ABSTRACT

Pritchard, Ewan Gareth David. Performance Modeling of Hybrid and Plug-In Hybrid Electric School Buses using ADVISOR (Under the direction of Dr. Richard R. Johnson.)

The hybrid electric vehicle is currently changing the automotive market at an impressive rate. While not as highly publicized, the transit bus market is being transformed at an equally great rate. As these markets move forward, the school bus market remains largely unchanged. As an unchanged market, there is still the opportunity to optimize a hybrid vehicle platform for school buses.

This study begins the modeling process of an existing class C school bus and investigates the potential that both series and parallel hybrids hold to reduce fuel consumption and emissions for a school bus. The primary focus of this study is to investigate the potential benefits of adding an electricity grid interconnection to hybrid electric school buses, allowing them to add to the hybrid potential with a pre-charged battery pack from the electric utility grid. These vehicles are known as plug-in hybrids

The school bus models shown in this paper were generated in a Matlab/Simulink-based program developed by NREL called ADVISOR. ADVISOR is used by vehicle manufacturers as a tool to experiment with different vehicle configurations. In this study both a generic series hybrid and a generic parallel hybrid are generated and then each is used in both charge-sustaining and charge-depleting scenarios with varying sizes of battery packs to increase the “grid energy.” The results of each model are presented by both fuel economy and emissions reductions taking into account the power plant emissions and electricity costs.

The results of the study show that by adding a plug-in connection to existing hybrids, significant savings can be achieved, both in fuel costs and in overall emissions. By analyzing the emissions both at the power plant level and at the vehicle level we show that emission of NO_x, Particulate Matter and Carbon Dioxide emissions can all be reduced while saving on fuel costs. This study also shows that some models of traditional hybrid can be operated as plug-in models with little or no change to the system to gain significant benefit from the initial charge.

PERFORMANCE MODELING OF HYBRID AND PLUG-IN HYBRID ELECTRIC SCHOOL BUSES USING ADVISOR

by
Ewan Gareth David Pritchard, P.E.

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APPROVED BY:

James W Leach
Dr. James W. Leach
Advisory Committee

Nancy Ma
Dr. Nancy Ma
Advisory Committee

Richard R Johnson
Dr. Richard R. Johnson
Chair of Advisory Committee

Dedicated to my wife Lora and my daughter Kira

BIOGRAPHY

Ewan Pritchard was born in Bedford, England in 1973. In 1977, his parents Gail and David and sisters Sera and Vicky, moved to Cary, North Carolina in the United States. In the United States, his father worked to open a fire hose manufacturing plant in Angier, North Carolina.

From hiking in England, and the mountains of North Carolina, to working in the garden, Ewan loves to spend time in the outdoors. As a child, Ewan developed allergies and asthma and needed to use an inhaler before exercise. A likely cause of the asthma and allergies are from the pollution problems seen in the Research Triangle area in the early '80s. This condition, while not critical, likely caused Ewan to be more conscious of potential environmental issues.

Ewan attended Enloe High School in Raleigh, North Carolina and was fortunate enough to have the opportunity to take an engineering class under the leadership of Mr. Tom Blanford. Mr. Blanford enabled the students to learn engineering in a creative way. As part of the class, Ewan worked on a project designing a model solar powered car. During the course of this project Ewan realized that he wanted to dedicate his career to investigating and promoting the use of alternate-fueled vehicles.

Ewan attended NC State University and received a degree in Mechanical Engineering in 1997. In his senior year at NCSU, he met his future wife, Lora Neel, then a sophomore in mechanical engineering. After graduation, he found an internship at the North Carolina

Alternative Energy Corporation (NC AEC). Shortly following his acceptance of the position at AEC, the company changed its name to Advanced Energy to match the new drive to promote efficient energy sources rather than exclusively alternative energy sources. He left AEC after a few months to accept a full engineering position at GKN Automotive as a forging engineer, designing warm form punches for the manufacture of constant velocity joints. GKN was a deviation from his career goal of alternate fueled vehicles, and he accepted an engineering position back at Advanced Energy in late 1997, where he was given the opportunity to attend graduate school while he worked on Centennial Campus of NCSU. Ewan began graduate school at NCSU on a part time basis in the spring of 1998. Ewan and Lora were married a year later in the summer of 1999, shortly after her graduation from NCSU. In November of 2003, their first child, Kira was born. Since Kira's birth, Ewan has doubled his efforts to promote the plug-in hybrid electric school bus. It is Ewan's hope that someday Kira will actually be riding on a plug-in hybrid electric school bus.

While working as an engineer at Advanced Energy, Ewan developed expertise in energy-efficient technologies such as infrared, radio frequency and induction heating, powder coating, electric vehicles, and energy efficient electric motors. Through his knowledge of electric motors and electric vehicles, he began a project to promote plug-in hybrid electric vehicles. This investigation is a part of that effort.

ACKNOWLEDGEMENTS

A lot of effort has gone into the Hybrid Electric School Bus project. The advisory group now has almost 30 members from school bus agencies, environmental groups, academia, and manufacturers, I would like to thank all of them for their involvement and dedication to the project and encourage all of them to keep up the support, we have a long way to go. Thanks to Advanced Energy for their support of innovative projects and for the atmosphere of creativity that has helped this project exist. I would especially like to thank the agencies that are funding the hybrid school bus feasibility study, of which this is a small part. Thanks to the North Carolina Energy Office, Duke Power, and Progress Energy.

I would like to thank my wife, Lora, for encouraging me to go back to graduate school and work on alternative fueled vehicles. I would also like to thank Dr. Richard R. Johnson for all of his patience and time spent with me throughout graduate school and especially during the implementation of this project. I would also like to thank my mom and dad for inspiring me in all areas of knowledge, particularly science. To my sister Sera, the technical editor, thanks for spending time reviewing this paper. If you find commas in funny places or extra capitalized letters, it would now be her fault. Thanks to my sister Vicky for her emotional support during my work, she often calmed me down when things were getting too stressful. I would especially like to thank my daughter Kira, who spent her first four months of life thinking that her father was just some guy attached to a laptop in the kitchen – I promise I will play with you now.

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1. INTRODUCTION

Hybrid electric vehicles are a far cry from a new technology. In fact, early in the development of the automobile, around 1900 there were several models of hybrid vehicles available. At that point in time, the hybrids available could be run using either electricity or combustion fuel. In some vehicles, the combustion process would generate electricity to operate an electric motor. The hybrid electric vehicles being developed today have significant advantages over the vehicles that were developed in the early 1900s. The most significant development is the ability to easily and cost effectively control the flow of energy to an electric motor through the use of a drive or controller.

The primary reasons to move to a hybrid system today are to reduce vehicle fuel consumption, emissions, and maintenance. All of these objectives are achieved in a hybrid system by reducing the variability of the load on the combustion engine. A typical vehicle is subjected to a constantly varying load at varying speeds throughout the cycle as shown in Figure 1.1. It is not reasonable for the combustion engine to be at its highest efficiency and its lowest emission level at all times while providing the wide range of torques and speeds necessary to drive the wheels of the vehicle. As vehicle manufacturers design increasingly complex transmissions, we reach closer and closer to the optimal torque-speed relationship to reduce emissions and increase efficiency. However, when a vehicle is forced to provide torques many times the average value of the overall torque required, the task becomes very difficult.

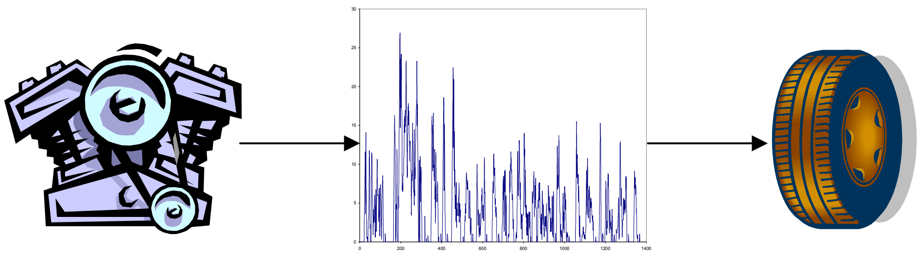


Figure 1.1. Instantaneous power needs during a representative trip

Since they have relatively flat efficiency curves and instantaneous torque, electric motors fit the ideal vehicle drive needs quite well. A typical hybrid electric drive system essentially provides a buffer between the torque and speed requirements of the final drive by adding an electric motor and battery system between the combustion engine and the drive wheels (Figure 1.2). By buffering the system, the combustion engine is only required to deliver the average power needs of the system, and can operate at a specifically designed speed and efficiency.

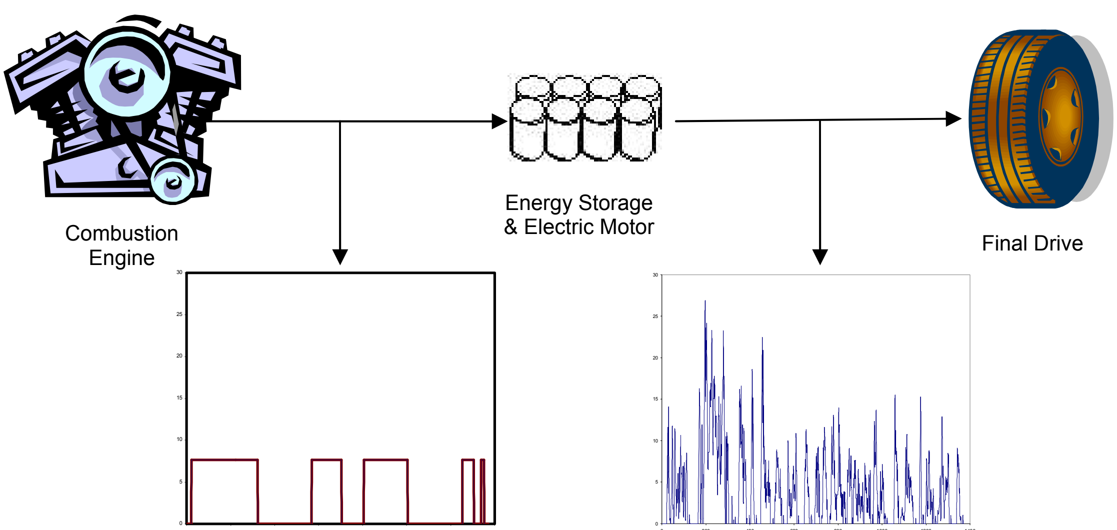


Figure 1.2. Power flow in a series hybrid vehicle

1.1 Vehicle Losses

There are a wide variety of losses in a conventional vehicle. A relatively simple means of quantifying these losses is as internal and external losses. The external losses of a typical vehicle can be split into four categories:

