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Characterization of heavy duty engine fuel maps used for model based simulation tools

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ABSTRACT

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Characterization of fuel consumption is of critical importance for framing or modifying federal regulations for trucking industry. Due to its complexity, fuel consumption is often only known for a few test cycles which generally represent limited types of vehicle activity. It is known that vehicle fuel consumption strongly depends on the vehicle activity, chassis design and engine model year (MY), and hence poses a significant challenge while predicting fuel consumption of heavy-duty vehicles over real-world vehicle activity.

Upcoming Greenhouse Gas (GHG) regulation for 2017, engine manufacturers are required to assess heavy-duty engine fuel economy using vehicle simulation tools. With recent focus on fuel economy and GHG emissions, regulatory agencies are progressively relying on vehicle simulation tools that allow prediction of the fuel consumption for a variety of vehicles over different test cycles.

Autonomie simulation tool developed by Argonne National Laboratory was used in this study to predict the fuel consumption over different cycles and then the prediction of simulation tool was compared with chassis and engine dynamometer data to check the accuracy of the simulation tool.

Autonomie simulation results were compared with the chassis dynamometer test data and the results showed a 5.93% and 11.53% difference in engine work and brake-specific fuel consumption (bsfc) respectively. When Autonomie simulation results were compared with engine dynamometer test data, the difference in work done, integrated fuel consumption and bsfc were found to be 13.21%, 4.92%, and 8.32% respectively.

Autonomie generated fuel consumption simulation data was compared with a dynamic vehicle simulator, Greenhouse Gas Emissions Model (GEM). The method was able to predict ARB transient cycle within 10% error, with an absolute error of 6.38%.

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My parents deserve special recognition for raising me and taught me the values of responsibility and hard work. I can't imagine where I would be without their support and example.

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Nomenclature

ANL	Argonne National Laboratory
APRF	Argonne's Advanced Powertrain Research Facility
Bhp	Horsepower
Bsfc	Brake Specific Fuel Consumption
CAA	Clean Air Act
CAFE	Corporate Average Fuel Economy
CAFEE	Center for Alternative Fuels, Engines, and Emissions
CARB	California Air Resource Board
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOE	Department of Energy
DOT	Department of Transportation
DPF	Diesel Particulate Filter
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ER	Emission Rate
FC	Fuel Consumption
FTP	Federal Test Procedure
GEM	Greenhouse Gas Emissions Model
GHG	Greenhouse Gas
HC	Hydrocarbons
HD	Heavy Duty
HDDT	Heavy Heavy-Duty Diesel Truck Schedule
HWFET	Highway Fuel Economy Test
Hp	Horsepower
MD	Medium Duty

MOVES	Motor Vehicle Emissions Simulator
MY	Model Year
Mph	Miles per hour
NHTSA	National Highway Traffic Safety Administration
NRC	National Research Council
NOx	Oxides of Nitrogen
PM	Particulate Matter
PSAT	Powertrain System Analysis Toolkit
PEMS	Portable Emissions Measurement Systems
SCR	Selective Catalytic Reduction
SET	Supplemental Emissions Test
US	United States

1. INTRODUCTION

In 2010, heavy duty truck fuel costs amounted around $1100 per household (ATDynamics SAE, 2014). Unless policies are adopted to change underlying trends, this amount is expected to grow considerably during the next two decades (Cooper, 2014). Implementing fuel saving technologies could lower heavy duty truck fuel consumption by 7-24% and yield a net savings to consumers. In the future availability of fuel is likely to be far more constrained as existing reserves become depleted and production declines. Improving fuel economy of the vehicle will reduce oil dependence and increase energy sustainability.

Accurate prediction of fuel economy of heavy-duty vehicles is necessary while considering the pathways to reduce energy consumption from transportation sector. Several tools are currently employed to predict heavy-duty. However model assumptions may present significant errors in prediction. Usually researchers consider tool predicted fuel economy as the standard fuel economy of an engine but there are various factors, which can vary and will certainly affect the fuel economy of the vehicle. There is always a possibility that you will find certain difference in the actual fuel economy of vehicle and the tool calculated fuel economy. In the future, model based simulation tools will work more efficiently as we will be aware of the inaccuracy.

Current research on heavy-duty diesel engines is focused on improving fuel and engine efficiency. Upcoming 2017 vehicle fuel efficiency and greenhouse gas emission standards require further improvements to engine efficiency from baseline MY 2010 HD diesel engines. Vehicle fuel consumption is directly related to the engine work, which in turn depends on the road load forces. The road load force includes aerodynamic drag, friction and vehicle inertia. Aerodynamic drag is a function of frontal area of the vehicle, vehicle speed and the drag coefficient of the vehicle chassis.

Typically, real-world fuel consumption of heavy-duty vehicles is evaluated using a heavy duty chassis dynamometer or fuel economy test procedure according to SAE J1321 (ATDynamics SAE, 2014). Fuel consumption on chassis dynamometer will depend on the characteristics of the driving cycle used. Also, heavy-duty engines are associated with multiple chassis depending on vocation.

As a result, a single cycle cannot be used to evaluate fuel economy. Therefore the use of simulation tools is needed to evaluate fuel consumption characteristics for a vehicle's powertrain.

Simulation tools like Autonomie can predict fuel consumption as a combination of engine, powertrain and chassis design features, which is widely accepted in the automotive industry. Autonomie has provided researchers with comfort of modeling an entire vehicle as simple block models. Autonomie offers ability to play with vehicle parameters that affect the road load equation and auxiliary loading system in vehicles to understand their effects on the fuel consumption. However, in Autonomie the accuracy of predictions directly depends on the vehicle model blocks.

In Autonomie, the fuel map (which is a function of engine speed and torque) is vital to calculate fuel consumption when simulating driving cycles.

1.1 Objective

The primary objective of this study is to evaluate the differences in fuel economy projected by Autonomie and results of engine and chassis dynamometer study. The data utilized to predict the fuel consumption that are presented in this study was collected at the West Virginia University. Specifically, the data was measured and collected in a laboratory on a chassis dynamometer.

The secondary objective of this study is to characterize the fuel map of a USEPA 2010 compliant heavy-duty diesel engine experimentally and then using those maps in Autonomie to predict fuel economy. Autonomie helps in predicting and analyzing the fuel efficiency of the vehicle. After predicting the fuel economy from the simulation tool, fuel economy from chassis and engine dynamometer was compared with Autonomie's predicted fuel economy. This will help out in future testing, as we will be aware of percentage difference in Autonomie's prediction and chassis and engine dynamometer data in advance.

With that in mind, the literature review includes an overview of the discussion of the various model based simulation tools, federal regulations for Heavy-duty vehicles, fuel consumption for HD vehicles and a summary of prior approaches for accurate prediction of fuel consumption.

2. LITERATURE REVIEW

2.1 Heavy-duty vehicle fuel consumption

In September 2011, National Highway Traffic Safety Administration (NHTSA) and United States Environmental Protection Agency (USEPA) set the first ever joint federal regulations for the commercial heavy-duty vehicles. These regulations do not become effective until 2014-2018 so that manufacturers have enough time to meet the requirements of these regulations. The reasons behind setting up these regulations were to reduce fuel consumption of heavy-duty diesel engines and adversity of greenhouse gases on global warming (Krupnick & Harrington, 2012).

Study from National Research council (NRC), evaluated new technologies that will contribute to the engine efficiency in 2015-2020 period and the result of this study showed a reduction in fuel consumption by 7-24% in heavy duty vehicles. This study also states that the cost involvement is going to be much higher than the cost involved in 2010 (Krupnick & Harrington, 2012).

EPA and NHTSA recognize that aerodynamic and tire rolling resistance improvements to trailers represent a significant opportunity to reduce fuel consumption and GHGs as evidenced, among other things, by the work of the EPA SmartWay program (NHTSA, 2014) (Federal Register, 2011).

EPA's voluntary SmartWay Transport Partnership program encourages shipping and trucking companies to take actions that reduce fuel consumption and CO_2 by working with the shipping community and the freight sector to identify low carbon strategies and technologies, and by providing technical information, financial incentives, and partner recognition to accelerate the adoption of these strategies. Through the SmartWay program, EPA has worked closely with truck manufacturers and truck fleets to develop test procedures to evaluate vehicle and component performance in reducing fuel consumption and has conducted testing and has established test programs to verify technologies that can achieve these reductions. Over the last six years, EPA has developed hands-on experience testing the largest heavy-duty trucks and evaluating improvements in tire and vehicle aerodynamic performance. In 2010, according to vehicle manufacturers, approximately five percent of new combination heavy-duty trucks will meet the SmartWay performance criteria demonstrating that they represent the pinnacle of current heavy-duty truck reductions in fuel consumption (Federal Register, 2011)

Class	Description/examples	Empty weight range	Gross weight range	Typical fuel intensities	
		Tons	Tons	Gallons per thousand miles	Gallons per thousand ton-miles
1c	Passenger cars	1.2–2.5	<3	30–40	67
1t	Small light-duty trucks (including SUVs and minivans)	1.6–2.2	<3	40–50	58
2a	Standard pickups, large SUVs	2.2–3	3–4.25	50	39
2b	Large pickups, utility vans	2.5–3.2	4.25–5	67–100	39
3	Utility vans, minibuses	3.8–4.4	5–7	77–125	33
4	Delivery vans	3.8–4.4	7–8	83–140	24
5	Large delivery vans, bucket trucks	9.2–10.4	8–9.75	83–166	26
6	School buses, large delivery vans	5.8–7.2	9.75–13	83–200	20
7	City bus, Refrigerated truck, fire engine	5.8–7.2	13–16.5	125–250	18
8a	Dump/refuse trucks, city buses, fire engines	10–17	16.5–40	160–400	9
8b	Large tractor trailers, bulk tankers	11.6–17	16.5–40	133–250	7

Table 1 Vehicle categorization based on weight and present fuel intensities (Krupnick & Harrington, 2012)

EPA has categorized all the on-road vehicle on the basis of different classes. Table 1 shows the different classes of vehicles, their empty and gross weight range and typical fuel intensities. These parameters are the baseline for vehicle categorization.

EPA came out with emission standards for different vehicles based on their model year. Table 2 shows the engine and vehicle standards by model year and fuel consumption predictions for different categories of heavy duty engines.

	Engine standards (expressed as percentage emission rate reduction from baseline), by model year (MY)[a]					
	Proposed			Final		
	Baseline (gallons per Kbhp-hr)[a]	2014 MY standard[b]	2017 MY standard	Baseline (gallons per Kbhp-hr)[a]	2014 MY standard[b]	2018 MY standard
Medium-heavy duty engines (Class 7)	5.09	4.93 (3%)[b]	4.78 (6%)	5.09	4.93 (3%)	4.78 (6%)
Heavy-heavy duty engines (Class 8)	4.81	4.67 (3%)[b]	4.52 (6%)	4.81	4.67 (3%)	4.52 (6%)
Vehicle standards (expressed as percentage emission rate reduction from baseline)[c]						
	Baseline (gallons per Kton-mi)	2014 MY Standard	2017 MY Standard	Baseline (gallons per Kton-mi)	2014 MY Standard	2018 MY Standard
Class 7 day cab						
Low roof	11	10.3 (6.4%)	10.1 (8.2%)	11.4	10.5(7.9%)	10.2 (10.5%)
Mid roof	11	10.3 (6.4%)	10.1 (8.2%)	12.6	11.7 (7.1%)	11.3 (10.3%)
High roof	12.8	11.6 (9.4%)	11.4 (10.9%)	13.6	12.2 (10.3%)	11.8 (13.2%)
Class 8 day cab						
Low roof	8.3	7.8 (6%)	7.7 (7.2%)	8.7	8.0 (8.0%)	7.8 (10.3%)
Mid roof	8.3	7.8 (6%)	7.7 (7.2%)	9.4	8.7 (7.4%)	8.4 (10.6%)
High roof	9.4	8.6 (8.5%)	8.5 (9.6%)	10.1	9.0 (10.9%)	8.7 ((13.9%)
Class 8 sleeper cab						
Low roof	7.4	6.3 (14.9%)	6.3 (14.9%)	7.8	6.7 (14.1%)	6.5 (16.7%)
Mid roof	8.0	6.9 (13.8%)	6.8 (15%)	8.7	7.4 (14.9%)	7.2 (17.2%)
High roof	8.7	7.1 (18.4%)	7.0 (19.5%)	9.3	7.3 (21.5%)	7.1 (23.7%)

Table 2 Engine standards and vehicle standards by model year and fuel consumption predictions for various future vehicles (Krupnick & Harrington, 2012)

Engine standards (expressed as percentage emission rate reduction from baseline)						
	Baseline (gallons per Kbhp-hr)	2014 MY standard	2017 MY standard	Baseline (gallons per Kbhp-hr)	2014 MY standard	2017 MY standard
Light heavy-duty engines	6.19	5.89 (5%)	5.57 (9%)	6.19	5.89 (5%)	5.57 (9%)
Medium-heavy duty engines	6.19	5.89 (5%)	5.57 (9%)	6.19	5.89 (5%)	5.57 (9%)
Heavy-heavy duty engines	5.74	5.57 (3%)	5.45 (5%)	5.74	5.57 (3%)	5.45 (5%)
Vehicle standards						
	Baseline (gallons per Kton-mi)	2014 MY standard	2017 MY standard	Baseline (gallons per Kton-mi)	2014 MY Standard	2017 MY Standard
Light heavy-duty class 2b–5	37.6	35.2 (6.3%)	33.8 (10%)	40.0	38.1 (4.8%)	36.7 (8.2%)
Medium heavy-duty class 6–7	22.3	20.8 (6.6%)	20 (10.3%)	24.3	23.0 (5.3%)	22.1 (9%)
Heavy heavy-duty class 8	11.3	10.7 (5.2%)	10.5 (7%)	23.2	22.2 (4.3%)	21.8 (6%)

Table 3 Fuel consumption standards (both engine standards and vehicle standards) for various heavy duty engines (Krupnick & Harrington, 2012).

Categorization of heavy duty vehicle standards was done on the basis of their different classes i.e. light heavy-duty, medium heavy-duty and heavy heavy-duty. Table 3 shows the engine (expressed as percentage emission rate reduction from baseline) and vehicle standards based on MY.

Table 4 shows the emissions for the different categories of heavy duty vehicles based on CO_2 grams per ton-mile and gallons of fuel per 1000 ton-mile.

	Day cab		Sleeper cab
	Class 7	Class 8	Class 8
2014 Model Year CO_2 Grams per Ton-Mile			
Low Roof	107	81	68
Mid Roof	119	88	76
High Roof	124	92	75
2014–2016 Model Year Gallons of Fuel per 1,000 Ton-Mile [59]			
Low Roof	10.5	8.0	6.7
Mid Roof	11.7	8.7	7.4
High Roof	12.2	9.0	7.3
2017 Model Year CO_2 Grams per Ton-Mile			
Low Roof	104	80	66
Mid Roof	115	86	73
High Roof	120	89	72
2017 Model Year and Later Gallons of Fuel per 1,000 Ton-Mile			
Low Roof	10.2	7.8	6.5
Mid Roof	11.3	8.4	7.2
High Roof	11.8	8.7	7.1

Table 4 Heavy duty combination tractor CO2 emissions and fuel consumption standards (Electronic code of federal regulations, 2014)

2.2 USEPA heavy-duty Greenhouse Gas Emissions and Fuel Efficiency Standard

USEPA has decided to implement the use of a MATLAB/Simulink-based model named Greenhouse gas Emissions Model (GEM) as a regulation for all fuel economy and emissions standards for future engine models. USEPA first introduced first version of GEM (GEM 1.0v) to all the engine manufacturers and stakeholders to get their feedbacks about the simulation model (United States Environmental Protection Agency, 2014).

Engine manufacturer association (EMA) submitted their comments about making necessary changes in the model to the agencies after a peer review. National Automobile Dealer association (NADA) argued that the MY 2014–2017/2018 phase-in period was inadequate to fulfill the stability requirement (Federal Register, 2011). Agencies considered some of their possible requirements and introduced improved version of GEM named GEM Version 2.0. The important revisions to GEM were the introduction of new driver model, simplified electric system model, enhancements to the model validations, additional data were added to the model database, improvements to GUI, and ambient conditions of GEM were changed following the SAE standards (United States Environmental Protection Agency, 2014).

