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Medium and Heavy Duty Hybrid Electric Vehicle Sizing to Maximize Fuel Consumption Displacement on Real World Drive Cycles

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Abstract

Over the past couple of years, several advanced powertrain technologies, including electric vehicles (EV), hybrid electric vehicles (HEV), hybrid hydraulic vehicles (HHV) and alternative fueled vehicles have been implemented in medium and heavy duty applications. However, due to the limitation of component availability, the existing small market for these vehicles and the variety of applications, significant research remains necessary to properly size the components to maximize fuel displacement while minimizing costs. In this study, several advanced powertrain configurations were selected and implemented on a transit bus application and were then modeled in Autonomie, Argonne vehicle modeling and simulation tool. This paper will describe a generic sizing algorithm process and evaluate the impact of advanced technologies on fuel efficiency for real world drive cycles.

Keywords: Medium and Heavy Duty Vehicles, Hybrid Electric Vehicles (HEV)

1 Introduction

Numerous hybrid electric powertrain configurations have been introduced in the market for medium and heavy duty vehicles. However, it remains unclear how each component should be sized to maximize fuel displacement while minimizing cost. In addition, while several powertrain configurations have been introduced to the market and tested in fleets, due to the fact that the vehicles do not have the same performances and characteristics, it is very difficult to evaluate the benefits of different options.

The objective of the study is to evaluate the benefits of medium and heavy duty vehicles with similar performance characteristics under real world driving conditions. The first section of the study focuses on developing vehicle sizing algorithm to properly size the different components. Once the sizing has been performed, the second section will compare the fuel consumption benefits of two powertrain configurations (series and power split) on a series of real world drive cycles.

The transit bus application will be used as the main example to develop and test the algorithms.

Argonne in-house developed software Autonomie, which is a MATLAB-based software environment and framework for automotive control-system design, simulation, and analysis [1] will be used to perform the simulations.

2 Vehicle Sizing Algorithm

2.1 Transit Bus Requirements

The American Public Transportation Association (APTA) aims to organize and activate communication around all public transportation (bus, light rail, transit bus) in America. Regularly, they publish a Standard Bus Procurement Guideline suggesting multiple requirements for Transit Bus vehicles as components mileage life or performance limit. In the October, 2010 release, APTA recommends two performances test at Gross Vehicle Weight Rating (GVWR), acceleration and gradeability with few different levels.

The Texas Department of Public Safety publishes also each year a Specification Paper for School Bus. Comparing to APTA performance tests, only their gradeability requirements are changing by the speed test. Beside these modifications, both entities suggest a very similar guideline.

Table 1 compares the different performance requirements. As APTA is a federal association, their results were taken as reference values to test and sized our vehicles.

Acceleration (s)	
0-10 mph	5
0-20 mph	10
0-30 mph	18
0-40 mph	30
0-50 mph	60
Max Speed	>65mph
Gradeability	
15 mph	10%
40 mph	2.50%

Acceleration (s)	
0-10 mph	5
0-20 mph	10
0-30 mph	18
0-40 mph	30
0-50 mph	60
Max Speed	>65mph
Gradeability	
>0 mph	20%
25 mph	5%
50 mph	1.50%

Table 1: Performance Requirements: (left) APTA, (right) Texas

In order to properly size the vehicles, algorithms need representative cycles. Three chassis dynamometers from United States have been selected for this study: UDDS, Manhattan, and Orange County Transit Authority (OCTA)

2.2 Vehicle Sizing

Several powertrains were considered as described below.

2.2.1 Conventional Powertrain

Since conventional vehicles are mainly defined by their engine, the sizing rule will be focused on calculating the mechanical power to match the requirements. The algorithm has been defined to meet the different performance targets provided by APTA.