- Aerodynamic force, F_A
- Rolling resistance force, F_R
- Dynamic energy, F_V
- Potential energy, F_G

1.1.1 Aerodynamic Force

The wind drag felt as a vehicle moves is completely lost in friction to the air. For a conventional school bus, the coefficient of aerodynamic drag, C_D will range from 0.59 at speeds (below about 8 miles per hour) and quickly drop to about 0.46 at typical driving speeds (above approximately 10 miles per hour). For both a conventional vehicle and a hybrid vehicle, aerodynamic drag is a non-conservative force, which means the energy is completely lost at the time it is generated. This helps explain why many designers of new hybrid have worked so hard to minimize the coefficient of drag. The aerodynamic forces, F_A, in an object are a function of the drag coefficient, the frontal area of the object, A, the density of air, ρ, and the velocity, V, of the vehicle.

$$F_A = C_D A(\rho V^2 / 2) \qquad (1\text{-}1)$$

1.1.2 Rolling Resistance

The rolling resistance is a representation of the necessary friction of the tires with the road. While this friction helps transfer power to the road, there are losses associated with the transfer. For the tires, this loss is quantified using the coefficient of rolling resistance (C_R), and the weight of the vehicle (mg).

$$F_R = C_R mg \tag{1-2}$$

1.1.3 Dynamic Forces

It takes a large amount of energy to bring a vehicle up to a particular speed. In a conventional vehicle, most of the inertial energy is lost to heat in brake pads. A hybrid vehicle can recapture a portion of this energy in batteries by using the electric drive motor as a generator. Though a separate generator can be used, most hybrid vehicles simply use the electric drive motor as a generator. The force of inertia is a function of the vehicle mass (m) and the rate of change of velocity (dV/dt) or acceleration.

$$F_V = m(dV / dt) \tag{1-3}$$

1.1.4 Gradability Force

A vehicle will gain potential energy as it climbs a grade at the cost of the work to elevate the vehicle. The energy lost while climbing a hill can be recaptured by increasing the speed of a vehicle while it travels downhill. Typically, however, a driver is closely holding a constant speed so this energy will often be used as engine braking or even wheel braking where all of the energy will be lost. In the case of a hybrid electric vehicle, much of this energy is regained in regenerative braking. The force to climb a grade is a function of the weight of the vehicle (*mg*) and the grade being climbed (*G*).

$$F_G = mgG \tag{1-4}$$

1.1.5 Internal Losses

Internal losses in the vehicle are quantified in terms of efficiency such as the driveline efficiency, η_T. A hybrid vehicle works well to reduce internal losses, such as allowing the combustion engine to operate at a designed operating point to reduce combustion losses. Accessory losses can also be reduced by electrification of pumps, fans and compressors, allowing each to operate independently of the speed of the combustion engine. Most manufacturers are moving toward electric accessories regardless of the hybrid drivetrain. To reduce drivetrain losses some hybrid driveline manufacturers have opted for independent electric drive motors at each wheel, which completely eliminates the need for a rear axle.

1.2 Emissions

When talking about environmental emissions, there are different areas of concern depending on the source of the emission. For example, when talking about power plants, the reported emissions of concern are carbon dioxide (CO_2), sulfur oxides (SO_x), and nitrogen oxides (NO_x). With automobiles, the reported emissions are NO_x, particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO). And finally when discussing local non-attainment issues, emissions are primarily reported in ozone and particulate matter less than 2.5 microns in size ($PM_{2.5}$). Sulfur oxides (SO_x) and nitrogen oxides (NO_x) use the subscript x due to the nature of emissions to change form while airborne. They often leave a facility in a somewhat harmless state and become harmful after reacting in other areas of the atmosphere.

For the purpose of this study only discuss PM, NO_x, and CO_2 are discussed. Each of these emissions lends itself strongly to a particular growing health problem.

1.2.1 Particulate Matter

Particulate matter is a general term for any emission with a particle larger than a molecular size emitted, greater than 0.001 microns (Seinfeld 1998). Often large particulate matter, greater than 10 microns, settles out quickly and is of less concern than smaller particulates. The US EPA currently breaks small particulate matter into two segments: all particulate matter smaller than 10 microns in size (PM_{10}), and “fine” particulate matter, smaller than 2.5 microns in size ($PM_{2.5}$). Particulate matter smaller than 10 microns is considered small enough to enter the respiratory system and cause severe respiratory issues such as asthma. Fine particulate matter, $PM_{2.5}$, is considered small enough to block the alveoli, which perform the oxygen exchange in the lungs. Smaller particulate matter smaller than 0.1 microns can pass through the alveoli entering the blood stream. This particulate matter is considered a major culprit of the increased rate of heart disease. Once in the blood stream the particles can cause abrasions on the inner walls of the arteries which promote a buildup of plaque and increased blood pressure along with other severe heart problems (Bhatnagar 2004). Particulate matter has been proven to be a serious health concern, but school-age children are considered at greater risk since they breathe 50% more air by body mass than adults.

1.2.2 Nitrogen Oxides

The emission of nitrogen oxides are a great concern due to the precursor nature of nitrogen dioxide (NO_2), to the generation of ground-level ozone in the presence of sunlight and volatile organic compounds. Once ozone is formed it has a generally short life before it recombines with other molecules. In other forms NO_x often migrates and behaves again as a precursor to later formation of ozone, allowing it to travel larger distances.

Nitrogen oxides are formed primarily as NO and NO_2 during high temperature combustion. The generation is specifically a function of the temperature of combustion and the composition of the air intake. Because of the nature of NO_x generation, many alternate fuels do not work well to reduce its emission. A reduction on the combustion temperature and a reduction in the levels of air required for combustion can help reduce emissions. A popular and effective solution to reducing NO_x emission is adding a catalyst to the exhaust system.

The primary health concern from ozone is oxidation of lung tissue and damage to respiratory function. The same oxidation effect is felt by a person when cleaning with harsh bleach cleaners in an enclosed space like the shower. The oxidation creates an irritation in the lungs which causes coughing. Like exposure to particulate matter, ozone has been linked to numerous lung ailments, specifically asthma.

1.2.3 Carbon Dioxide

The emission effects of carbon dioxide emission are a popular political debate, since this emissions is considered in the scientific community to be the largest contributor to the greenhouse effect. The greenhouse effect is a condition where gases prohibit the natural cooling mechanism of the earth and the resulting heat build-up slowly destroys the polar ice caps along with affecting global climates and severe weather phenomenon.

The generation of carbon dioxide is directly proportional to the combustion of carbon-based fuel. The best way to reduce the emission of CO_2 is to increase the overall energy efficiency of the process. Moving to electric processes can often reduce CO_2 emissions, because over 20% of US electric generation is from a non-combustion processes that emit no CO_2.

1.3 ADVISOR

ADVISOR, or NREL's Advanced VehIcle SimulatOR, was originally written in 1994 to model advanced vehicle drive systems. The program is written in MATLAB/Simulink and has been adapted to handle many hybrid drive systems being developed. Most major auto manufacturers use ADVISOR to develop hybrid and advanced vehicle drivetrains.

ADVISOR is a backward facing modeling system which means it takes drive cycle, which is a set velocity and elevation data over time every second and applies the demand for acceleration of the vehicle to the wheels as shown on the left side of Figure 1.3. A calculation for the power demand required to turn the wheels is then translated upwards throughout the driveline and into the vehicle. The resulting model is a prediction of performance, fuel economy, and emissions. It is the purpose of this study to show the relevance of building plug-in hybrid electric school buses and that ADVISOR can adequately model the results of several potential systems. The open source programming of ADVISOR allows the user to customize the simulation and add unique aspects to each model through the easy use of the block diagrams like the one shown in Figure 1.3.

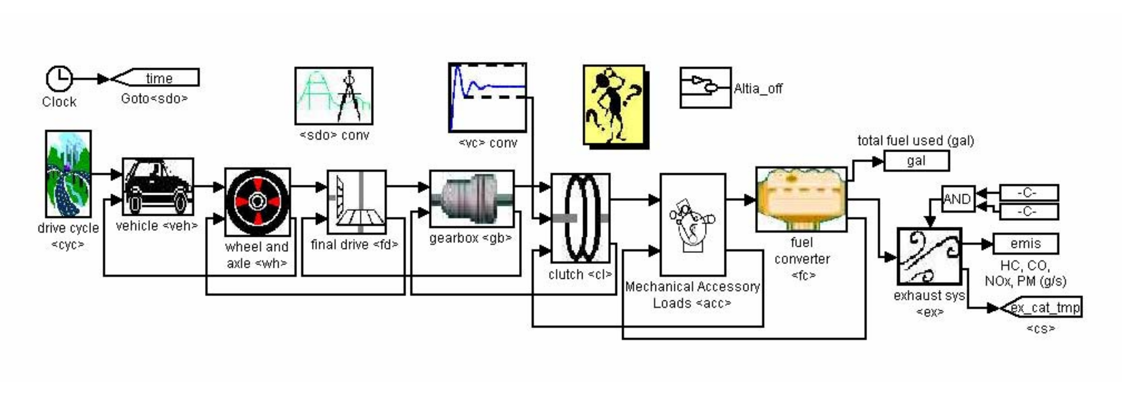


Figure 1.3. Basic ADVISOR Block Diagram

2. BASELINE SCHOOL BUS MODELING

Over 60% of school buses on the road in North America are classified as type C, or conventional, buses. These buses have a front engine compartment that extends beyond the area in front of the driver. The remaining school buses are type D, a transit style bus, or types A and B, which consist of smaller chassis and special needs buses. The easiest way to identify type D buses is by the flat front on the bus. It should be noted that type D buses have the engine either underneath the driver in the front or in the rear of the bus.

