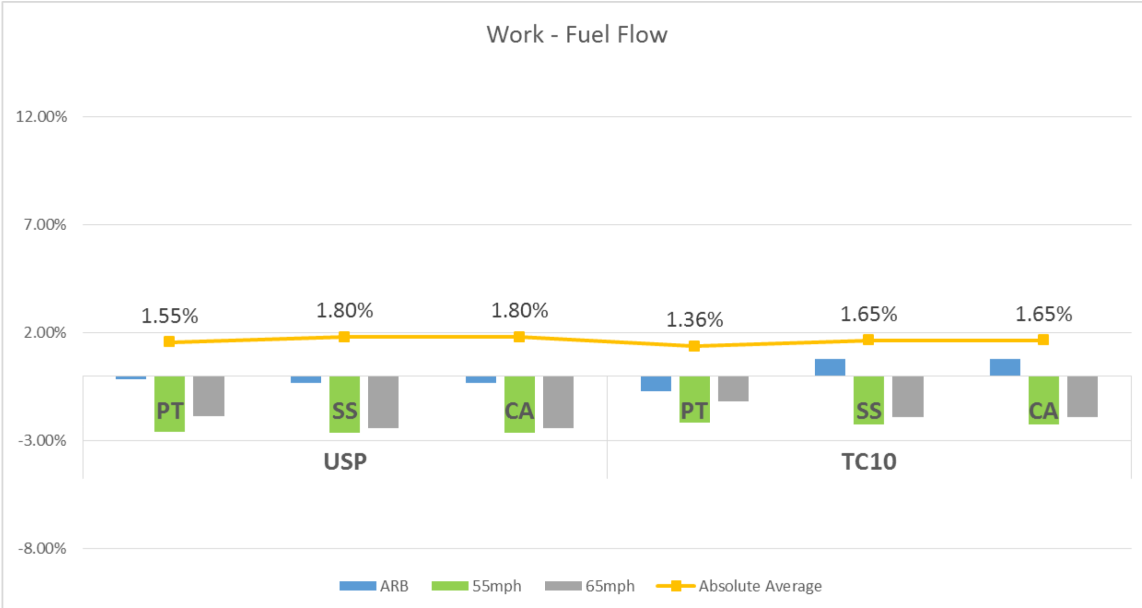


Figure 62. Comparison of transmission output work results obtained with GEM, against powertrain experimental results.

Fuel consumption estimation works well when based on fuel flow measurements with all three GEM methods for the AMT with an average error of less than 1%, but the automatic transmission results are much worse, especially on the transient cycle. (See Figure 63.) This might be due to inaccuracies in the automatic transmission model which could be corrected with more time to calibrate the model to match the experiment.

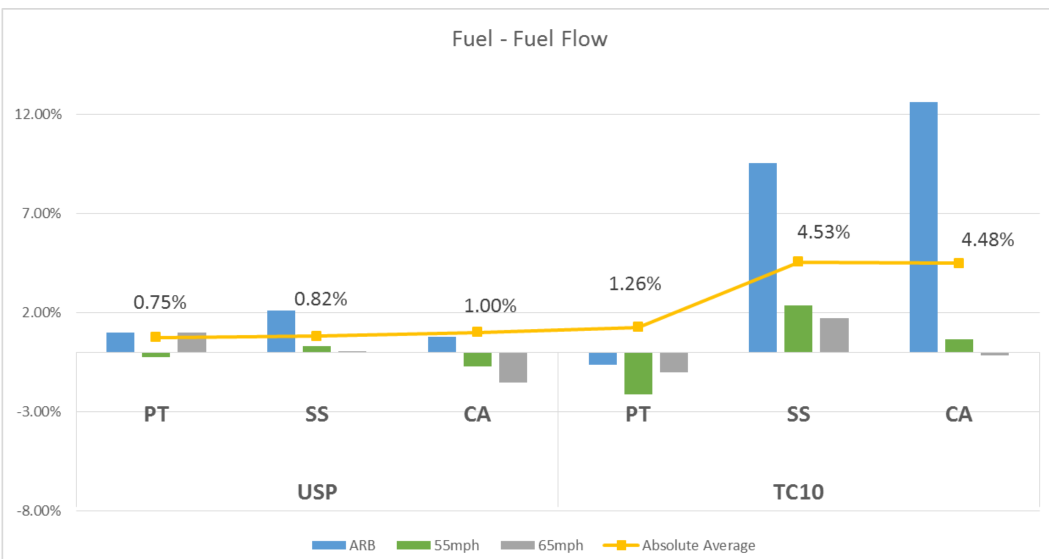


Figure 63. Comparison of fuel mass results obtained with GEM, against powertrain experimental results (using fuel flow measurements).

Estimation of fuel consumption based on carbon balance is less accurate than estimation of fuel consumption based on fuel flow measurement. The powertrain cycle average map performs better than the other methods. (See Figure 64.)

The automatic transmission results over the transient drive cycle are still significantly worse than the AMT when looking at the steady-state engine map and engine cycle average map. Both methods rely on the same transmission model; this might point toward some inaccuracies in the model parametrization.

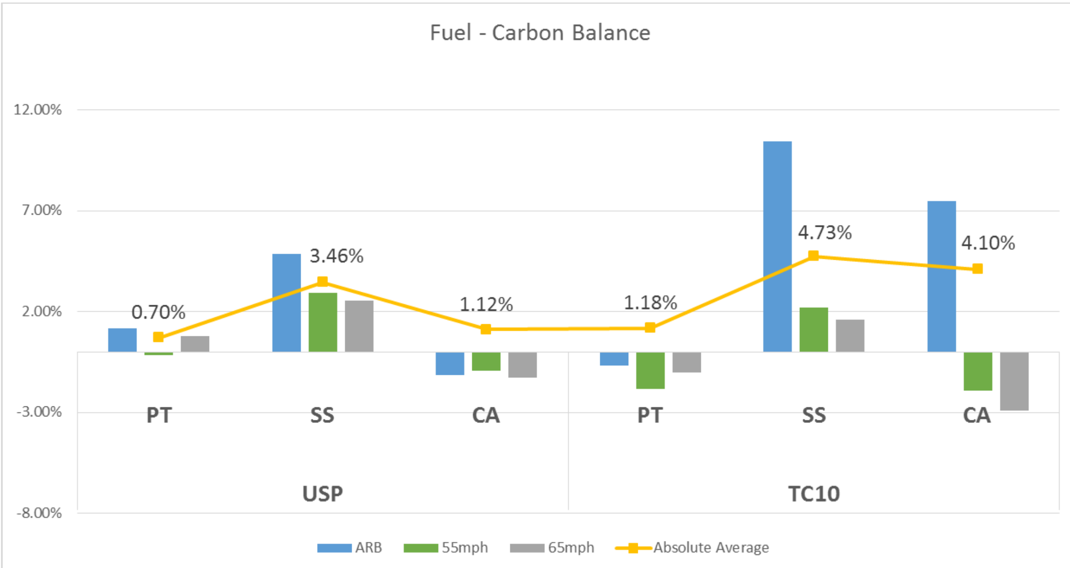


Figure 64. Comparison of fuel mass results obtained with GEM, against powertrain experimental results (using carbon balance calculations).

2.2.2.3 Comparison of ISX 400 GEM results with ISX 400 powertrain experimental results

GEM 2.0RC17b was benchmarked against experimental data collected on the VSI Laboratory and described in section 2.1.3.2 and 2.1.4.2.1, where a 15l ISX engine with a 400 hp calibration was used instead of the 450 hp calibration used previously. (See Section 2.2.2.2.)

2.2.2.3.1 Comparison of steady-state ISX 400 engine map GEM results with experimental ISX 400 powertrain results

GEM was run with the steady-state engine map option, where the ISX 400 engine input file is identical to the ISX 450 engine input file except for the engine torque curve, which corresponds to the ISX 400 calibration.

GEM outputs are compared with experimental results obtained while testing the same powertrain (ISX 400+USP or ISX 400+TC10) inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Transmission output work exhibits a 2% to 3% mismatch on cruise cycles and less than 1% on the transient cycle. (See Figure 65.)

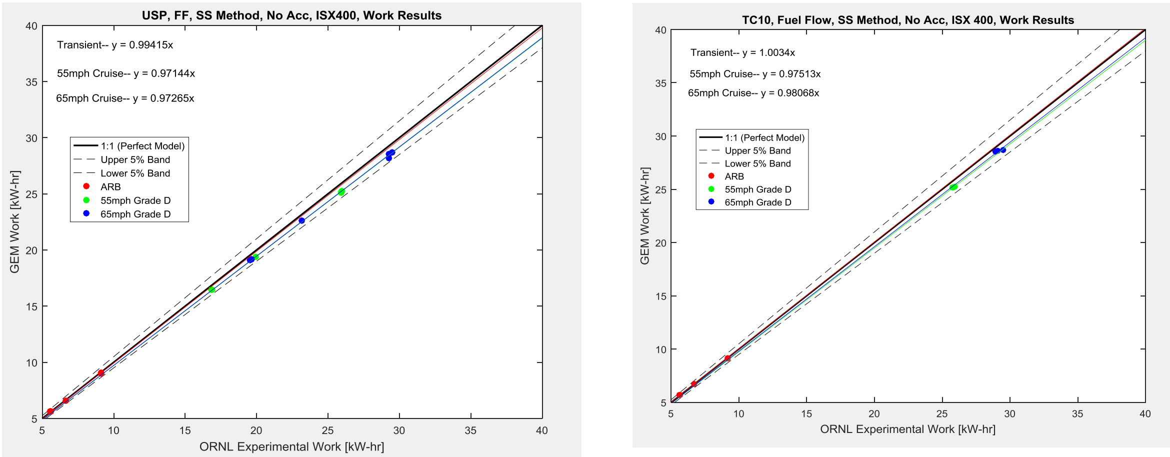


Figure 65. Comparison of transmission output work results obtained with GEM steady-state ISX 400 engine map option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

Fuel mass results derived from fuel flowmeter measurements matched very well for the USP transmission: the difference is less than about 1% for all cycles. For the TC10 transmission, the match is excellent on cruise cycles (within 1%) but is about 9% on the transient cycle. (See Figure 66.)

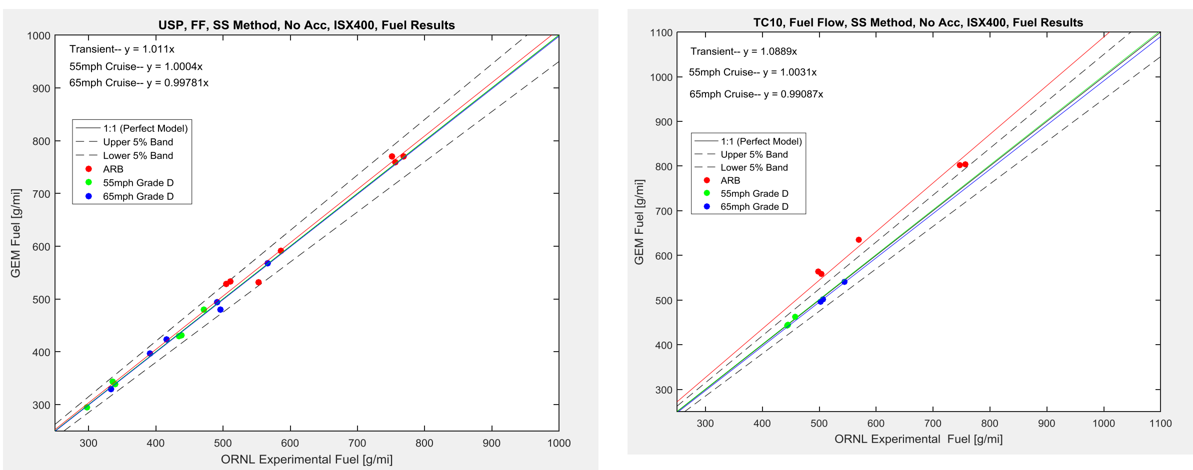


Figure 66. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM steady-state ISX 400 engine map option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.3.2 Comparison of ISX 400 engine cycle average GEM results with experimental ISX 400 powertrain results

GEM was run with the engine cycle average option, where the ISX 400 engine input file contains the cycle average map extracted from experimental results described in 2.1.5.3.2.

GEM simulation outputs are compared with experimental results obtained while testing the same powertrain (ISX 400+USP or ISX 400+TC10) inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Fuel mass results derived from fuel flowmeter measurements matched very well for the USP transmission on the transient and 55 mph cruise cycle (the difference is less than 1.0%), but the 65 mph cruise cycle exhibits an error or 3% due to a couple of outlier points. For the TC10 transmission, cruise cycles results are within 3.5% of experiment but the transient behavior is more than 12% off. (See Figure 67.)

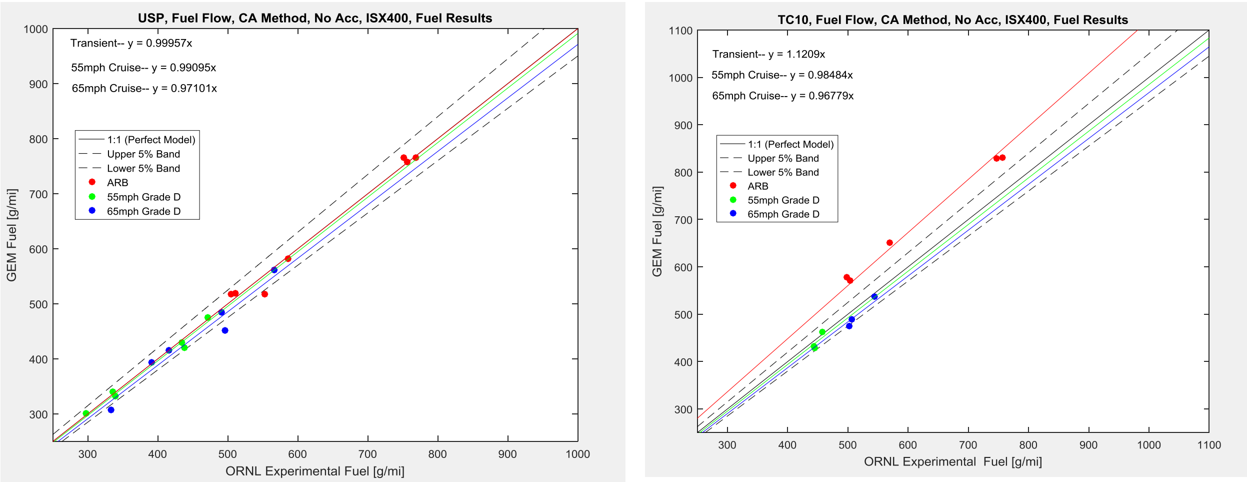


Figure 67. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM ISX 400 engine cycle average option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.3.3 Summary of Comparison of GEM results with experimental ISX 400 powertrain results

GEM results for each method were summarized based on the linear regression coefficient that fits through all vehicle configurations tested in this study. We cannot compare powertrain cycle average method for the ISX 400 because the ISX 400 powertrain was not mapped for the cycle average method.