First, the grade power on each level is computed. The sizing allows the user to define several grade levels. Then, the algorithm enters an acceleration loop. At the end, the time to reach the target (i.e. 50 mph in 60 second) is compared with the simulated data. At that time, the engine power might be updated. Because any component variation influences the overall weight, the same step has to be run again to check if the requirements are valid. The tests and component tuning will be done on each level and the engine will be sized with the maximum value. Finally, the grade requirements are verified with the updated weight. This is the main condition to exit the routine.

Table 2 shows the validation of the conventional vehicle sizing algorithm compared to the Blue Bird Vision.

Blue Bird Vision			
	Reference	Sized	error (%)
General information			
GVWR (lbs)	29000	class 6	
SLW (lbs)	23250	23296	0.20
Seat	27		
Engine			
Model	Cummins ISB		
Fuel Type	Diesel		
Displacement	6.7 l		
Power (W)	178968	179355	0.22

Table 2: Blue Bird Vision Specifications

2.2.2 Series Powertrain

The series powertrain has additional degrees of freedom, leading to a higher complexity in the sizing algorithm. Figure 1 shows the routine which can be separated in four parts.

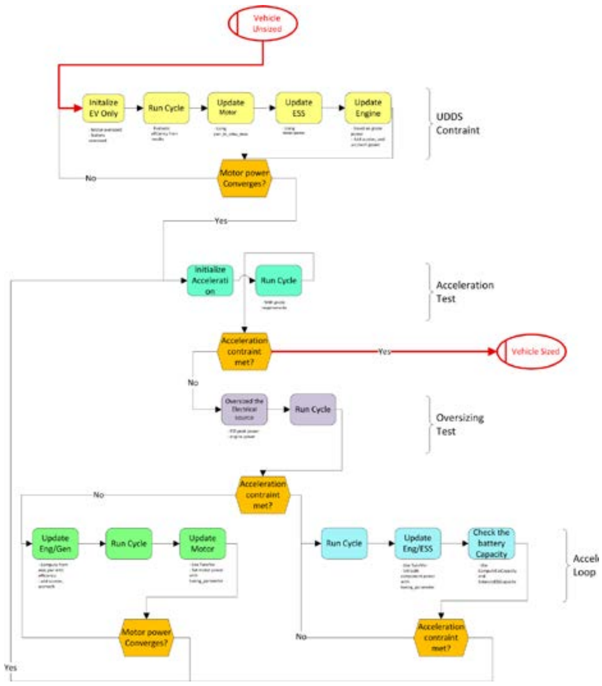

Figure 1: Series Algorithm

The first one, called here "*UDDS Constraint*", computes the electric machine power. The engine power is defined to match grade requirement while the motor and the battery powers are oversized to allow the vehicle to run the cycle without issues. The objective is then to calculate the minimum motor power value to let the vehicle run the referent cycle without missing the trace. At the end of the simulation, the electric machine power value is saved. Once the first step is completed, the vehicle viability is checked by an *Acceleration Test*. If the acceleration test fails, a second test is performed. Following the results, the code enters an *Acceleration Loop* and updates the components power and weight. The global philosophy of this loop is similar to the one used for a conventional vehicle.

Since it is not possible to capture all the regenerative braking during a cycle, a regenerative power rate is available to set the percentage of the power catch by the motor during the cycle (i.e. users can decide to capture 60% of the regenerative braking energy). The sizing rule ends when the vehicle meets both acceleration and cycle requirements.

2.3 Motor Power Rate Impact on Series Sizing

Based on the series sizing rule and the OrionVII baseline, different buses have been sized with multiple rate of motor power. Since buses are designated to specific towns, it is necessary to adopt sizing rules which are able to compute motor, engine and battery power for dedicated cycles.

Figure 2 displays OrionVII's motor power on a Manhattan cycle.