For the purposes of this study, the advisory group determined that the most valuable chassis style to analyze would be the type C bus due to its high production volume and applicability across the nation. A baseline model of a conventional school bus was built to both qualify the modeling technique and to establish a fair model for comparison once the hybrid models were created.

2.1 Parameters

Based on the specifications of Florida, North Carolina, and South Carolina, a baseline chassis model was selected that most closely fits all three states specifications for a class C, 65-passenger school bus. The resulting chassis specifications are listed in Table 2.1.

Table 2.1. Chassis Specifications

Baseline School Bus Chassis Specifications		
Parameter	Value	Source
Length	400”	Schroyer 2003
Width	96”	Gattis 1998a
Height	120”	Schroyer 2003
Weight	18,500 lb	Thomas Built Bus
Center of gravity height	44”	Thomas Built Bus
Drag coefficient	0.55	Schroyer 2003
Wheelbase	254”	Schroyer 2003
Front wheel weight %	35%	Patterson 2001

Once the chassis was modeled, the individual drive components were added. For modeling purposes, particular systems were selected because of their use in the specifications for school bus purchases. Each of the individual components is given in Table 2.2.

Table 2.2. Baseline Bus Specifications

Baseline School Bus Drive Specifications			
Component	Model	Notes	Source
Engine	Navistar T444-230 HP	Scaled to 210 HP	Graham 2002 Patterson 2001 Schroyer 2003
Transmission	Allison 2000	Assumed efficiency 96.13%	Graham 2002 Schroyer 2003
Final drive	AVM RS-23-160	6.14:1 Drive ratio	Schroyer 2003
Tires	Michelin ZXE	11R-22.5	Graham 2002 Patterson 2001 Schroyer 2003
Accessories	Carrier AC	Dual TM-21 compressors	Carrier
Exhaust	No after treatment		

For the simulation, components other than the transmission and the diesel engine were given zero weight, as they are considered in the overall weight of 8391 kg (18,500 lb). All of the other components are considered common for both traditional and hybrid school buses. The weights of the transmission and the combustion engine were considered in the model and backed out of the overall weight.

2.1.1 Engine

For the baseline model, a Navistar T444-230 HP engine was used due to availability of the engine fuel and emission data. The 230 HP engine was linearly scaled to 210 HP by torque through the ADVISOR program. International currently uses a 210 HP, T444 product in their school buses but is moving towards a VT-365 which has similar speed characteristics, but higher torque in the middle range of speeds (Figure 2.1). Thomas Built buses currently use a 210 HP, MBE-906 engine.

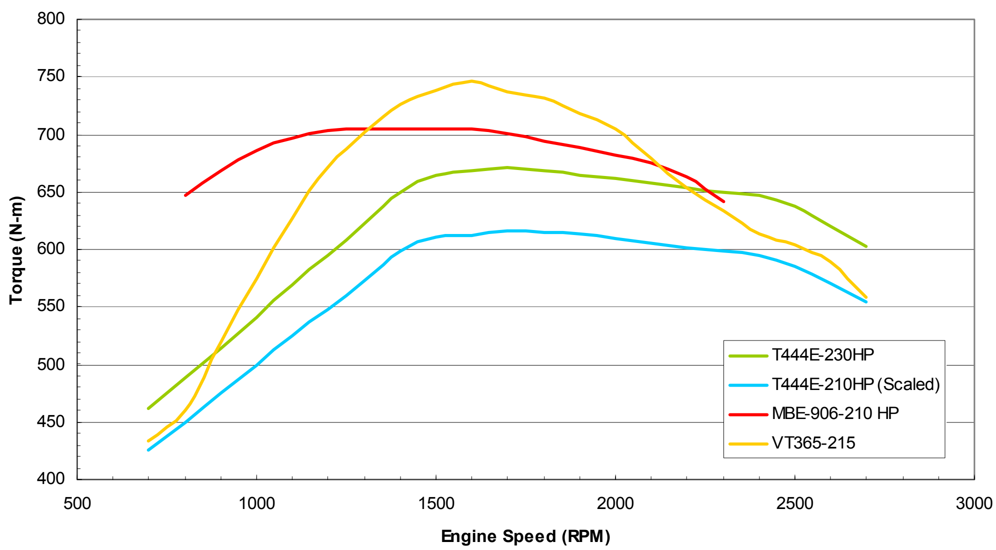


Figure 2.1. Engine Torque Curves

While the torque characteristics of each engine differ quite significantly, the power curves of each engine shown in Figure 2.2 are quite similar. Emissions of each engine are expected to be lower for model year 2004, but the results of this study will not show that reduction in emissions. It should be noted; however, that each of the hybrid models was simulated using the same engine scaled to a smaller size, and the emissions of other hybrid products will be reduced by a similar percentage. The source data files have been included in the appendix so that future studies can show the effects of the newer engines on the plug-in hybrid.

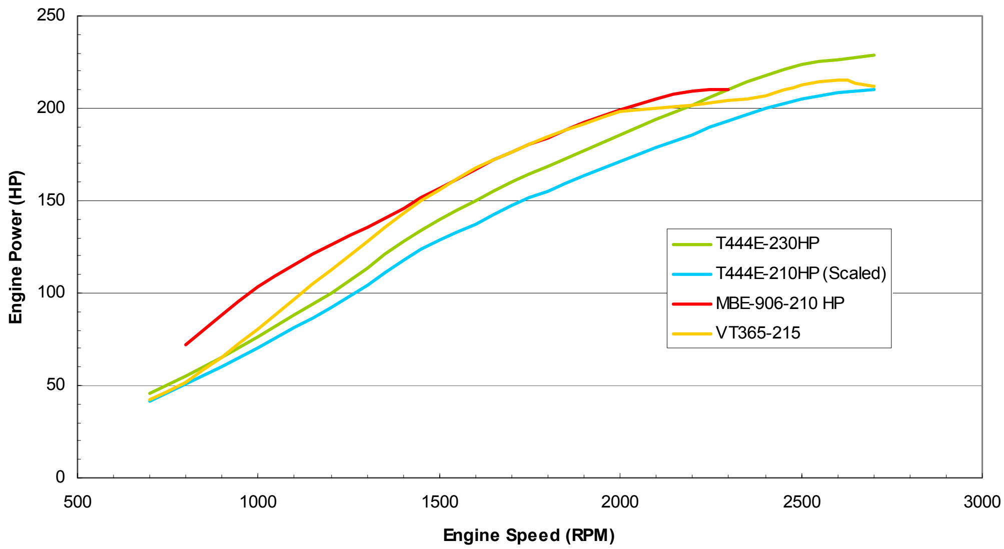


Figure 2.2. Engine Power Curves

The use of engine scaling is not preferred, as each engine can be made to operate at different powers by incorporating different levels of turbo charging or other methods which do not result in linear translation of the engine data. The engine scaling function is regarded as highly accurate when the total displacement is scaled by a like amount such as moving from an 8 cylinder version of an engine to a six cylinder version with little change in operation characteristics. This is not considered a flaw of ADVISOR but rather an observation for future study.

2.1.2 Transmission & Final Drive

The selection of the Allison 2000 transmission was based on the specification of the transmission in North Carolina, South Carolina, and Florida. The model is based on data published in the Allison 2000 specification sheet as shown in Table 2.3. Several final drive ratios are used in school buses ranging from 7.17:1 for many North Carolina buses to 6.14:1 in Florida. It is assumed that this final driveline will continue to be used in the respective buses on future hybrid models. Based on Florida testing specifications, a constant driveline efficiency of 96.13% has been assumed.

Table 2.3. Transmission Specifications

Allison 2000 Transmission Specifications	
Parameter	Value
Weight	330 lb
Ratio 1st	3.51:1
Ratio 2nd	1.90:1
Ratio 3rd	1.44:1
Ratio 4th	1.00:1
Ratio 5th	0.74:1
Final Drive Specifications	
Parameter	Value
Drive Ratio	6.14:1

2.1.3 Tires

The importance of tires for the modeling is to determine the translation of rotation speed (rpm) to vehicle speed in miles per hour, and to establish the relationship between forces on the bus and the torque in the drive shaft. The model will also determine if the vehicle will lose traction and skid the tires. Based on existing ADVISOR data files, a coefficient of rolling resistance of 0.09 was assumed. In the North Carolina specifications, the tires are specifically called out as 11R22.5; Examples listed are Michelin ZXE or Goodyear G-159. According to product literature, the Michelin ZXE has an inflated diameter of 41.5 inches and an operating speed of 501 revolutions per mile.

2.1.4 Accessories

The accessory category integrates all of the loads from the 12-volt battery system and other engine driven loads such as air conditioning compressors, the water pump, and the engine fan. A breakdown of accessory loads is given in Table 2.4.

Table 2.4. Accessory Loads

Accessory Loads		
Accessory	Load	Source
Air Conditioning Compressor	5200 Watts	Carrier
Heat Exchanger Fans	800 Watts	Carrier
Other Electronics	500 Watts	Estimate
Engine Fan	7450 Watts	Estimate (Operating 50% of the time)
Water Pump	2000 Watts	Estimate
Hydraulic Pump	1500 Watts	Estimate

For emission and fuel economy calculations, the intent is to accurately model typical operation, where air conditioning will be intermittent if used at all. Using the assumed accessory loads, the emission and fuel economy models use 11,450 watts. For performance modeling the Florida specifications specify that all accessories shall be running when performing the test. Based on this specification all performance tests in this study were run using 24,900 watts (33.4 HP).

2.1.5 Exhaust

The modeled exhaust system is only a pass-through system. Current engine standards do not encourage the use of exhaust system catalysts, but the reduction of gases within the engine itself. Additionally, most catalytic systems are prone to clogging in a diesel system due to particulate matter emissions. A data file was created that models a pass through system. Currently, due to the engine maps, only NO_x and PM emissions are used in these models.

2.2 Route

To determine the fuel economy and average emissions for the bus requires knowledge of typical school bus usage profiles. One recent study of school bus emissions used the City Suburban Heavy Vehicle Cycle, CSHVC (Ullman 2002). The use of the CSHVC in this study was based on an SAE study where several heavy vehicles were compared using the same cycle (LeTavec 2000). A speed versus time profile of the CSHVC is given in Figure 2.3.