2.3 Heavy-duty chassis testing facilities in North America

Chassis dynamometer test procedure is used to simulate the on-road driving under controlled laboratory conditions. Dynamometer simulates the inertia of the vehicle as well as aerodynamic drag and tire friction on the vehicle while the vehicle is running on rolls. In chassis dynamometer testing, the vehicle is controlled by a driver who follows the instruction of driving cycle from the computer. Depending on the driving cycles used chassis testing can be considered to be closest to the real world driving conditions (National Renewable Energy Laboratory (NREL), 2013).

In North America, there are only 12 fully equipped laboratories for chassis dynamometer testing (United States Environmental Protection Agency, 2014)

- Air Resources Board Heavy-Duty Emissions Testing Laboratory in Los Angeles, California
- California Truck Testing Services in Richmond, California
- Colorado School of Mines, Colorado Institute for Fuels and Research in Golden, Colorado
- Environment Canada in Ottawa, Ontario, Canada
- Southwest Research Institute in San Antonio, Texas
- West Virginia University Transportable Heavy-Duty Vehicle Emissions Testing Laboratory
- National Renewable Energy Lab in Golden, Colorado
- University of Houston in Houston, Texas
- US EPA in Research Triangle Park
- Argonne National Lab (up to 14,000 lb.)
- National Vehicle Fuel and Emissions Lab in Ann Arbor, Michigan (up to 14,000 lb.)
- University of California, Riverside, CE-CERT

2.4 Validation of GEM

GEM was validated by USEPA before announcing it as a regulation for all engines manufactured in the beginning of MY 2014. GEM is the only simulation model which is built using codes which follows the regulatory program of USEPA and NHTSA. Few user input parameters are required to run simulation on GEM, including rolling resistance, aerodynamic drag coefficient, and vehicle weight reductions (United States Environmental Protection Agency, 2014).

Agencies validated GEM using another commonly used tool named GT-Drive which was developed by Gamma Technologies. Comparisons were made using the same test data for both the tools. As the result of comparison, both simulation tools turned out to be almost equally accurate when compared with experimental chassis test data (United States Environmental Protection Agency, 2014).Table 5 shows the specifications of the vehicles which were used for the validation of GEM are:

Tractor / Model	International Prostar
Year Model	2009
Type	Day Cab with Flatbed
Engine OEM	Cummins ISX
Engine Family	9CEXH0912XAK
Displacement	15 liters
Horsepower Rating	425 @ 1,800 RPM
Final Drive	3.73
Transmission Model	Eaton Fuller FRO-16210B
Transmission Type	10 speed manual
Steer Axle Tires	Good year
Tire Size	295/75R22.5

Tractor / Model	International Prostar
Year Model	2008
Type	High Roof Sleeper
Engine OEM	Cummins ISX
Engine Family	7CEXHO912XAK
Displacement	15 liters
Horsepower Rating	408 @ 1,800 RPM
Final Drive	2.64
Transmission Model	Fuller FR15210B
Transmission Type	10 speed manual
Steer Axle Tires	Michelin XZA3
Tire Size	275 / 80 / 22.5
Front Rims / make	Accuride DOT T
Drive Axle Tires	Michelin XDA Energy
Tire Size	275 / 80 / 22.5
Drive Rims / Make	Accuride DOT T

Table 5 Class 7 tractor and engine specifications b) Class 8 Truck 555 tractor and specifications (United States Environmental Protection Agency, 2014)

Then comparison between GT-Drive and GEM was done for different vehicles of Class 7 and 8 combination vehicles, and vocational vehicles (vocational vehicles, and all of the subcategories for combination tractors), which explained that there is a certain amount of percentage difference between GEM and GT-Drive fuel economy (mpg) results which is showed in Table 8 (United States Environmental Protection Agency, 2014). The validation of the vocational vehicle model is less challenging than combination tractors because the inputs are limited to the steer and drive tire rolling resistance.

Table 6 and 7 shows the fuel economy comparison between chassis data and GEM results for class 8 and class 7 tractor, respectively.

Cycle	ProStar Chassis Test (mpg)	GEM (mpg)	GEM error (%)
ARB Transient	3.51	3.55	- 1.14 %
65 mph	6.90	6.86	0.58 %
55 mph	8.20	8.10	1.22 %

Table 6 Fuel economy (miles per gallon) comparison between chassis test data and GEM for a class 8 tractor (United States Environmental Protection Agency, 2014)

Cycle	ProStar Chassis Test (mpg)	GEM (mpg)	GEM error (%)
ARB Transient	4.10	4.13	-0.73 %
65 mph	7.74	7.66	1.03 %
55 mph	9.12	9.20	-0.88 %

Table 7 Fuel economy (mpg) comparison between chassis test data and GEM for a class 7 tractor (United States Environmental Protection Agency, 2014)

It should be mentioned that vehicle certification using the GEM is conducted on a relative basis, which compares the 2014 and 2017 vehicle model results with 2010 baseline results. The differences among all of these different year models are mainly in the engine fuel maps together with few standard inputs to the GEM, such as aerodynamic drag coefficient, rolling resistance, vehicle weight reduction, and extended idle reduction (United States Environmental Protection Agency, 2014).

	Cycle	GEM	GT-Drive	Error
Class 8 Combination - Sleeper Cab - High Roof	ARB Transient	3.47	3.53	-1.73%
	65 mph **	6.13	6.19	-0.98%
	55 mph **	7.36	7.38	-0.27%
Class 8 Combination - Sleeper Cab - Mid Roof	ARB Transient	3.6	3.66	-1.67%
	65 mph **	6.75	6.80	-0.74%
	55 mph **	7.96	7.99	-0.38%
Class 8 Combination - Sleeper Cab - Low Roof	ARB Transient	3.61	3.68	-1.94%
	65 mph **	7.31	7.39	-1.09%
	55 mph **	8.52	8.54	-0.23%
Class 8 Combination - Day Cab - High Roof	ARB Transient	3.51	3.57	-1.71%
	65 mph **	6.18	6.24	-0.97%
	55 mph **	7.42	7.44	-0.27%
Class 8 Combination - Day Cab - Low Roof	ARB Transient	3.66	3.72	-1.64%
	65 mph **	7.37	7.45	-1.09%
	55 mph **	8.61	8.63	-0.23%
Class 7 Combination - Day Cab - High Roof	ARB Transient	4.4	4.49	-2.05%
	65 mph **	6.65	6.74	-1.35%
	55 mph **	8.40	8.52	-1.43%
Class 7 Combination - Day Cab - Low Roof	ARB Transient	4.64	4.73	-1.94%
	65 mph **	8.16	8.19	-0.37%
	55 mph **	9.97	10.12	-1.50%
Heavy Heavy-Duty Vocational Vehicle (Class 8)	ARB Transient	3.48	3.47	0.29%
	65 mph **	5.69	5.69	0.00%
	55 mph **	6.81	6.78	0.44%
Medium Heavy-Duty Vocational Vehicle (Class 6-7)	ARB Transient	6.42	6.54	-1.87%
	65 mph **	7.37	7.41	-0.54%
	55 mph **	9.43	9.45	-0.21%
Light Heavy-Duty Vocational Vehicle (Class 2b-5)	ARB Transient	8.09	8.15	-0.74%
	65 mph **	8.44	8.48	-0.47%
	55 mph **	10.84	10.90	-0.55%

Table 8 Comparison between GT-Drive and GEM (United States Environmental Protection Agency, 2014)

2.5 INTRODUCTION TO AUTONOMIE AND GEM

2.5.1 Autonomie

Autonomie is a Simulink/Matlab based simulation tool which constructs a model of desired vehicle by using information provided by GUI and XML file. XML was chosen because of its flexibility and it easy to understand for both software and humans. As a language, it is specifically designed to create domain-and application-specific sublanguages, and to pass information easily between software. The XML file or run file consists all the information that user provides via GUI. The information in this file is used by the model building feature, such as the configuration and initializing files. The configuration files has all the information about all the parts of the system connected together and initialization files contain all the inputs given by the user like fuel maps. The layout files show all the information about absolute position of all the vehicle parts and displays how all the parts are connected together. All the blocks are connected to each other exactly like Simulink and it makes easier to understand the whole working procedure of the vehicle model (Halbach, Sharer, Pagerit, Folkerts, & Rousseau, 2010).

The layout files are of three different types:

1. Static layout files: These files are a simple translation of the Simulink model into the required XML Argonne Model description Specification (XAMDS). The drawback of these type of static files is that these files cannot be used for all the systems.
2. Dynamic layout files: These files already have XAMDS elements which gets resolved while building the vehicle and consists other elements which are already in the library of simulation model. These files are flexible in comparison to Static layout files and can easily be used for different systems.
3. Abstract Dynamic Layout files: These files are most flexible and can be used easily for almost all the systems and these files are normally determined at the build time of the vehicle model.

All these above mentioned layout files and associated with an XML file, which contains metadata used to manage the file. These XML files are the most important part of Autonomie as they are connected with all layout files and they contain all the information required to build an efficient vehicle model. XML files explains all the details of the system and the vehicle model, that's why they are collectively known as "definition files" (Halbach, Sharer, Pagerit, Folkerts, & Rousseau, 2010).

All these layout files are controlled by GUI and Autonomie's GUI provides as easy access to all the correct files and displays the whole model which makes it easy to understand the working procedure of the vehicle model.

Figure 1 shows the vehicle architecture which is categorized as container and terminating systems. Subsystems of container system contains all the files used to define the system while terminating system consist of a model that defines the behavior of the system and files that are required for inputs and calculating outputs.

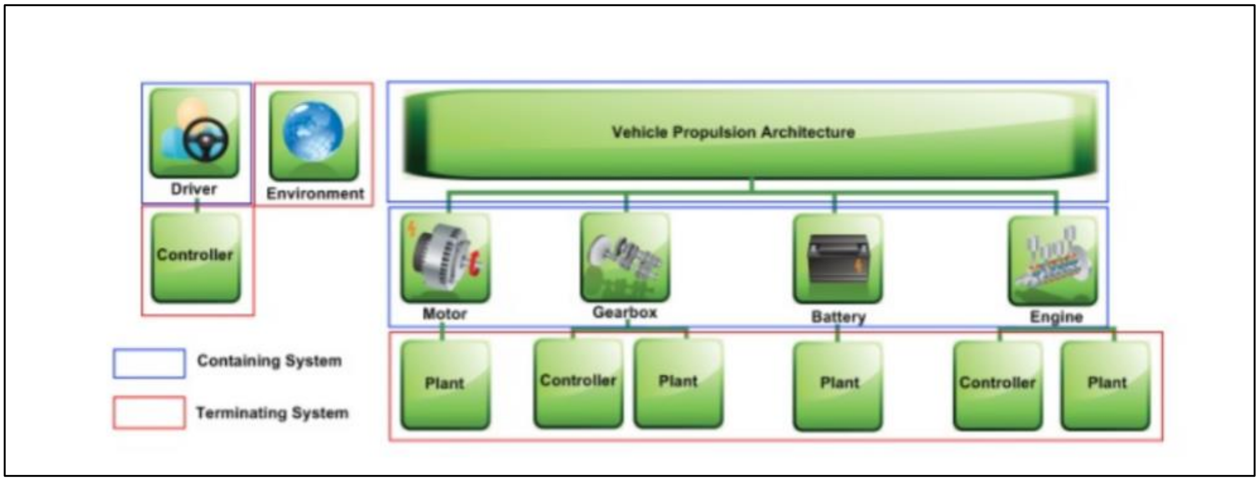

Figure 1 CONTAINER and TERMINATING SYSTEM (Halbach, Sharer, Pagerit, Folkerts, & Rousseau, 2010)

Other contents of Autonomie tool are: environment, driver, vehicle propulsion controller for advanced powertrain vehicles which shows the entire vehicle propulsion architecture. This VPA system contains all powertrain components which are essential in simulating the vehicle such as engine, transmission, battery etc.

Autonomie has been used in various studies of Argonne National Laboratory and Department of Energy (DOE) like energy consumption prediction of a vehicle along the user specified Real-world trip, vehicle simulation and testing, Hybrid Electric Vehicle modeling etc.

2.5.2 GREENHOUSE GAS EMISSIONS MODEL (GEM) v1.0

The agencies have finalized to use GEM as the primary simulation tool for future certification of vocational vehicles and tractor combinations. EPA developed Greenhouse gas emissions model for Class 2b-8 compliance which is a MATLAB/Simulink based tool. GEM works like other MATLAB/Simulink based tools, derives certain governing equations which describes driveline components, engine and vehicle. In the form of output, GEM gives transient engine speed and engine torque. Simulation models like GEM reduces manufacturer's burden of conducting chassis dynamometer testing (United States Environmental Protection Agency, 2014).

Figure shows the GEM input screen which provides the user the ability to enter parameters in the model. User can enter two types of parameters in GEM – ones required to give information to EPA and NHTSA, other which copies information from input screen to output screen. Figure 4 shows all the required input parameters in GEM 1.0v:

- Manufacturer name
- E-mail Address
- Date
- Verify User ID
- Vehicle Family
- Engine Family
- Verify ID
- Vehicle Sub Family
- Engine Sub Family
- Vehicle Model Year
- Engine Model Year

Other input parameters are selecting Regulatory Class and Simulation Inputs (coefficient of aerodynamic drag, steer tire rolling resistance, drive tire rolling resistance, vehicle speed limiter, vehicle weight reduction and extended idle reduction). Figure 4 shows the GUI of GEM (United States Environmental Protection Agency, 2014).

The results in GEM 1.0v version are displayed in MATLAB once all parameters are entered in input screen and user selects “RUN”. GEM automatically conducts simulation for all the drive cycles at 65 mph and 55 mph. Output consists of both gram CO_2/ton-mile and gallon 1000/ton-mile results (United States Environmental Protection Agency, 2014).

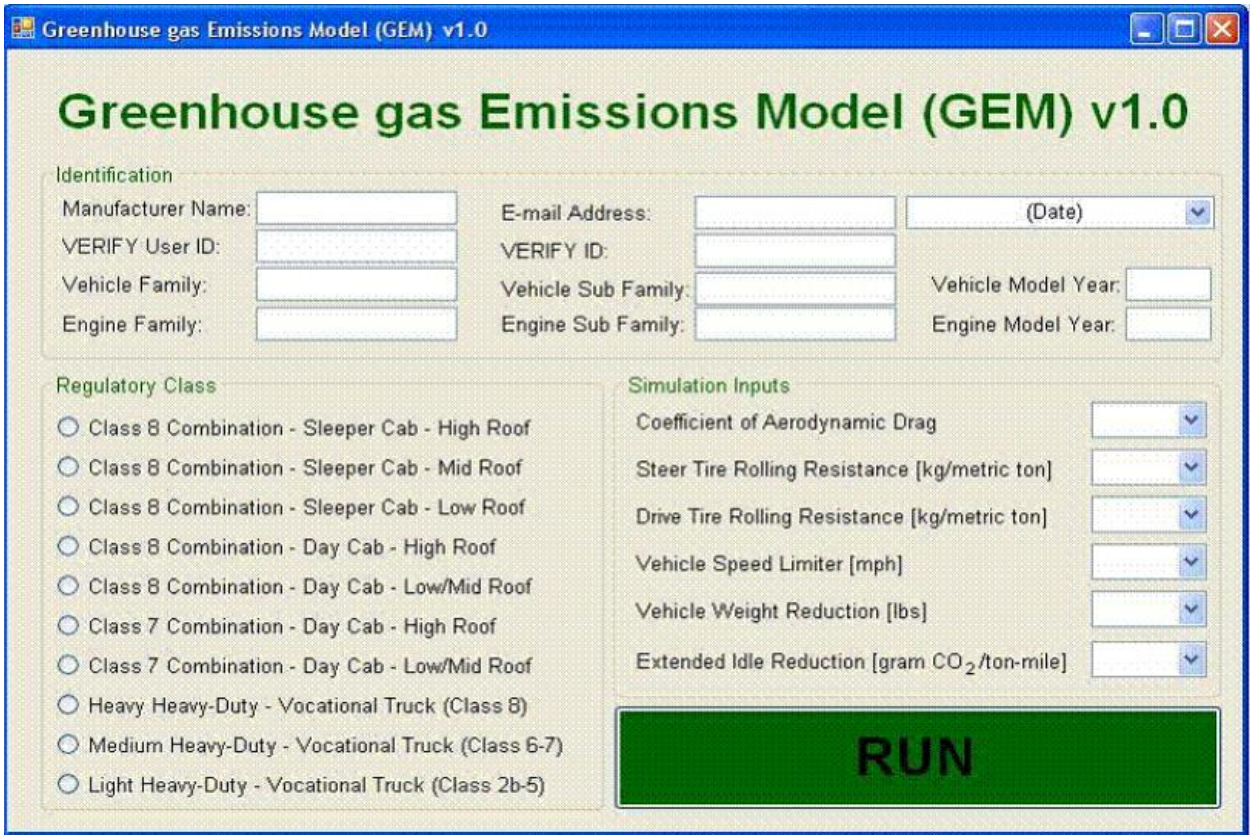

Figure 2 Graphical User Interface of GEM (United States Environmental Protection Agency, 2014)

2.6 VALIDATION AND COMPARISON OF SOME SIMULATION TOOLS

2.6.1 Validation of Powertrain system Analysis Toolkit (PSAT) using Hybridization of a Class 8 tractor trailer truck

A study was done, in which Hybridization of a Class 8 Line-Haul tractor trailer trucks was modeled using Argonne National Laboratory's modeling and simulation tool, PSAT (The Mathworks, 2014) (Argonne National Laboratory, PSAT (Powertrain Systems Analysis Toolkit), 2014) (Rousseau, Sharer, & Besnier, 2004). Two different vehicles were modeled namely full-hybrid truck and mild-hybrid truck. Full-hybrid truck was modeled on the concept of series-parallel hybrid and had large electric components and still it offers highest fuel savings because of electric-only mode. While in the case of mild hybrid, engine shut-downs at idle, and mild assists and regenerative braking possible, but with no electric-only mode. The components used in the mild-hybrid are smaller in comparison to full-hybrid therefore the upfront investment was comparatively less. It was noticed that in urban driving, hybridization of these vehicles leads to significant fuel consumption reduction, 20-40 % for full-hybrid and 10 % for mild-hybrid (Karbowski, Delorme, & Rousseau, "Modeling the Hybridization of a Class 8 Line-Haul Truck,", 2010).