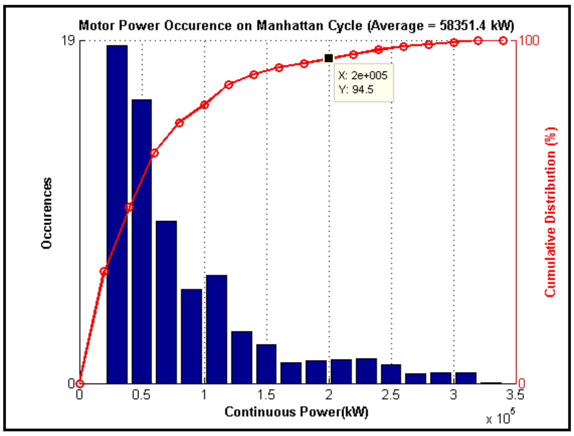

Figure 2: Motor Power

We notice that the maximum value (i.e. 340kW) occurred only a few times. In addition, only 5% of the simulation points need more than 200kW of motor power. The percentage of occurrence displaying on the vertical axes would be defined as the motor power rate and could be set by the users.

In this study, this rate has been decrease from 100% by step of 5%. Sizing has been done considering that the vehicle has to regenerate 100% braking power available and has to be able to run *"UDDS_truck"*, *"Manhattan'* and *"OCTA"* cycles with less than 1% trace missed. Based on this condition, the rate cannot be lower than 70% without impacting the regenerative rate. The six sized vehicles have been simulated on the 33 Real World Drive Cycles available for Transit Bus.

Figure 3 shows the impact on performance of decreasing the electric machine power (performance increases from 28 second to 37 second). We observe that the curb slope is higher with small rate than high rate which means accelerations test would be quickly failed if the rate still drops.

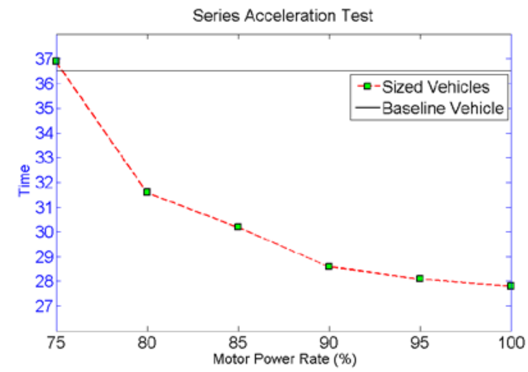

Figure 3: Acceleration Results

Comparing each vehicle in Figure 4, one observes that there is not a significant difference in the fuel consumption for each vehicle.

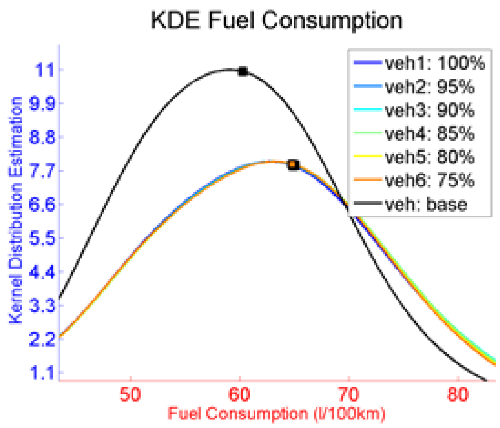

Figure 4: Fuel Consumption Results

Figure 5 shows the impact of electric machine sizing on the percentage of time the trace is missed by 2%. As one notices, the electric machine size can be significantly decreased without incurring a large increase in percentage of time the trace is missed. As a consequence, the algorithm may not need to use the maximum value of the drive cycle to calculate the electric machine peak power.

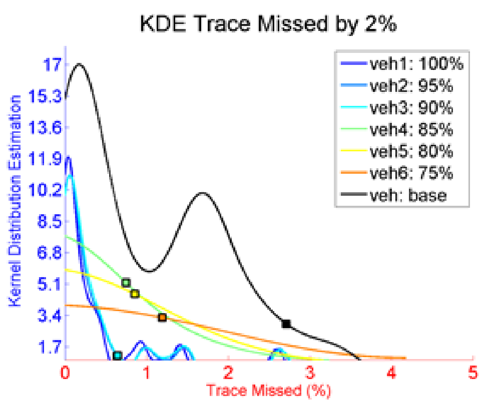

Figure 5: Time Trace Missed

3 Fuel Consumption Impact on Real World Drive Cycles

3.1 Vehicle Descriptions

3.1.1 Conventional Vehicle

The conventional bus selected for the study is a conventional Class 8 Bus with an automatic gearbox, and a test weight of 19230 Kg. The gearbox and the engine used are:

- Engine Diesel Corp. Series 50
- Automatic Alisson B500 gearbox

The Table 2 gives some of the specifications of the bus:

Table 2: Conventional Bus Specifications

Components	Value
Final Drive	4.33
Engine Power	243 kW
Test Weight	19230 kg

3.1.2 Series Vehicle

The series transit bus was sized accordingly to a target test weight (20230 kg). The powertrain of the series transit bus is composed of the following components:

- Engine: Cummins ISB 260
- Transmission : BAE HybriDrive

Table 3 gives a quick overview of the different powertrain components key parameters.

Table 3: Series Bus Specifications

Components		Sized Values
Final Drive		4.1
Engine Power (kW)		184
Motor Power (kW)		203 peak
Generator Power		173.2 peak
Energy Storage	Type	Li-ion
	Power (kW)	200
Test Weight (Kg)		20231

3.1.3 Power Split Vehicle

The power Split 2-mode transit bus selected for the study is based on the New Flyer DE60LF.

The powertrain is composed of the following components:

- Engine Caterpillar C9
- Motor
- Generator
- Energy Storage System
- Dual Power Inverter Module

Table 4: Power Split Vehicle Specifications

Components		Value
Final Drive		3.42
Engine Power (kW)		246.1
Motor Power (kW)		75 nominal, 150 peak
Generator's Power		75 nominal, 150 peak
Energy Storage	**Type**	Li-ion
	Power (kW)	164
Test Weight (in Kg)		20230

3.2 Real World Drive Cycles

3.2.1 NREL Drive Cycles

From April 1, 2005 to March 31, 2006, the National Renewable Energy Laboratory ran an evaluation study on King County Metro Transit buses. The KCM tested fleet contained 30 conventional (D60LF model) buses and 235 hybrid buses (DE60LF model).

The data accessible for the current study is a set of 8 cycles. However the data does not contain any grade information or road type. Grade information does affect the overall vehicle fuel consumption. Figure 6 shows an example of the real world drive cycles.

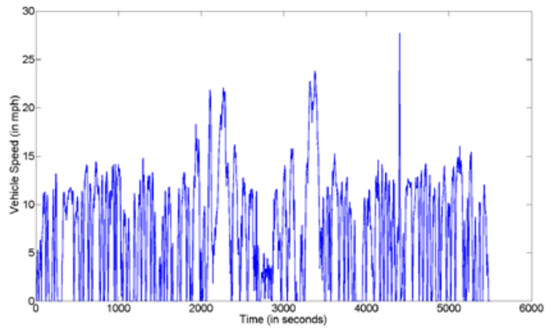

Figure 6: NREL Cycle Example

3.2.2 ORNL Drive Cycles

Through the Medium-Truck Duty Cycle Project (MTDC) of Oak Ridge National Laboratory, access was given to daily transit buses' RWDCs. These cycles have been acquired through a partnership with the Knoxville Area Transit, who has a fleet composed of diesel, CNG/LNG and hybrid buses. The data accessible for the current study is a set of 20 daily RWDCs. The data contained the bus vehicle speed, the road's grade (in percent), and the type of road (freeway or a surface street).

From the 8-day cycles, 22 actual cycles where extracted, those cycles' varies from 7.41 minutes to over 14 hours.

In addition, several "standard" drive cycles were considered, including the UDDS, Manhattan and OCTA.

3.3 Individual Powertrain Fuel Economy Results

3.3.1 Conventional Vehicle

As shown in Figure 7, the fuel economy average of the conventional powertrain ranges from 3 to 4.5 miles per gallon. The maximum occurrences are obtained for a Fuel Economy of 3 mpg and the mean value is 3.76.