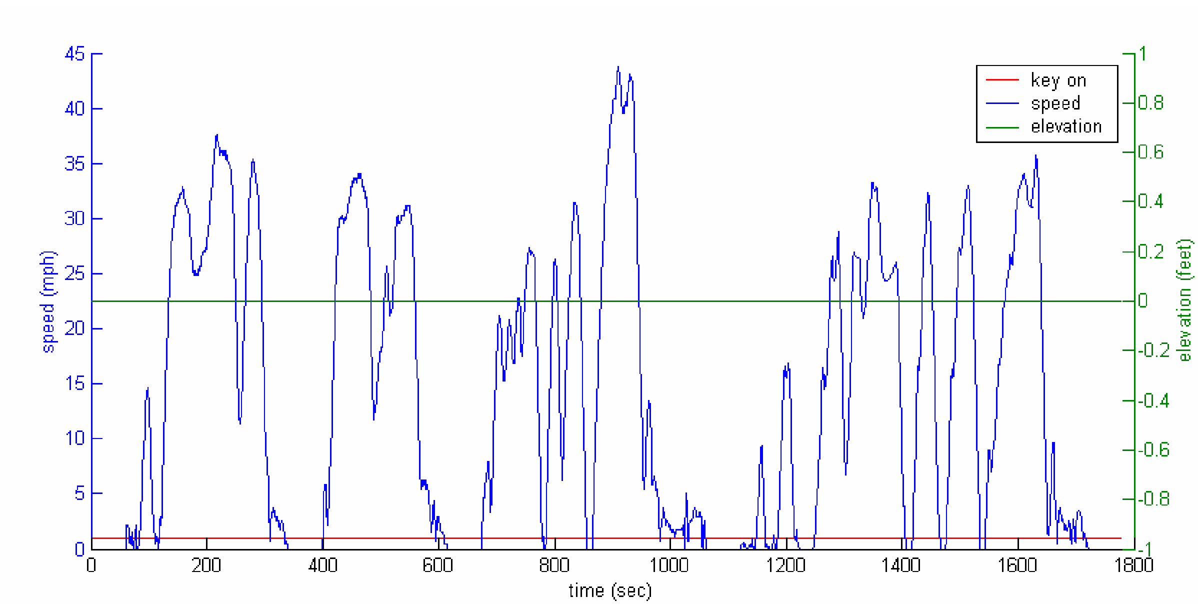


Figure 2.3. City Suburban Heavy Vehicle Cycle

Speeds range up to 44 miles per hour for the CSHVRC and average at about 14 miles per hour. Recently, a study was completed at North Carolina State University (NCSU) through the Institute for Transportation Research and Education (ITRE) that observed the use of a global positioning system (GPS) to monitor the paths a bus takes to find better routes. The author of that study donated the source data from that study for use in this study (Rhoulac 2003). The GPS data was then used to establish a typical school bus route. From the ITRE study, two routes were established; the ITRE-Suburban School Bus Cycle, and the ITRE-Urban School Bus Cycle. The suburban cycle is a representative 3-hour, 68-Mile trip (Figure 2.4), where speeds averaged around 24 mph and speeds varied up to 47 mph.

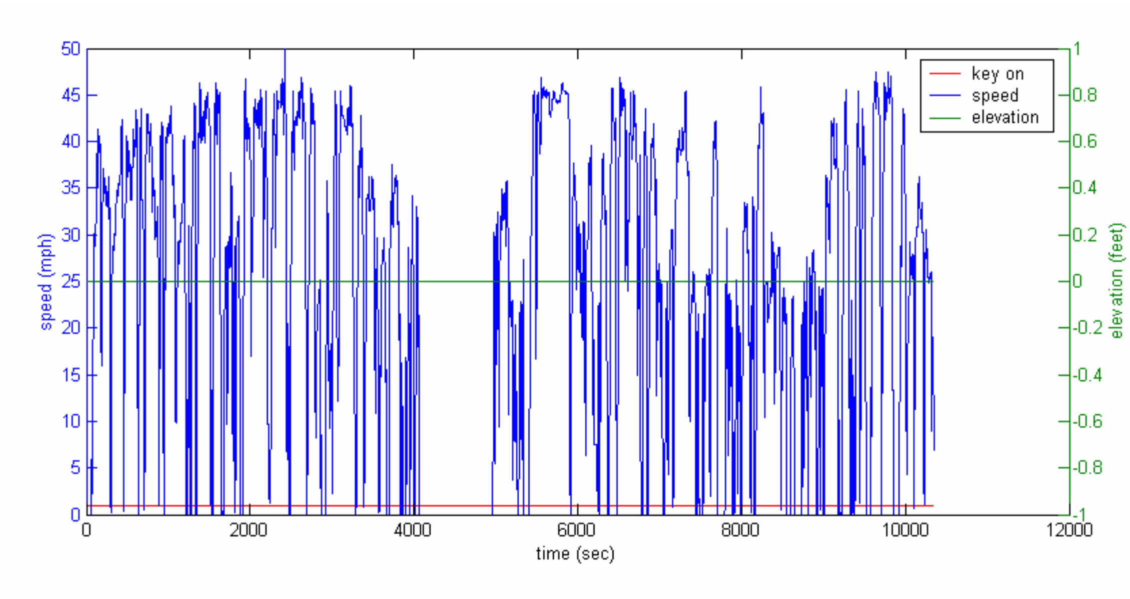


Figure 2.4. Suburban Route from ITRE Study

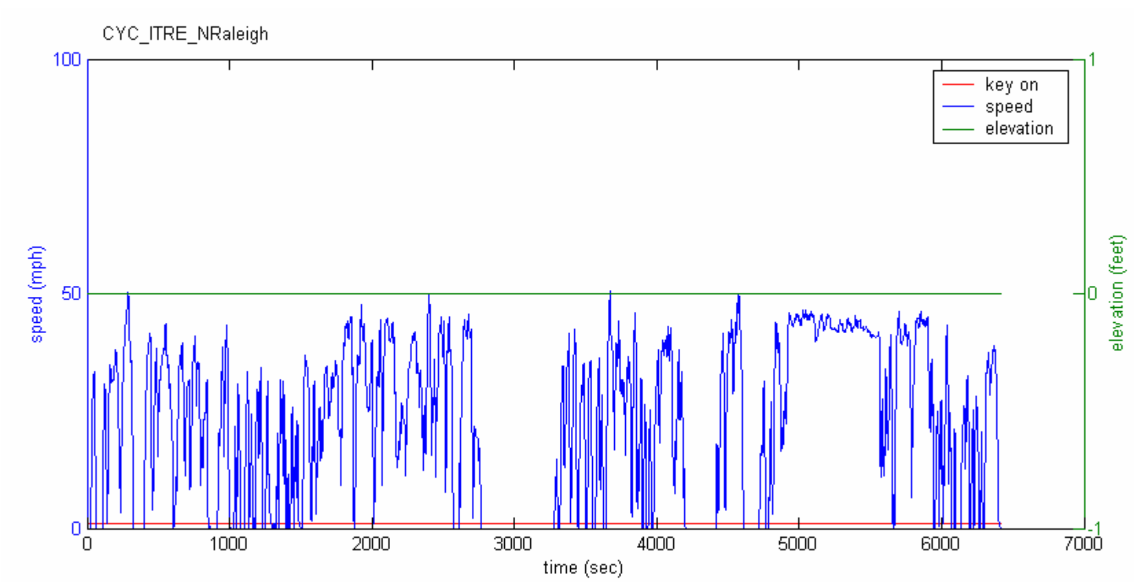
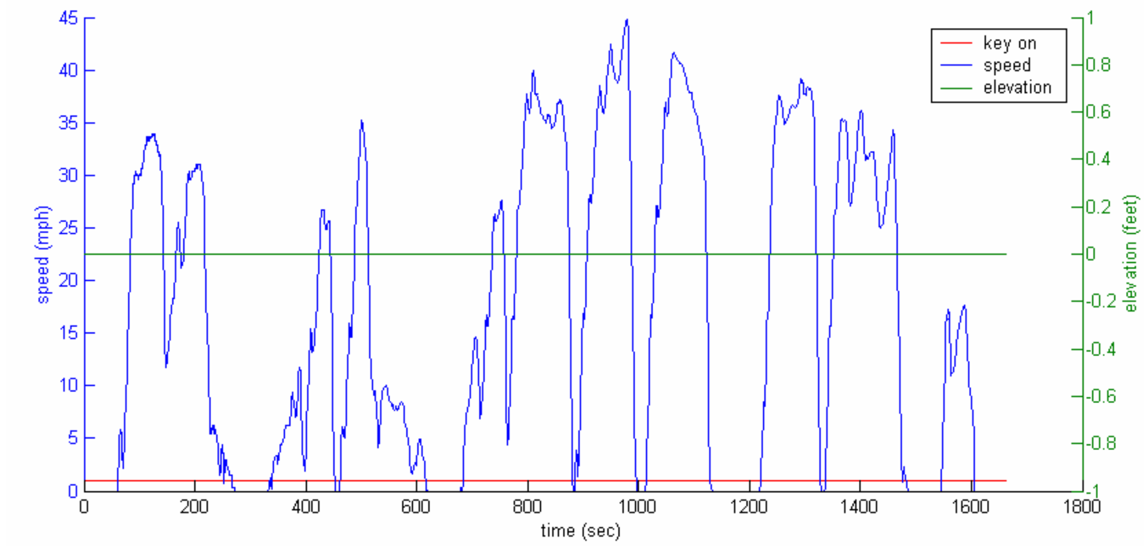


Figure 2.5. Urban Route from ITRE Study

Another well established route that is a standard input file for ADVISOR is the West Virginia Suburban Cycle (WVUSUB). The WVUSUB has an average speed of 16.07 mph and a max speed of 44.8 mph.



It is important to note that each cycle is greatly different when looked at as a percentage of time at a particular speed. As can be seen in figures 2.6-2.9, the percentage of time at higher speeds (30-40 mph) is much greater in the ITRE cycles.

