Simulation of hybrid buses: a study of fuel economy and emissions

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Abstract

The purpose of our project is to assess hybrid buses to see how they may perform under a variety of operating conditions and duty cycles. Technologies we assess are those that have had rigorous evaluations so that a real database can be developed. Clearly, the best way to do so, short of purchasing vehicles, is through simulation.

There is a concomitant need to validate any simulation software so that reasonable recommendations can be made. The simulation software we employ is PSAT (Powertrain System Analysis Toolkit) developed by the United States Department of Energy Argonne National Laboratory. PSAT is validated code for automobiles and compares well with tested cars.

Our goal is to use PSAT in an urban environment looking at heavy duty transit buses. To do so, we selected several possible hybrid electric buses – several 60 ft vehicles and one 40 ft bus, all with dynamometer data available for comparison – and three duty cycles for implementation. For the latter we use the standard CBD cycle, the Manhattan cycle and a new cycle derived from the Manhattan, which includes hill climbing/descending, that we have named the Jerusalem cycle.

Our results, when compared to the vehicle testing, indicate excellent agreement between fuel economy and CO_2 emissions.

Keywords: hybrid buses, simulations, emissions, PSAT, duty cycles.

1 Introduction

In many cities world-wide, there is a growing interest in the use of hybrid electric vehicles (HEVs). This is especially true in those cities where the

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confluence of climate change and environmental issues are coming to the fore and where, at some sites, there are older and historic buildings adversely affected by emissions.

The overarching purpose of our project is to assess hybrid buses to see how they may perform under a variety of operating conditions and duty cycles. We need to evaluate these bus technologies under various duty cycles so that adequate prediction of performance can be obtained. Clearly, the best way to do so, short of purchasing vehicles, is through simulation.

However, there is a concomitant need to validate any simulation software so that reasonable recommendations can be made. The simulation software we employ here is PSAT (Powertrain System Analysis Toolkit) developed by the United States Department of Energy Argonne National Laboratory. PSAT is validated code for automobiles and compares well with tested cars. It has not gone through the same rigorous analysis and testing with heavy duty transit buses. Our goal, then, in this paper is to carry out a PSAT validation in an urban environment looking at heavy duty transit buses.

In this introductory section, it is perhaps worthwhile to briefly summarize some of the characteristics of this package. Because of time and cost constraints, designers cannot build and test each of the many possible powertrain configurations for advanced vehicles. Thus, developing fuel cell and hybrid electric vehicles (HEVs) requires accurate, flexible simulation tools. Argonne National Laboratory of the United States Department of Energy (USDOE) undertook a collaborative effort to develop the Powertrain System Analysis Toolkit under the direction of and with contributions from Ford, General Motors, and DaimlerChrysler. PSAT is sponsored by USDOE.

In carrying out our work to validate the software and thus offer guidance to cities looking to purchase HEVs, we selected several possible hybrid electric buses for simulation. In this phase of work we primarily studied 60 ft, articulated vehicles for which dynamometer data is available:

- NABI 60 LFW (diesel)
- New Flyer DE60LF (hybrid)
- New Flyer DE60LF-BRT (hybrid)
- Wrightbus StreetCar RTV (hybrid)
- Gillig 40 ft (hybrid)

The first was chosen so that a comparison of results with a standard diesel could be obtained. We also include one 40 ft vehicle, the Gillig, for which there is an available database.

To do this we selected three duty cycles for analysis:

(1) The central business district (CBD), which appeared as the Society of Automotive Engineers (SAE) recommended practice J1376, is commonly used to evaluate transit buses; it is included as one the many driving cycles available from within PSAT;

(2) The Manhattan cycle, which more accurately reflects actual service routes in many transit districts and also available within PSAT;

(3) A new cycle, derived from the Manhattan cycle with a modified grade that includes hill climbing and descending.

A complete critique of these cycles and their applicability are discussed later in this paper.

Fuel economy and emissions results are among the major outputs of PSAT. We develop these for the several buses and the various cycles comparing, where possible, to detailed experimental results.

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2 PSAT

PSAT is a simulation tool that aids in the evaluation and design of various vehicle systems. The architecture of the software package is superior with an easy to navigate environment. The domain of this utility is extensive, and consists of facilities for the modelling of technologies ranging from conventional fuels to hybrids, from light to heavy-duty vehicles.