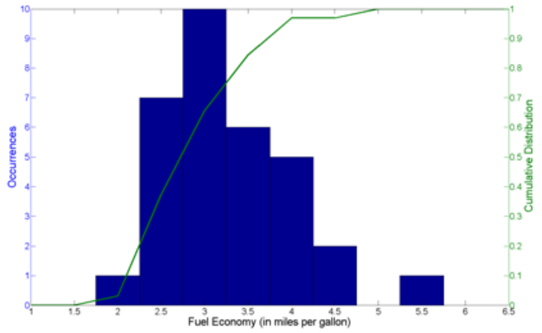

Figure 7: Fuel Economy (Conventional)

Figure 8 shows the average engine power across all cycles. The engine mean power value ranges from 50 kW to 70 kW. Since the vehicle is only propelled by the engine, its output power is closely related to the vehicle speed.

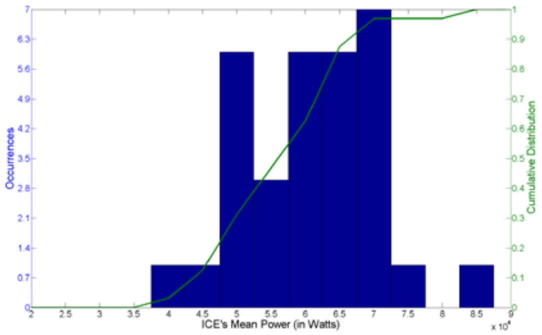

Figure 8: Average Engine Power (Conventional)

The shifting-events-per-minute distribution (Figure 9) can be characterized as bell-shaped, with a mean value close to 250 events per hour.

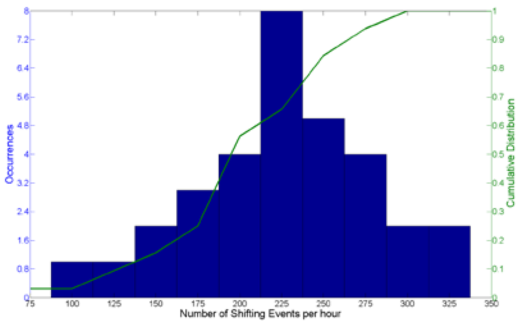

Figure 9: Number of Shifting Events (Conventional)

3.3.2 Series Vehicle

The fuel economy for the series hybrid (Figure 10) is close to 4 miles per gallon. Compared to the Conventional, it is not simply an upward translation of the pattern. Since the engine is not directly connected to the wheels, its output power can be operated more freely (Figure 11), also during stops and decelerating time, the ICE can be switched off (Figure 12).

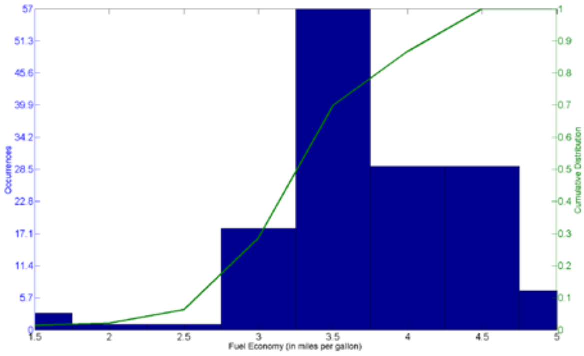

Figure 10: Fuel Economy (Series)

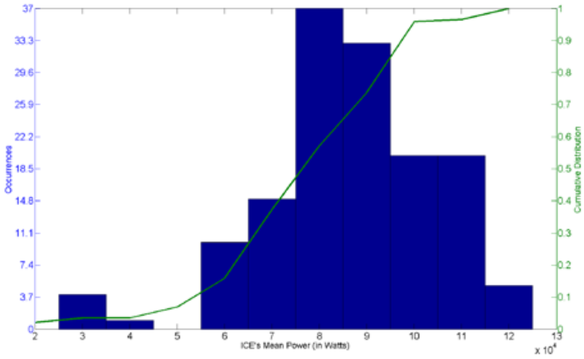

Figure 11: Average Ice Power (Series)

The average percentage of ICE on/off (Figure 12) for the series hybrid is close to 77%. The design and vehicle controller regulates the switch of the engine: whenever the battery state of charge is below 50 percent, the engine is turned ON. Depending on the battery capacity, the engine could be turned off more often, since the capacity would be higher and/or the switching percentage can be lowered.