Figure 3 shows the overall model of the series-parallel configuration which is used in validation of PSAT. In a pre-transmission position (Karbowski, Sylvain, Kwon, & Rousseau, 2009), the electric machine is between the clutch and the gearbox. In a post transmission, the electric machine is between the gearbox and the final drive (or transfer case).

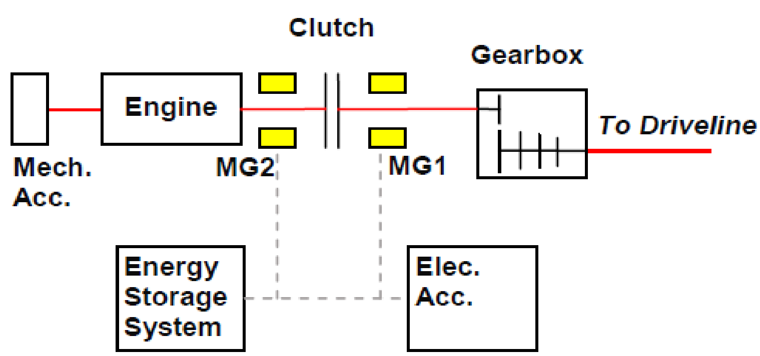

Figure 3 Schematic of the Series-Parallel Configuration (full-hybrid) (Karbowski, Delorme, & Rousseau, 2010)

When these vehicles were tested for highway type cycles, the fuel consumption reduction reduced to single digits in both the cases.

Both these vehicles along with conventional vehicle were simulated on various standard cycles, both highway (HHDDT 65, HHDDT Cruise, HHDDT High Speed) and transient/urban (HHDDT Transient, UDDS Truck) using PSAT. Figure 4 shows the fuel consumption of conventional and hybrid trucks at 50 % load for different cycles.

Figure 5 shows the fuel savings of conventional and hybrid trucks at 50 % load depending upon the cycle.

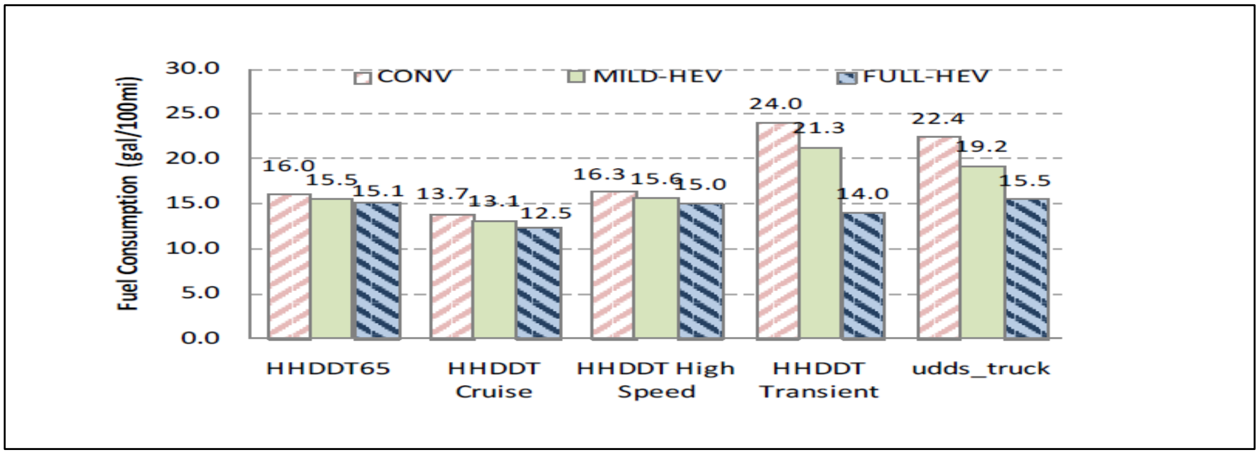

Figure 4 Fuel consumption of conventional and hybrid trucks (50 % load) on standard cycles (Karbowski, Delorme, & Rousseau, 2010)

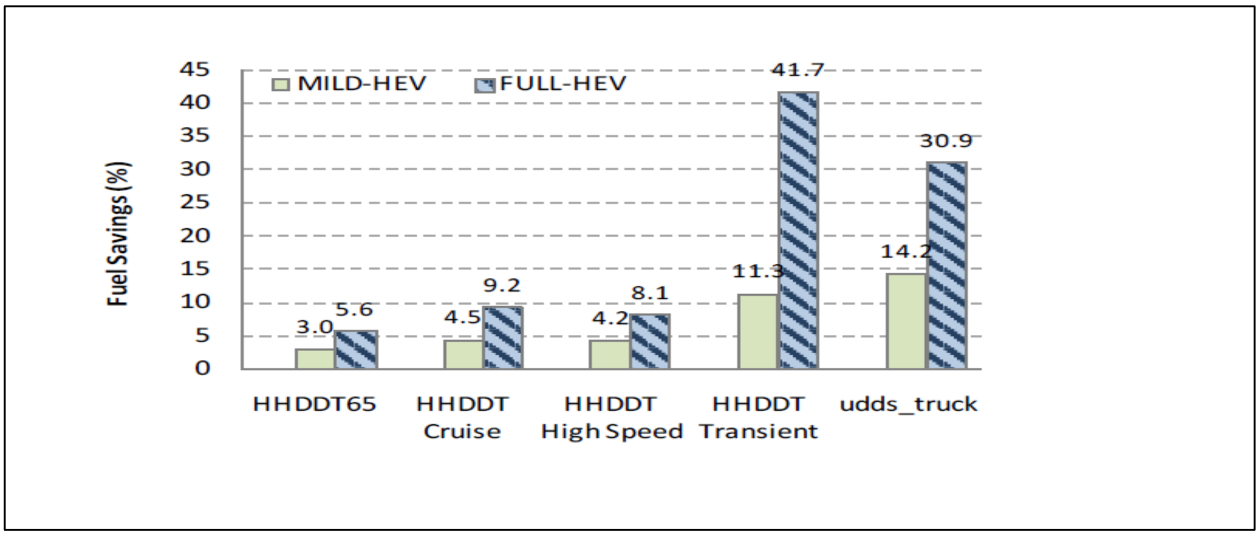

Figure 5 Hybrid truck fuel consumption reduction with respect to conventional truck (50 % load) (Karbowski, Delorme, & Rousseau, 2010)

2.6.2 Comparison in PSAT and EPA MOVES binning Methodology

In this study, fuel economy was predicted by using two different methodologies, i.e. simulation using PSAT and EPA Binning Method. PSAT is used to estimate the wheel torque needed to achieve desired speed by sending commands to different parts (Argonne National Laboratory, PSAT (Powertrain Systems Analysis Toolkit), 2014). The data used in this study was measured at Argonne's Advanced Powertrain Research Facility (APRF) ((SAE), Society of Automotive Engineers, 2010). PSAT was considered as an efficient fuel economy prediction tool as it predicted fuel economy within 5% for several hybrid vehicles. MOVES was designed to predict fuel consumptions and emissions using Vehicle Specific Power (VSP), which is a road load-based criterion. A “binning” approach was taken to predict fuel economy in which operational bins were defined on VSP under pre-defined speed ranges. An assumption was taken into account that all the vehicles were characterized in terms of vehicle speed and VSP (Kwon, Rousseau, & Sharer, 2007). Figure 6 shows the MOVES and PSAT fuel consumption estimation process model.

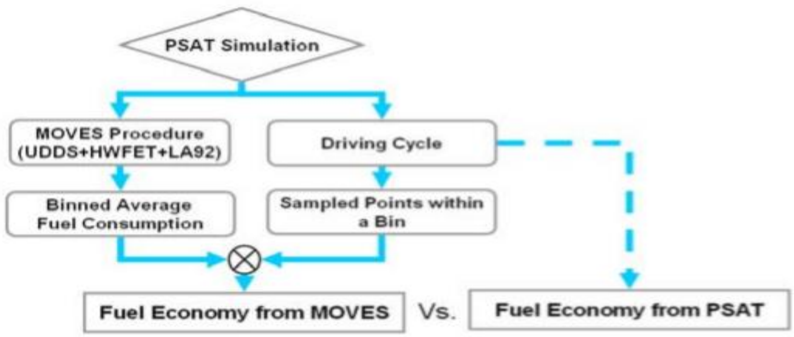

Figure 6 MOVES and PSAT Fuel Consumption Estimation Process Using PSAT (Kwon, Rousseau, & Sharer, 2007)

Figure 7 shows the percentage difference in fuel economy of PSAT and binning method for different cycles.

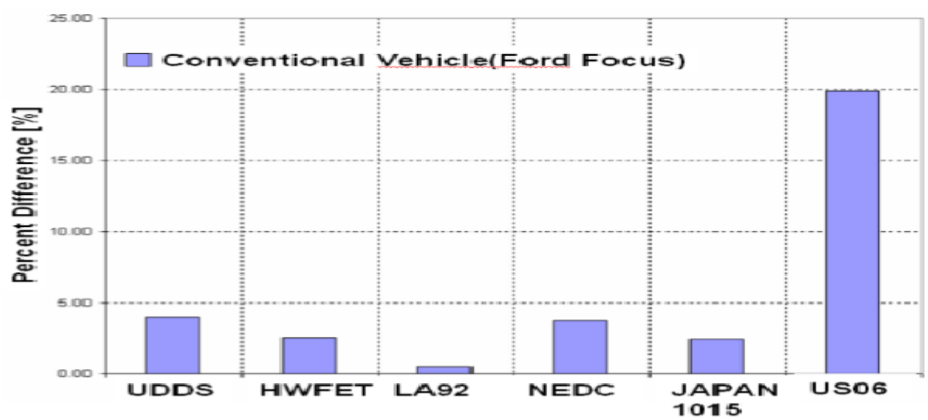

Figure 7 Percentage difference in fuel economy of PSAT and MOVES for Ford Focus

The fuel economy differences showed for the cycles used in the MOVES procedure are fairly small (4 %), which is close to the analysis performed by EPA (Koupal, et al., 2005). Results in the Figure

7 shows there are small differences in NEDC and Japan1015 (4% and 3%, respectively) while the main difference is seen with the US06 cycle at 20%.

Table 9 shows the percentage difference in results of PSAT simulation and Binning method for different cycles namely UDDS, HWFET and LA92 (Koupal & Srivastava, "MOVES 2004 Validation Results", 2005).

Vehicle Configuration	UDDS			HWFET			LA92		
	FE from PSAT Simulation	FE from EPA Binning Method	% Diff	FE from PSAT Simulation	FE from EPA Binning Method	% Diff	FE from PSAT Simulation	FE from EPA Binning Method	% Diff
Compact Conventional (Ford Focus)	27.46	26.37	3.97	40.22	39.19	2.56	25.83	25.70	0.50
Compact Fuel Cell (Ford Focus)	32.52	32.02	1.54	50.31	50.76	-0.89	30.06	30.14	-0.27
Compact Series Fuel Cell HEV	74.54	74.91	-0.50	83.07	84.33	-1.52	61.88	60.97	1.47
Compact Split HEV (Toyota Prius)	72.44	75.03	-3.58	65.35	70.09	-7.25	58.08	53.39	8.08
Midsize Parallel HEV with SOC Correction	36.64	37.45	-2.22	44.67	42.70	4.40	30.87	32.04	-3.81
Midsize Parallel HEV without SOC Correction	37.17	36.78	1.06	44.62	42.77	4.14	29.94	31.95	-6.71
Midsize PHEV	66.73	58.62	12.15	64.96	64.67	0.45	40.49	43.40	-7.19
Midsize Parallel HEV ISG	33.27	32.85	1.24	45.96	44.95	2.20	30.35	31.11	-2.50
Conventional	27.46	26.37	3.97	40.22	39.19	2.56	25.83	25.70	0.50

Table 9 Fuel economy comparison between PSAT and MOVES procedures for various vehicles (Kwon, Rousseau, & Sharer, 2007) (Koupal & Srivastava, 2005)

Table 10 shows the percentage difference in results of PSAT simulation and Binning method for NEDC, Japan 1015 and US06 (Koupal & Srivastava, 2005).

Vehicle Configuration	NEDC			Japan1015			US06		
	FE from PSAT Simulation	FE from EPA Binning Method	% Diff	FE from PSAT Simulation	FE from EPA Binning Method	% Diff	FE from PSAT Simulation	FE from EPA Binning Method	% Diff
Conventional	29.19	28.10	3.73	23.89	23.31	2.43	27.03	32.41	-19.90
Fuel Cell	35.55	34.12	4.02	28.54	27.20	4.70	31.92	37.95	-18.89
Series Fuel Cell HEV	70.01	75.84	-8.33	67.38	69.81	-3.61	53.84	60.69	-12.72
Split HEV	58.62	54.43	7.15	72.03	74.16	-2.96	44.90	50.62	-12.74
Parallel HEV with SOC Correction	41.77	39.28	5.97	36.08	37.16	-2.99	28.22	34.43	-22.04
Parallel HEV without SOC Correction	38.26	37.93	0.87	35.38	36.91	-4.33	27.82	34.39	-23.61
PHEV	75.92	60.65	20.11	88.23	64.16	27.28	34.98	41.59	-18.90
Parallel HEV ISG	35.51	35.15	1.01	30.94	29.59	4.39	31.70	36.79	-16.06
Conventional	29.19	28.10	3.73	23.89	23.31	2.43	27.03	32.41	-19.90

Table 10 Fuel Economy Comparison between PSAT and MOVES Procedures for various vehicles (Kwon, Rousseau, & Sharer, 2007) (Koupal & Srivastava, 2005)

2.6.4 STAR (Scania Truck and Road Simulation) and Dymola

In another experiment the fuel consumption of a test truck in highway driving is measured. The altitude of the road is recorded with a barometer and used in the corresponding simulations. Despite of the limited accuracy of this equipment the simulation program manage to predict level of fuel consumption only 2 % lower than the real measurements. Modular design method was used in this simulation tool which allows models to be reused for the future simulations. The main purpose of this simulation model is to study the influence on fuel consumption for different powertrain configurations. The simulation tool used in this study was Dymola which fulfilled all requirements of this study like fast simulation of long driving distances, allows a modular design, has an easy way of exchanging modules of data and manages external source code (Sandberg, 2001).

It was easier to build vehicle in Dymola but there was a requirement of proper GUI, so STAR was used. Figure 8 shows the graphical user interface of the simulation tool STAR with all the inputs mentioned. In STAR, 30 different types of engines were available which made this tool quite flexible. Parameters like weight, the frontal area, the coefficient of air resistance, air temperature and air pressure can be changed in STAR. All the data was uploaded in Matlab and fuel maps were made for simulation in STAR. After the simulation is done, the results were processed and presented in Matlab (Sandberg, 2001).