PSAT modelling is a system description process. "Vehicle definition" requires identifying a vehicle drivetrain configuration, drivetrain components, and operating parameters.

In PSAT, the selection of a system drivetrain configuration forms the basis of a vehicle model design. This provides a default template for subsequent vehicle-defining characteristics including drivetrain components and controllers. A vehicle drivetrain configuration dictates the arrangement of the energy sources (internal combustion engine, electric motor) relative to the main transmission axis, as well as the distribution of motive power to propel the vehicle. It varies among one of several configurations available in the PSAT line-up, such as conventional vehicles, parallel hybrids, series hybrids, fuel-cell hybrids, among others. For our purpose, based on the vehicles (buses) of interest, we find the parallel hybrid, series hybrid, and conventional (diesel-only) drivetrain configurations sufficient.

Drivetrain components arise as a consequence of the selection of a drivetrain configuration. In essence, the type of components that result, such as the presence or absence of a generator as in a series or parallel hybrid respectively, are dependent on the configuration, i.e. series or parallel hybrid. The same is true for the vehicle controller. Vehicle system components vary between vehicle types (light, heavy-duty), as well as vehicle technologies (conventional fuels, hybrids), and will be identified appropriately within the context of this paper.

Generally, the PSAT library constitutes a good selection base for vehicle component models. This means that there are adequate predefined models of existing technologies/components that are available for use. On occasions where PSAT models are found to be inadequate, a scaling system (when available) is used to size-up or size-down the best-fit model to specific criteria. However, options like this often do not portray the correct scenario of the component performance capability and it should be understood that results can lose accuracy and credibility. They are then best viewed as close approximations or best alternatives (within the context of the project).

Once a model vehicle exists, simulation is conducted on a selected duty cycle in a real-time environment using Simulink. Simulink provides the means to operate the selected vehicle according to the chosen duty cycle (see Section 3, below).

3 Vehicles selected and duty cycles

In this section we begin the detailed discussion of the actual simulations performed. We discuss both the buses selected and the duty cycles employed for each run.

3.1 Vehicles selected

As cities look to switch their vehicles to alternative fuels, they are faced with a wide array of choices. These choices include the use of hybrid propulsion systems and a variety of sizes – from the traditional 40 ft vehicle to articulated buses at 60 ft to double decked buses – all of which are aimed at improving efficiency in performance. For our study we chose those which would best meet the criteria for the duty cycles envisioned for operations and, in part, for those that had dynamometer data available to help validate the simulation results. As a consequence we looked at the following:

- NABI 60 LFW (diesel) – see Figure 1
- New Flyer DE60LF (hybrid) – see Figure 2
- New Flyer DE60LF-BRT (hybrid) – this bus is very similar to the other New Flyer, see Figure 3
- Wrightbus StreetCar RTV (hybrid) – see Figure 4
- Gillig 40 ft (hybrid) – see Figure 5.

The PSAT models developed were designed to match the specifications of the vehicles as closely as possible. For simulation purposes, it is important to be cognizant of the elemental vehicle components that dominate the outcome of a simulation result. These are components, among others, that make up the vehicle type as defined by its drivetrain configuration. Consequently, a conventional

Figure 1: NABI 60LFW.

Figure 2: New Flyer DE60LF.

Figure 3: New Flyer DE60LF-BRT.

Figure 4: Wrightbus StreetCar RTV.

Figure 5: Gillig 40ft hybrid.

		NABI 60LFW
Application		Transit Bus
Vehicle Type		Articulated (conventional)
Drivetrain Type		Single-Mode (diesel)
Length (ft)		60
GVW (lb)		65000
Engine	*Make*	Cummins
	Fuel Type	Diesel
	Power (hp/kw)	330/246
Transmission	*Type*	Allison (B500R), ZF
Wheel Axle	*Drive Configuration*	2wd
	Primary	1
	Secondary	2

Figure 6: Vehicle initialization parameters: NABI 60lfw.

diesel drivetrain consists primarily of the engine, gearbox and final specification of the selected buses. We identify these components on the basis of drive differential, and wheel/axle. A parallel hybrid drivetrain consists of an engine, energy storage unit (battery), motor, gearbox, final drive differential, and wheel/axle; a series hybrid drivetrain consists of an engine, energy storage unit (battery), generator, motor, gearbox, final drive differential, and wheel/axle.

Each vehicle is parameterized according to the specifications shown in Figures 6-9.