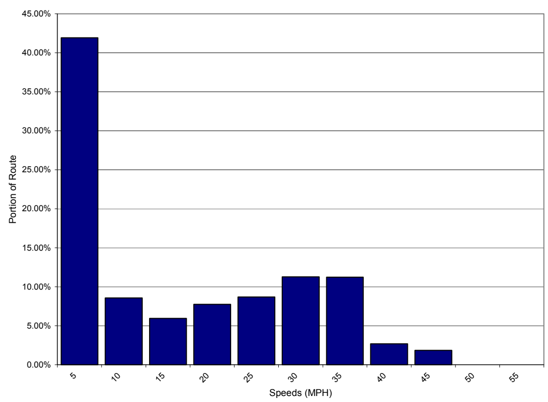


Figure 2.6. CSHVC Distribution

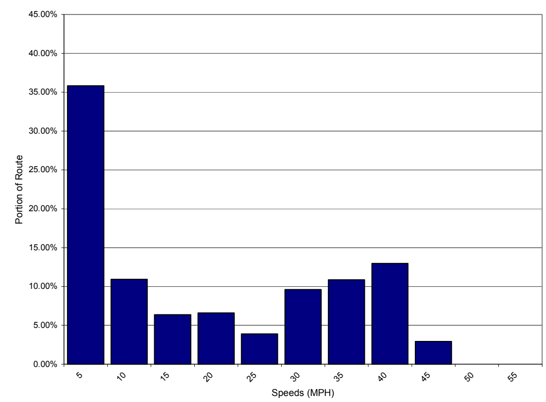


Figure 2.7. West Virginia Suburban Distribution

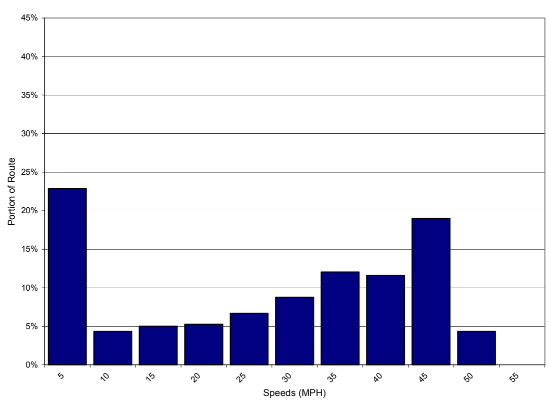


Figure 2.8. ITRE Suburban Route Distribution

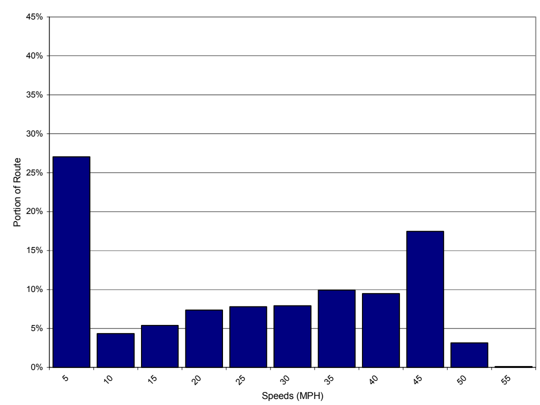


Figure 2.9. ITRE Urban Route Distribution

While the results of the ITRE routes show quite dissimilar usage to both the West Virginia and the CSHVC cycles, noise in the ITRE cycles rendered them unusable for this study. From the profiles, however, it was determined that rather than following in the trend of other studies, it would be more representative to use the West Virginia suburban cycles for future modeling of the hybrid buses. This analysis highlights the need for future study to generate a standard school bus route for future analysis.

2.3 Performance

The tests for performance were based on performance required in the state specifications for the state of Florida (Schroyer 2003). These performance specifications require that the bus be fully utilize the accessories, including air conditioning compressors. The bus should be loaded with the driver and one passenger. Based on these conditions the bus must meet the following:

Table 2.5. Performance Results

Baseline School Bus Performance		
Criteria	Florida spec.	Test result
0-10 mph	3.4 sec.	2.7 sec.
0-20 mph	6.2 sec.	6.7 sec.
0-30 mph	12.0 sec.	12.0 sec.
0-40 mph	20.0 sec.	20.1 sec.
0-50 mph	32.2 sec.	31.3 sec.
25 mph gradability	5 %	10.9 %
55 mph gradability	1.5 %	1.9 %
Max acceleration	None	5.7 ft/sec2
Distance in 5 sec	None	67.2 ft
¼ Mile time	None	29.1 sec
Max Speed	Min 60 mph	71.1 mph

Each of the resulting values is within the expected range for the school bus, with exception to the 25 mph gradability and the maximum achievable speed where the baseline simulation far exceeded the performance requirements.

2.4 Baseline Fuel Economy and Emissions

To find fuel economy and emissions on a per mile basis, the model was run on several cycles to show the variability. The bus was loaded with 11 students, or 25% of its high school student capacity of 44 students. Each student was estimated to weigh 130 lb and carry a 13-lb backpack. Additionally a 175 lb driver was added, for a total of 1748 lb. For the purposes of this study we have settled on using the WVUSUB cycle. The resulting fuel economy was 7.4 miles per gallon, with 11.578 grams/mile of NO_x and 0.183 grams per mile of particulate matter.

Table 2.6. Fuel Economy and Emission Results

Baseline School Bus Fuel Economy and Emissions				
Criteria	Test result (ITRE-Suburban)	Test result (ITRE-Urban)	Test result (CSHVC)	Test result (WVU-Sub)
Fuel economy	8.3 MPG	7.2 MPG	6.5 MPG	7.4 MPG
PM	0.119 g/mi	0.132 g/mi	0.213 g/mi	0.183 g/mi
NOx	11.408 g/mi	13.446 g/mi	12.655 g/mi	11.578 g/mi

As can be seen from the results above the model has a high sensitivity to driving style and route. Comparing this variability to the variability in the model sensitivity analysis shows a high degree of importance on selecting a more representative route. The results were compared to published dynamometer data conducted at the Southwest Research Institute, where type D buses were tested on three cycles of the CSHVC (Ullman 2002) and found to be slightly higher than expected but well within reason. The results for the SWRI study found emissions of 14.127 g/mi of NO_x, 0.184 g/mile of PM and 6.59 miles per gallon. It should be noted that the bus used in the SWRI study was a type D bus weighing 11,800 kg and equipped with a 275 HP engine.

2.5 Model Sensitivity

Each variable in this study is based on the best available data; however, each of the assumed variables carries with it some level of uncertainty. In an effort to capture the importance of several key variables, the sensitivities of each variable on the model results were calculated. Point variables that were closely questioned during the study were vehicle weight, accessory loading, final drive ratio, transmission efficiency, and coefficient of drag. Other variables considered were the route file, the engine used, and the transmission controls. For the point variables, a simple band sensitivity analysis was conducted, with many of the variables changed by 10% both positive and negative, and the results reported on a percentage basis. The results of the point-variable sensitivity are presented in Table 2.7. The sensitivity analysis was conducted using the ITRE-Urban cycle.

Table 2.7. Point Variable Sensitivity to Select Variables

Baseline Model Fuel Economy and Emission Sensitivites				
Criteria	Vehicle weight 20,350-16,650 (±10%)	Final drive ratio 6.754-5.526 (±10%)	Transmission efficiency 95.13-97.13 (±1%)	Coefficient of drag 0.605-0.495 (±10%)
Fuel economy (MPG)	6.9-7.5 (±4.2%)	7.1-7.3 (±1.4%)	7.3-7.2 (+1.4%,-0%)	7.2-7.3 (-0%,+1.4%)
Particulate matter (g/mi)	0.132-0.131 (+0%,-0.8%)	0.136-0.131 (+3%,-0.8%)	0.132-0.132 (±0%)	0.131-0.132 (-0.8%,+0%)
Oxides of nitrogen (g/mi)	14.33-12.56 (±6.6%)	13.202-13.621 (-1.8%,+1.3%)	13.355-13.593 (-0.7%,+1.1%)	13.648-13.262 (+1.5%,-1.4%)

3. SERIES HYBRID MODEL

A series hybrid is one in which all energy is converted into electrical energy and the final drive of the vehicle is completely driven by an electric motor. The design process for a series hybrid vehicle is much easier than a parallel hybrid, as each component must be sized correctly for the entire drive needs of the vehicle. The series hybrid schematic shown in Figure 3.1 takes chemical energy in the form of diesel fuel and converts it to mechanical energy through the combustion engine.. Energy then flows through the drive shaft to an electric motor (generator) where the energy is converted to electrical energy. At this point the energy is stored in the battery pack for use by another motor, often referred to as the traction motor, where the energy is converted back to mechanical energy at the rate dictated by the needs of the vehicle.

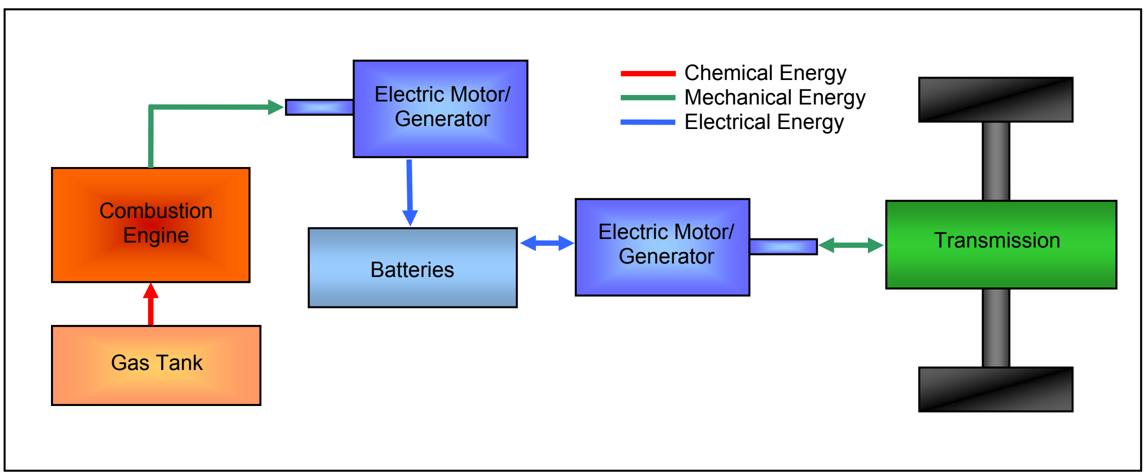


Figure 3.1. Series Hybrid Electric Schematic

Series hybrid systems benefit by operating the engine at a desired operating point where they can achieve the highest efficiency or lowest emissions of a selected type. The series hybrid can also allow engine designers to design an engine where the emissions at the highest efficiency are as low as possible without regard to other operating points of the engine

3.1 Component Sizing

The design of a series hybrid is very methodical because each component is fully dependent of the component before it. A clear methodology for the design of a series hybrid electric vehicle has been conveyed in a paper by Texas A&M (Rahman 1999). In the case of the series hybrid school bus, the design begins with an electric motor using the power requirements established by the acceleration and gradability in the baseline model.