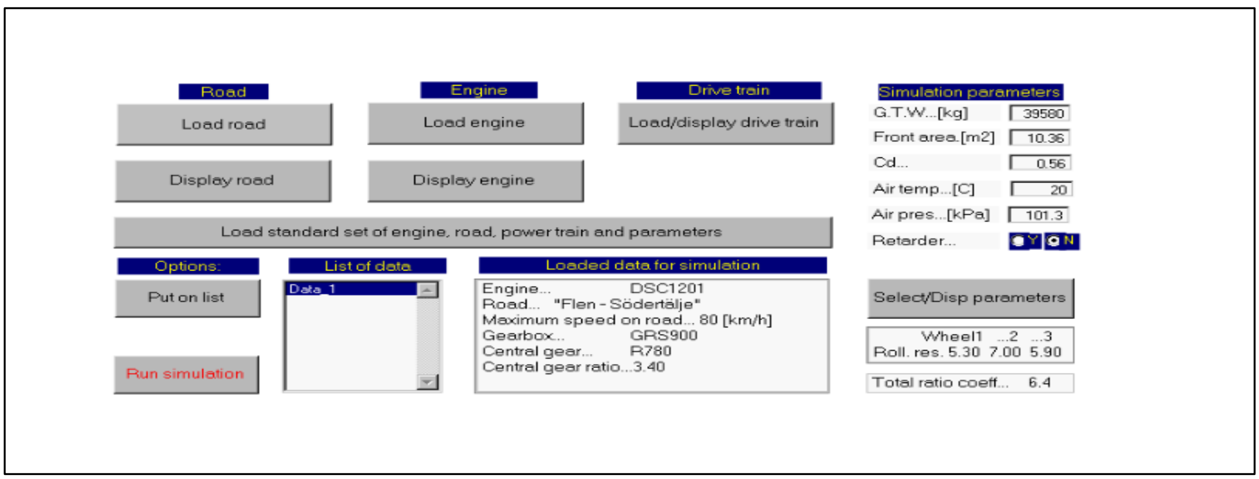

Figure 8 Graphical User Interface in STARS for specifying input data (Sandberg, 2001)

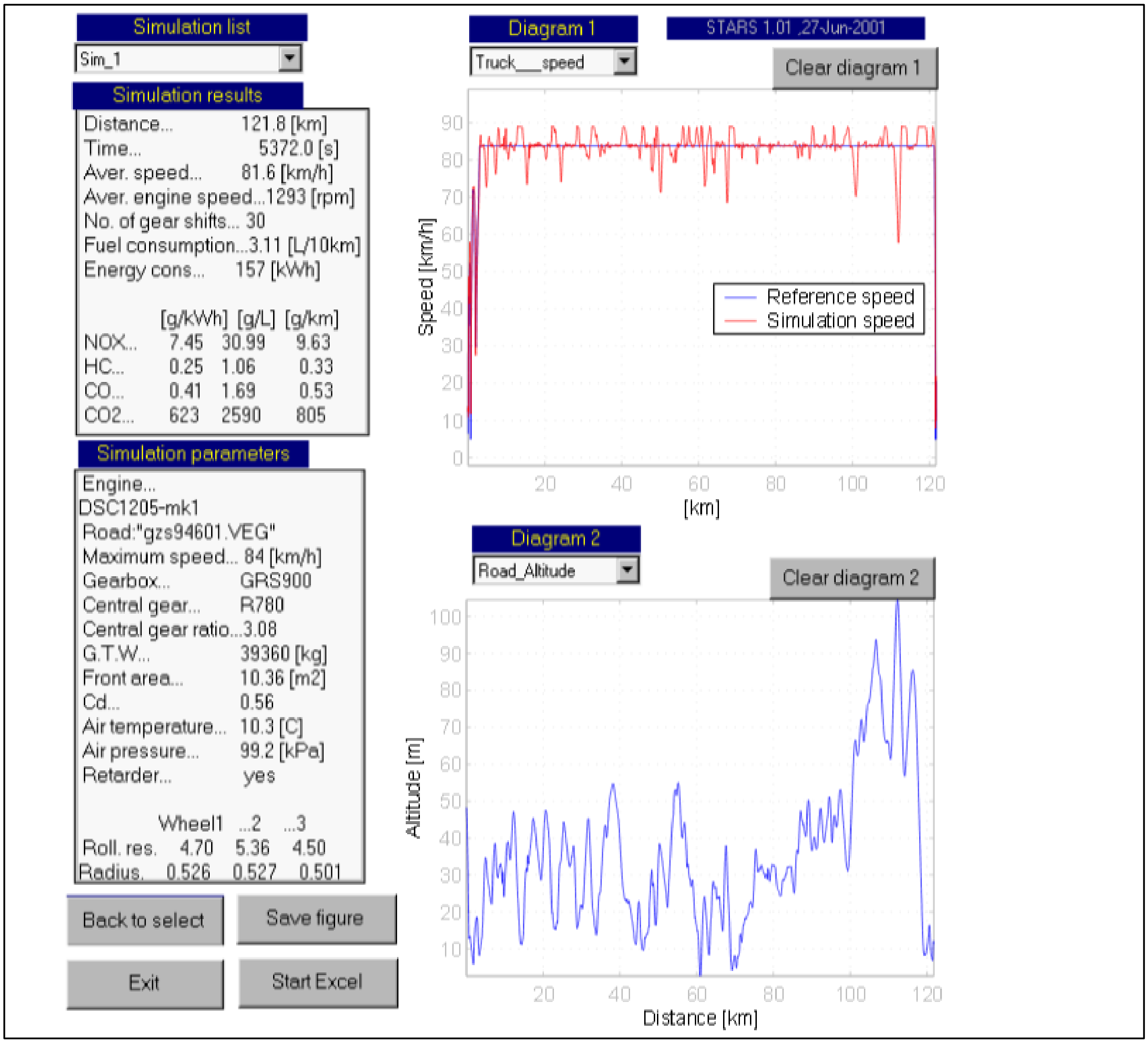

Figure 9 Result window in the simulation program STAR (Sandberg, 2001)

Figure 9 shows the output screen of the Graphical User Interface of STAR simulation tool. Simulation results include distance travelled, time taken, average vehicle speed, average engine speed, number of gear shifts, fuel consumption and energy consumption. It also displays the emission results like NO_x, HC, CO and CO_2. The graphs of the output screen show a comparison of reference and simulation speeds.

Table 11 shows the comparison of real and simulated fuel consumption for a 40 ton truck on the test road.

	Road	Measure via control unit (L)	Simulated (L)
Day 1	Part 1	39.97	37.99
	Part 2	41.34	38.99
Day 2	Part 1	39.07	38.15
	Part 2	43.78	38.76
Day 3	Part 1	40.48	38.37
	Part 2	41.21	39.05

Table 11 Real and simulated fuel consumption (L) for a 40 ton truck on the test road (Sandberg, 2001)

The results showed that there was only difference of 2 % in the real calculations and simulated calculations. Simulated calculations came out to be 2 % lower in case of fuel consumption (Sandberg, 2001).

2.6.5 VALIDATION OF ADVISOR

In 1997, the most widely used simulation tool ADVISOR (Advanced Vehicle Simulator) for HEV was validated in Virginia Polytechnic Institute and State University (Merkle, 1997). This program operates on MATLAB/Simulink based platform. ADVISOR can predict the fuel economy, emissions, acceleration, and grade sustainability of a given vehicle and plot or data log any number of intermediate and final values. In comparison to other available simulation tools in 1997, ADVISOR had an extra feature, i.e. well-refined GUI which made it easier for user to select from custom or pre-defined vehicles (Senger, 1998). Figure 10 shows the flow chart of the Advisor Series HEV data flow with all the components included.

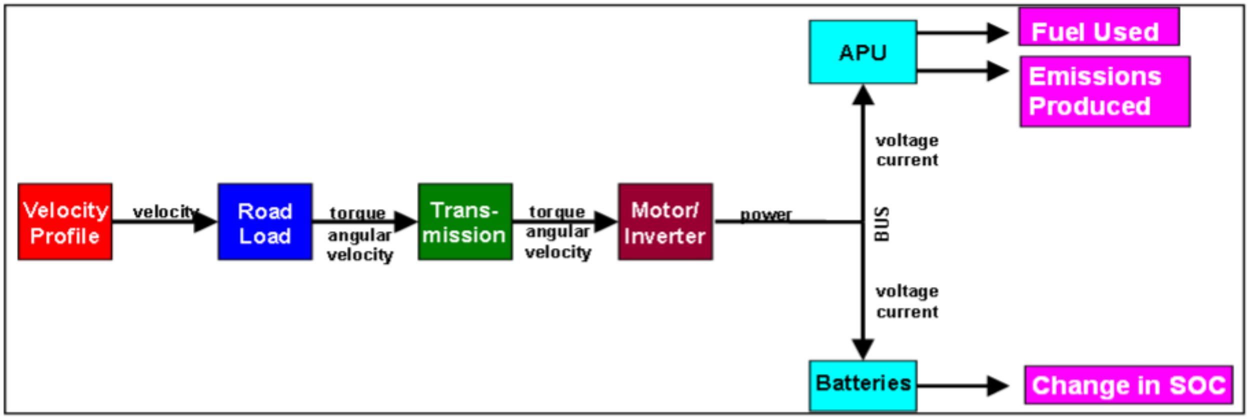

Figure 10 ADVISOR SERIES HEV DATA FLOW (Senger, 1998)

In this study, some modifications were made in the Original ADVISOR code like, a change was made in APU loading calculation. Normally, ADVISOR determined the APU load from the single, pre-defined single operating speed and torque. The APU controller adjusts the throttle in such a way that the vehicle runs on the constant speed under different torques required by the vehicle. Figure 11 shows the comparison of fuel economy using different methods for different cycles.

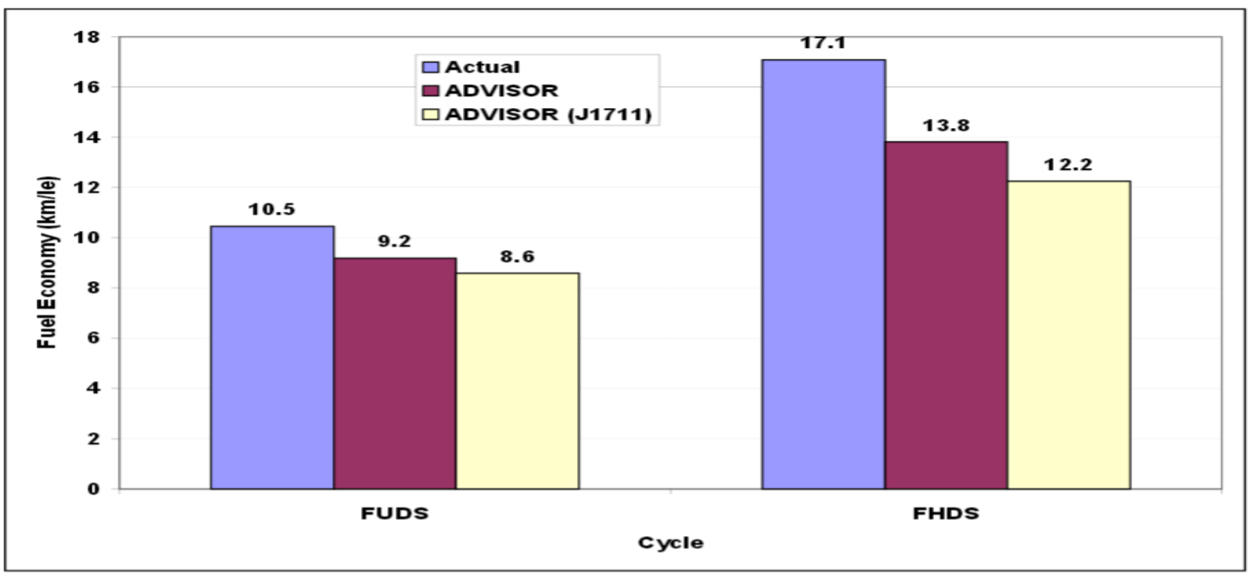

Figure 11 SOC corrected Fuel Economy comparison (Senger, 1998)

FUDS and FHDS were used to imitate urban and highway driving pattern. The FUDS is 1371 seconds in length and covers a distance of 12.0 km (7.5 mi). The average vehicle speed for the test is 31.5 km/hr (19.6 mph) with a maximum speed of 91.2 km/hr (56.7 mph).

The FHDS is 765 seconds long and covers a distance of 16.5 km (10.3 mi). The average speed during the test is 77.7 km/hr (48.3 mph) with a maximum of 96.4 km/hr (59.9 mph) (Senger, 1998)

The ADVISOR predictions differ from the measured values by 12.2% and 19.2% for the city and highway, respectively. Considering the uncertainty surrounding the 1996 FCC fuel economy numbers, these numbers indicate that ADVISOR can provide reasonable predictions of SOC-corrected fuel economy (Senger, 1998).

3. Experimental Setup

The heavy-duty engine with its after-treatment system was installed in the test cell. The alternator was also not operated on the engine test cell. While all of these auxiliaries are expected to consume power while in-use (power consumption will be heavily dependent on vehicle duty cycle), these components are not consuming power during the engine dynamometer testing and therefore are excluded from the engine fueling map. On the other hand, the power consumption of some engine related auxiliary components that are essential for engine operation is being measured during the test, and are already implicitly covered by the resultant fueling maps. Table 12 shows the engine auxiliaries that are included and excluded during testing.

Table 12 Engine auxiliaries included and excluded during engine fueling map testing

Included (accounted for in the map)	**Excluded (not accounted for in the map)**
Water pump	Cooling fan
Oil pump	Alternator
Fuel pump	Air conditioning compressor
	Air compressor
	Power-steering pump
	Power take-off

3.1 Test Cell Integration

The heavy-duty Mack MP8 505C engine was removed from a Class 8 tractor and installed in the test cell. Since the engine in the truck interfaces multiple vehicle components, it was necessary for WVU, to procure wiring harness and to connect engine control unit (ECU), after-treatment ECU and the test cell control. Also, the engine and after-treatment system communicate with each other and with the vehicle interface through a separate controller area network (CAN) bus, and as a result the engine required certain vehicle specific parameters such as ambient temperature, vehicle speed and ECU clock to be provided by the test cell computer for proper functioning of engine and after-treatment system. Volvo North America supported the study by providing the necessary CAN messages and procedures to complete the integration of engine in the test cell. With the complexity of after-treatment integration, it was important to ensure that the engine was able to communicate with all units of the after-treatment system, in order to prevent engine de-rate and possible non representative open loop fuel control. The DPF and SCR was used in the state that they were when removed from the engine and no regeneration was performed previous to testing.

3.2 Test Procedure

The test procedure was aimed at characterizing the fuel consumption in a heavy-duty diesel engine. The engine instrumentation, testing procedure and modeling methodology will be explained in this section.

3.2.1 Engine Instrumentation

Figure 12 shows the schematic of the instrumentation performed on the test engines. In order to estimate the energy flows in the air, exhaust, coolant, oil pathways, and thermocouples were installed on all fluid flow pathways to capture the energy flow in air, coolant and oil pathways. Intake air mass flow rate, coolant flow rate and engine exhaust flow rate were also measured. All data channels where recorded at a frequency of 10 Hz.

The fuel flow measurement for the study was accomplished using an AVL fuel flow meter. The AVL fuel flow meter and conditioning system measures instantaneous fuel flow measurement using the Coriolis principle. The fuel flow meter is capable of fuel flow and density measurements with an accuracy of 0.12%. In addition to the AVL fuel flow measurement, ECU reported fueling was also recorded.