		New Flyer DE60LF, BRT
Application		Transit Bus
VehicleType		Articulated
Drivetrain Type		Dual-Mode (hybrid)
Length (ft)		60
GVW (lb)		66,000
Engine	Make	Cummins ISL
	Fuel Type	Diesel
	Power (hp/kw)	330/246
Transmission	Type	Allison EP System
Energy Storage	Type	Battery (NiMH)
	Voltage (volts)	600
Motor	Type	AC Induction
	Total Power (kw)	200
Wheel Axle	Drive Configuration	2wd
	Primary	1
	Secondary	2

Figure 7: Vehicle initialization parameters: New Flyer DE60lf, BRT.

		Wrightbus Streetcar RTV
Application		Transit Bus
Vehicle Type		Articulated Hybrid
Drivetrain Type		Dual-Mode (series)
Length (ft)		60
GVW (lb)		62,000
Engine	Make	-
	Fuel Type	Diesel
	Power (hp/kw)	260/194
Transmission	Type	-
Generator	Type	Permanent Magnet Synchronous Generator
	Power (hp/kw)	215/160
Energy Storage	Type	Battery (NiMH)
	Voltage (volts)	600
Motor	Type	AC Induction
	Total Power (kw)	160
Wheel Axle	Drive Configuration	2wd
	Primary	1
	Secondary	2

Figure 8: Vehicle initialization parameters: Wrightbus Streetcar RTV.

3.2 Duty cycles

A duty cycle (also known as a drive cycle) is a modelled traffic scenario that portrays the rate of vehicle movement – speed, acceleration and deceleration, associated with likely impending traffic conditions, as well as the frequency of scheduled passenger pick-ups during operation. Simulation of the above buses was carried out with two duty cycles, both available from within PSAT, which are standards for the evaluation of urban transit vehicles.

		Gillig 40ft Bus*
Application		Transit Bus
VehicleType		Non-Articulated
Drivetrain Type		Dual-Mode (hybrid)
Length (ft)		40
GVW (lb)		42,600
Engine	*Make*	Cummins ISL
	Fuel Type	Diesel
	Power (hp/kw)	260/194
Transmission	*Type*	Allison EP System
Energy Storage	*Type*	Battery (NiMH)
	Voltage (volts)	600
Motor	*Type*	AC Induction
	Total Power (kw)	200
Wheel Axle	*Drive Configuration*	2wd
	Primary	1
	Secondary	1

Figure 9: Vehicle initialization parameters: Gillig 40ft bus.

Of particular interest to us is the Manhattan cycle. This is a test cycle that was developed based on actual observed driving patterns of urban transit buses in the Manhattan core of New York City. The Manhattan cycle consequently describes an erratic drive pattern comprising of several steep rise and falls, indicative of the vehicle speed demand in relation to time. It covers 2.05 miles over 1089 seconds, and is characterized by frequent stops and very low speeds.

Of equal importance in our efforts, at least for the purpose of establishing comparison and trend data, were running simulations on yet another standard drive cycle: the Central Business District (CBD) cycle. The CBD, which appeared as the Society of Automotive Engineers (SAE) recommended practice J1376, is made up of 14 identical sections containing acceleration to 20 mph, a cruise at 20 mph, braking to a stop, then dwell. The total cycle covers 2.0 miles over 600 seconds. While the CBD cycle is repeatable from a driver in the loop standpoint, it has several drawbacks. The acceleration rate is fixed which tends to favour buses with five speed transmissions and larger engines. The cycle is dominated by the 20-mph cruise, which penalizes buses that are not geared for optimum efficiency at that particular speed. The deceleration from 20-mph is twice as fast as the acceleration to 20-mph, 4.5 seconds versus 9 seconds, which is not typical of actual in-use driving. The average speed for the CBD cycle is 12.6 mph, generally faster than that observed by most transit operation.

Each individual drive cycle as described above is presented below for clarity. This presentation consists of a cycle speed demand curve as well as a brief summary of the graphical pictorial, see Figures 10 and 11. Additional details for these well-known cycles maybe found in the literature.