Work estimation is pretty consistent between methods. It seems to be consistently underestimating cruise cycle work by about 2% to 3% on cruise cycles but is within 1% on the transient cycle, as shown in Figure 68. The average listed in the graph is an absolute value.

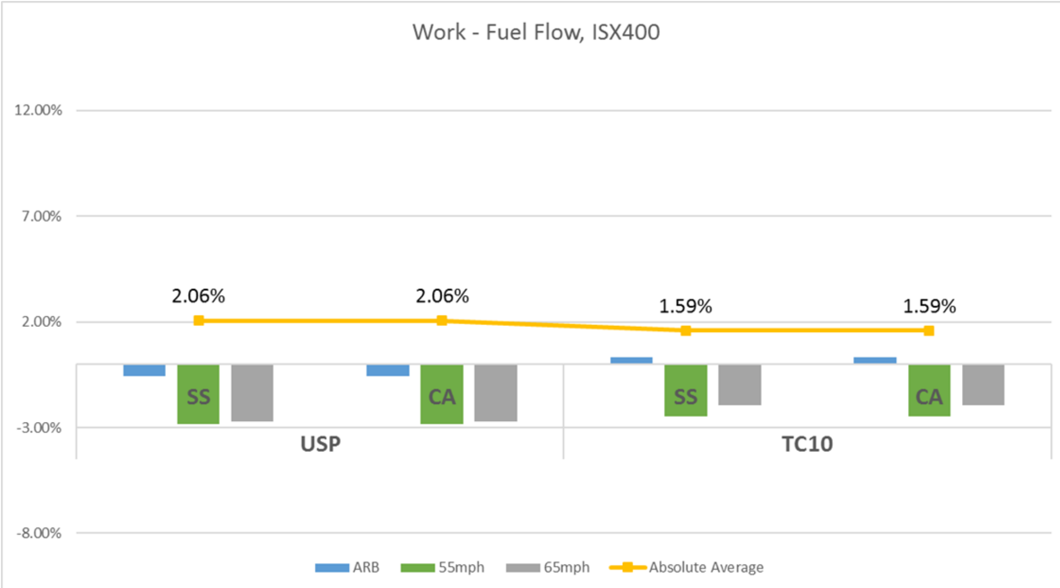


Figure 68. Comparison of transmission output work results obtained with GEM ISX 400 model, against ISX 400 powertrain experimental results.

For fuel mass estimation, engine cycle average method errors are larger than the steady-state method, but both methods are within 3%. (See Figure 69). As mentioned for the ISX 450 case, ISX 400 transient cycle results are much less accurate (up to 12%) for the automatic transmission, which is expected to be improved by further refinement of the GEM transmission model.

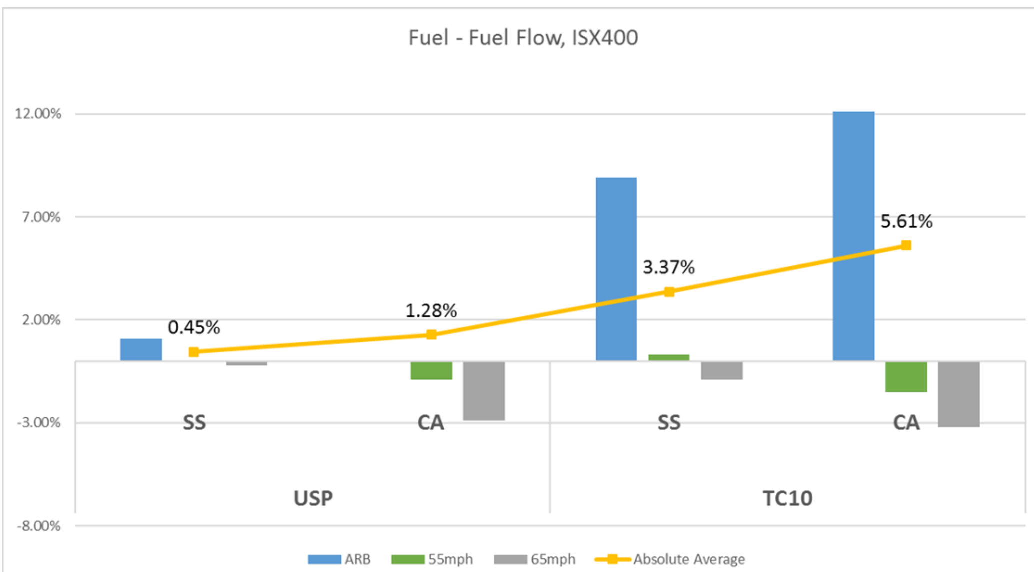


Figure 69. Comparison of fuel mass results obtained with GEM ISX 400 model, against ISX 400 powertrain experimental results.

2.2.2.4 Comparison of ISX 450 GEM results with ISX 400 powertrain experimental results

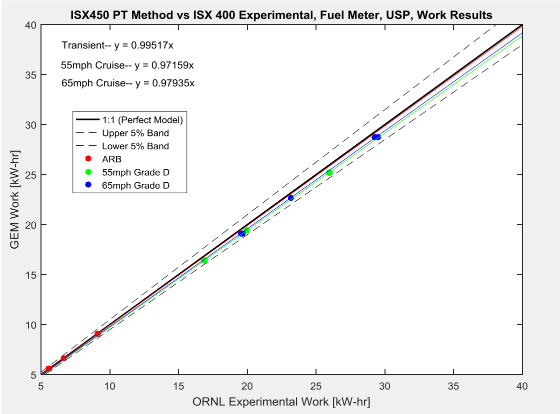
GEM 2.0RC17b was benchmarked against experimental data collected on the VSI Laboratory and described in section 2.1.4.2.1 and 2.1.4.2.2 where a 15l ISX engine with a 400 hp calibration was used instead of the 450 hp calibration used previously in this study.

This section compares GEM results obtained with the ISX 450 engine model to quantify whether that model can represent child ratings of the same engine.

2.2.2.4.1 Comparison of ISX 450 powertrain cycle average GEM results with experimental ISX 400 powertrain results

First, GEM was run with the powertrain cycle average option. The powertrain map was generated with the ISX 450 engine. The output of GEM is compared with results obtained while testing the powertrain consisting of the ISX 400 engine and the same transmission defined in GEM.

Difference on work is in within 3% for all cycles, as shown in Figure 70.



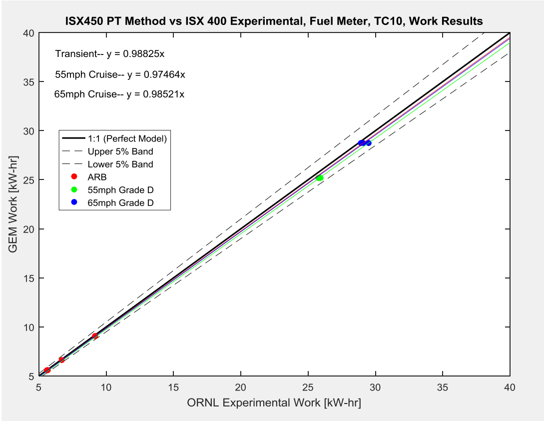


Figure 70. Comparison of transmission output work results obtained with GEM ISX 450 powertrain cycle average option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

Fuel mass results derived from fuel flowmeter measurements matched very well for the USP transmission: the difference is less than 2% on all cycles. Errors increase up to 4.5% for the TC10 transmission. (See Figure 71.)

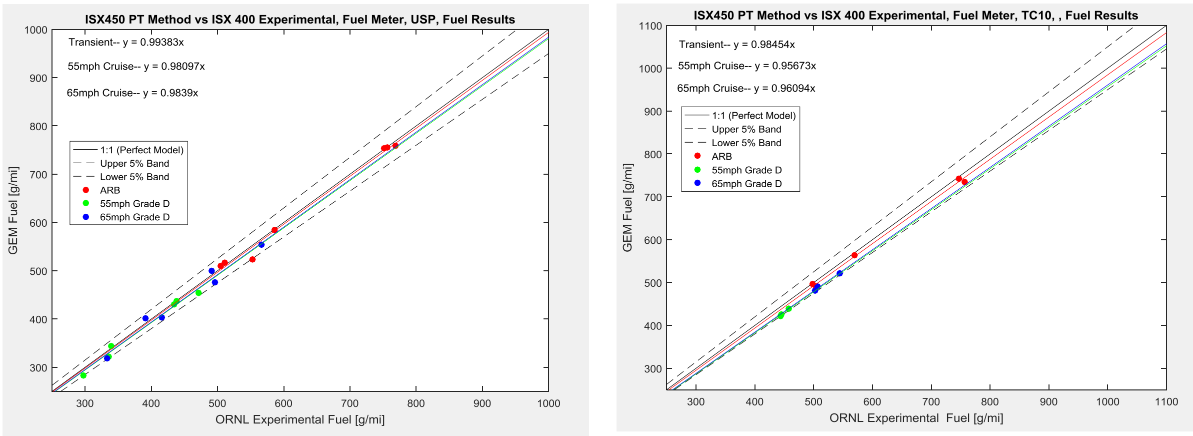


Figure 71. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM ISX 450 powertrain cycle average option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.4.2 Comparison of ISX 450 steady-state engine map GEM results with experimental ISX 400 powertrain results

GEM was run with the ISX 450 steady-state engine map option. GEM outputs are compared with experimental results obtained while testing the ISX 400 powertrain (ISX 400+USP or ISX 400+TC10) inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Transmission output work exhibits a 2% to 3% mismatch on cruise cycles and less than 1% on transient cycle. (See Figure 72.)

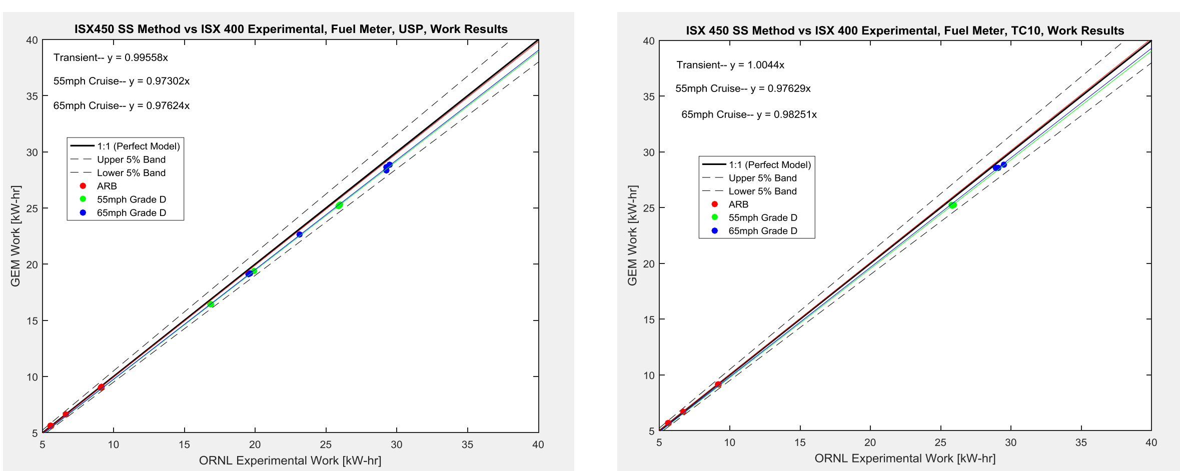


Figure 72. Comparison of transmission output work results obtained with GEM ISX 450 steady-state engine map option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

Fuel mass results derived from fuel flowmeter measurements matched very well for the USP transmission: the difference is less than 0.5% on cruise cycles and 2% on the transient cycle. For the

TC10 transmission, the match is excellent on cruise cycles (within 1%) but is about 10% on the transient cycle. (See Figure 73.)

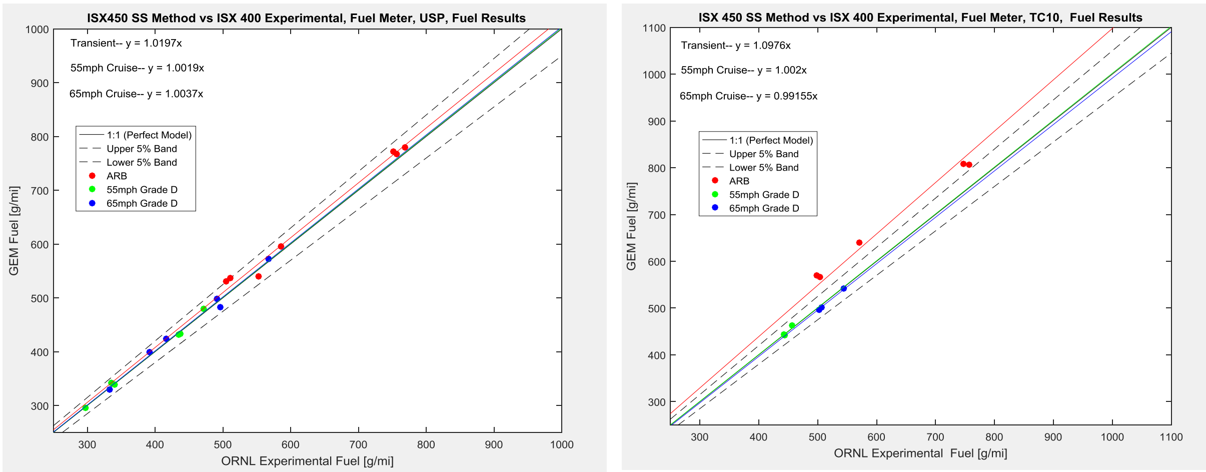


Figure 73. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM ISX 450 steady-state engine map option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.4.3 Comparison of ISX 450 engine cycle average GEM results with experimental ISX 400 powertrain results

GEM was run with the engine cycle average option, where the ISX 450 engine input file contains the cycle average map extracted from experimental results described in 2.1.5.2.2.

GEM simulation outputs are compared with experimental results obtained while testing the ISX 400 powertrain (ISX 400+USP or ISX 400+TC10) inside the VSI Laboratory operating in powertrain-in-the-loop mode emulating the same vehicle configurations defined in GEM.

Fuel mass results derived from fuel flowmeter measurements matched very well for the USP transmission on the transient cycle (the difference is less than 1%) and the match is a reasonable 3% on cruise cycles. For the TC10 transmission: cruise cycles results are within 3% of experiment, but the transient behavior is 13% off. (See Figure 74.)