3.1.1 Motor

The electric motor for a series hybrid needs to be large enough to provide all of the necessary energy to drive the vehicle. The energy needed to drive the vehicle is a combination of four aspects: acceleration, increase in elevation, overcoming wind drag, and tire friction losses. Combined they make up the vehicle power equation given in

(3-1.

$$P_{Vehicle} = \frac{V\left[F_A + F_R + F_V + F_G\right]}{\eta_t} \qquad (3\text{-}1)$$

Because acceleration data is based on flat elevation, the power equation was used first to evaluate the necessary engine size to accelerate the vehicle. To evaluate the acceleration of the bus a curve was fit to velocity data from a study of North Carolina school bus accelerations (Gattis 1998). The resulting power requirement from the acceleration data was approximately 120kW, assuming a mass of 10,000 kg. It is also necessary to calculate the necessary power required to climb the specified grades. The acceleration at the speed required to climb the grades required was set to zero, as this is the maximum speed achievable at the specified grades. The requirements were 55 mph at 1.5% grade and 25 mph at 5% grade. The resulting power requirements were 100 kW to climb to 1.5% grade at 55 mph, and 140 kW to climb the 5% grade at 25 mph. The final drive motor of the bus will need to provide a maximum of 140 kW of instantaneous power to achieve the desired drive requirements. A standard AC motor was selected from the stock of files included in ADVISOR. This motor is similar in magnitude to the scale used in New York transit buses for the BAE HybriDrive Series hybrid system, where the traction motor is 187 kW. It should be noted that the power requirements for a typical 40 foot transit bus are approximately 33% greater than a school bus or 280 HP versus 210 HP.

3.1.2 Battery

The batteries used for the simulation of the Series hybrid vehicle were taken from stock files in the ADVISOR library. DOE had modeled the Series Hybrid Orion buses being built in New York using the BAE HybriDrive system from published data. The BAE buses are using Advanced Lead Acid modules that are on the order of 85 A-h each. These battery data files were used as they are supplied by ADVISOR for the modeling of the transit bus. At all times these batteries will need to supply the peak energy needed by the electric motor of 140 kW. Preliminary calculations showed that only 15 batteries are needed to provide the necessary power using a fully charged battery pack. Several models were run to optimize the size of the battery pack and the peak efficiency was seen at around 30 modules. For comparison, BAE uses 42 batteries in the HybriDrive system.

Scaling the BAE battery back by 33% also reaches around 30 modules. Based on the optimization, 30 battery modules were used for the series hybrid school bus.

3.1.3 Generator

A series hybrid requires a generator to convert power from the fuel converter to electricity and feed it to the battery pack. The rate of energy needed by the battery pack is dictated by the designed state of charge and the maximum expected average rate of discharge of the battery pack. This value is somewhat subjective since the averaging time and designed route can vary quite greatly. The generator used in the Orion transit buses with the BAE HybriDrive is 170 kW. Sizing the generator to be of a similar size relative to the drive motor yields a generator size of 113 kW.

3.1.4 Transmission

The electric motor is rated for 10,000 rpm, but from Figure 3.2, it is apparent that the efficiency and torque actually decay significantly beyond about 7500 rpm. For the purposes of this model the transmission was designed to operate at 7500 rpm when the bus is traveling at 60 mph.

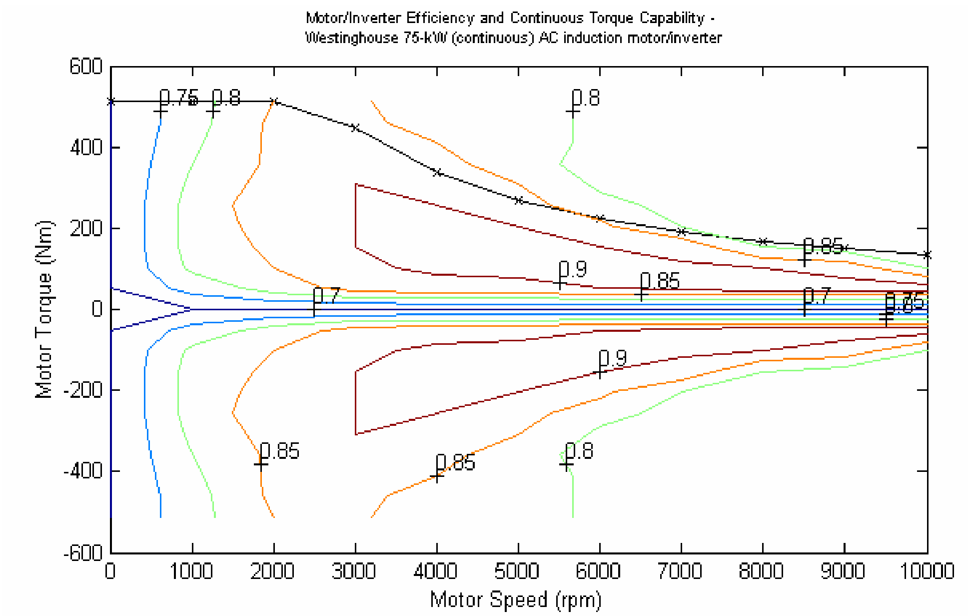


Figure 3.2. Motor/Controller Operating and Efficiency Curves

The process for calculating the overall transmission ratio is given in equation 6.2

$$i_t = \frac{\pi \cdot n_{\max}}{30 \cdot V_{\max}} = 29.28 \qquad (3.2)$$

Where n_{max}, is the maximum motor speed 7500 rpm, V_{max} is the maximum vehicle speed 26.8 m/s, and r is the radius of the tire, 0.571 meters. Dividing the overall ratio by the stock rear axle ratio of 6.14 provides the necessary transmission ratio of 4.77.

3.1.5 Combustion Engine

The combustion engine used for the series hybrid is the same engine used for the conventional vehicle, yet the engine has been scaled to a smaller size. The determination of the size for the combustion is fairly straightforward. From the determined generator size of 91 kW, several efficiencies were to be backed out to determine the combustion engine power. The peak efficiency of the generator is 95%; however, it is likely to operate at about 90%, and adding a 95% coupling efficiency provides a size of 106 kW (142 HP). We also need the ability to operate the combustion engine outside of its peak power to allow for emissions and fuel economy improvements. Due to availability we have proposed a 131 kW (175 HP) engine. Several models were run with a 112 kW (150 HP) engine, which is readily available, but these did not provide acceptable results for both fuel economy and emissions.

3.2 Series System Summary

The design method resulted in the system specifications given in Table 3.1. The resulting system design for the series hybrid is further verified by the similar sizing to the BAE component sizes, but scaled to approximately 33% smaller.

Table 3.1. Series Hybrid System Specifications

Series Hybrid Electric School Bus Specifications		
Component	Model	Size (Scaled)
Engine	Navistar T444-230 HP	131 kW (175 HP)
Transmission	Single speed	4.77:1 ratio
Final drive	AVM RS-23-160	Same as baseline
Tires	Michelin ZXE	Same as baseline
Accessories	Same as baseline	Same as baseline
Traction motor	AC 3Φ induction (75 kW)	141 kW (190 HP)
Battery pack	Advanced PbA 85 Ah	35 Modules
Generator	Permanent magnet (95 kW)	91 kW (122 HP)
Control	On-Off from SOC	20% low 80% high
Tested weight	10,227 kg	22,546 lb

The performance of the series hybrid system showed a 10% improvement in fuel economy, a 15% reduction in NO_x and 64% reduction in particulate matter. The results of this system did not show the level of improvement that has been documented on the New York Transit fleets of 30%-50% increase in fuel economy, 56% reduction in NO_x, and over 90% reduction in PM. This is likely due to the use of particulate traps and a NO_x catalyst on the BAE buses. The reduction in emissions would allow a smaller engine to be run in a more efficient region.

4. PARALLEL HYBRID MODEL

A parallel hybrid is one in which part of the drive energy to the wheels comes from the internal combustion, while another part comes from an electric motor. The design process for a parallel hybrid vehicle is very open, since the level of hybridization can essentially be picked by the size of the electric motor. The internal combustion engine can then be reduced in size an equal amount, or throttled to operate more efficiently or at points where emissions are lower. A parallel hybrid schematic is shown in Figure 4.1.

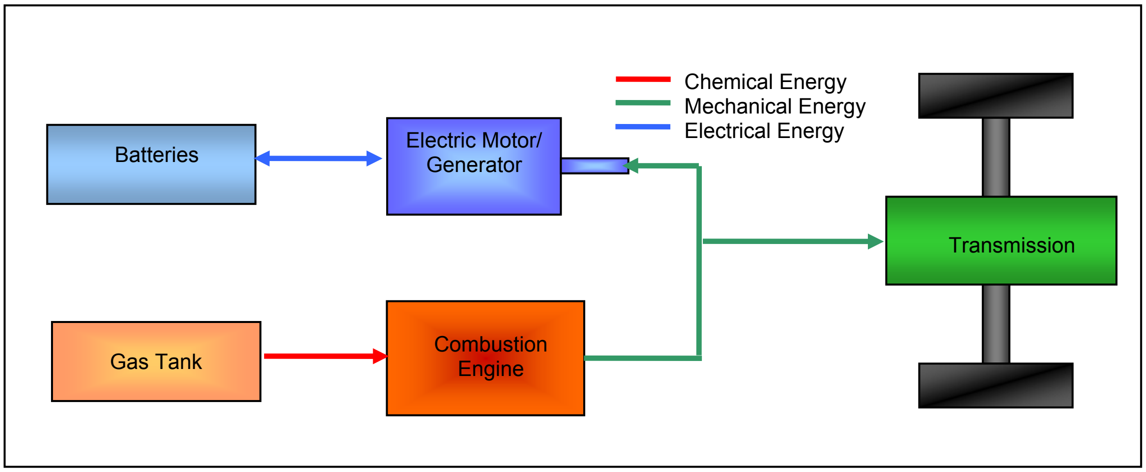


Figure 4.2. Parallel Hybrid Electric Schematic

The largest manufacturers of parallel hybrid drivelines for heavy duty vehicles at this time are Eaton Corporation and GM/Allison Transmission. Each manufacturer uses a different configuration for integrating the electric motor into the driveline. The model used for this study is a highly simplified version of the drivelines designed by both manufacturers.