The highlight of a simulation attempt on either of the above drive cycles, we reiterate, is the establishment of data for a comparison study between results obtained from simulation and existing dynamometer tests. The inference of this study is aimed at validating PSAT as a credible simulation tool. Consequently,

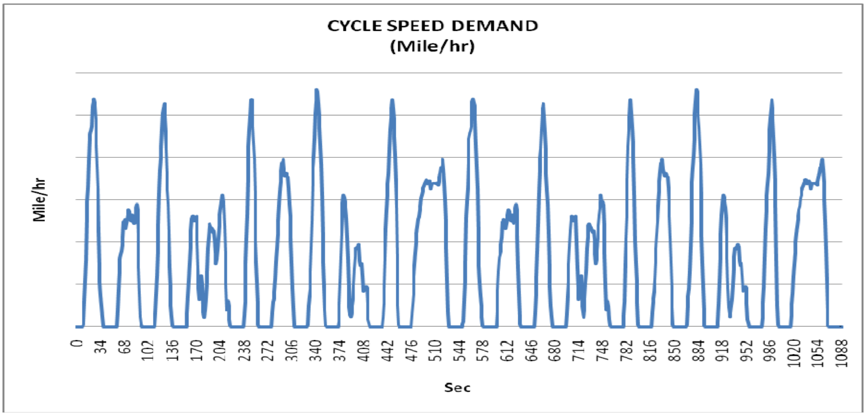

Figure 10: Manhattan drive cycle.

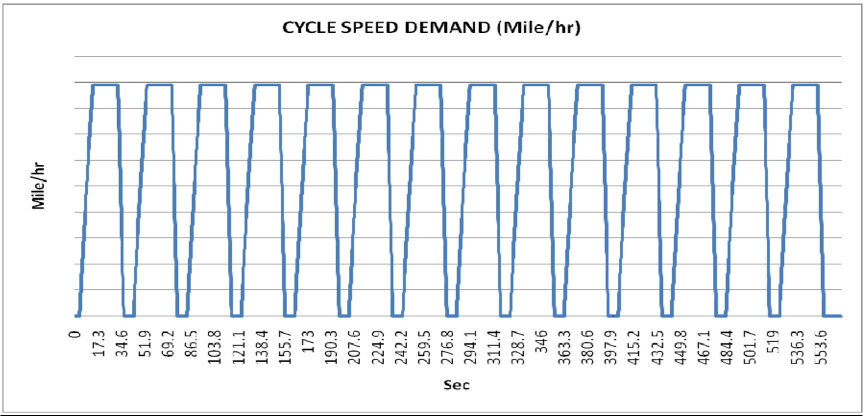

Figure 11: CBD-14 drive cycle.

successful validation permits improvisation at deducing estimate results for a variety of needs including alternate vehicle designs and/or duty cycles.

This project features a modified duty cycle as a derivative of the existing Manhattan drive cycle; the result is meant to serve as an approximate representative for such cities that exhibit dense traffic with large hill climbing terrains such as Jerusalem

Characteristically, the Manhattan drive cycle constitutes a default zero-gradient as documented in the summary table of Figure 8. Contrary to this, we note significant undulation in the topography of the Jerusalem landscape (including the regular bus service route), so that we formulated/constructed a modified Manhattan drive cycle. For convenience we name this the Jerusalem drive cycle, and combine Figure 10 with the hill shown in Figure 12. Final simulations are run on this cycle for the purpose of conducting a prediction study as to the performance of hybrid buses in hilly regions.

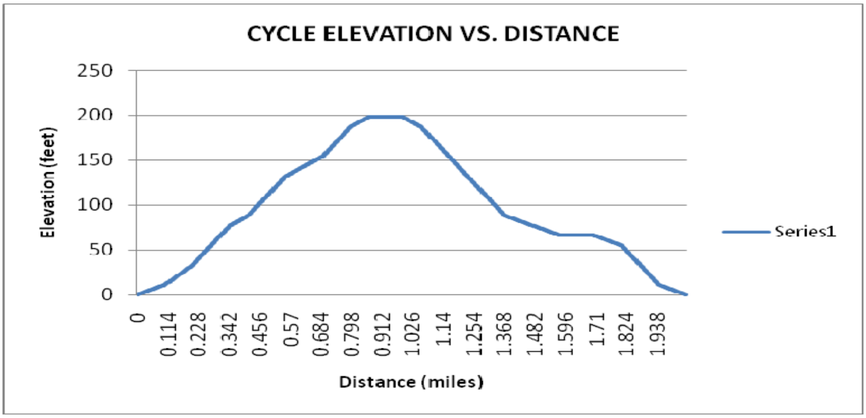

Figure 12: Jerusalem drive cycle.