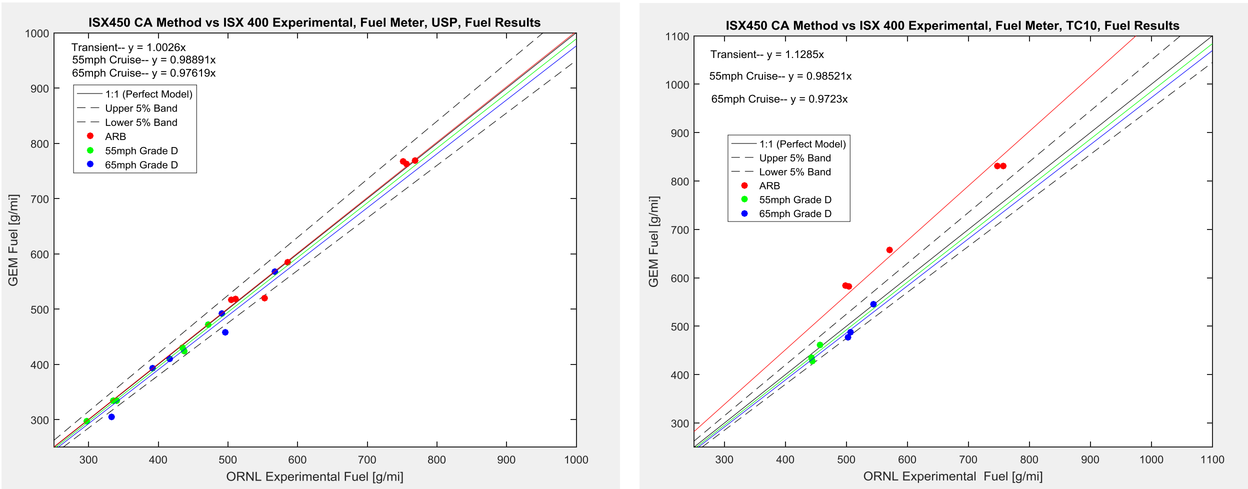


Figure 74. Comparison of fuel flowmeter based fuel mass estimation results obtained with GEM ISX 450 engine cycle average option, against ISX 400 powertrain experimental results (USP results on left hand side, TC10 results on right hand side).

2.2.2.4.4 Summary of Comparison of GEM ISX 450 results with experimental ISX 400 powertrain results

GEM results for each method were summarized based on the linear regression coefficient that fits through all vehicle configurations tested in this study.

Work estimation is pretty consistent between methods, but it seems to consistently underestimate cruise cycle work by about 2%, as shown in Figure 75. The average listed in the graph is an absolute value.

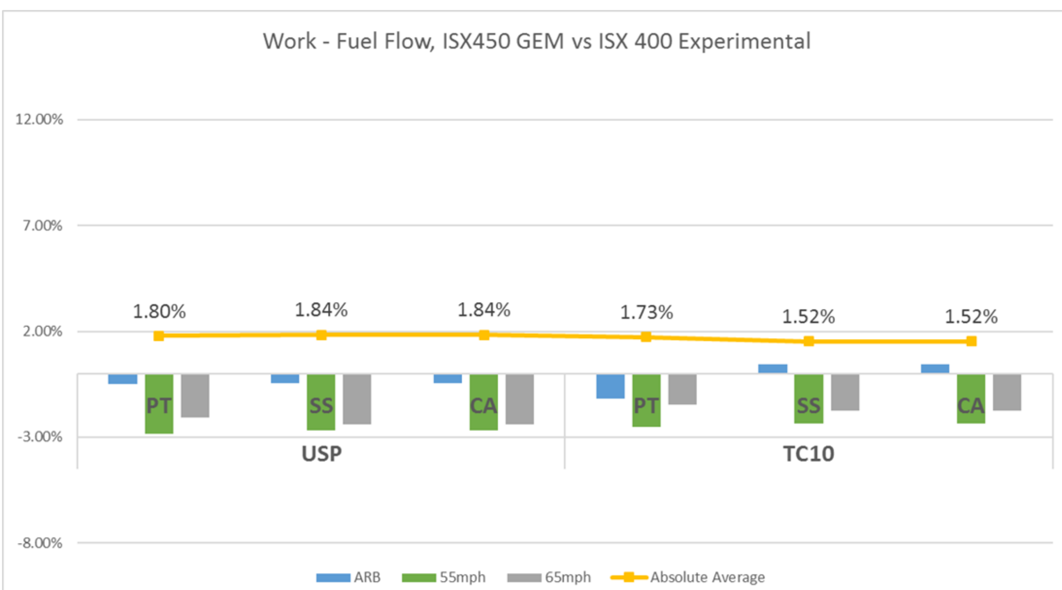


Figure 75. Comparison of transmission output work results obtained with GEM (using ISX 450 engine data), against ISX 400 powertrain experimental results.

Fuel consumption estimation works well when based on fuel flow measurements with all three GEM methods for the AMT with an average error around 1%, but the automatic transmission results get worse (above 3%), especially on the transient cycle. (See Figure 76). This might be due to inaccuracies in the automatic transmission model, which could be corrected with more time to calibrate the model to match the experiment.

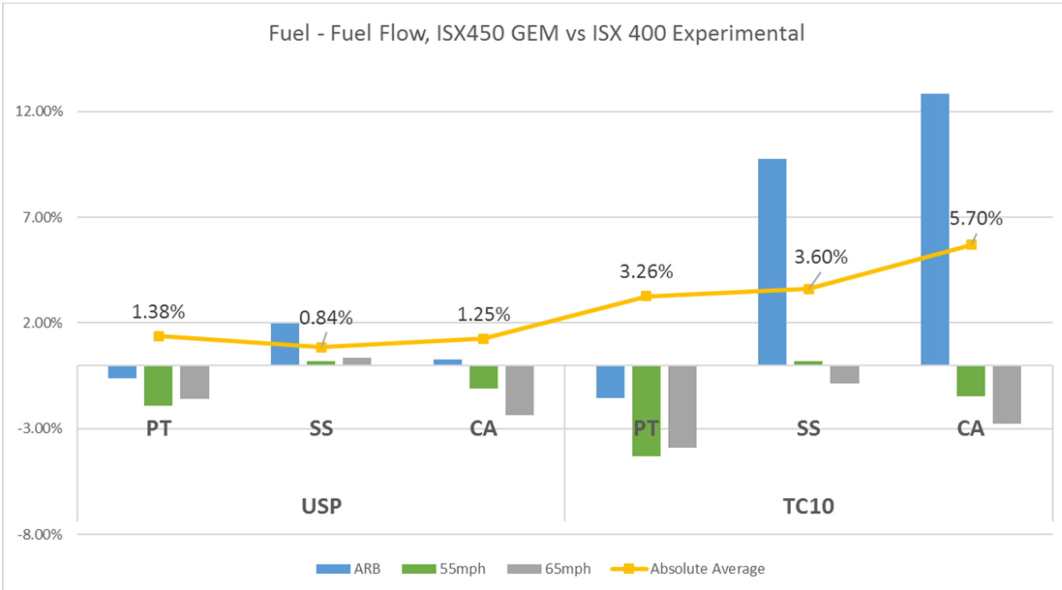


Figure 76. Comparison of fuel mass results obtained with GEM (using ISX 450 engine data), against ISX 400 powertrain experimental results.

2.2.3 Data analysis for combined steady-state map and alternate engine-mapping procedure (i.e., "Hybrid Approach")

The goal of this study is to identify the minimum number of points required to map the engine steady-state operation without losing fidelity when estimating CO_2 mass on the 55 mph and 65 mph cruise cycles with road grade.

The 1036.535 procedure specifies 143 points (13 different speeds and 11 load conditions), but not all of those points will be encountered when running cruise cycles, so it will offer some opportunity to reduce the number of points to be collected when mapping the engine, without affecting the model fidelity.

First, 9 vehicle configurations were selected for each powertrain (Allison TC10 automatic transmission and the Eaton USP AMT). These 18 vehicle configurations correspond to the powertrain mapping points described in sections 2.2.2.1.1 and 2.2.2.1.2. They cover a wide ranging of vehicles conditions that will force the engine to operate in a variety of speed and loads such that effects of a sparser fuel map will be more evident. Figure 77 is a plot of N/V against work, showing the combinations for all test vehicle used in this study.

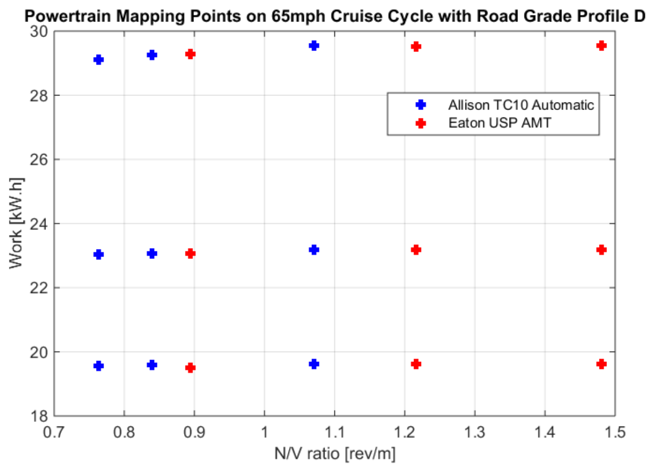


Figure 77. (N/V, Work) vehicle combinations selected for this study.

For each powertrain, cumulative engine speed and load operation over the nine vehicle configurations was plotted on the same graph to better visualize where the engine operates the most. Therefore, map areas are highlighted where a fine resolution is required and where it can be sparser. (See Figure 78 for the Eaton USP transmission and Figure 79 for the Allison automatic transmission.)

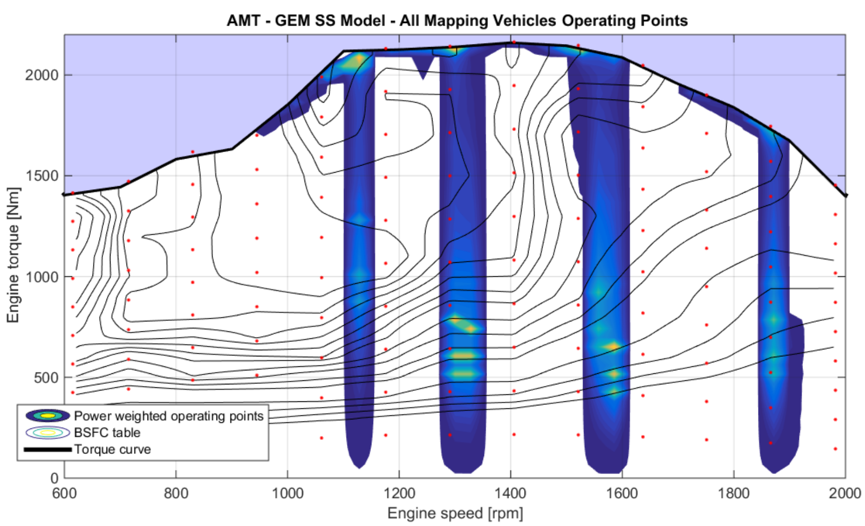


Figure 78. Engine operation during 55 mph and 65 mph cycle for 9 different vehicle configuration fitted with an automated manual transmission.

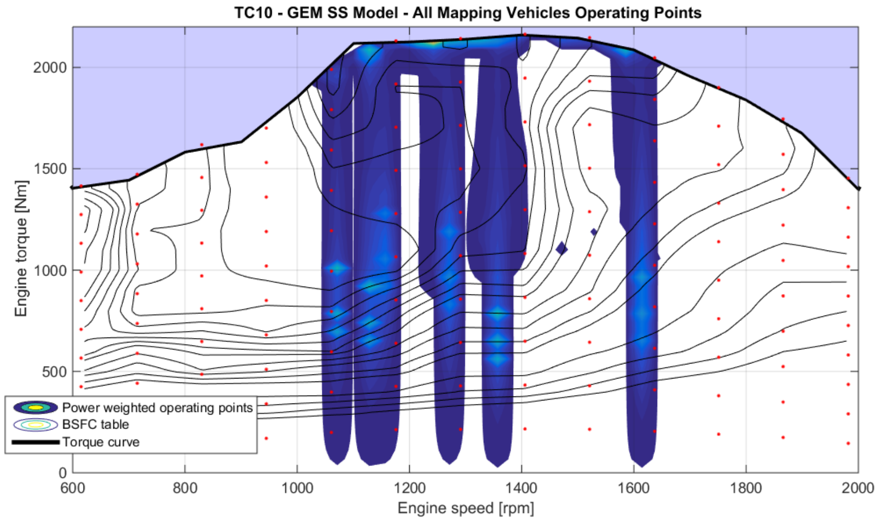


Figure 79. Engine operation during 55 mph and 65 mph cycle for 9 different vehicle configuration fitted with an automatic transmission.

Figure 78 and Figure 79 show how six different speeds are barely used for all those vehicles and transmission configurations (615, 715, 830, 945, 1751, and 1982 rpm). Also from a load perspective, the energy level is very low for the following load conditions: 10%, 70%, 80%, and 90%.

Figure 80 show the effect of removing the 715, 945, 1751, and 1982 rpm speed points. It has a limited effect (less than 0.1% error compared to fully populated map with 143 points) except for the high final drive ratio application with a USP transmission, which operates around 1900 rpm on the 65 mph cycle.

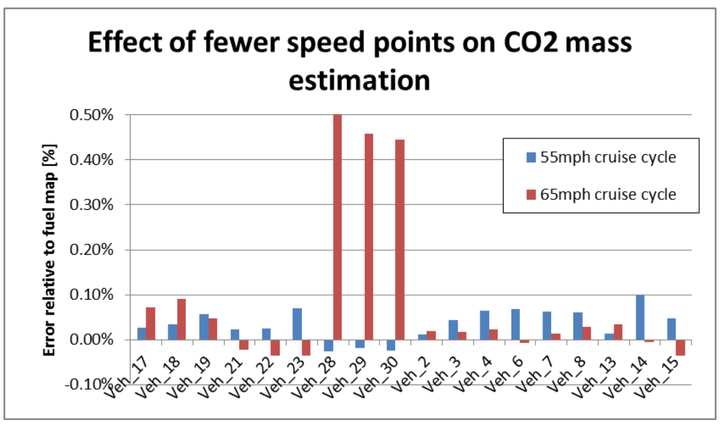


Figure 80. Effect of removing 715 rpm, 945 rpm, 1751 rpm and 1982 rpm speed points on CO_2 mass estimation when compared with fuel 143-point map.

High-speed points were removed one at a time to access the effect of each speed. Figure 81compiles those results and shows that in order to maintain an error of less than 0.1%, all high speed points have to be maintained.

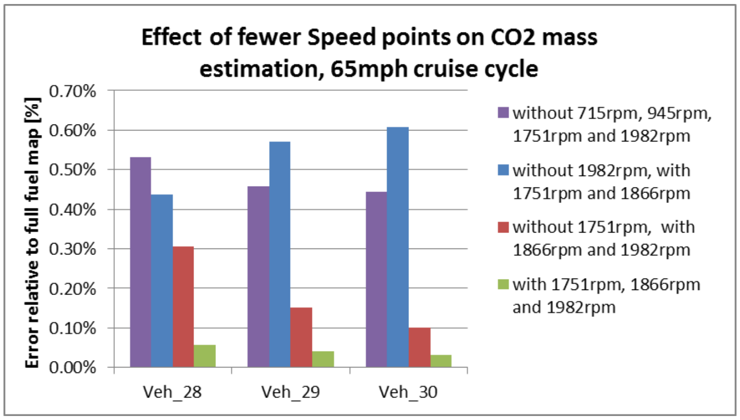


Figure 81. Effect of removing high speed points on CO_2 mass estimation when compared with fuel 143-point map.