4.1 Component Sizing

4.1.1 Motor

The electric motor for a parallel hybrid does not need to be as large as for a series hybrid since the motor does not perform all of the work of the final drive. The design of a parallel hybrid is a lot more open for designers to decide the ratio of electric power to combustion power. The manufacturers have come to call hybrids that favor the combustion engine more strongly, “mild” hybrids. To represent a system similar to the motor in the major manufacturer’s systems, a 75kW, 3-phase AC induction motor was selected. Several models were run at varying power ratings which showed this to be the ideal motor size given the sizes of other components. This compares to Eaton’s use of a 44 kW electric motor in their FedEx trucks, and with GM/Allison’s use of 160 kW in their transit buses.

4.1.2 Battery

Currently the manufacturers of parallel hybrid architectures are offering more advanced batteries than the manufacturers of series hybrid buses. Eaton Corporation is using lithium ion battery packs which bear a higher cost than most other types, but offer the highest life and power densities along with the lowest weight. GM/Allison is offering nickel metal hydride (NiMH) battery packs, which are used extensively in the major automobile market for hybrids. A significant advantage to using the NiMH batteries is the benefit of better life, lighter weight, and greater power density while tying the cost of the packs to a larger market, allowing for price reductions as more hybrid units are sold.

For the parallel model we use a NiMH battery with data included in the ADVISOR library. The battery modules provide 28 A-h each and are 8-Volt cells. The base parallel model uses 40 modules and operates at a nominal 268 VDC.

4.1.3 Engine

After all other components were selected, the size of the combustion engine was chosen based on several key qualities.

- Availability
- Power
- Ability to meet performance
- Emissions

While a much smaller engine was able to operate with much higher fuel economy, each model had higher emissions than the base model. A full parametric study of the design engine can help provide a much better sizing of the combustion engine. Since it was the primary intent of this study to analyze the effects of the plug-in system on overall performance, a value for engine size was settled upon which afforded lower NO_x emissions but did not achieve the full fuel economy benefits represented by manufacturers. The settled-upon engine size was 190 HP, or 142 kW. At this size the engine is allowed to run cooler and more to the left side of the efficiency curve where efficiency is high (Figure 4.3) while NO_x emissions are low (Figure 4.4).

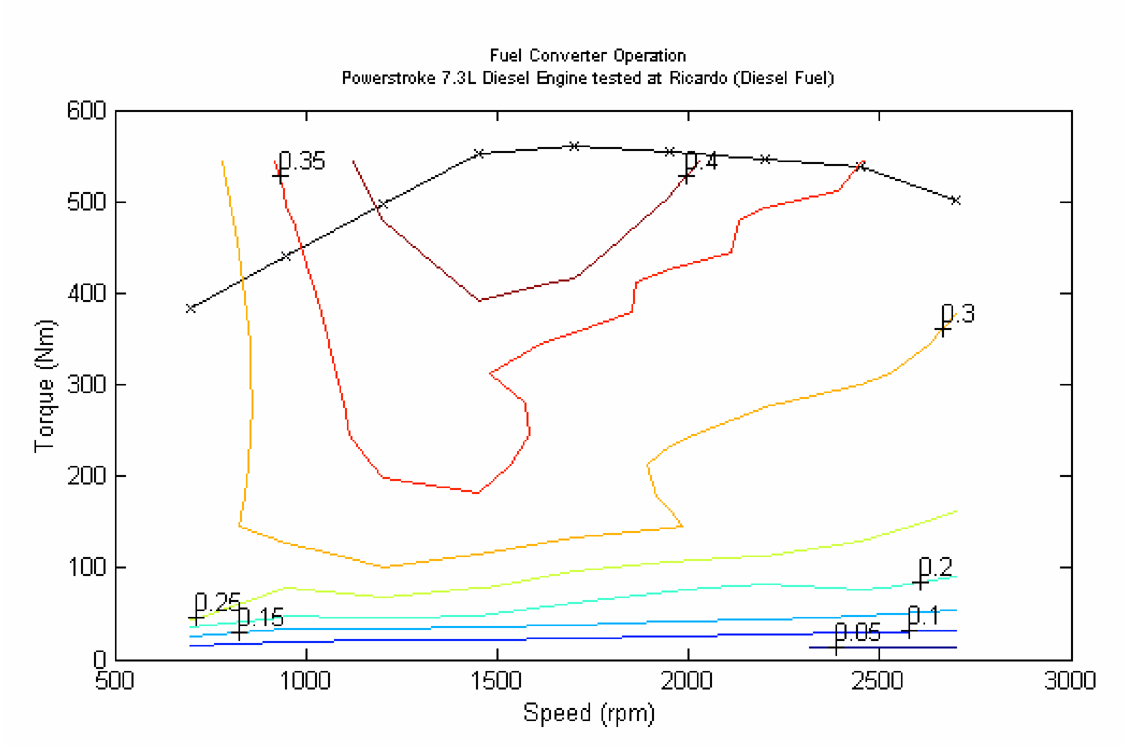


Figure 4.3. Efficiency Isopleths of 190 HP Engine

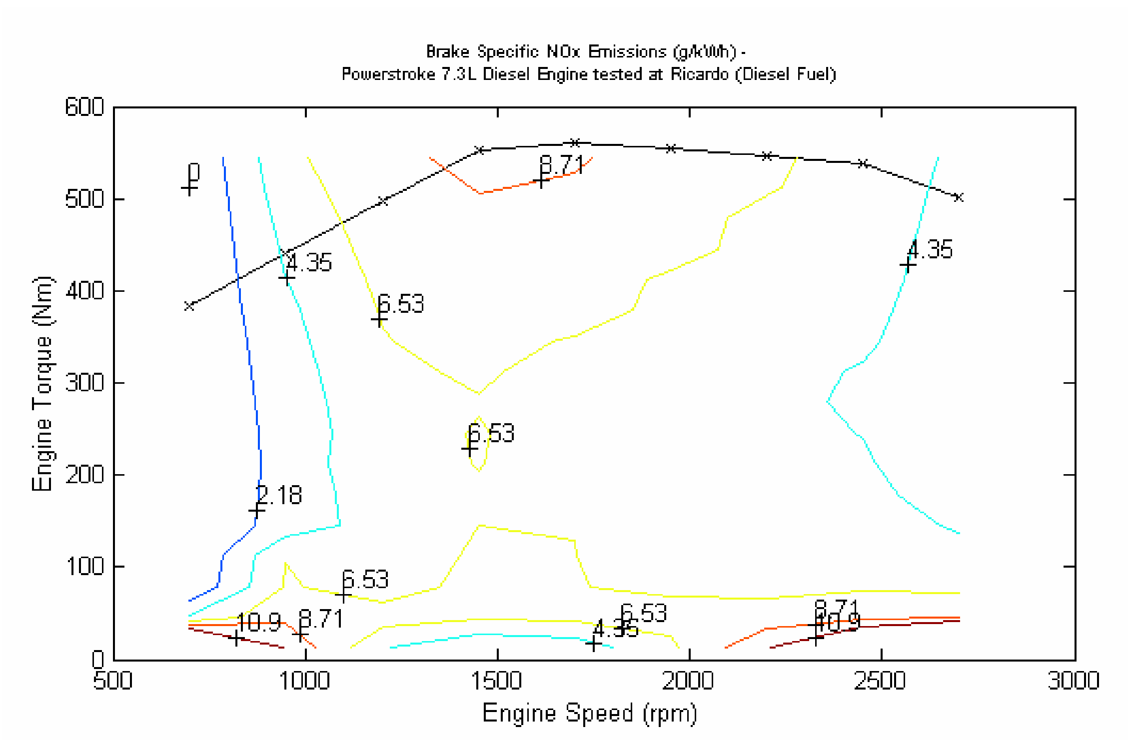


Figure 4.4. NO_x Isopleths of 190 HP Engine

4.2 Parallel System Summary

Overall, the designed parallel hybrid system was sized very similarly to the commercial products available. The engine size was only reduced by 20 HP to allow for more NO_x reduction.

Table 4.1. Parallel Hybrid System Specifications

Parallel Hybrid Electric School Bus Specifications		
Component	Model	Notes
Engine	Navistar T444 230 HP	Scaled to 142 kW (190 HP)
Transmission	Allison 2000	Same as baseline
Final drive	AVM RS-23-160	Same as baseline
Tires	Michelin ZXE	Same as baseline
Accessories	Carrier AC	Same as baseline
Exhaust	No after treatment	Same as baseline
Motor/controller	AC 3Φ Induction (75 kW)	As is – 75 kW
Battery pack	NiMH 28 Ah 8-V cell	40 modules
Torque coupling	Dummy	Stock file in ADVISOR
Control	On-Off from SOC	20% low 80% high
Tested weight	9580 kg	21,120 lb

Overall, the results of the parallel hybrid system yield a 15% increase in fuel economy, a 15% reduction in NO_x and a 24% reduction in particulate matter. This is a large contrast to published results for GM/Allison's hybrid system which show a 50% increase in fuel economy and NO_x emissions and over a 90% reduction in PM. It should be noted, however, that the GM/Allison buses are being equipped with a particulate trap and catalyst system, which would allow this system to be tuned for energy reduction more than emissions.