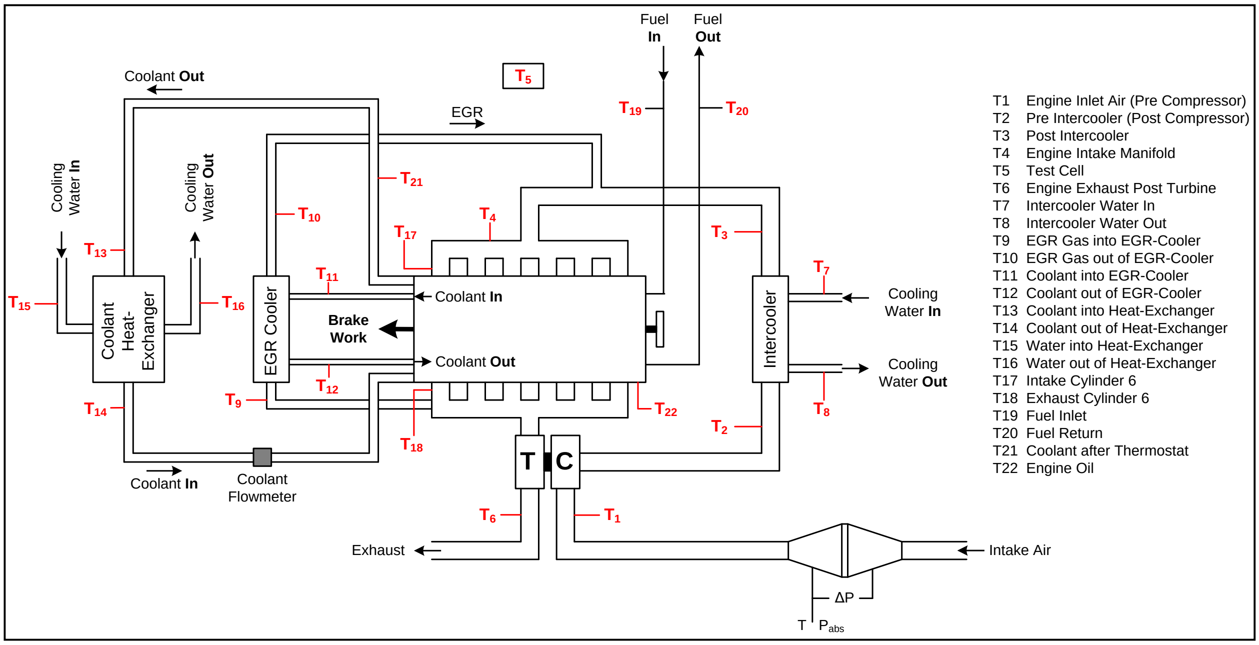

Figure 12 Schematic of engine instrumentation

The engine instrumentation included also the after-treatment systems, however, the control volume for the engine testing was restricted only to the outlet of the turbocharger.

3.2.2 Engine Lug Curve

Engine lug curve procedures were used to measure the peak torque and peak power curves of the engine as a function of engine speed. Engine mapping is important to understand the proposer functioning of all components of the engine in order to deliver the peak torque and power specified on the engine tag.

The engine was warmed up to stabilize the coolant and oil temperatures prior to the procedure. WVU test cell software tracks the engine coolant and oil temperature to determine stability to begin the engine mapping procedure. Upon stabilization the control software performs a wide-open-throttle (WTO) (i.e., 100% throttle) sweep over the engine speed range (i.e., from idle to governed speed) continuously increasing the speed at a rate of in 4 rpm/s. intervals. Three consecutive tests are performed to validate the final torque and power curves. These curves are also used as upper boundaries for the fueling mapping process and are required inputs for the engine dynamometer test bench to run FTP and DOE test cycles.

3.3 Fuel Map Development

In order to efficiently cover the operational envelope of the engine, two different design of experiments space filling designs (Gaussian and Latin Hypercube) were used to characterize the engine fuel consumption map. Each method provided 25 points under the lug curve for a total of 50 points. A transient test which covered the 50 points while following a “random walk” pathway between the points was conducted. The test captured both steady-state fueling at the individual 50 points and transient fueling while moving from one point to another. These test cycles also suggested the sequence of points to optimize the covered area under the lug curve and to capture the change of fuel consumption rates while moving between the chosen 50 points. The test cycles generated for the fuel map development process was aimed at measuring steady fueling rates at chosen 50 points as well as measuring fuel consumption while moving between the steady state points. This process provides a wealth of data to train the model for transients, if significant differences are observed between measured and predicted fuel consumption over the FTP cycle.

For the Gaussian fitting process, data of the 50 steady state points were extracted from the complete cycle data to train the fuel map prediction mode shown in figure 13. Only steady state data points were used on the Gaussian fitting process, due to limitations of the JMP software to handle a large data set. Hence, a second order surface fit was used to fit the entire data set that included the entire cycle data to analyze for differences in fuel maps generated by the different approach. The resultant 2^{nd} order surface was used to populate a 25x25 fuel consumption map with 625 points under the lug curve. This data drive approach utilizes the whole data set and is expected to produce more accurate results than a simpler steady-state modes approach.

The resulting fit data was verified using a FTP test where the predicted fuel rate for the FTP was compared against the measured fuel rate during the FTP. The FTP cycle was used only for the verification of the model and not for training of the model.

It is to be noted that unlike fuel consumption, the losses in an engine could be non-linear and as a result accuracy of the loss prediction in certain regions of the lug curve could be lost. For example brake thermal efficiency (BTE) in a heavy-duty engine could be optimized in certain regions of the lug curve to provide optimum engine performance, and if the measured data did not capture the multiple regions in which the BTE is optimized, the model will fail to predict the BTE in those regions accurately. The prediction of losses accurately over the entire region of the lug curve will require extensive engine dynamometer testing to characterize the losses and efficiency at a finer resolution under the engine lug curve.

As previously discussed, since the loads associated with oil pump, water pump, backpressure and EGR pumping loads are highly dependent on engine transients, a transient cycle was justified in lieu of traditional measurement of steady-state points. In this way, the model is trained with both transient and steady-state fuel consumption data and the fuel rates in the map will be more representative and produce more accurate fuel consumption predictions. This methodology could help avoid the use of a transient correction factors to modify the steady-state engine fueling maps.

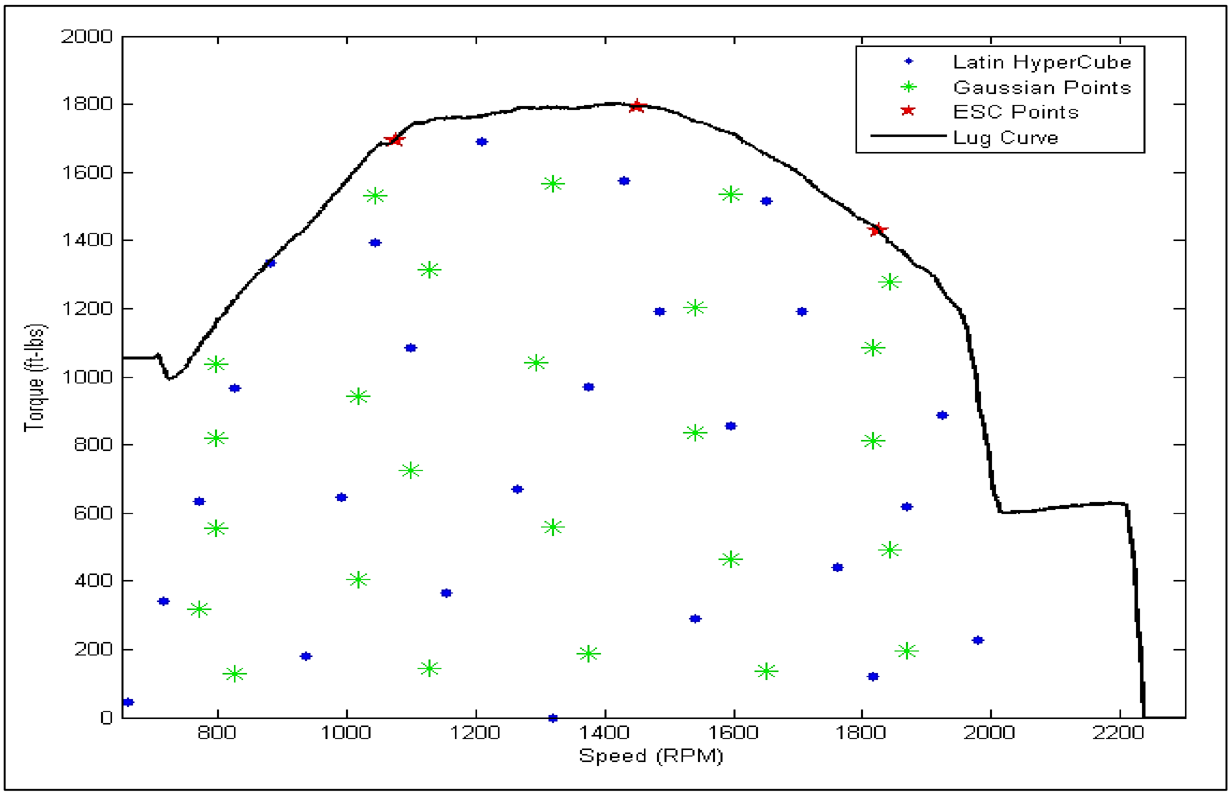

Figure 13 DOE test matrix with Gaussian and Latin Hypercube test points

It is to be noted that the fuel consumption characteristics measured for this study are representative of the engine operation on the test bench, under the conditions imposed by the engine dynamometer. Engine management strategies that include but are not limited to aftertreatment thermal management, extreme ambient conditions calibration adjustments, DPF regeneration events, and fuel saving strategies during highway cruise driving are used by manufacturers during on-road operation and may be dependent on many other parameters and sensor feedbacks, which are not covered/controlled on the engine test bench. Hence, on-road fuel economy can be different from engine dynamometer results.

The 2010 MY fuel map, which was generated using steady state data in MATLAB was used to make the initialization file. This initialization file serves the input for the Autonomie simulation tool. Vehicle speed from the chassis data is taken into account to run the simulation in the Autonomie. Once the simulation is done, Autonomie generates an output file which can be accessed using MATLAB. Autonomie also generates a summary of the cycle which is shown in Table 13.

Summary		
Vehicle		
Vehicle Propulsion Architecture		
System Name		conv_10_speed_manualtrans_class8_linehaul_nitin
Simulation Folder		2014_0527_1823_04_769
Process Name		Run neardock_n Cycle
Cycle Name		neardock_n
Distance Traveled	mile	5.5431
Cycle Distance	mile	5.5974
Start Time	s	0
End Time	s	3045
Percent Time Trace Missed by 2mph	%	0.068963
Driver Performance Index (SAE J2951)		-3.8153
Percentage of energy spent during idling	%	14.5006
Fuel Economy	mile/gallon	4.0198
Fuel Consumption	l/100km	58.5146
CO2 Emission	g/mile	2507.0838
Load Specific Fuel Economy	gallon/100mile/ton	0.9618
Load Specific Fuel Consumption	l/100km/ton	2.2623
Load Specific CO2 Emission	g/km/ton	60.2294
Fuel Economy Gasoline Equivalent	mile/gallon	3.589
Electrical Consumption	W.h/mile	0.01743
Initial SOC	%	70
Final SOC	%	69.9951
Delta SOC	%	-0.0049265
Percent Regen Braking at Battery	%	vpa.results.regen.percent_recovered
Percent Regen Braking at Wheel	%	vpa.results.regen.percent_at_whl
Percent of energy used for the cycle from regen	%	vpa.results.percent_erj_forcycle_fromregen
Regen Braking Energy Recovered at Battery	W.h	vpa.results.regen.erg_recovered
Regen Braking Energy Available at Wheel	W.h	vpa.results.regen.erg_at_whl
Total Braking Energy at Wheel	W.h	vpa.results.regen.erg_brake_total_at_whl

Table 13 Summary of the simulation done using Autonomie simulation tool for real-world cycle

4. RESULTS

The results are representative of the testing conducted on Mack MP8 engine, conducted on the chassis lab and engine dynamometer testing. Chassis data was used to run simulation on Autonomie to calculate fuel economy for UDDS and Regional cycles. Mack MP8 2010 fuel map used for this study is shown in figure 14. Actual fuel flow rate and predicted fuel flow rate was compared for 2010 Mack MP8 engine shown in figure 15.

% OF LOW IDLE TO HIGH IDLE SPEED \ % OF PEAK TORQUE	0%	4%	8%	13%	17%	21%	25%	29%	33%	38%	42%	46%	50%	54%	58%	63%	67%	71%	75%	79%	83%	88%	92%	96%	100%
0%	2%	4%	6%	8%	9%	11%	13%	15%	17%	19%	21%	23%	25%												
4%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%	26%												
8%	2%	4%	6%	8%	10%	13%	15%	17%	19%	21%	23%	25%	28%	30%	32%										
13%	2%	4%	7%	9%	11%	13%	15%	18%	20%	22%	25%	27%	29%	32%	34%	36%	39%								
17%	3%	5%	7%	9%	12%	14%	16%	19%	21%	24%	26%	29%	31%	33%	36%	38%	41%	43%							
21%	3%	5%	7%	10%	12%	15%	17%	20%	22%	25%	28%	30%	33%	35%	38%	41%	43%	46%	49%	51%					
25%	3%	6%	8%	11%	13%	16%	18%	21%	24%	26%	29%	32%	35%	37%	40%	43%	46%	49%	52%	54%	57%	60%			
29%	3%	6%	9%	11%	14%	17%	19%	22%	25%	28%	31%	34%	37%	40%	43%	45%	48%	51%	54%	57%	60%	63%	66%		
33%	4%	6%	9%	12%	15%	18%	20%	23%	26%	29%	33%	36%	39%	42%	45%	48%	51%	54%	57%	61%	64%	67%	70%		
38%	4%	7%	10%	13%	16%	19%	22%	25%	28%	31%	34%	37%	41%	44%	47%	51%	54%	57%	60%	64%	67%	70%	74%		
42%	5%	7%	10%	13%	17%	20%	23%	26%	29%	33%	36%	39%	43%	46%	50%	53%	57%	60%	64%	67%	71%	74%	77%		
46%	5%	8%	11%	14%	18%	21%	24%	28%	31%	34%	38%	42%	45%	49%	52%	56%	60%	63%	67%	70%	74%	78%	81%		
50%	6%	9%	12%	15%	19%	22%	25%	29%	33%	36%	40%	44%	47%	51%	55%	59%	63%	66%	70%	74%	78%	81%	85%		
54%	6%	9%	13%	16%	20%	23%	27%	31%	34%	38%	42%	46%	50%	54%	58%	62%	66%	70%	74%	77%	81%	85%	89%		
58%	7%	10%	14%	17%	21%	24%	28%	32%	36%	40%	44%	48%	52%	56%	60%	64%	69%	73%	77%	81%	85%	89%	93%		
63%	7%	11%	14%	18%	22%	26%	30%	34%	38%	42%	46%	50%	54%	59%	63%	67%	72%	76%	80%	85%	89%	93%			
67%	8%	12%	15%	19%	23%	27%	31%	35%	39%	44%	48%	52%	57%	61%	66%	70%	75%	79%	84%	88%	93%	97%			
71%	9%	12%	16%	20%	24%	28%	33%	37%	41%	46%	50%	55%	59%	64%	69%	73%	78%	83%	87%	92%	96%				
75%	9%	13%	17%	21%	26%	30%	34%	39%	43%	48%	52%	57%	62%	67%	71%	76%	81%	86%	91%						
79%	10%	14%	18%	22%	27%	31%	36%	40%	45%	50%	55%	59%	64%	69%	74%	79%	84%	89%							
83%	11%	15%	19%	24%	28%	33%	37%	42%	47%	52%	57%	62%	67%	72%	77%	82%									
88%	12%	16%	20%	25%	29%	34%	39%	44%																	
92%	12%	17%	21%	26%	31%	35%	40%	45%																	
96%	13%	18%	22%	27%	32%	37%	42%	47%																	
100%	14%	19%	23%	28%	33%	38%	44%	49%																	

Figure 14 Fuel Flow rates for MY 2010 Mack MP8

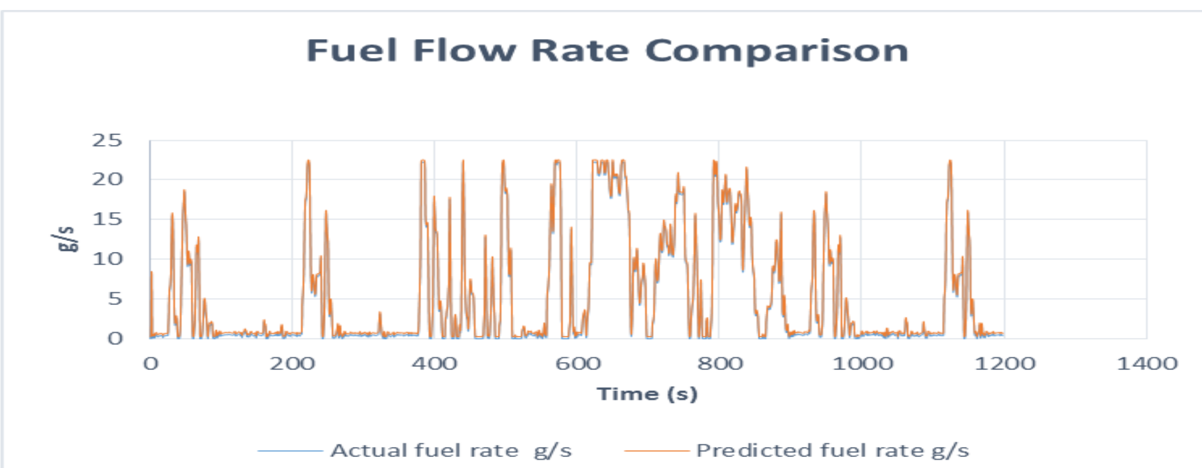

Figure 15 Actual vs Predicted fuel flow rate comparison

4.1 Fuel Map Differences due to different surface fits

These fuel maps were created in MATLAB using the curve fitting tool. Different types of fits were used to see the accuracy of data taking the R-square value into account. Steady state data was used for the different kinds of fits where the inputs were engine torque, engine speed and fuel flow rate.