A similar study was conducted with load points: the 10%, 70%, and 90% loads were removed out of GEM steady-state fueling map. It caused less than 0.1% effect of CO_2 mass compared to GEM model with fuel steady-state map for most vehicles except for high final drive ratio vehicle with AMT, where error is around 0.2%. (See Figure 82.)

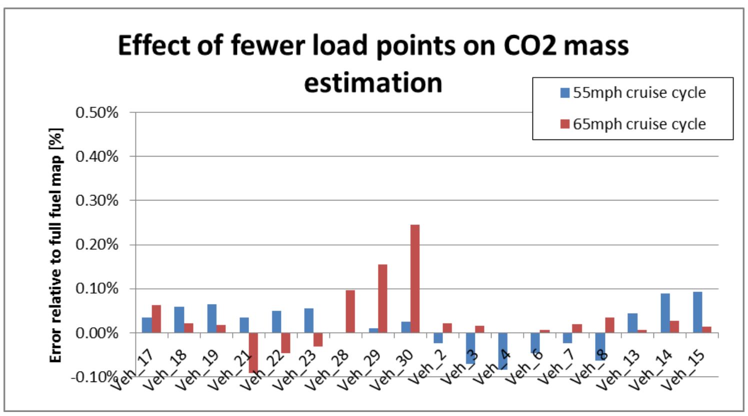


Figure 82. Effect of removing 10%, 70%, and 90% loads points on CO_2 mass estimation when compared with fuel 143-point map.

The high final drive ratio vehicles are also studied in more detailed by remove only one load point at a time (i.e., all 10% load points but keeping 70% and 90% points). The results are shown in Figure 83.

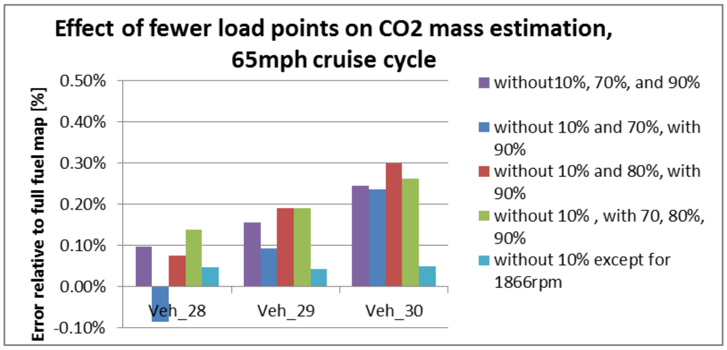


Figure 83. Effect of removing individual load points on CO_2 mass estimation when compared with fuel 143-point map.

To keep error below 0.1%, 10% load points can be removed except for the 1866 rpm speed point. It was determined that the map can be reduced to 89 points by

- removing 715 rpm and 945 rpm speed points,
- removing 10%, 70% and 90% load points, and
- Keeping the 10% point at 1866 rpm.

This causes a 0.2% effect of CO_2 mass compared to GEM model with fuel steady-state map for most vehicles. (See Figure 84.)

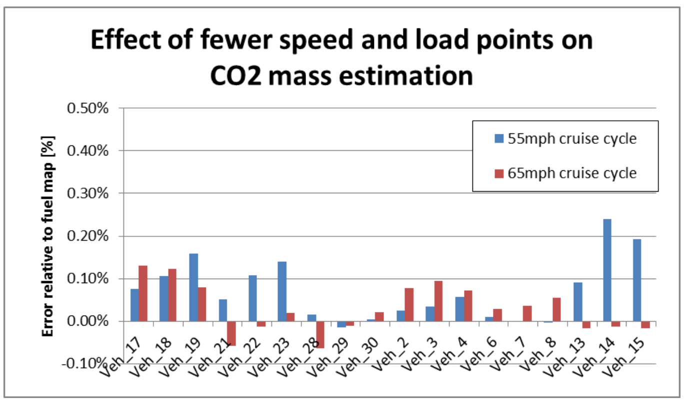


Figure 84. Effect of removing 715 rpm and 945 rpm speed points and 10%, 70%, and 90% loads points on CO_2 mass estimation when compared with fuel 143-point map.

2.2.3.1 Effect of uniform 10*10 matrix

Instead of removing points out of the 13*11 matrix collected during the mapping exercise, a new 10*10 equally spaced points map was generated by interpolation. Figure 85 shows the original 13*11 map (red dots) as well as the newly generated 10*10 map (green dots).

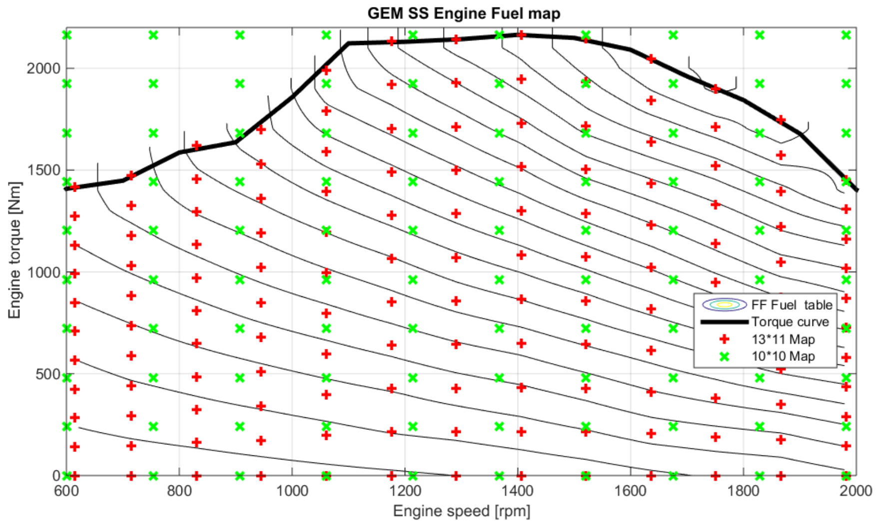


Figure 85. 13*11 fuel map (red cross) and 10*10 fuel map (green x) for ISX 450 engine.

The new map was used with the steady-state option of GEM and compared with the same GEM model fed with a 13*11 fuel table.

Error is larger than previously observed by removing points out of unused regions of the map. It can be larger than 2.5%, and most of the time, the 10*10 map underestimates CO_2 mass, most likely because the coarser matrix flattens the fuel map at higher loads. (See Figure 86.) Some of the error observed below is due to the interpolation operation performed to convert the 13*11 matrix into a 10*10 matrix.

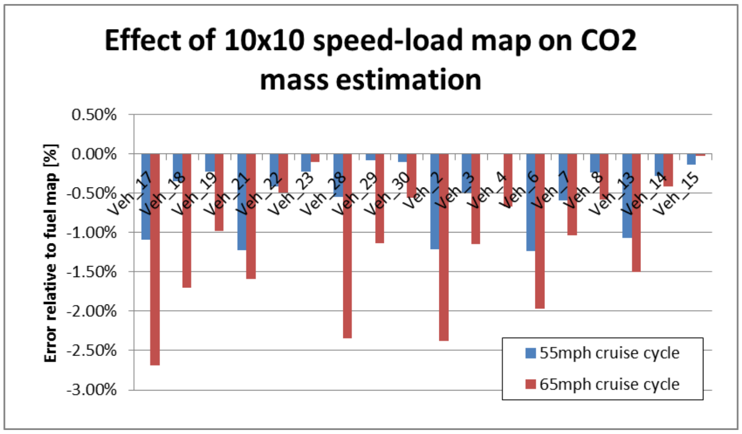


Figure 86. Effect of coarser 10*10 fuel map on CO_2 mass estimation when compared with fuel 143-point map.

2.3 OTHER POWERTRAIN TESTING RELATED STUDIES

2.3.1 Powertrain Torque Curve

2.3.1.1 Automated Manual Transmission powertrain torque curve

The powertrain torque curve was performed on the powertrain consisting of a Cummins 15l ISX 450 engine and an Eaton USP AMT.

The test procedure consisted of first warming up the engine and transmission and then placing the dynamometer on speed mode to apply a constant speed ramp of 8 rpm/s on the transmission output shaft while the engine was commanded with a 100% pedal signal. The procedure was repeated several times with the gear selector in “drive” or “manual” in order to force the transmission in a gear to cover a wider speed range, as shown in Figure 87.

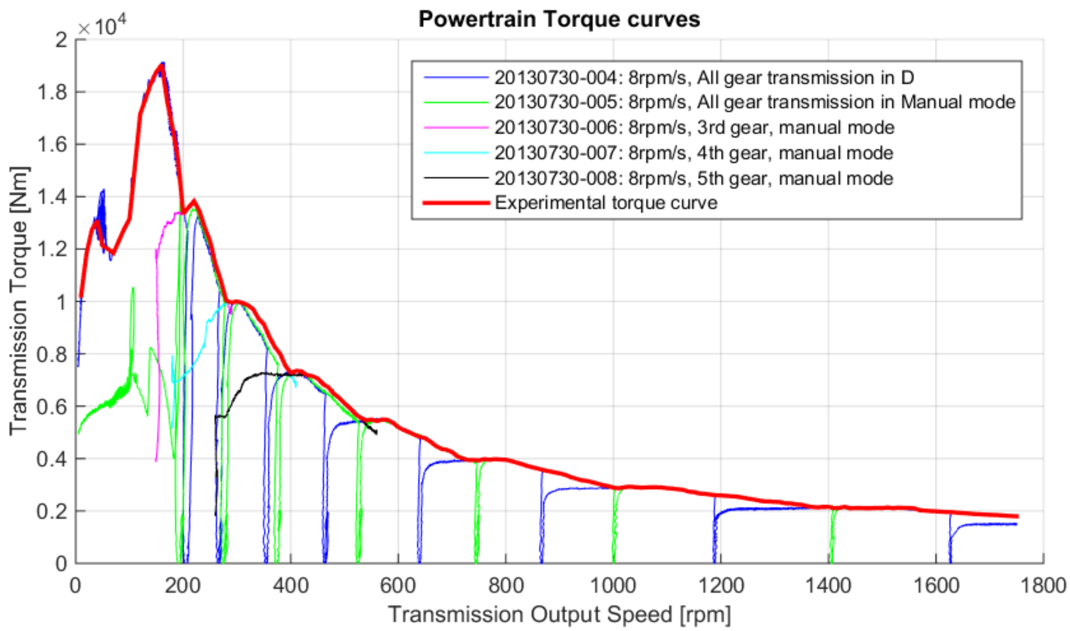


Figure 87. USP Transmission experimental Powertrain torque curve.

The resulting experimental powertrain torque curve is compared to the theoretical torque in Figure 88.

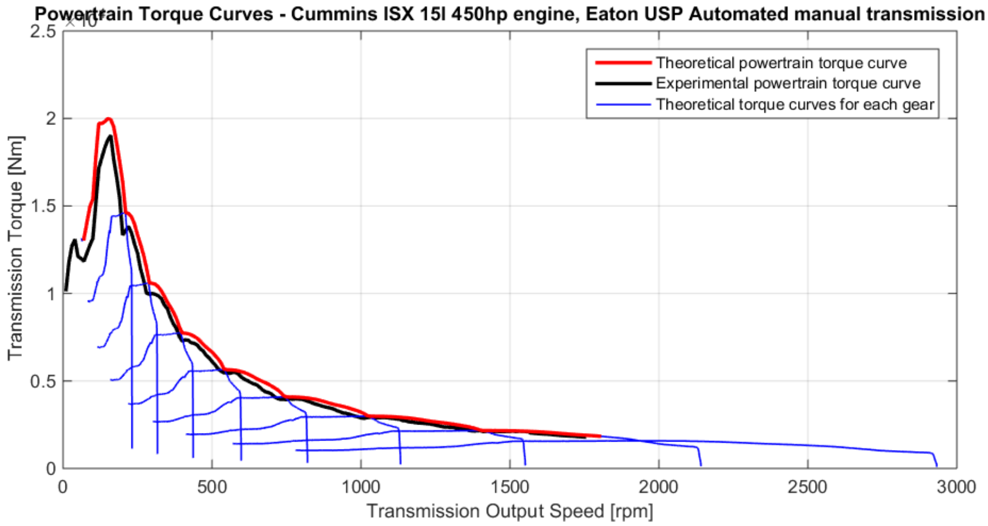


Figure 88. USP Transmission experimental and theoretical Powertrain torque curves.

The experimental powertrain torque curve lies beneath the theoretical torque curve because the latter does not account for transmission inefficiencies.

The test cell was then set up in powertrain-in-the-loop mode and was configured to represent two class 8 trucks, one with a realistic gross vehicle weight (GVW) of 30000 kg and one with an unrealistic GVW of 60000 kg in order to test the worst-case scenario from a powertrain torque perspective.

Results are shown in Figure 89 with the theoretical and experimental torque curves as well. Even in second gear, the powertrain should not generate more than 10000 Nm.

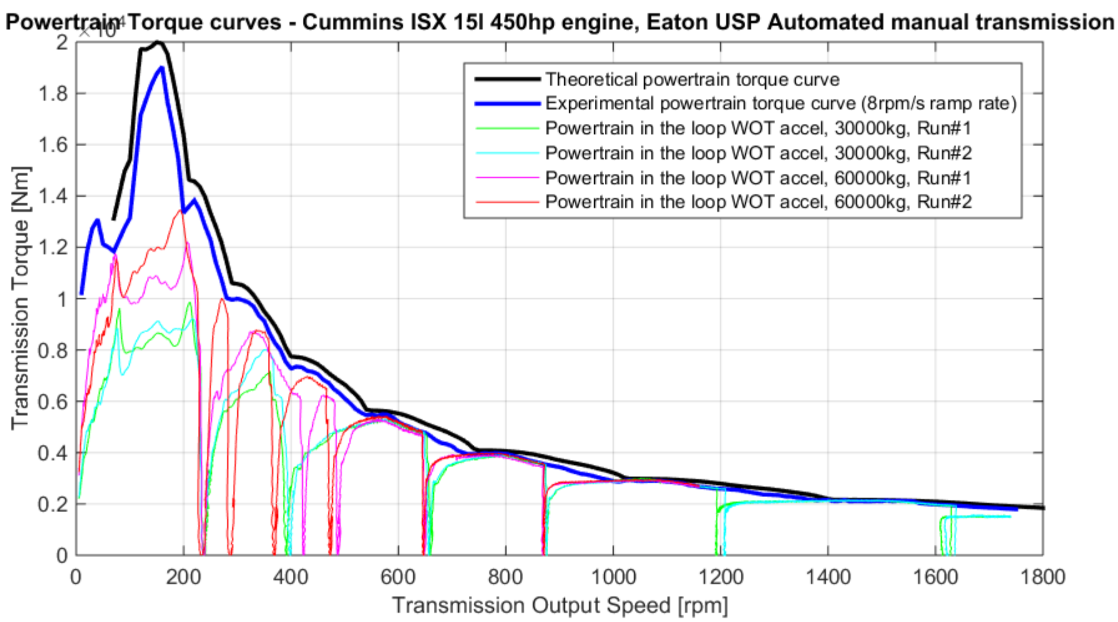


Figure 89. USP Transmission experimental and theoretical powertrain torque curves as well as powertrain torque during powertrain in the loop wide open acceleration tests.