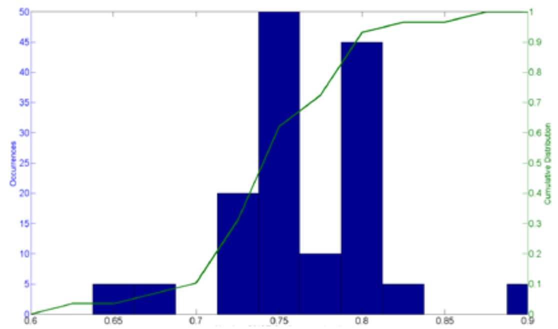

Figure 12: Number of ICE ON (Series)

3.3.3 Power Split Vehicle

For the split 2-mode, the fuel economy (Figure 13) ranges from 4 to 6.5, with an average value of 5.2

miles per gallon. The fuel economy distribution is bell-shaped, so the fuel economy occurrences are normally distributed around the mean value. As a difference with the two previous powertrain technologies studied before, the fuel economy is somewhat independent of the cycle's speed. This is achieved by the powertrain structure as the strategy of the split 2-modes enables the engine to work, most of the time, in his best efficiency area.

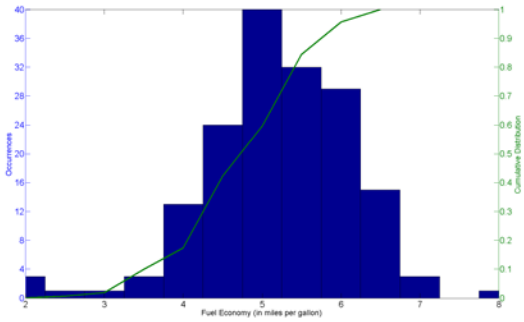

Figure 13: Fuel Economy (Split)

As stated before, the vehicle designed is based on the New Flyer DE60LF, used by the KCM transit agency in Seattle. The table below summarizes the result for fuel economy of the conventional and the split for the simulation and from the KING COUNTY METRO TRANSIT HYBRID ARTICULATED BUSES: FINAL EVALUATION RESULTS by K. Chandler & K. Walkowicz.

Table 5: Comparison with NREL RWDC

	Conv	HEV	Improvement
NREL	2.50	3.46	38.4%
Simu	3.76	5.18	37.5%

As shown in Figure 14, the maximum number of engine ON occurrences is located between 30 and 50 percent.

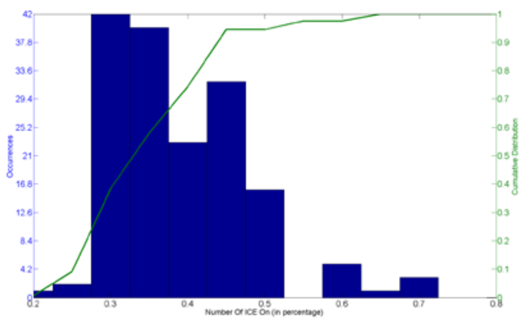

Figure 14: Number of Engine ON (Split)

Figure 15 shows that the average engine power is close to 120 kW for all the cycles. The mean engine power is high since the split 2-mode design enables the engine to operate within its best-fuel-efficiency area: the engine feeds the battery close to its best efficiency and propel the vehicle when both speed (engine and vehicle) are close.