4.1.1 Linear Fit

Linear fit was used in the curve fitting tool taking steady state data into account which included engine torque, engine speed and fuel flow rate. R-square and SSE values were found out to be 1 and 0.0017.

Goodness of fit:	
SSE (Summed square of residuals)	0.0017
R-square:	1

Table 14 Summary of linear fit for Mack MP8

Figure 16 shows the fuel flow rate (gm/sec) points at different values of engine speed (rpm) and engine torque (ft-lbs).

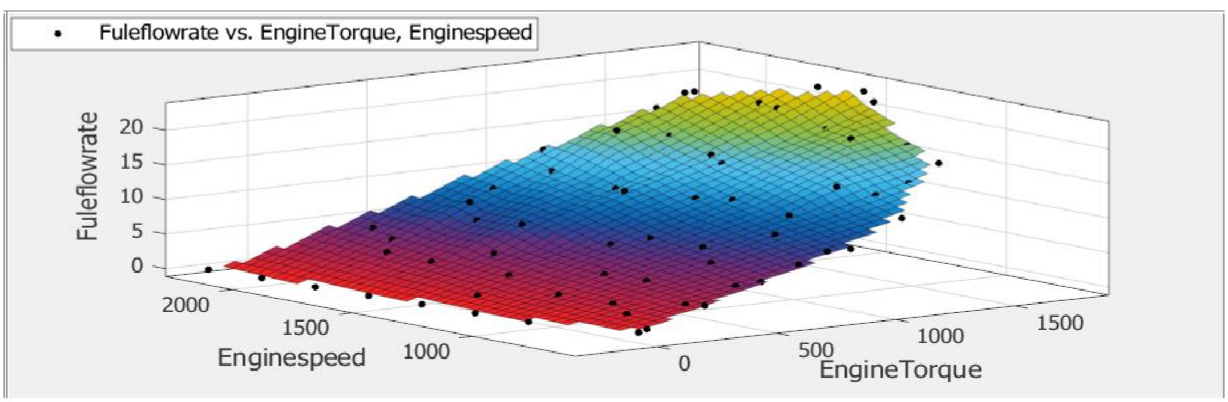

Figure 16 Linear fit generated from the curve fitting tool for 2010 MY engine

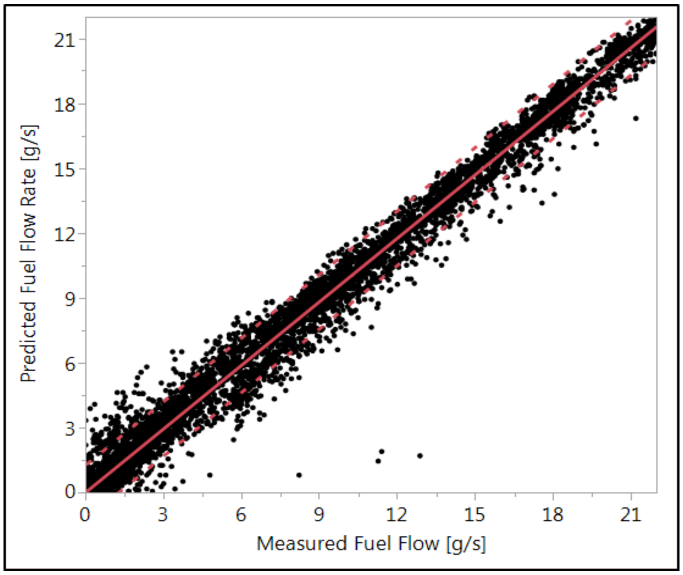

Figure 17 Scatter plot using linear method over FTP

4.1.2 Polynomial 2x2

Second order fit equation was derived from the datasets. Table 15 shows the summary of fit for the 2nd order equation developed using the steady state data points. A R^2 of 0.99 and root mean square error (RMSE) of 0.26 suggests a good surface fit of the data.

Goodness of fit:	
SSE:	4.389
R-square:	0.9987
Adjusted R-square:	0.9986
RMSE:	0.2683

Table 15 Summary of Polynomial 2x2 fit for Mack MP8

The equation used for calculating the fuel flow rate by curve fitting tool for second order fit:

Fuel Flow rate [g/s] = 0.7524 (0.01869, 1.486) + 0.0002422 (-0.0003006, 0.0007851)*Torque + -0.001059 (-0.002263, 0.0001454)*Speed + 6.696e-07 (4.63e-07, 8.763e-07)*Torque^2 + 6.792e-06 (6.496e-06, 7.088e-06)*Torque*Speed + 1.057e-06 (6.087e-07, 1.505e-06)*Speed^2

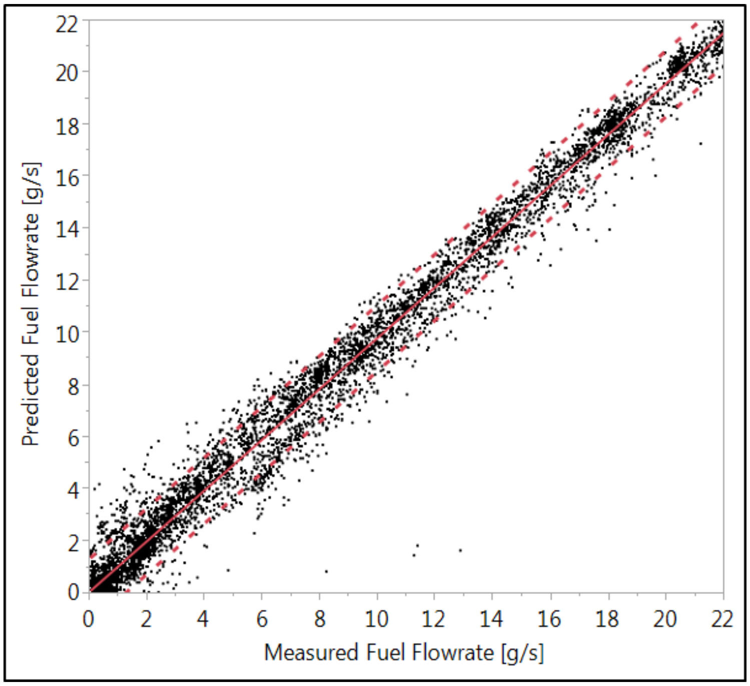

Figure 18 Scatter plot using second order polynomial equation over FTP

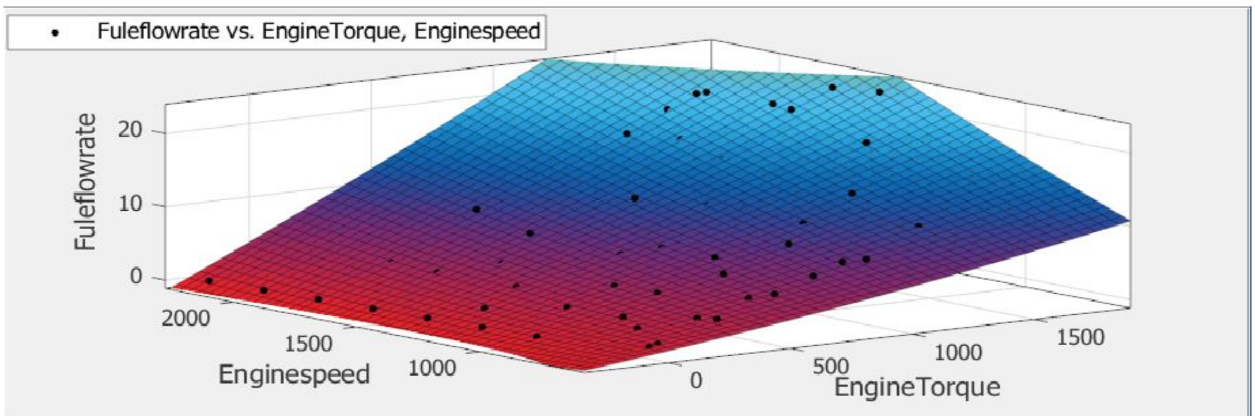

Figure 19 Polynomial 2x2 fit generated from the curve fitting tool for 2010 MY engine

4.2 Summary of UDDS cycle generated from Autonomie Simulation tool

UDDS cycle was used during this study for the comparison of Autonomie simulation results with chassis and engine dynamometer results. UDDS schedule was a basis for the development of the FTP transient engine dynamometer cycle. Table 16 shows the summary which is generated from Autonomie simulation tool for UDDS cycle. Summary shows that simulation resulted fuel economy for the UDDS cycle to be 4.10 miles/gallon. Vehicle travelled a distance of 5.32 miles in a duration of 1059 seconds, as per Autonomie simulation results.

Cycle Name	Unit	UDDS
Distance Traveled	mile	5.3261
Start Time	seconds	0
End Time	seconds	1059
Fuel Economy	mile/gallon	4.10

Table 16 shows the summary of results generated from Autonomie for UDDS cycle

4.3 Comparison of Autonomie simulation with chassis dynamometer data (Regional cycle)

Autonomie simulation output and chassis dynamometer data was compared using regional cycle, a real world cycle. Autonomie simulation was done using vehicle speed (chassis data) as the input parameter for the Autonomie tool. A 2010 Mack MP8 fuel map was generated using the steady state data and was used in the initialization file for Autonomie simulation. Figure 20 shows the varying vehicle speed during the regional cycle for chassis dynamometer testing. There is a visible difference in the engine speed comparison of autonomie and engine dynamometer in Figure 21. Engine speed in case of engine testing is comparatively higher than autonomie engine speed. The reason behind the difference in engine speed is autonomie ran the cycle on a higher gear in comparison to engine dynamometer which resulted in higher engine speed.

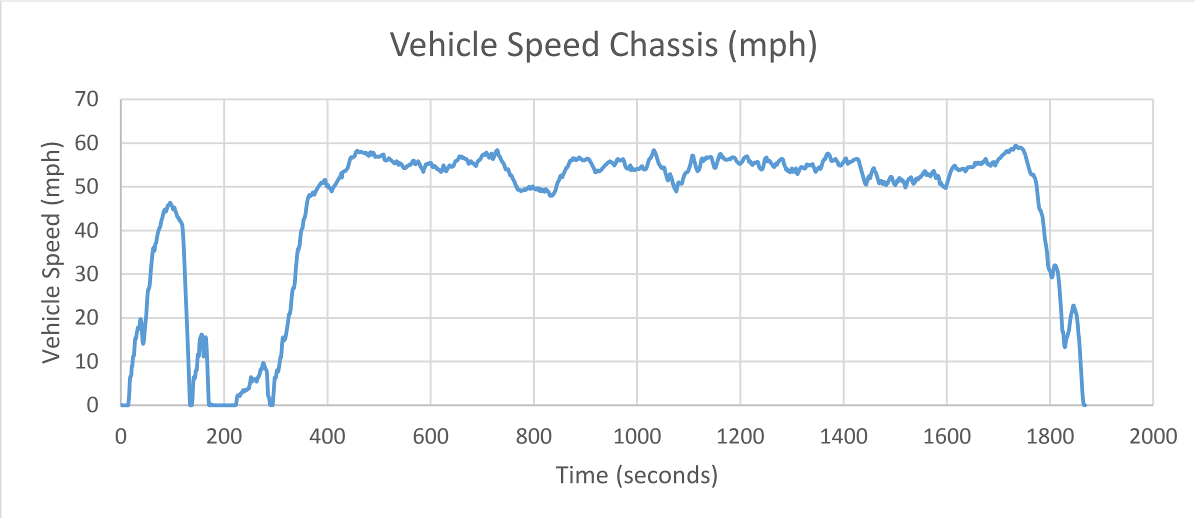

Figure 20 Regional cycle's vehicle speed for chassis testing

Another difference between test and simulation results was that the driver behavior in test could not be replicated in simulation which has a significant influence on the results.

A comparison between chassis data and Autonomie simulation output was done on the basis of engine torque and engine speed. Figure 21 shows the comparison of engine speed for regional cycle for both chassis dynamometer data and Autonomie simulation data.

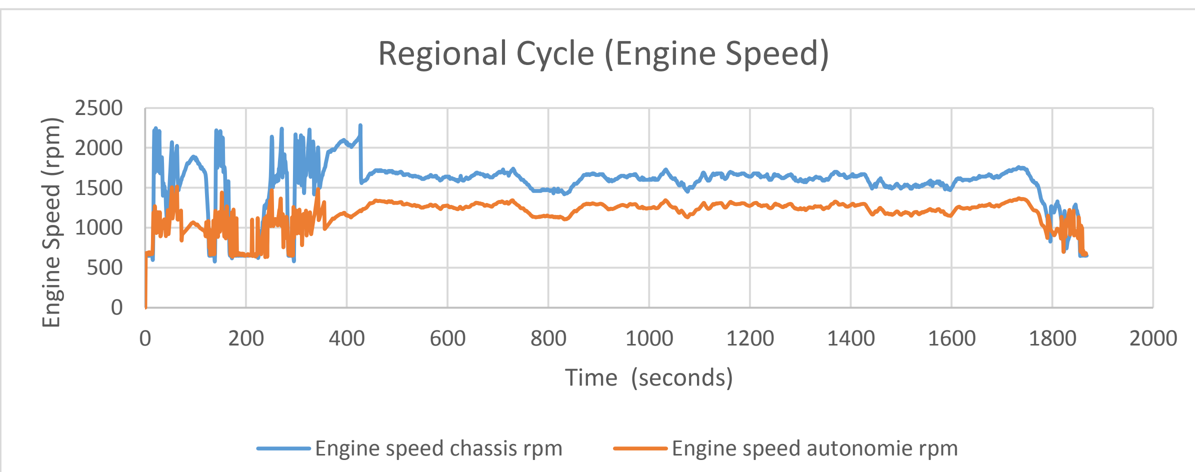

Figure 21 Comparison between chassis data and Autonomie data engine speed for regional cycle

Figure 22 shows the comparison of engine torque for regional cycle for chassis dynamometer and Autonomie simulation data.