This exemplifies that the dyno capability does not need to meet the theoretical maximum from the powertrain because the transmission does not spend enough time in the lower gears to produce full engine torque.

2.3.1.2 Automatic transmission powertrain torque curve

The powertrain torque curve was performed on the powertrain consisting of a Cummins 15l ISX 450 engine and an Allison TC10 automatic transmission.

The test procedure consisted of first warming up the engine and transmission and then placing the dynamometer on speed mode to apply a constant speed ramp of 8 rpm/s on the transmission output shaft while the engine was commanded with a 100% pedal signal. Wide-open-throttle acceleration in first gear exceeded the dynamometer maximum torque, so points between 120 rpm and 210 rpm were interpolated between known points.

The experimental powertrain torque curve lies beneath the theoretical torque curve except in first gear, where the torque multiplication property of the torque converter generates a larger torque.

The test cell was then set up in powertrain-in-the-loop mode and configured to represent a class 8 33000 kg truck. In first gear, the powertrain torque exceeds the theoretical torque curve and can generate more than 14000 Nm.

For an automatic transmission, the dynamometer needs to be sized with a safety factor that accounts for the torque converter that can multiply torque at low speeds and therefore can exceed the theoretical maximum powertrain torque curve, even in powertrain-in-the-loop mode.

2.3.2 Neutral Idle Study

2.3.2.1 Automated manual transmission powertrain results

AMT shows two different behaviors (see Figure 900):

- First it is engaged, where transmission input speed is zero.
- Then it transitions to disengaged (or neutral), where transmission input speed matches engine speed.

These modes result in different transmission output torques and small fuel flow differences as well. Surprisingly the engine consumes more fuel in disengaged mode, maybe from having to drag the input shaft along. (See Table 200.)

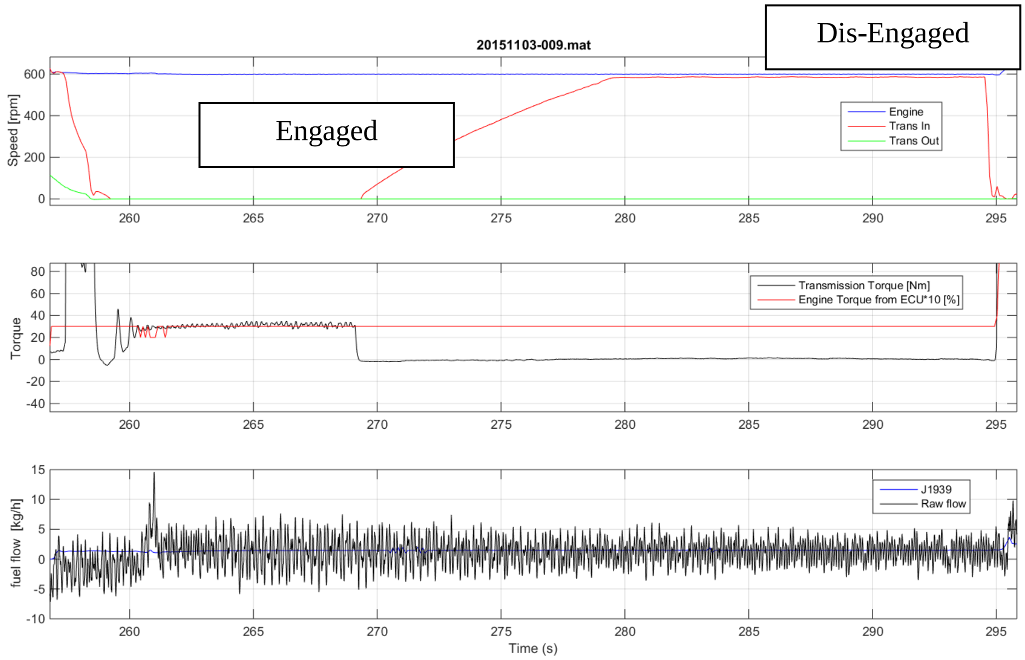


Figure 900. Engine idle behavior when coupled to an automated manual transmission.

Table 20. Engine idle behavior when coupled to an automated manual transmission

	Engine speed	**Transmission Torque**	Transmission Output speed	Transmission input speed	**Fuel flow from meter**	Fuel flow from ECU
	[rpm]	**[Nm]**	[rpm]	[rpm]	**[kg/h]**	[kg/h]
Complete idle sequence	**599.9**	**6.5**	0.0	336.2	**1.22**	1.47
Engaged Phase	600.4	31.1	0.0	0.0	1.18	1.35
Dis-engaged Phase	600.0	0.3	0.0	585.4	1.44	1.48

2.3.2.2 Automatic transmission powertrain results

When mated to an automatic transmission, the engine idle behavior is more uniform: after a brief engaged time, the transmission is decoupled, as shown on Figure 91.

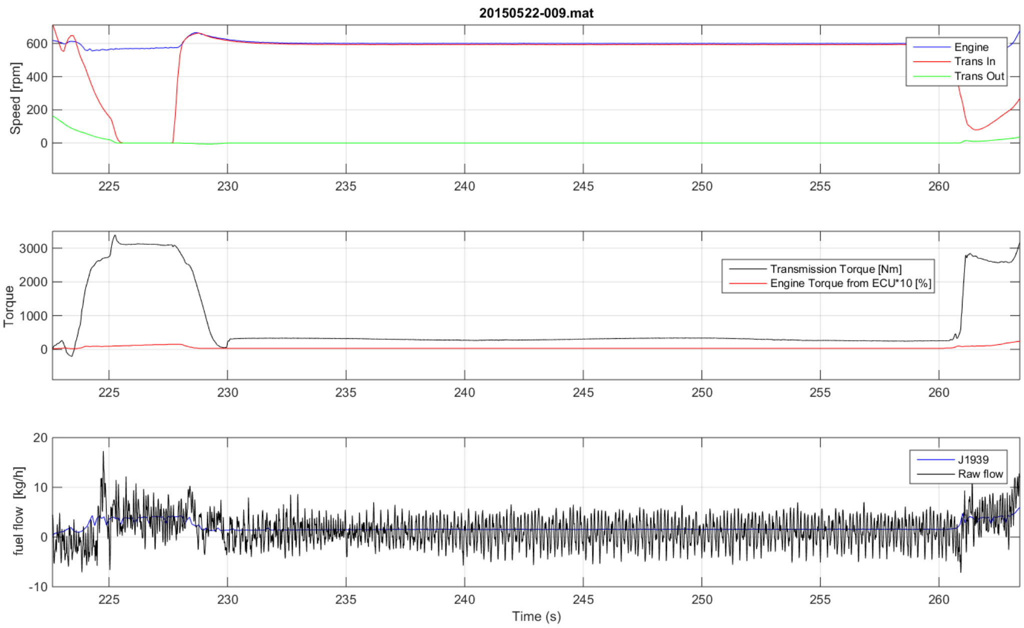


Figure 911. Engine idle behavior when coupled to an automatic transmission.

The overall idle flow is comparable to the AMT, as shown in Table 20.

Some additional tests were conducted in steady-state mode, looking at four different operating conditions on the TC10:

(1) Drive idle. Warm up the vehicle by operating it at 65 mile/h for 600 s. Within 10 s after concluding the preconditioning cycle, set the engine to operate at idle speed for 90 s, with the brake applied and the transmission in drive (or clutch depressed for manual transmission), and sample measurements over the last 30 s of idling.

(2) Parked idle. Warm up the vehicle by operating it at 65 mile/h for 600 s. Within 60 s after concluding the preconditioning cycle, set the engine to operate at idle speed for 600 s, with the transmission in park (or the transmission in neutral with the parking brake applied for manual transmissions), and sample measurements over the full 600 s of idling.

(3) Short parked idle. Warm up the vehicle by operating it at 65 mile/h for 600 s. Within 60 s after concluding the preconditioning cycle, set the engine to operate at idle speed for 90 s, with the transmission in park (or the transmission in neutral with the parking brake applied for manual transmissions), and sample measurements over the full 30 s of idling.

(4) Drive idle, without brake. Same as drive idle but without the brake pedal applied.

Due to the large confidence interval on fuel flow measurement (about +-0.15 kg/h in idle conditions), it is difficult to draw conclusion on the best idle strategies with the exception of the drive idle without brake pedal, which consumes four times more fuel. The other three methods are within the confidence interval. Yet surprinsgly, the “park idle”condition does not save a lot of fuel compared with the “drive idle, with brake” condition. (See Figure 92.)

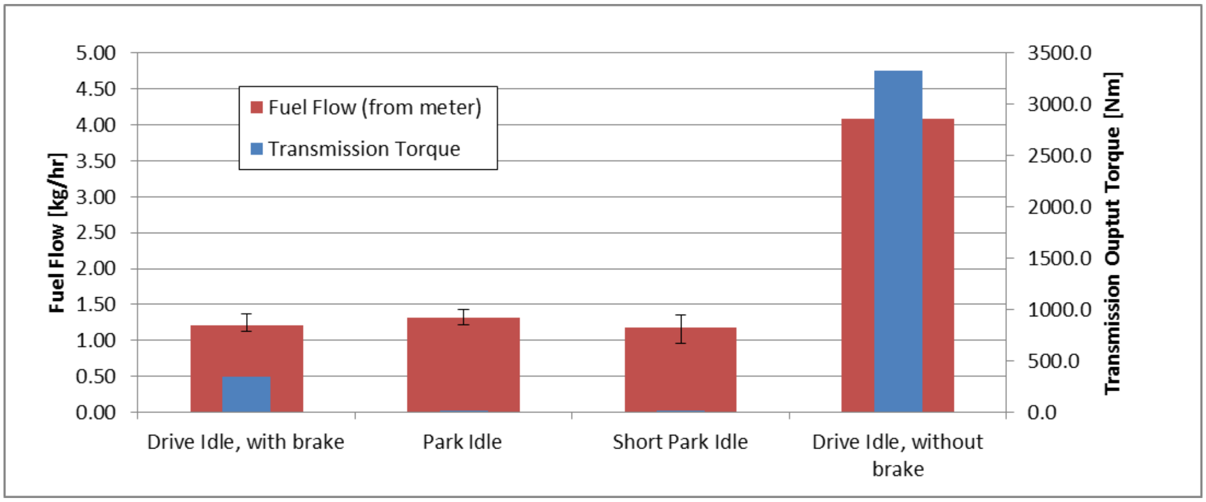


Figure 922. TC10 idle fuel flow and torques.

2.3.2.3 Engine-only idle results

Part of the engine-mapping procedure, the idle had been tests per 40 CFR 1065.510(b)(3) for a true idle position (no load) and the Curb-Idle Transmission Torque condition.

These engine-only results were compared to powertrain tests. Powertrain fuel flows are very close to engine only idle fuel flows, confirming that these transmissions are operating in neutral. (See Figure 93.)

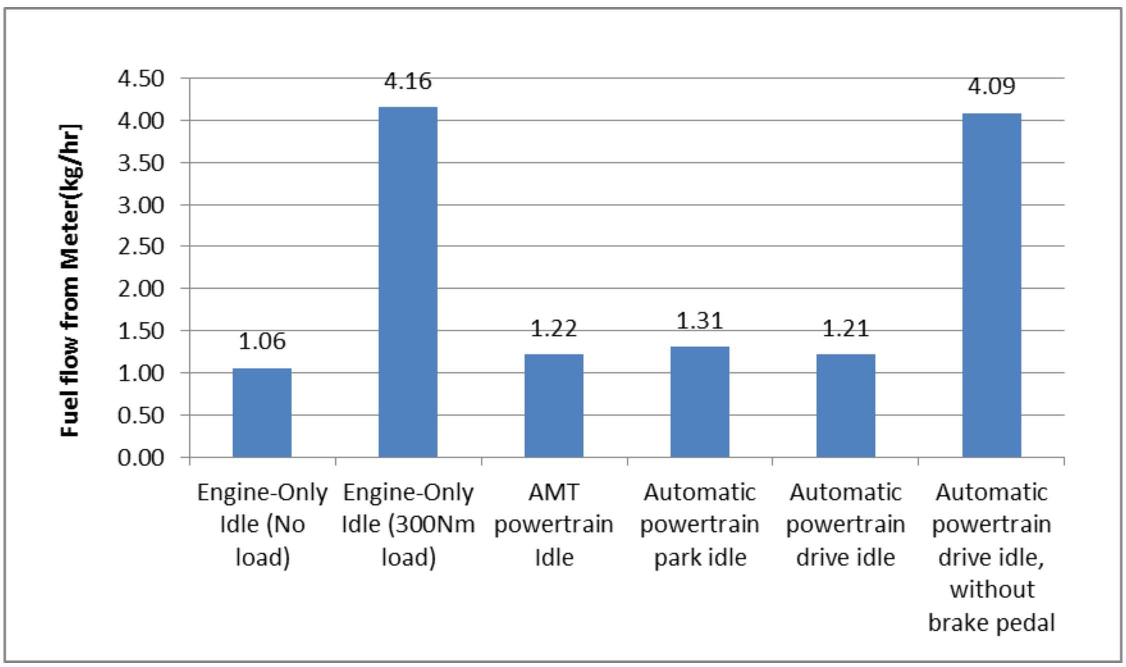


Figure 93. Powertrain and engine-only idle fuel flows.

2.3.2.4 Comparison with GEM

The experimental dynamic behaviors (blue trace in Figure 94 and Figure 95) were compared to GEM results (red trace). GEM input files specified neutral idle technology in the GEM input file.

The idle fuel estimation is higher on the model: 1.05kg/h compared to 0.6kg/h on the AMT experiment and 0.5kg/h on the automatic transmission experiment. (Figure 9494 and Figure 95).

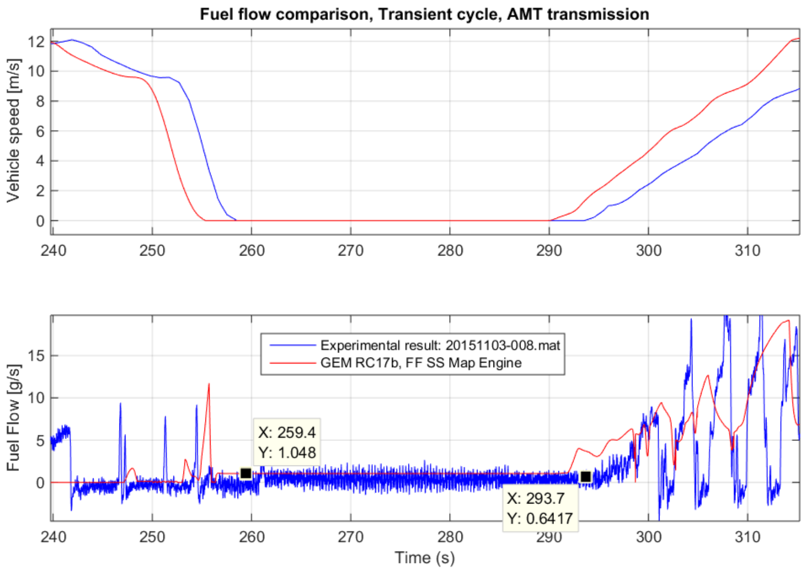


Figure 94. Comparison of idle behaviors between experimental results and GEM for automated manual transmission.