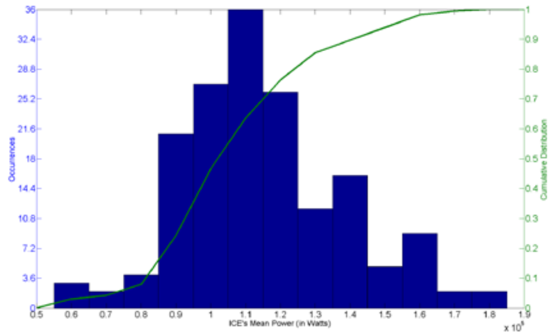

Figure 15: Average Engine Power (Split)

3.4 Fuel Economy Results Comparison

3.4.1 Fuel Consumption

As shown in Figure 16, the fuel economy for the power split configuration is better than the series, which is better than the conventional. The improvement from the split to the series is 21%, and the improvement from the conventional is 36%. The series improvement from the conventional is 12%. The split fuel economy is significantly higher than the two other vehicles, but the distribution is flatter, which means that there is a fewer probability, that among the 33 cycles, the fuel economy for the split is close to the mean, in comparison with the conventional or the series.

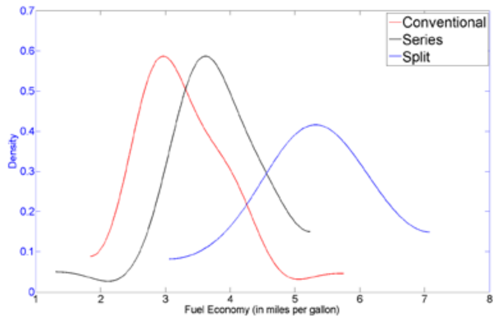

Figure 16: Fuel Consumption (different Powertrain)

Table 6 below shows the mean fuel economy values for each powertrain configuration:

Table 6: Mean Fuel Economies

Technology	Value (in mpg)
Conventional	3.76
Series	4.2
Split	5.1

3.4.2 Number of Engine ON Events

Despite the fact that the standard deviation of the split is higher, it is clear that for the entire set of data, the split engine on/off ratio is lower than for the series (about 80% reduction compared to the Mean).

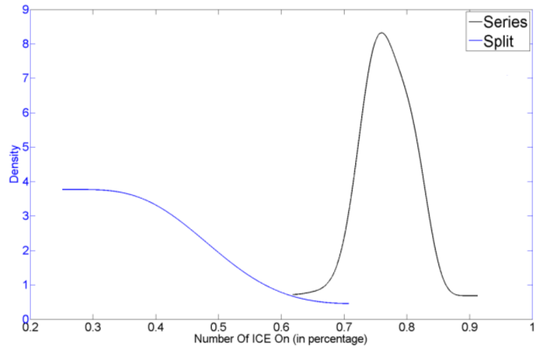

Figure 17: Number of ICE ON (different Powertrain)

3.4.3 Average Engine Power

The conventional vehicle demonstrates the lowest average engine power. The engine in the power split shows a 70% higher engine average power compared to the conventional vehicle. The series average engine power is only 85 kW, but the engine peak power is also lower than the two other technologies (around 245 kW). The reduction from peak power to mean power is about 53%, which is close to the reduction for the split (55%), and both are lower than the conventional (73%).

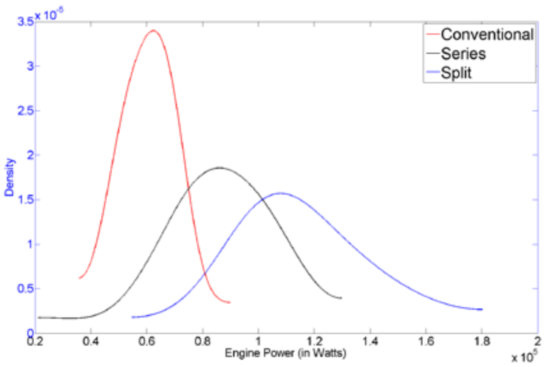

Figure 18: ICE's Power (different Powertrain)

Table 7: Ice Mean power for Each Technology

Technology	ICE Mean Power (kW)	ICE Peak Power
Conventional	65	243
Series	85	184
Split	110	246

3.4.4 Fuel Economy as a Function of Cycle Aggressiveness

For every technology, the fuel economy decreases with a more aggressive cycle. However, one notices that the conventional vehicles are more sensitive than electric drive powertrain. For all data sets, the fuel efficiency of the split 2-mode is better, but it appears that for the most aggressive cycles, the series fuel economy could be better.