		NABI 60LFW		New Flyer DE60LF, BRT		Wrightbus StreetCar RTV		Gillig 40ft	
		Dynamo	Simul	Dynamo	Simul	Dynamo	Simul	Dynamo	Simul
Fuel Econ *(mpg)*	CBD-14	2.19	2.22	3.25	3.25	n/a	2.87	6.01	5.43
	Manhattan	1.46	1.69	2.56	2.65	n/a	2.64	4.31	4.24
	Jerusalem	n/a	1.73	n/a	2.72	n/a	2.35	n/a	4.06
CO2 *(g/mile)*	CBD-14	4587	4523.69	2991	3110.69	n/a	175.6	1646.2	1862.97
	Manhattan	6714	5902.74	3771	3793.54	n/a	305.61	2287.95	2366.7
	Jerusalem	n/a	5745.5	n/a	3700.19	n/a	286.37	n/a	2477.42
NOx *(g/mile)*	CBD-14	19.67	98.13	14.44	65.17	n/a	13.66	10.72	50.79
	Manhattan	29.58	169.13	18.12	79.36	n/a	27.37	16.22	60.86
	Jerusalem	n/a	166.9	n/a	88.77	n/a	22.84	n/a	54.48
CO *(g/mile)*	CBD-14	1.77	0.62	1.55	0.47	n/a	0.02	0.53	0.32
	Manhattan	3.13	0.91	2.81	0.54	n/a	0.04	4.13	0.36
	Jerusalem	n/a	0.96	n/a	0.68	n/a	0.04	n/a	0.38
HC *(g/mile)*	CBD-14	0.12	6.75	0.03	2.81	n/a	18.48	0.18	2.22
	Manhattan	0.04	22.93	0.05	8.2	n/a	22.9	1.9	7.11
	Jerusalem	n/a	21.35	n/a	8.07	n/a	24.06	n/a	4.83

Figure 13: Comparison of simulation to dynamometer test results.

4 Results

With the vehicles specified and the duty cycles selected, we can implement these within PSAT. Results for the four buses and the three driving cycles are presented in Figure 16. For the CBD and Manhattan cycles, we show comparisons between dynamometer measurements and the simulation results. Note that there are no comparable dynamometer data for the Wrightbus. The values in Figure 13 are perhaps better understood by reference to the charts for fuel economy and carbon dioxide emissions, Figures 14 and 15.

Some comments are in order. Consider first fuel economy:

- The simulation does remarkably well in predicting fuel economy for the buses for which data is available.

- As might be expected, as the cycle becomes more realistic, fuel consumption degrades substantially. Indeed when we look at the Jerusalem data, with its attendant hills included, fuel usage is lower than for the other cycles.
- However, the employment of the hybrids markedly improves fuel use in any other cycle, often by 50% or more. This does suggest that hybrid technology is a suitable technology for the bus community looking to economize on fuel expenditures.
- While the Wrightbus looks excellent in all cycles, we must question the simulation. Without dynamometer data for comparison, perhaps this looks too good.

Next consider CO_2 emissions.

- As with the fuel economy, the CO_2 simulation well matches the experimental data.

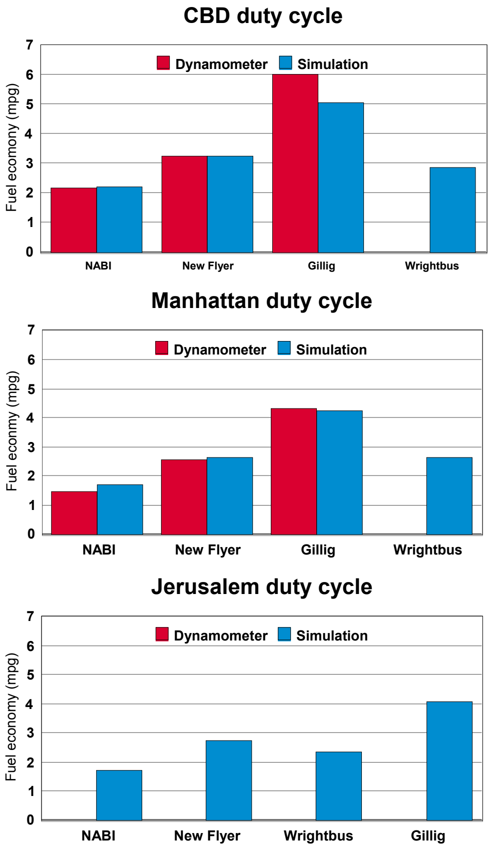

Figure 14: Fuel economy comparisons.