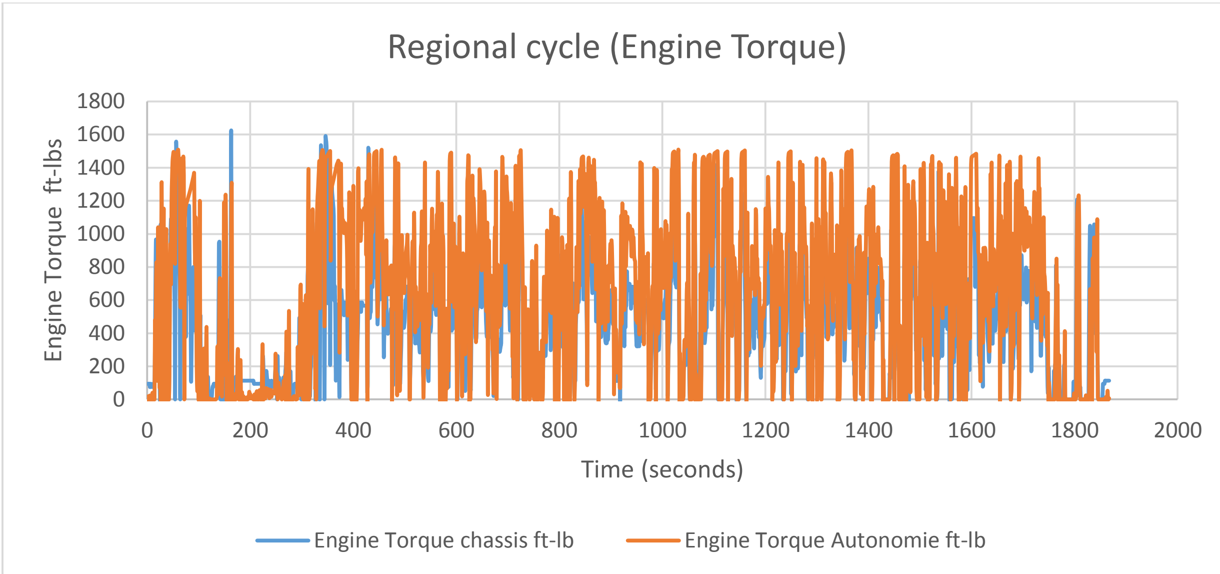

Figure 22 Comparison of engine torque for regional cycle for chassis dynamometer and Autonomie simulation data

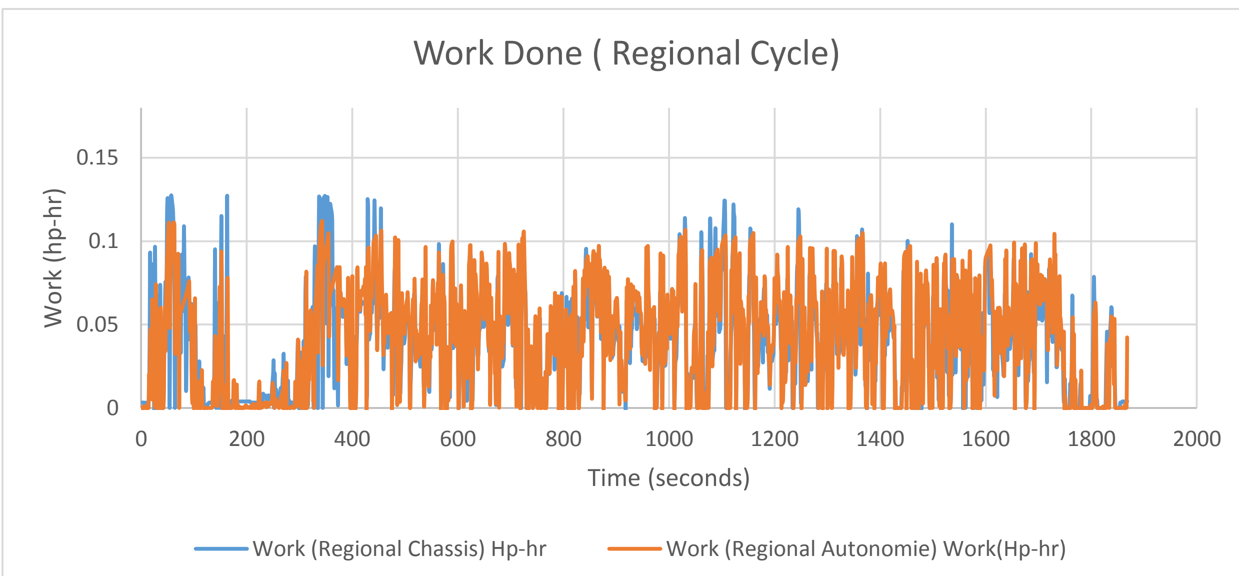

Figure 23 Comparison of work rate for regional cycle for chassis dynamometer and Autonomie simulation data

After doing the calculations, the difference between the work done of chassis data and autonomie data for regional cycle came out to be 5.93 %.

4.4 Comparison of Autonomie simulation with chassis dynamometer data (UDDS)

In the testing procedure, we confirmed that the engine speed and engine torque characteristics of the two testing patterns were similar.

Figure 24 shows the varying vehicle speed during the UDDS cycle for chassis dynamometer testing. Figure 25 shows the comparison of engine torque for UDDS cycle for both chassis dynamometer data and Autonomie simulation data.

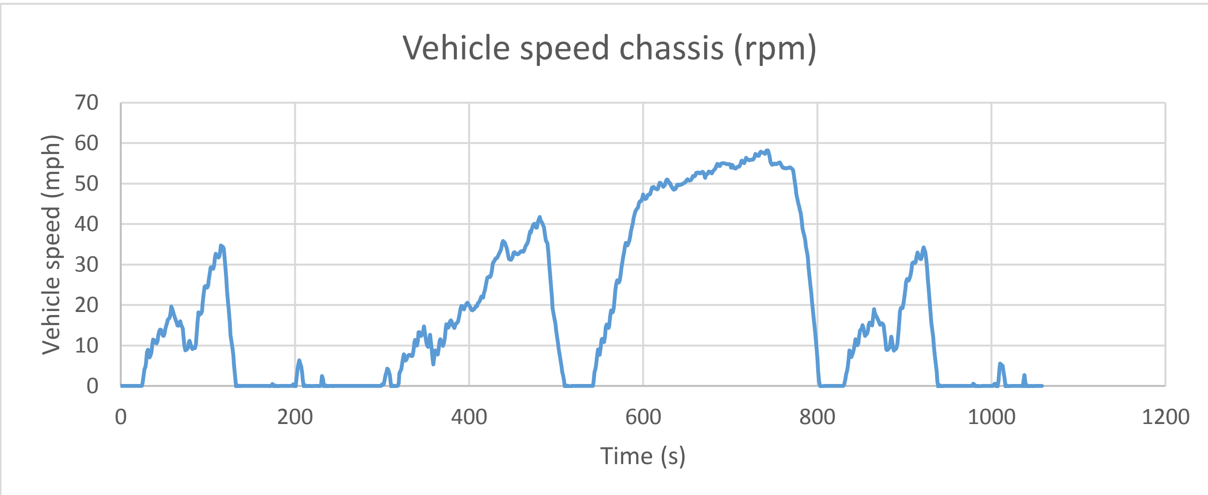

Figure 24 Varying vehicle speed during the UDDS cycle for chassis dynamometer testing

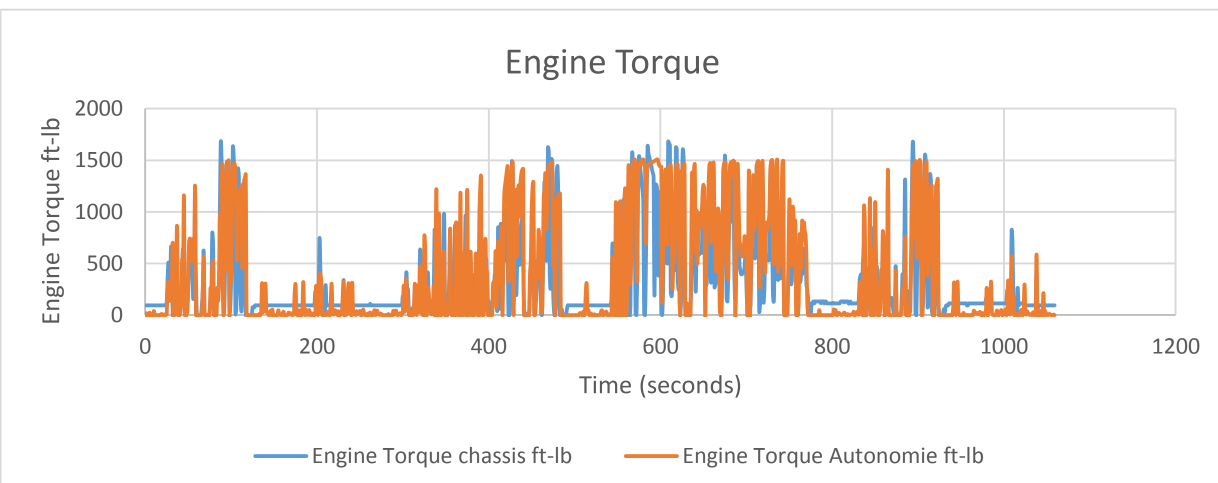

Figure 25 Comparison of engine torque for UDDS cycle for both chassis dynamometer data and Autonomie simulation data

Figure 26 shows the comparison of engine speed for UDDS cycle for both chassis dynamometer data and Autonomie simulation data. Operation of vehicle in a higher gear is the reason behind the difference in the engine speed of chassis data and Autonomie data.

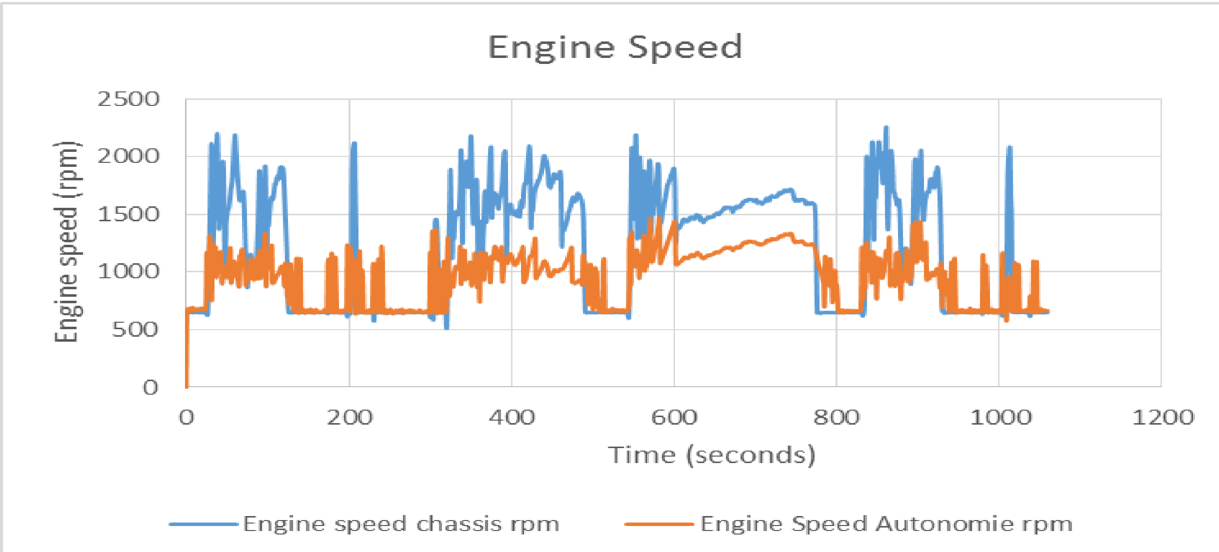

Figure 26 Comparison of engine speed for UDDS cycle for both chassis dynamometer data and Autonomie simulation data

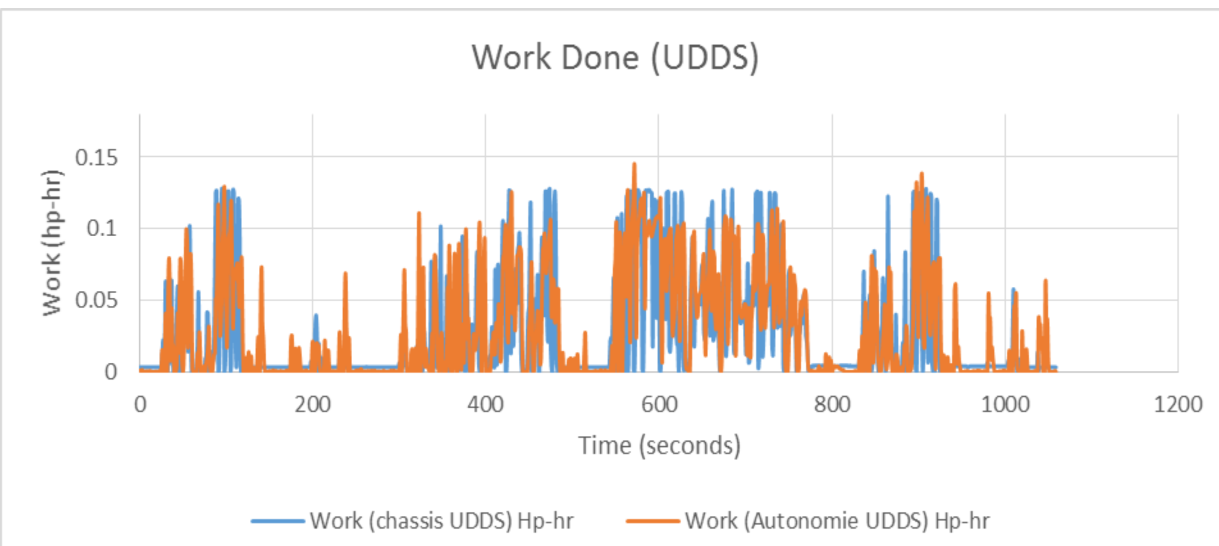

Figure 27 Comparison of work done for UDDS cycle for both chassis dynamometer data and Autonomie simulation data

After doing the calculations, the difference between the work done of chassis data and autonomie data for UDDS cycle came out to be 11.42 %.

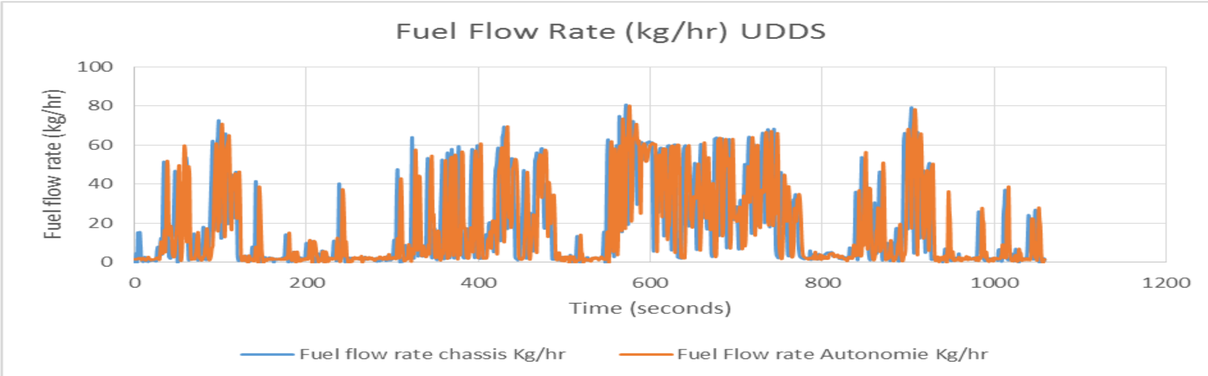

Figure 28 Comparison of fuel flow rate for UDDS cycle for both chassis dynamometer data and Autonomie simulation data

After doing the calculations, the difference between the fuel flow rate of chassis data and autonomie data for UDDS cycle came out to be 2.64 %, which is considerably very small.

4.5 Comparison of Autonomie simulation with Engine Dynamometer testing (UDDS)

Fuel flow rate and work rate were compared for engine dynamometer testing and autonomie simulation data. Figure 29 shows the fuel flow rate of engine dynamometer testing for UDDS cycle. Figure 30 and figure 31 shows the comparison of engine speed and engine torque respectively. Reason behind the visible difference in the engine speed comparison is the operation of vehicle in different gears.