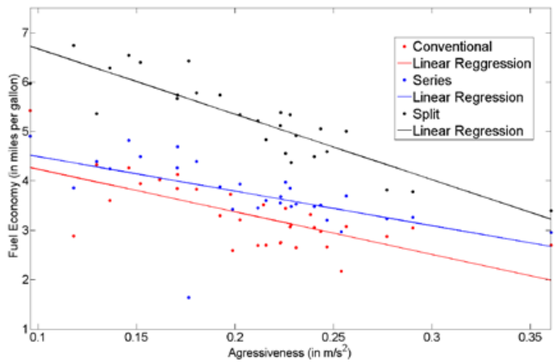

Figure 19: Fuel Economy against Aggressiveness

3.4.5 Fuel Economy as a Function of Vehicle Speed

Figure 21 shows that for both conventional and series technologies, the fuel economy increases with higher vehicle speed, the improvement being more important for the conventional. Similar behaviours have been noticed for light duty vehicles where the least efficient powertrains are more sensitive.

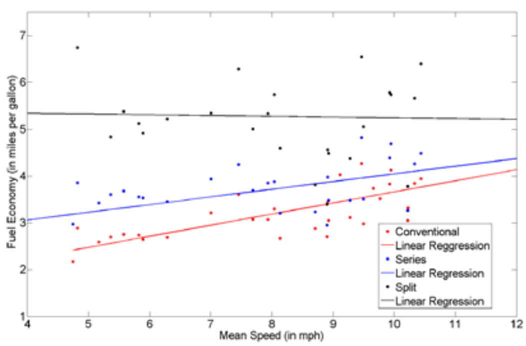

Figure 20: Fuel Economy Against vehicle Mean Speed

3.4.6 Fuel Economy as a Function of Distance

For all technologies, the fuel economy improves with the cycle distance. This improvement is of the same order of magnitude for both the hybrids but is slower (even flat) for the conventional.

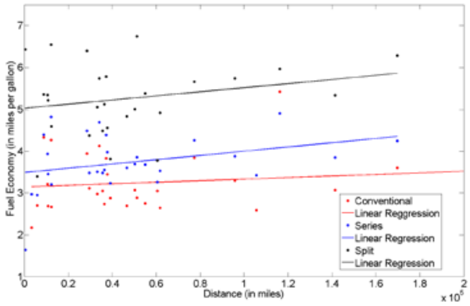

Figure 21: Fuel Economy against Distance

Conclusion

Several vehicle sizing algorithms were developed to automatically size different powertrain configurations for medium and heavy duty applications. While the philosophies remain similar as the light duty algorithms, specific implementation have been performed, including:

- Ability to select any drive cycle
- Ability to size the electric machine and the energy storage system to capture only a percentage of the regenerative braking or to perform a portion of the cycle in EV mode
- Ability to consider multiple performance and grade requirements

Three powertrain technologies (conventional series HEV and power split HEV) have been simulated for transit buses on other 30 real world drive cycles. The behavior is representative to driving one of these cycles and could be generalized to be representative of transit buses real journeys. The split 2-mode revealed to be the more efficient from a fuel-economy point of view.

Both the hybrid proved to have a significant fuel economy over conventional propulsion.

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References

[1] S. Halbach, P. Sharer, S. Pagerit, C. Folkerts, and A. Rousseau, Model Architecture, Methods, and Interfaces for Efficient Math-Based Design and Simulation of Automotive Control Systems, SAE 2010-01-0241, SAE World Congress, Detroit, 2010

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