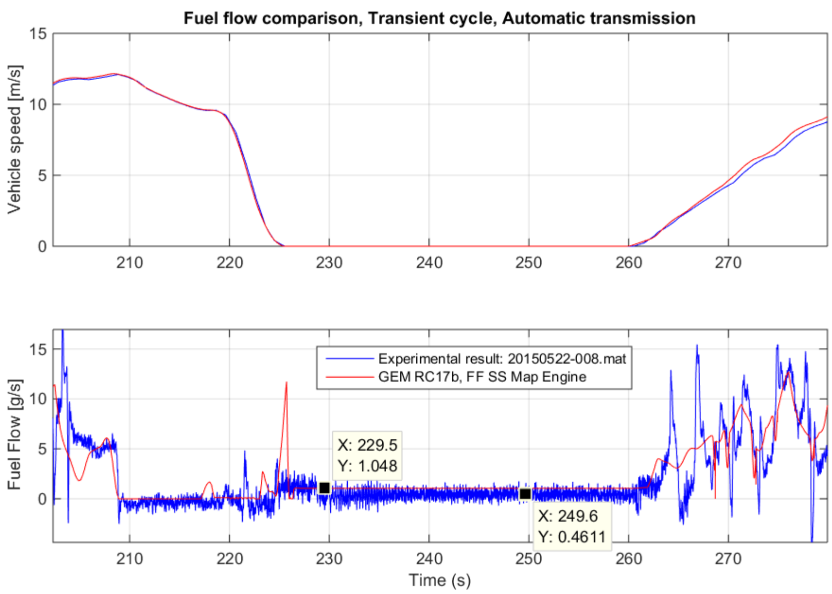


Figure 95. Comparison of idle behaviors between experimental results and GEM for automatic transmission.

2.3.3 Distance Compensation Study

GEM implements a distance compensation feature which forces vehicles to cover the same distance even if they are struggling to keep up with the speed profile. During powertrain in the loop testing, this feature was observed to maintain distance within 0.05% (or 4 m) on the AMT powertrain and 0.22% (17 m) on the automatic transmission powertrain for all cycles and vehicle configurations. (See Figure 96 and Figure 97.)

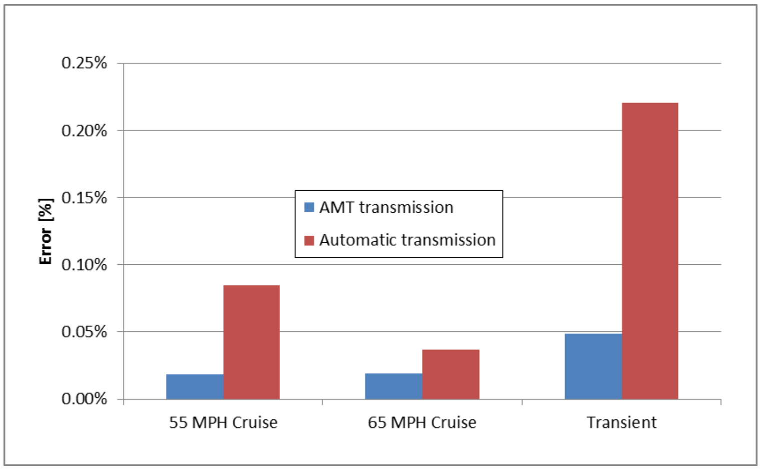


Figure 96. Distance compensation worst case error as a percentage over all vehicle configurations.

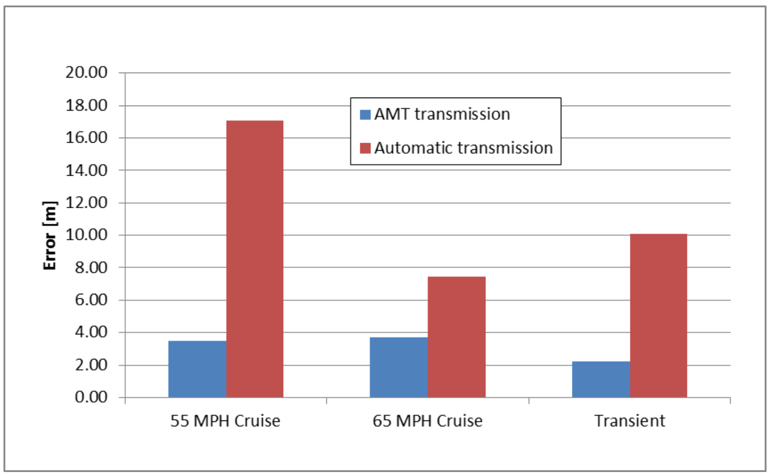


Figure 97. Distance compensation worst case error as a distance over all vehicle configurations.

The COV of post-transmission cycle energy for all vehicles with same mass and drag coefficient was calculated. These vehicles only differ by their final drive ratios. In most cases, the COV is within 0.4% in the case of the TC10 transmission. This can be explained somewhat by the different losses in the final drive axle. Transient cycles and the heaviest vehicle exceed 0.5% COV. (See Figure 98.)

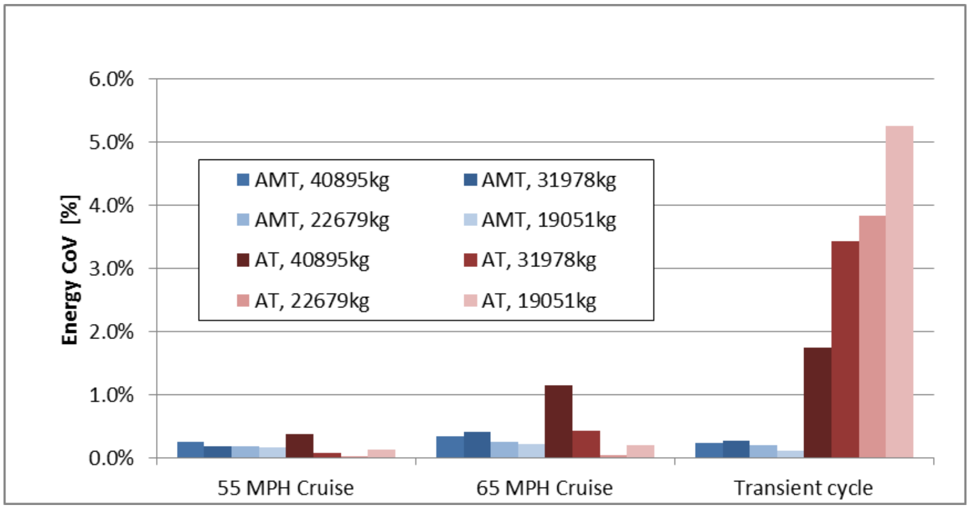


Figure 98. Powertrain output energy coefficient of variation as a function of vehicle mass.

This is can be explained by the fact that the higher final drive ratio can better keep up with the speed profile. Therefore it incurs more drag and rolling resistance, which requires more work out of the powertrain to overcome. In other words, it covers the same distance (thanks to the distance compensation feature) but faster, hence it takes more energy. (See Figure 99.)

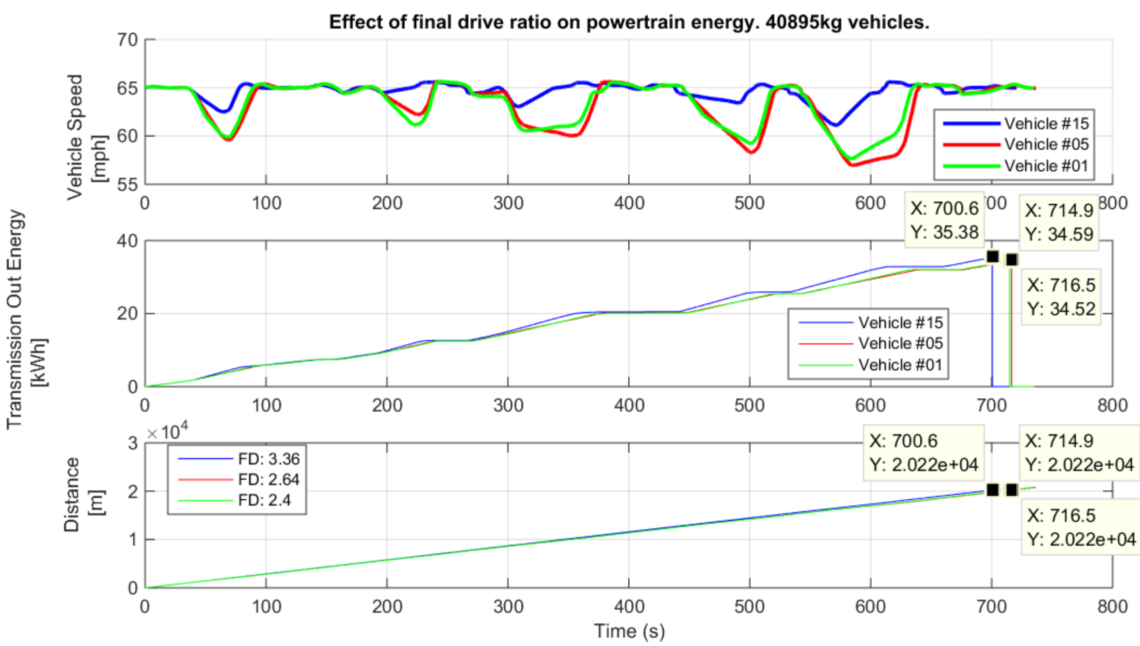


Figure 99. Example of energy consumption difference due to final drive ratios.

2.4 CONCLUSIONS

ORNL has conducted over 1000 tests for this project in its VSI Laboratory powertrain test cell. Four configurations were tested:

(1) stand-alone engine to map its steady-state operation,
(2) stand-alone engine in speed and load following mode,
(3) complete powertrain in speed and load following mode, and
(4) complete powertrain in powertrain in the loop mode.

All test configurations listed above exhibited very good test repeatability: the coefficient of variation is within 0.5% on both fuel mass and CO_2 mass, including transient cycles.

The experimental data were post processed to populate GEM as well as to validate GEM outputs.

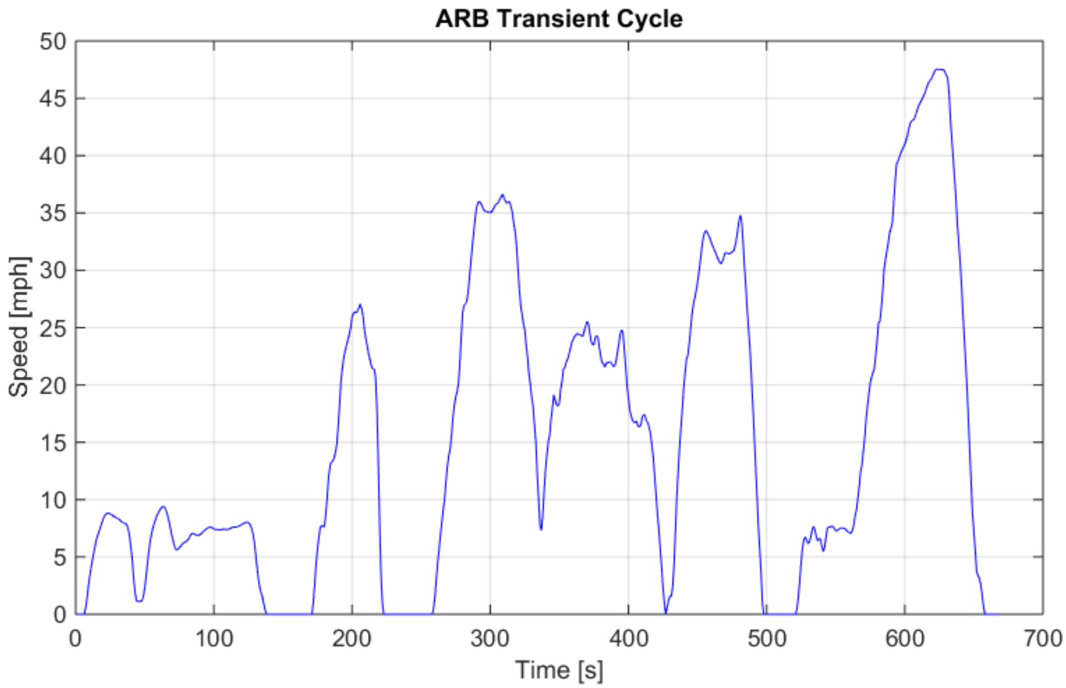
Several data analysis studies were conducted. First looking into interpolation routines used for the various cycle average maps. It appeared that method #6 which relied on torque and speed performed best for the engine maps but differences between methods were within 1%. For powertrain maps, the two methods considered, which did not involve torque, were essentially equivalent, but it is suggested that a local interpolation might perform better than a global regression. Second, the effect of map density of model accuracy was looked into and showed that the steady-state map could be reduced from 143 points to less than 100 with minimal loss of accuracy.

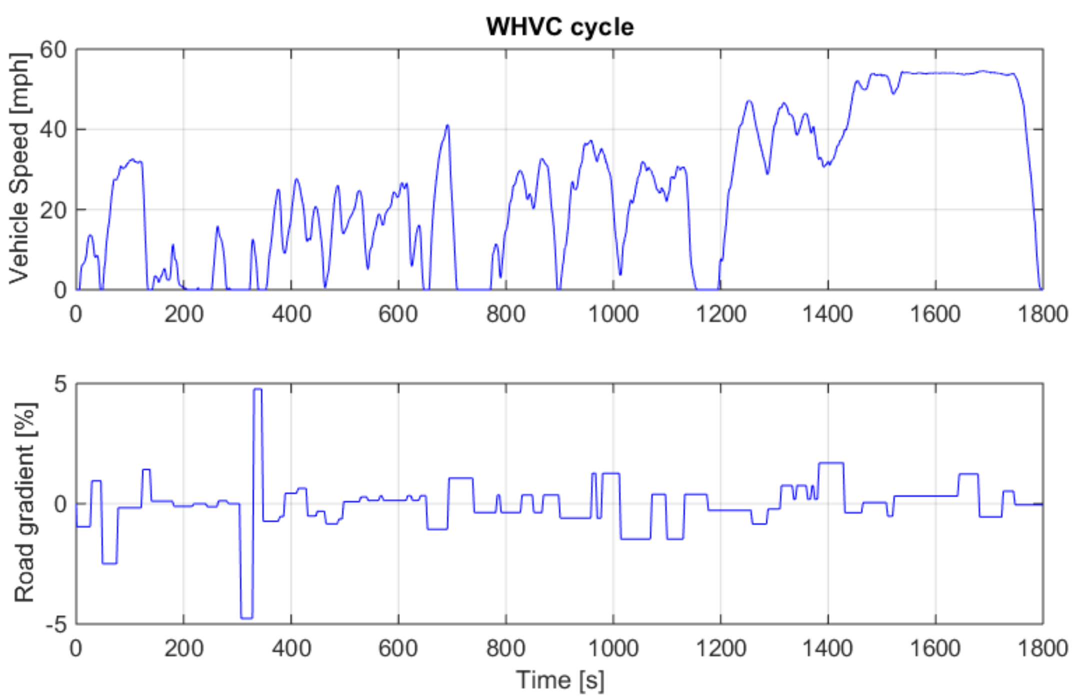
The three different GEM options available to characterize an engine or powertrain (steady-state engine map, engine cycle average map, and powertrain cycle average map) were compared to powertrain-in-the-loop experimental data. The powertrain cycle average map performed best over the cycles and transmissions tested in this study with a low overall error on both work and fuel mass. This methodology used a limited amount of test data and gives good results with child ratings of the same engine. The engine methods (steady-state map and engine cycle average) also exhibited low errors except for the transient cycle in the case of an automatic transmission, but that might be corrected by more development of the GEM model to match the transmission behavior.