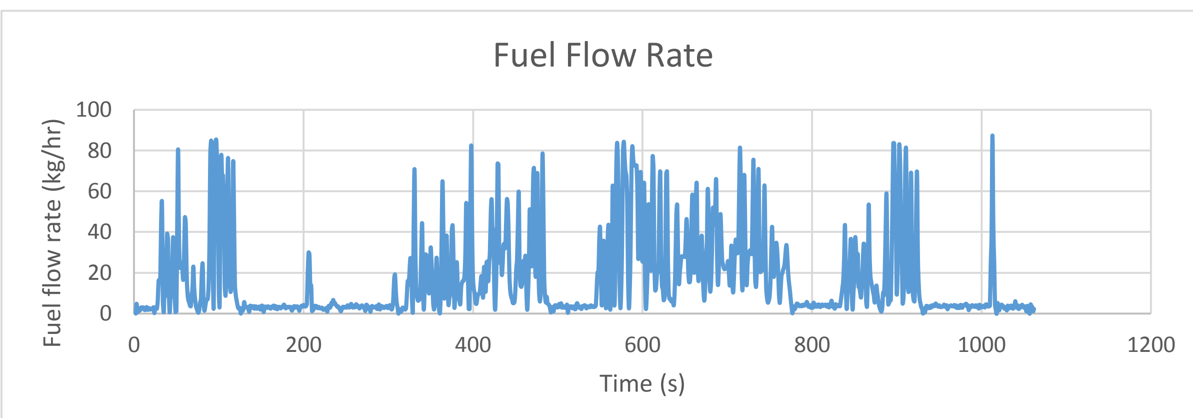

Figure 29 Fuel flow rate during the UDDS cycle for engine dynamometer testing

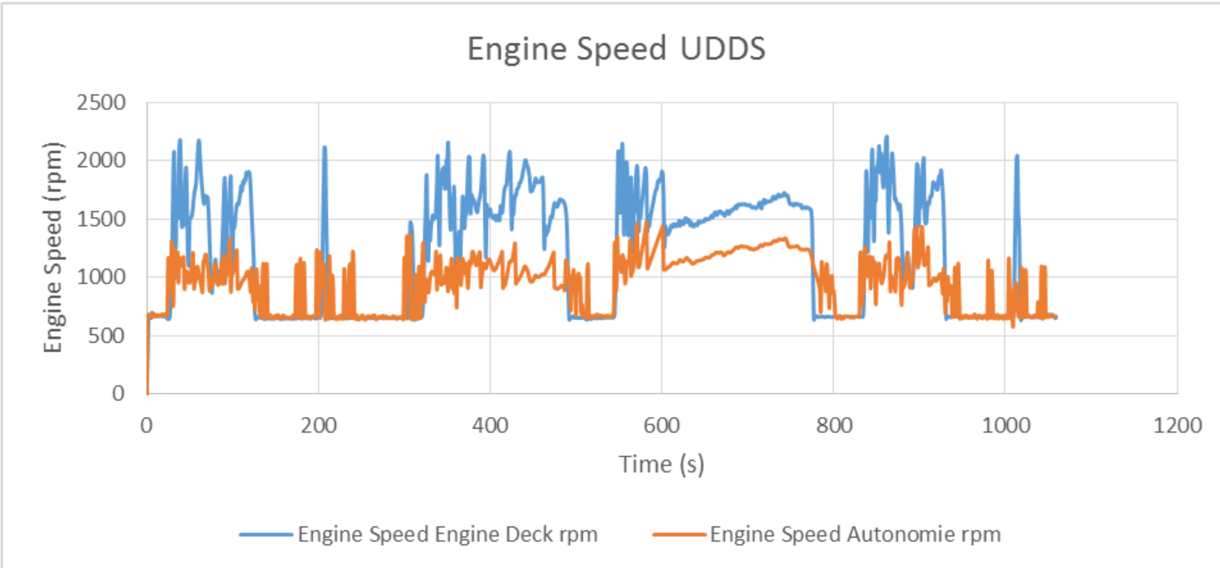

Figure 30 Comparison of engine speed for both UDDS engine dynamometer testing and UDDS Autonomie simulation tool

Another difference between test and simulation results was that the driver behavior in test could not be replicated in simulation which has a significant influence on the results.

Figure 31 and figure 32 shows the comparison of engine torque and engine speed for both UDDS engine dynamometer testing and UDDS Autonomie simulation tool, respectively.

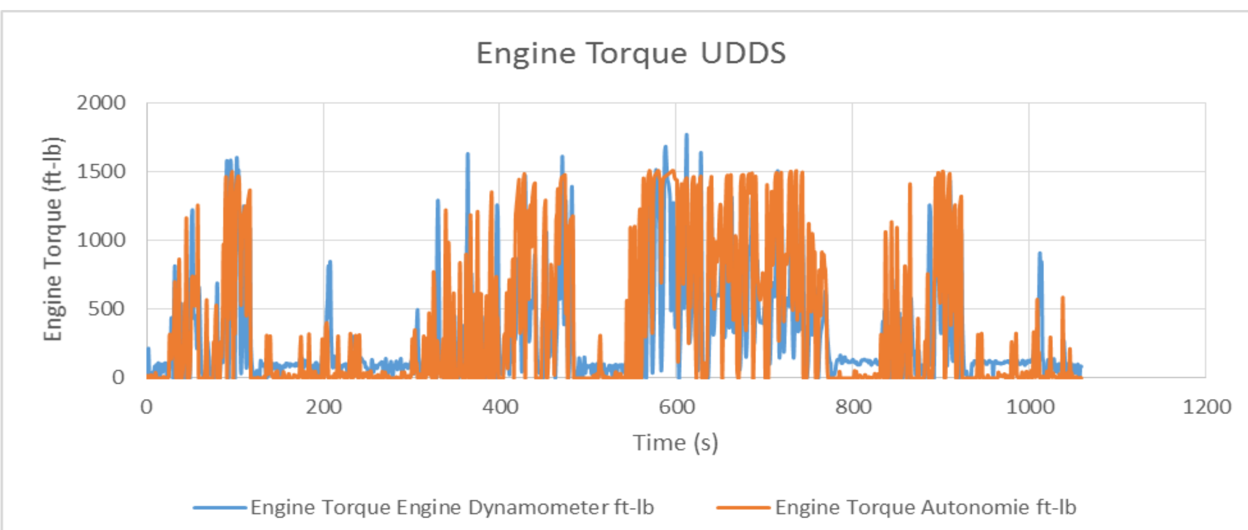

Figure 31 Comparison of engine torque for both UDDS engine dynamometer testing and UDDS Autonomie simulation tool

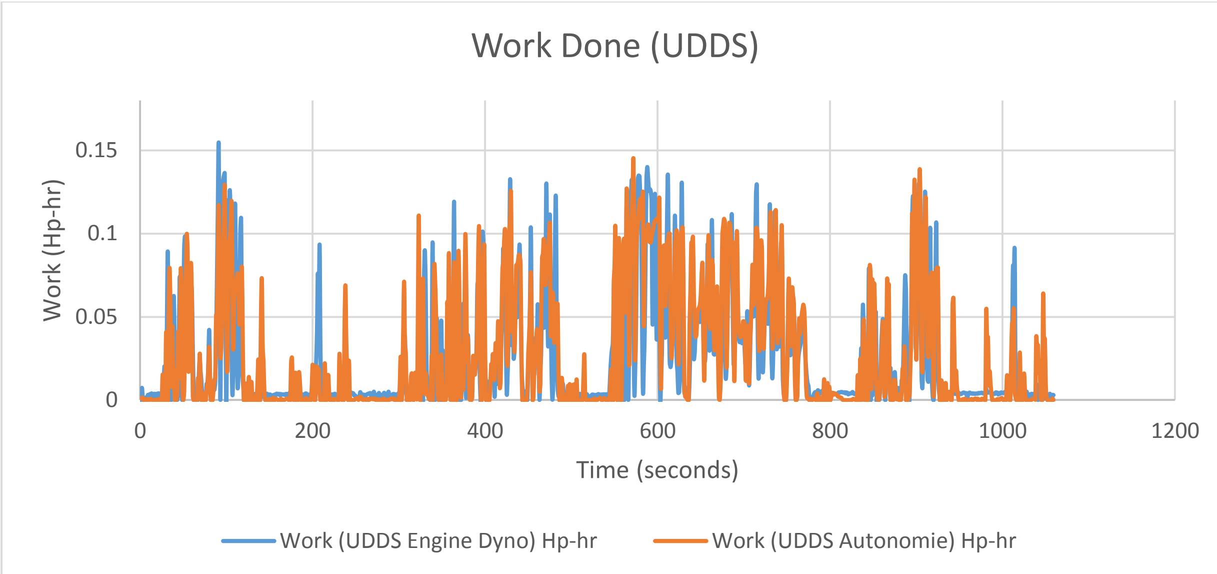

Figure 32 Comparison of work done for both UDDS engine dynamometer testing and UDDS Autonomie simulation tool

After doing the calculations, the work done of engine dynamometer data turned out to be more than Autonomie data for UDDS cycle and the difference came out to be 13.21 %. Fuel flow rate was also compared and variations on certain points were noticed which is shown in figure 33.

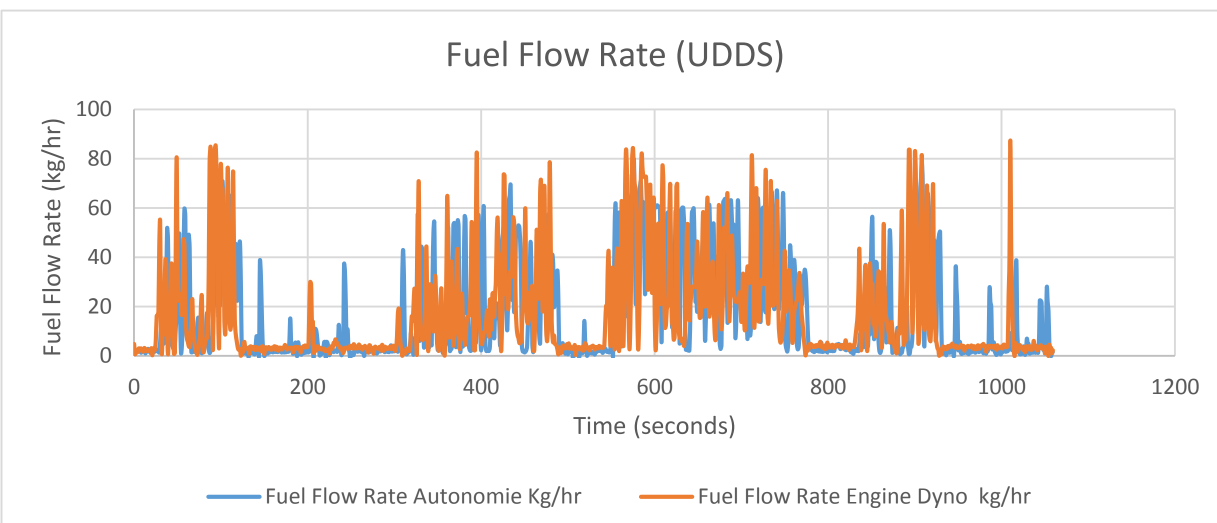

Figure 33 Fuel flow rate comparison of UDDS cycle for Autonomie data and Engine dynamometer data

After doing the calculations, the difference between the fuel flow rate of engine dynamometer data and Autonomie data for UDDS cycle was 4.92 %.

4.6 Comparison of Chassis Dynamometer, Autonomie and Engine Dynamometer work done and fuel flow rate data

Work done was calculated using the engine torque and speed. Work done anf fuel flow rate were compared for all three type of results i.e. data retreived from chassis data, Autonomie simulation data and engine dynamometer testing. With the comparison, we confirmed that the work done and fuel flow rate characteristics of the three results were similar. Figure 34 shows the comparison and noticable differences in the work done during the UDDS cycle. Figure 35 shows the comparison between fuel flow rates.

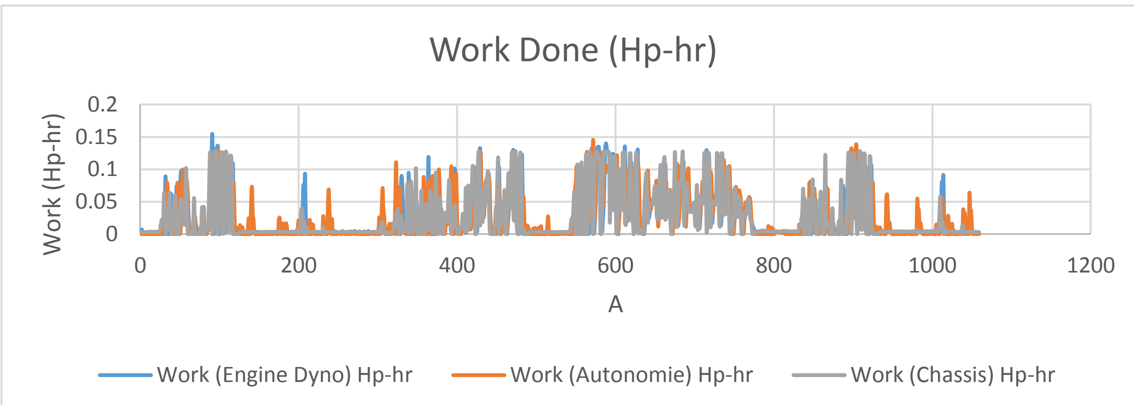

Figure 34 Work done comparison between chassis, Autonomie and Engine Dyno Data

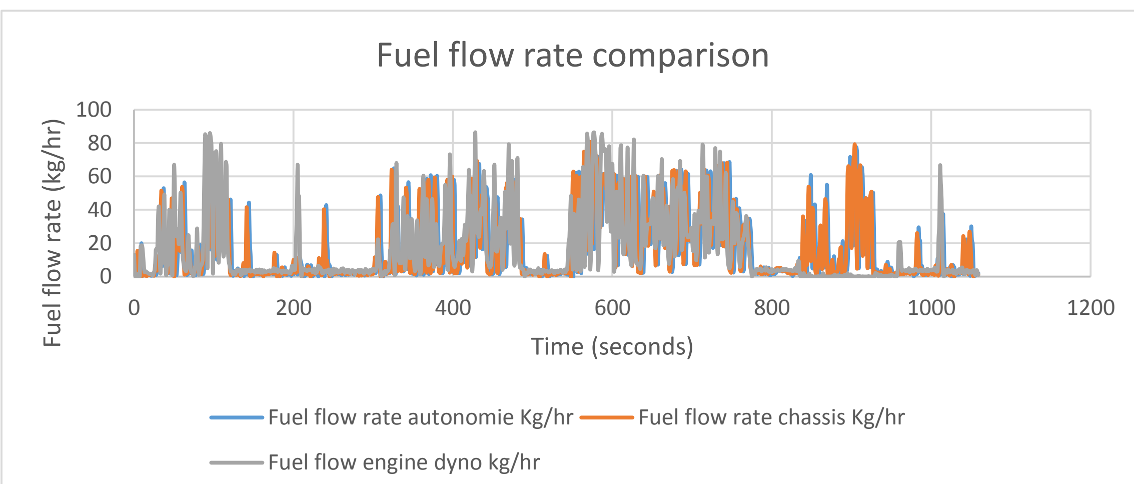

Figure 35 Fuel flow rate comparison between chassis, Autonomie and Engine Dyno Data

Brake specific fuel consumption was also calculated and compared for chassis data, engine dynamometer data and Autonomie data.

Table 17 shows the % difference on the basis of bsfc. The results are encouraging since the difference was within 12% error.

BSFC Comparison	% Difference
Comparison between Autonomie data and chassis data	11.53 %
Comparison between Autonomie data and engine dynamometer data	8.32 %

Table 17 BSFC comparison

4.7 Comparison of Autonomie to GEM

The GEM version 1.0, a MATLAB/Simulink based program, which was downloaded from the EPA's website. In this comparison, a baseline 2010 MY was selected for the analysis. The truck was simulated for only ARB Transient cycle to generate fuel consumption data. Table 18 shows the parameters of the vehicle used for GEM simulation. In the simulation process of GEM, vehicle model year, engine model year, coefficient of aerodynamic drag, drive and steer tire rolling resistance were taken into consideration and used as inputs.

Table 18 Parameters of the vehicle used for GEM

GEM Vehicle Parameter	
Vehicle Model Year	2010
Engine Model Year	2010
Coefficient of aerodynamic drag	0.75
Steer Tire Rolling Resistance (kg/ton)	7.8
Drive Tire Rolling Resistance (kg/ton)	8.2

GEM assumes a frontal area of 10.4 m^2 for Class 8, sleeper cab, high roof for C_dA= 7.8 m^2. Table 20 shows the result of simulation and the results are encouraging since the model was able to translate fuel consumption activities within 10% error.

Table 19 Result of Autonomie and GEM fuel consumption comparison

Cycle	Autonomie Fuel economy (mpg)	GEM Fuel Economy (mpg)	Percentage difference (%)
ARB Transient	4.07	3.81	6.38

5. Conclusions

A simulation model named Autonomie was used to predict HD vehicle fuel consumption and employing chassis dynamometer data and engine dynamometer data. Data for MACK MP8 was tested over up to 3 chassis dynamometer cycles, and data predicted by Autonomie was compared with chassis data and engine dynamometer data.

It was determined that when chassis data is compared with the output of Autonomie simulation tool, difference in work done is within 15 % and fuel flow rate is considerably low i.e. within 10 %. These percentage differences between measured and the predicted work done and fuel flow rates values are on the same level of the variance in measured work done and fuel rates between repeated chassis and engine dynamometer tests.

Autonomie predicted data was compared with the chassis data and difference in work done and bsfc turned out to be 5.93% and 11.53%. When Autonomie simulation data was compared with engine dynamometer, difference in work done, fuel flow rate and bsfc came out to be 13.21%, 4.92%, and 8.32% respectively.

Autonomie simulation tool was challenged using fuel consumption simulation data from a dynamic vehicle simulator, GEM. The method was able to predict ARB Transient cycle within 10% error, with an absolute error of 6.38%. Autonomie can be used to save simulation time and to fill possible gaps of information instead of performing simulations for each possible application and vehicle class.

6. References

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