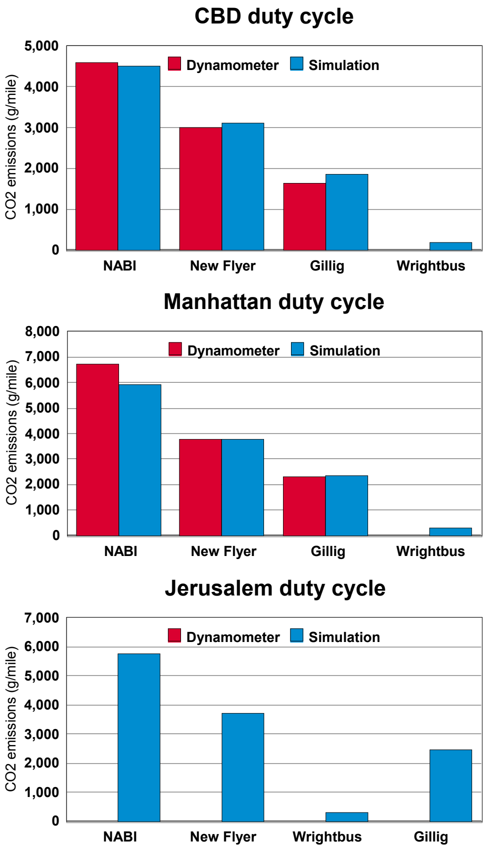

Figure 15: Carbon dioxide emission comparisons.

- Again as the cycle becomes more realistic emissions do not seem to change significantly. Perhaps this is an anomaly of PSAT and requires additional investigation. Note that the hybrids performs well and emissions only grow modestly as the cycles change, indicating the value of such technology in controlling green house gases.
- Here the Wrightbus seems to do very well; we make no other comment than that made above with regard to fuel economy.

Clearly the fuel economy and the CO_2 emissions are well-modelled. This perhaps should not be so surprising since if the first matches well then it is likely that the second will as well, given the relatively simple chemistry relations between the two.

Inspection of Exhibit 13 suggests that the same cannot be said for the other emissions: NOx, CO and HC (unburned hydrocarbons). Here too we make several observations:

- The order of magnitude of the emissions of these other pollutants is significantly lower than that of the carbon dioxide. This holds looking at the experimental, dynamometer results or the simulation output and for all the vehicles under any of the drive cycles.

- As a consequence the simulation is not tracking these well. The inherent chemistry is likely not well modelled and needs to be modified if representing these emissions is a goal of the study. Since, here, we are looking at cases to develop a means for screening buses, then perhaps it is not important to match these outputs; see Section 5, below for additional discussion of this point.
- In discussions with PSAT personnel, we learned that at some future date the reaction chemistry will be improved.

5 Conclusions

In this final section let us return to the original purpose of this paper. Our goal was to validate simulation software – in our case PSAT – and then offer some guidance to cities looking to purchase HEVs. Fuel economy and emissions results are among those parameters that we sought to match with experimental data. We also studied issues of duty cycle so that realistic performance would be obtained.

From the results provided in Section 4, above, it is clear that fuel economy and carbon dioxide emissions are well-modelled for these heavy duty vehicles. We believe that these major parameters can be used by the bus operators to determine which buses can successfully be used in their localities, at least from a screening point of view and that PSAT is a reasonably accurate simulation tool. In addition, these sorts of data on fuel use and CO_2 can be employed to determine the cost savings with hybrids as well as the reductions available in green house gas emissions and carbon footprint, at least for CO_2.

There may be a need to obtain results for the smaller pollutants, NOx, CO and HC. Then, either an improved PSAT would need to be employed which better models the reaction chemistry in the engine or vehicle testing can be extrapolated to the cycles of interest.

Next steps for our overall project are now to use these results to screen additional vehicles and address the issues cited in the introduction. Our plan is focus primarily on:

- environmental benefits (emissions of particulates, NOx, CO/CO_2, unburned hydrocarbons)
- economic benefits
- duty cycle consequences
- vehicle cost factors
- potential return on investment

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