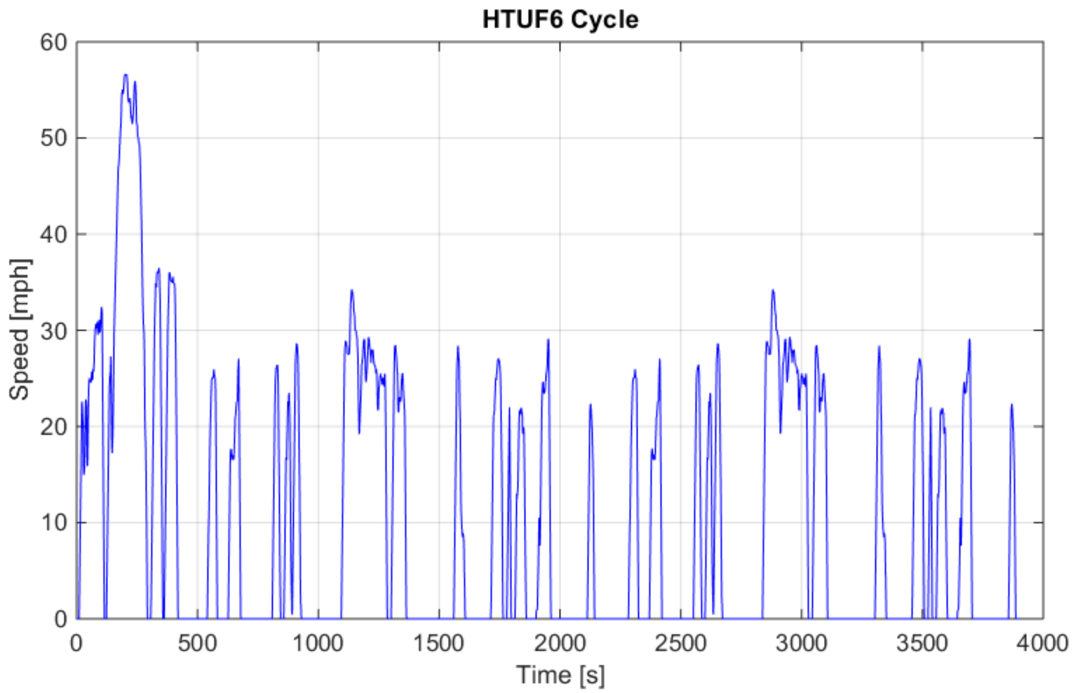
APPENDIX A. VEHICLE SPEED AND GRADE PROFILES USED IN HARDWARE IN THE LOOP TESTING

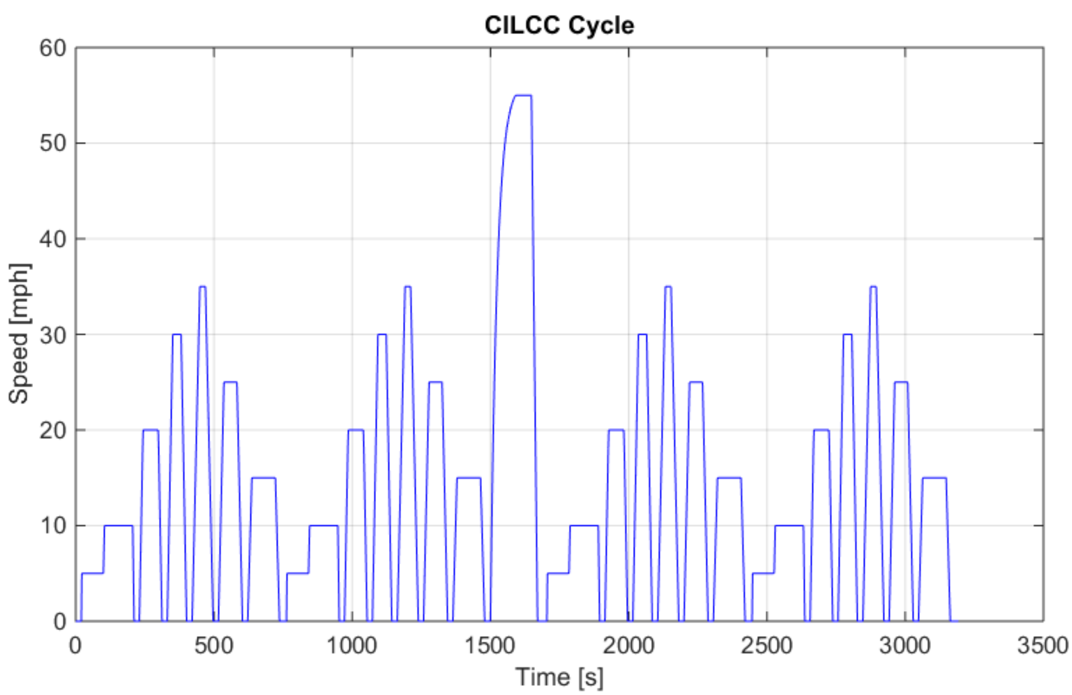
APPENDIX A. VEHICLE SPEED AND GRADE PROFILES USED IN HARDWARE IN THE LOOP TESTING

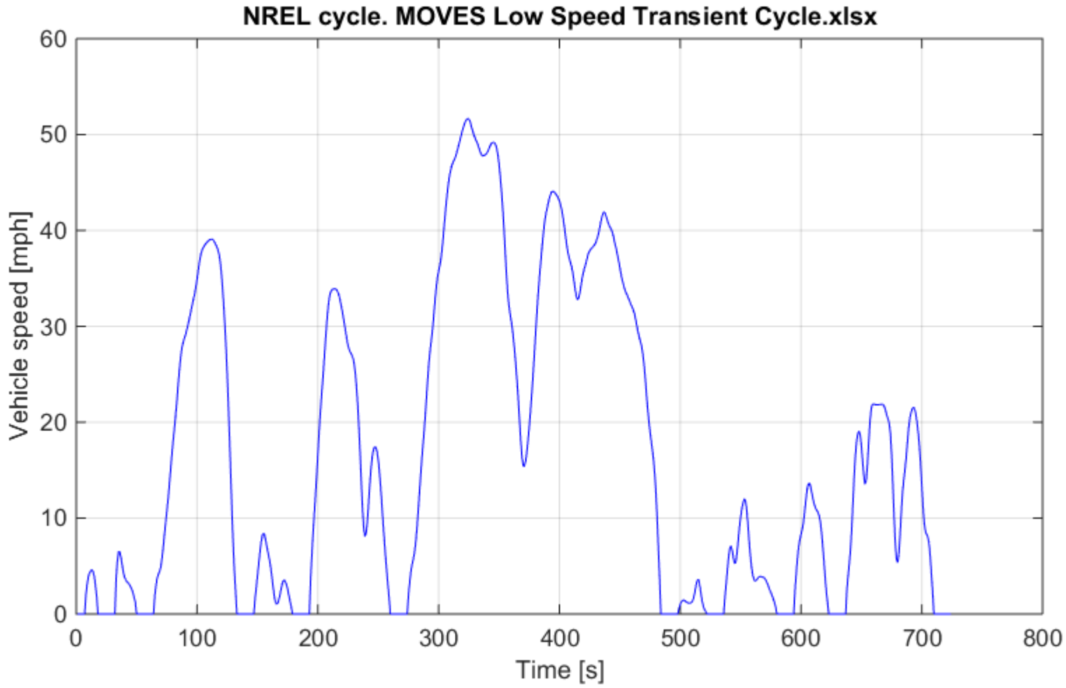
When grade is not shown on a speed profile plot it is because that drive cycles is performed without a grade profile (no elevation change)



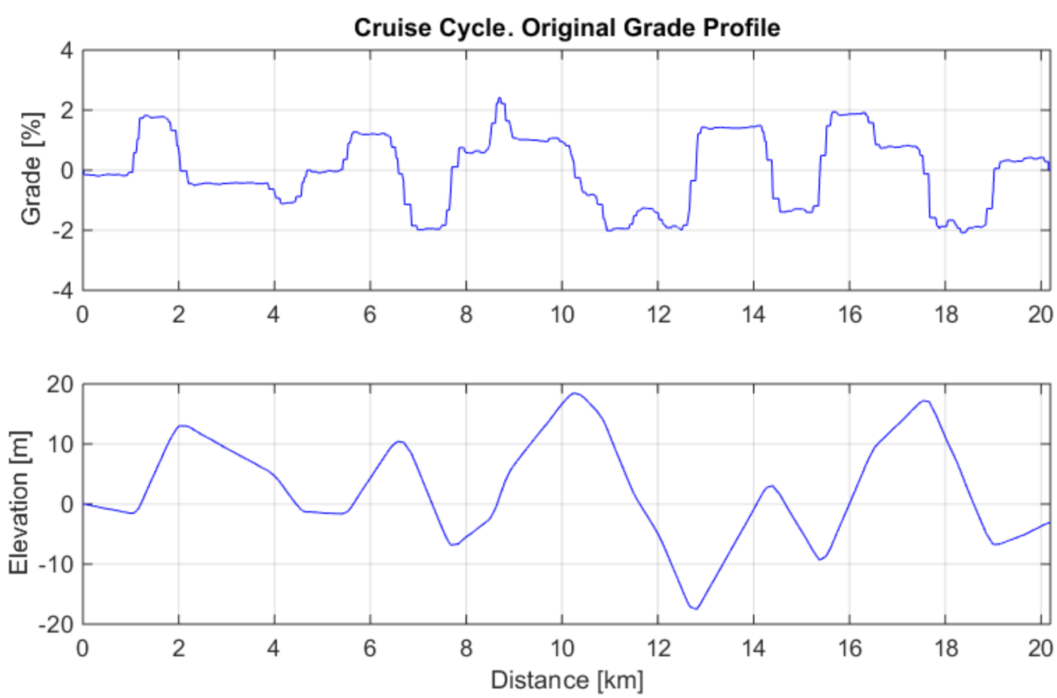


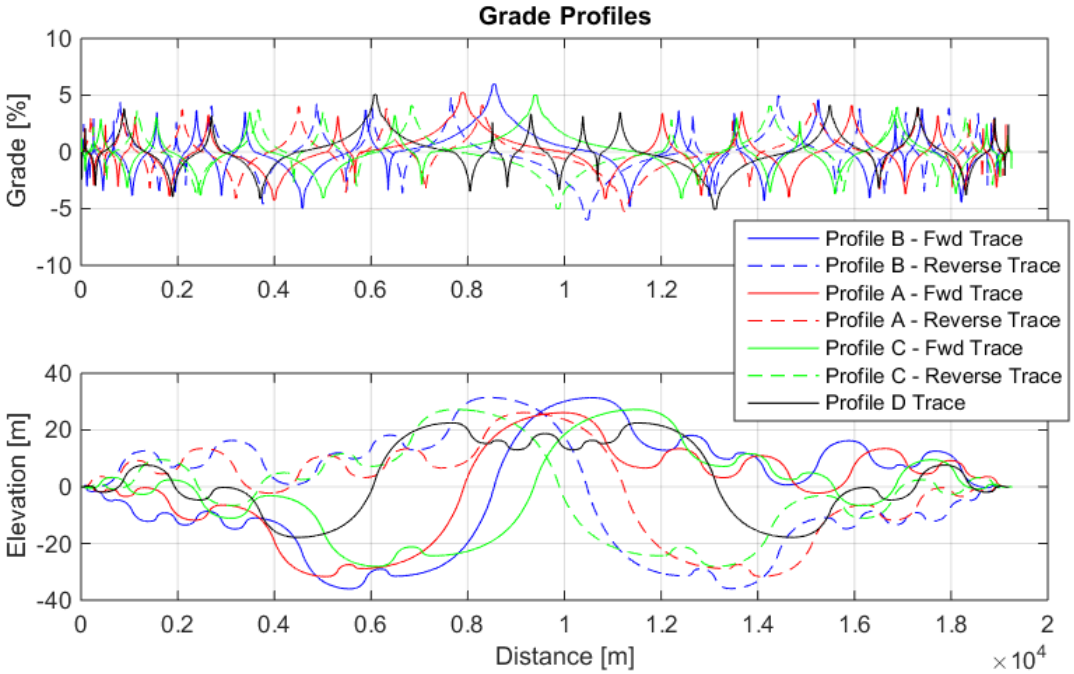

HTUF6 Cycle
Speed [mph]
Time [s]
0
10
20
30
40
50
60
0
500
1000
1500
2000
2500
3000
3500
4000


CILCC Cycle
Speed [mph]
Time [s]
0
10
20
30
40
50
60
0
500
1000
1500
2000
2500
3000
3500



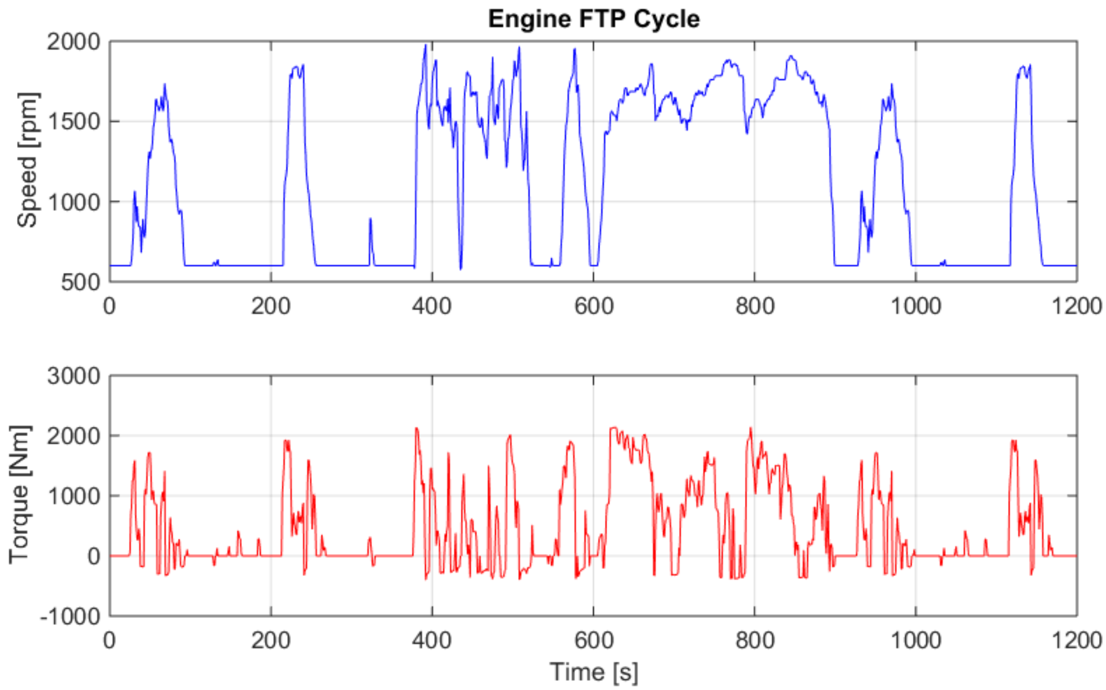
Cruise cycles were performed with a variety of grade profiles that are distance based not time based. The two plots below show grade profiles independently of the vehicle speed in order to minimize the number of figures

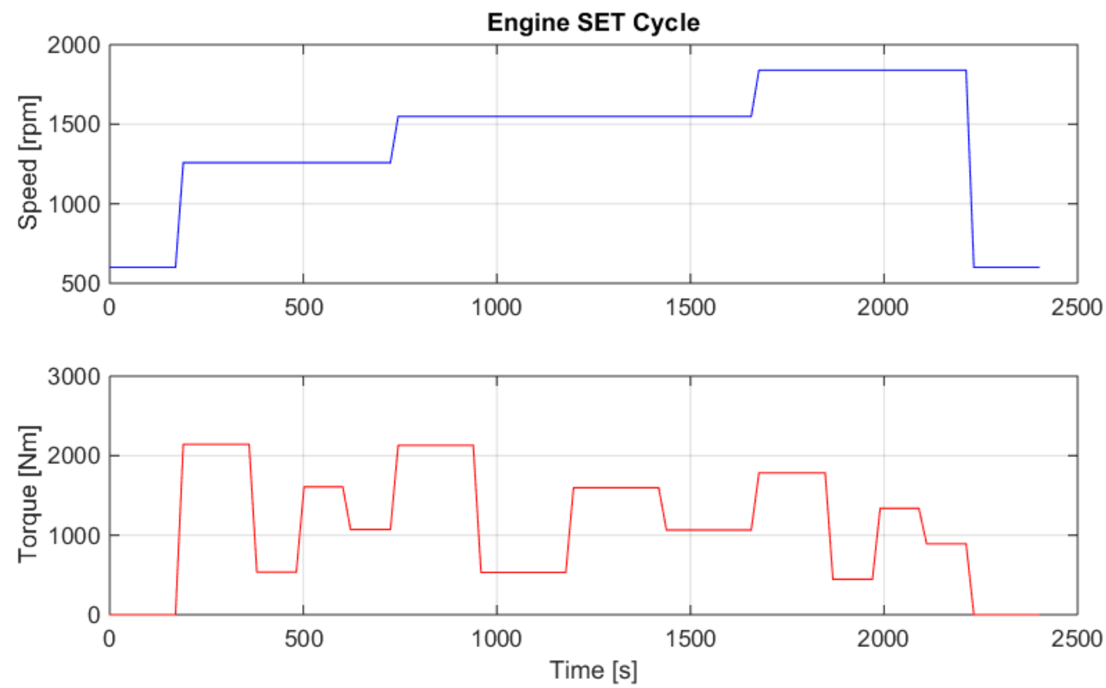


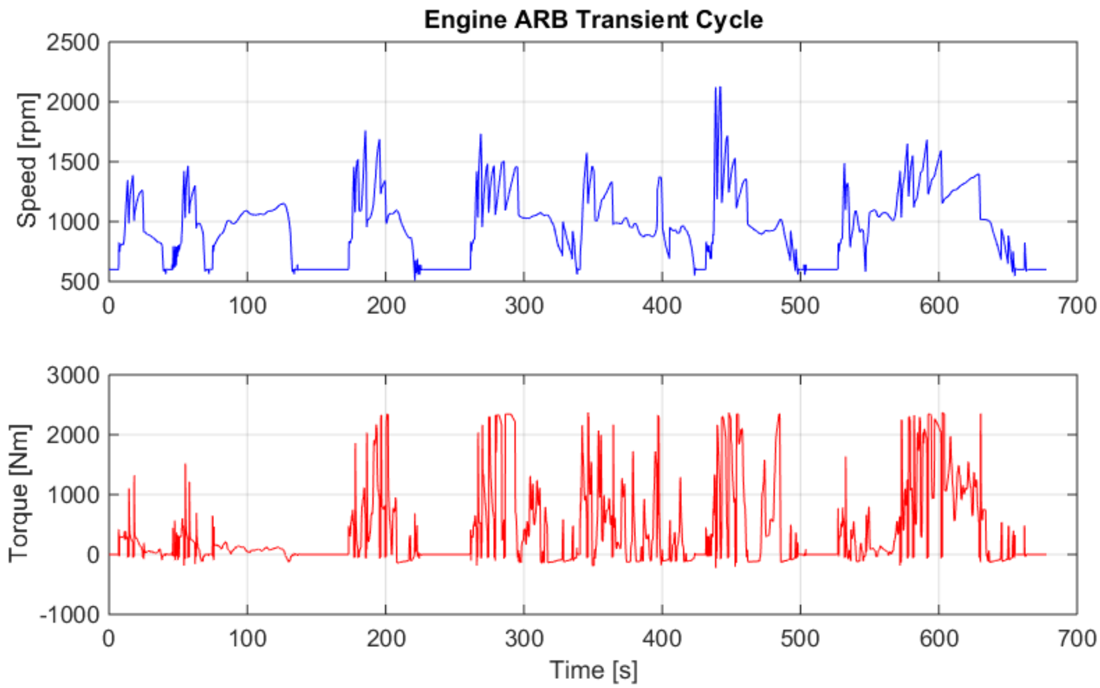

Grade Profiles
Grade [%]
Elevation [m]
Distance [m]
×10^4
Profile B - Fwd Trace
Profile B - Reverse Trace
Profile A - Fwd Trace
Profile A - Reverse Trace
Profile C - Fwd Trace
Profile C - Reverse Trace
Profile D Trace

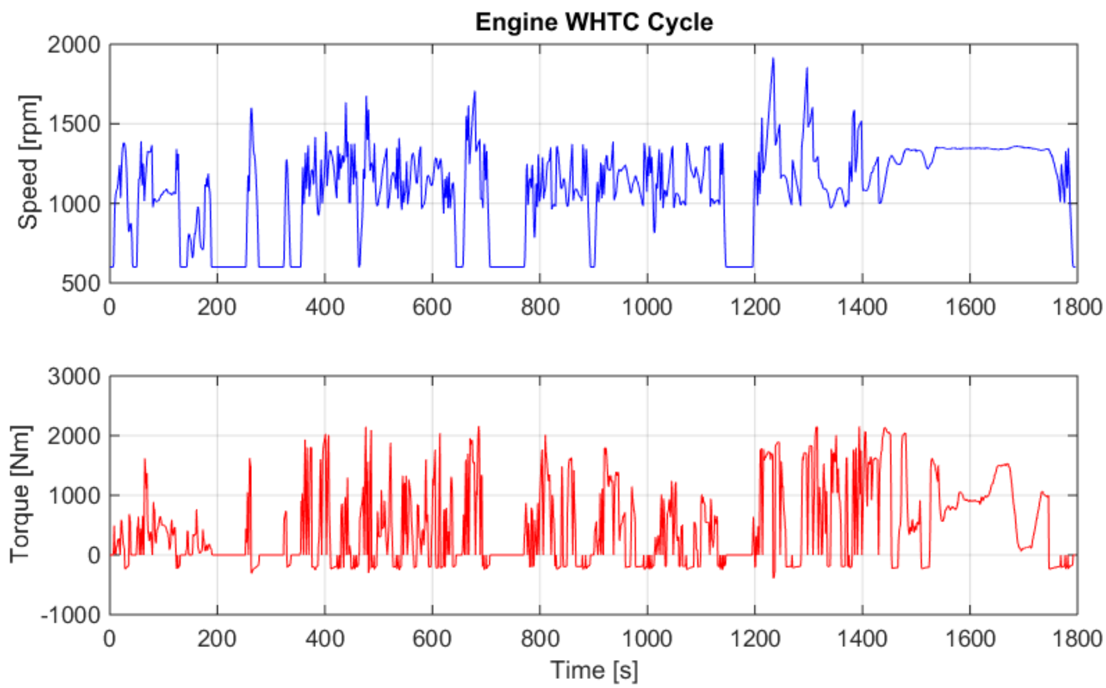
APPENDIX B. ENGINE SPEED AND TORQUE PROFILES USED IN PLAYBACK TESTING

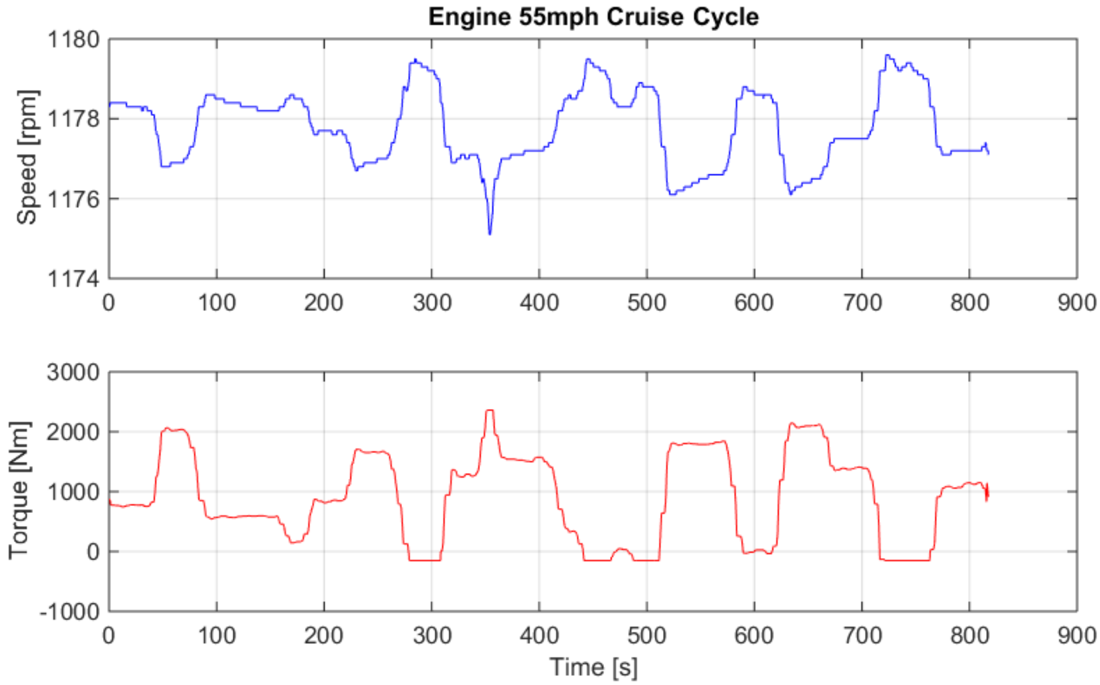
APPENDIX B. ENGINE SPEED AND TORQUE PROFILES USED IN PLAYBACK TESTING



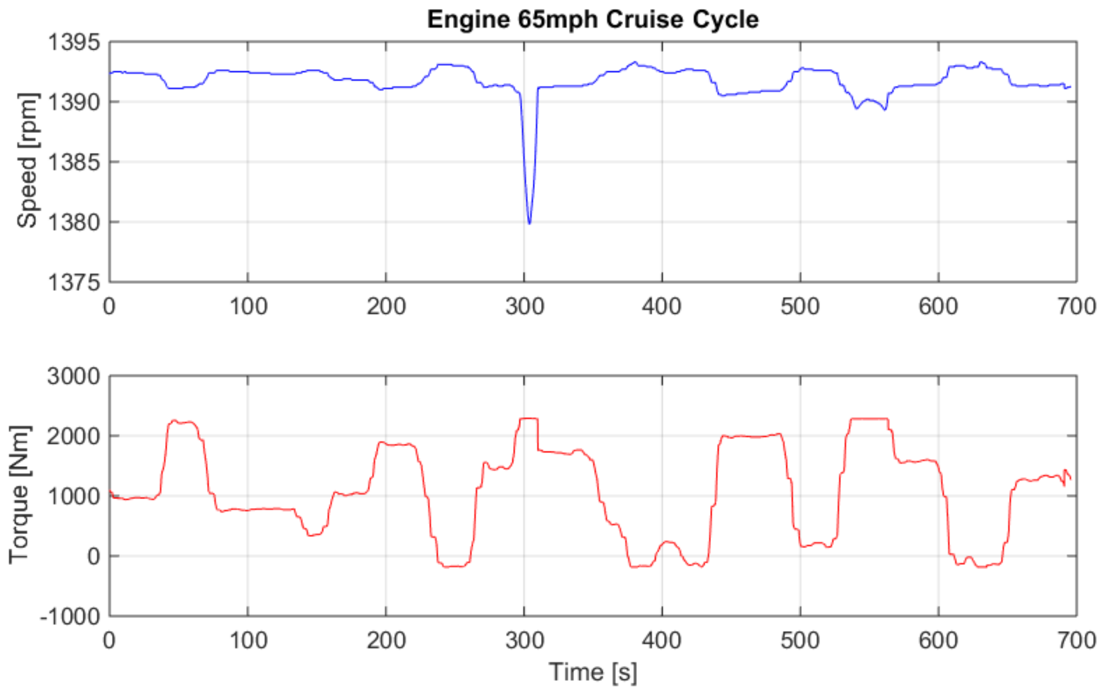



Engine ARB Transient Cycle
Speed [rpm]
Torque [Nm]
Time [s]


Engine WHTC Cycle
Speed [rpm]
Torque [Nm]
Time [s]



Engine 55mph Cruise Cycle
Speed [rpm]
1180
1178
1176
1174
Torque [Nm]
3000
2000
1000
0
-1000
0
100
200
300
400
500
600
700
800
900
Time [s]



Engine 65mph Cruise Cycle
Speed [rpm]
1395
1390
1385
1380
1375
Torque [Nm]
3000
2000
1000
0
-1000
0
100
200
300
400
500
600
700
Time [s]