5. PLUG-IN HYBRID MODELS

A plug-in hybrid allows the battery pack of a hybrid to be fully charged while the vehicle is sitting idle. The battery pack is considered to have 100% state of charge (SOC) when it is completely full. The SOC is an important factor in the design of a hybrid vehicle. In many cases, the addition of a plug-in capability can significantly increase the effective fuel economy of the vehicle. Plug-in hybrids can be charge-depleting, or charge-sustaining. A hybrid that is charge-depleting means that the SOC is decreasing over time. A charge-depleting hybrid is one where the combustion engine is not large enough to recharge the battery pack at the same rate it is discharging. A charge-sustaining hybrid is one where the combustion engine is able to keep up with the demands of the route by recharging the battery pack as fast as it is depleted. Most plug-in hybrids are able to be operated as charge-depleting hybrids, but at some designed set state of charge the vehicle becomes charge-sustaining. All of the designs studied here are charge-sustaining hybrids, which mean that if operators decide not to use the plug-in option the vehicle will still operate as effectively as a conventional hybrid.

The plug-in models were changed from the pure hybrid models in two ways to ensure that they could still be operated as charge-sustaining hybrids. The models were given an initial SOC of 100% and the number of batteries was increased to allow for increased plug-in capability in several increments. To fully test the capacity of each hybrid, each model was run once as a charge-depleting hybrid, and again as a charge-sustaining hybrid.

5.1.1 Plug-in Capacity

Some plug-in hybrids can operate for long distances on all electric, and for this reason they often have a designation based on the distance the vehicle can travel as an electric vehicle. This naming convention has been used in the form HEV-10 for a plug-in hybrid electric with a 10 mile electric range. This naming convention causes more difficulty when the vehicle uses the combustion engine for driving torque in the case of a parallel hybrid. For the purposes of this study we have adopted a convention based on the amount distance the hybrid travels before the bus becomes charge-sustaining. In each case the base hybrid model was operated as a plug-in model. In the case of the series bus the base series bus was able to travel 20 miles without adding any new batteries. In the case of the parallel bus, the base model was able to travel 3 miles before operating as a charge-sustaining hybrid. A summary of the plug-in hybrid models used in this study is shown in Table 5.1.

Table 5.1. Plug-in Hybrid Electric Models

Plug-in Hybrid Electric Models				
Name	Battery Type	Battery Modules	Battery Weight (kg)	Battery Power (kWh)
Series	PbA	35	872	36
Series - 20 mile	PbA	35	872	36
Series - 30 mile	PbA	48	1195	49
Series - 40 mile	PbA	60	1494	61
Parallel	NiMH	40	144	7
Parallel - 3 mile	NiMH	40	144	7
Parallel - 10 mile	NiMH	112	403	20
Parallel - 30 mile	NiMH	255	918	45
Parallel - 40 mile	NiMH	326	1174	57

5.1.2 Power Plant Emissions

The power plant emissions used for this study are based on 2002 average aggregate North Carolina emissions reported by the Energy Information Agency (EIA 2004). Emission factors were determined from the EIA report as shown in Table 5.2.

Table 5.2. EIA Reported 2002 North Carolina Power Plant Data

Plug-in Hybrid Electric Models		
Name	Total	Per Unit
Total power sold	122,686 GWh	-
NO_x Emissions	164,000 Tons	1.21 g/kWh
CO_2 Emissions	77,462,000 Tons	573 g/kWh
SO_x Emissions	483,000 Tons	3.57 g/kWh

It should be noted that these are aggregate emissions for all of the power produced in the state, actual emissions would likely take place during non-peak hours and are anticipated to be less based on charging times. North Carolina has enacted a bill to dramatically reduce power plant emissions over the next few years, the results of those reductions are not represented in the data.

5.1.3 Resulting Performance

The resulting performance of each model shows better than required performance in all categories. As the amount of power available to the electric motor is increased by enlarging the battery pack, the performance of each vehicle also increases as seen in Figure 5.1.

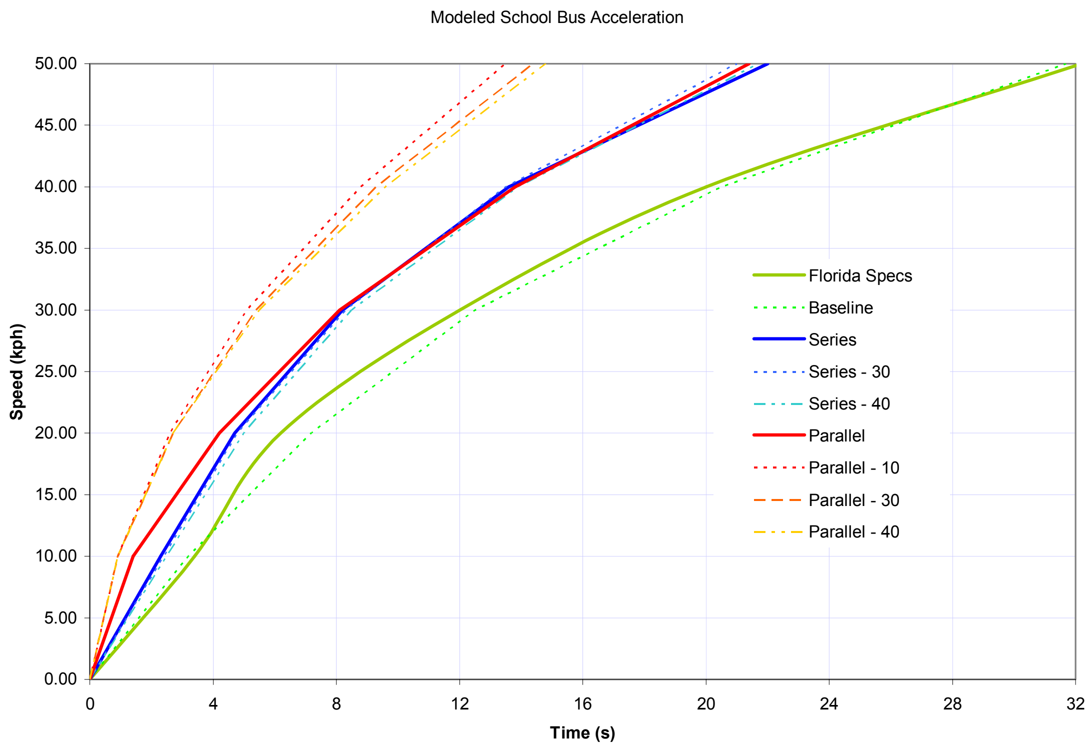


Figure 5.1. Acceleration Performance for Selected Hybrid Electric Models

For actual design purposes, each individual vehicle would be designed with a smaller electric motor to more accurately match the desired performance curves without exceeding them by as large of a margin. This study worked to keep as many variable consistent in order to accurately measure the performance of the plug-in capabilities. Further performance results are included in APPENDIX B.

5.1.4 Series Hybrid Fuel Economy

The fuel economy for plug-in hybrids presented in Figure 5.2 shows significant improvements in the plug-in hybrids. The straight fuel economy, however, can be misleading because a portion of the fuel economy is based on electricity from the plug.

The results for fuel economy for the series hybrids reached over 20 miles per gallon for the 30 mile plug-in series model.

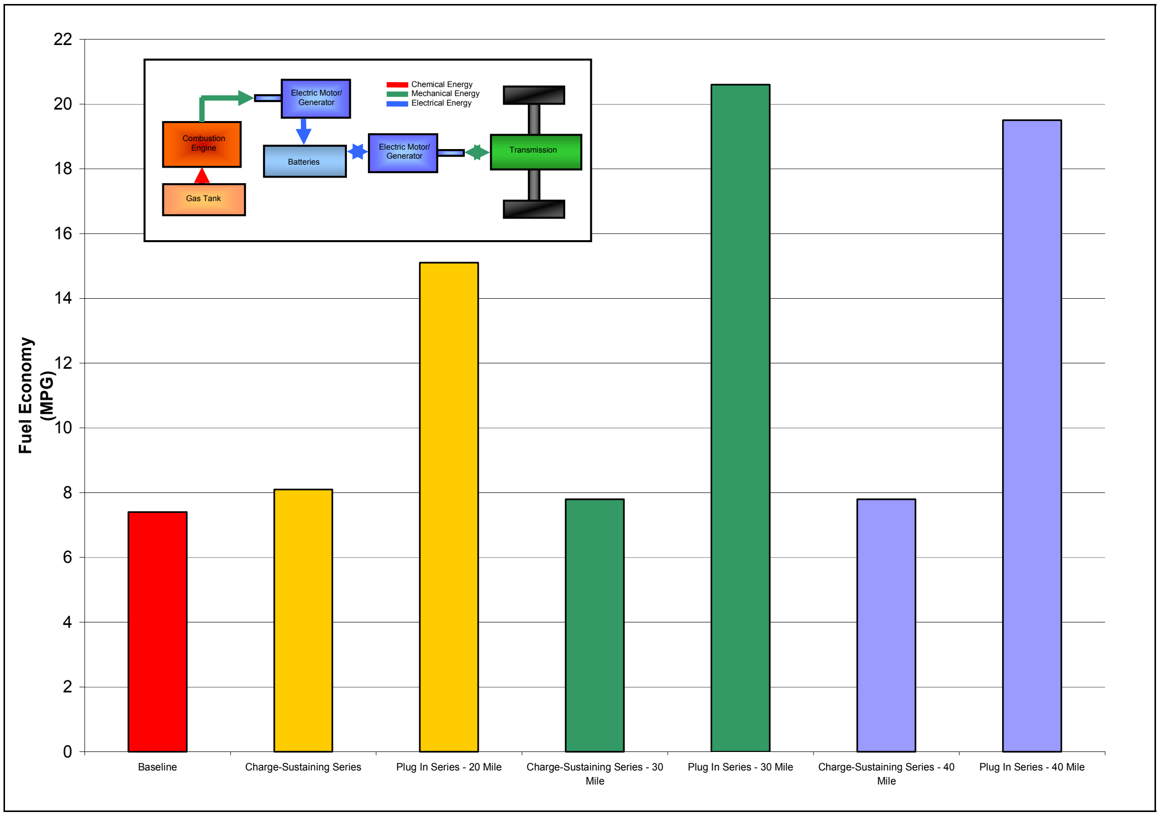


Figure 5.2. Fuel Economy for Series Hybrids

A more appropriate means of looking at fuel economy is cost per mile. Figure 5.3 shows an estimated cost per mile for the series hybrids. In the figure, the cost of the added electricity has been included assuming a typical commercial/governmental electricity rate for North Carolina of 6.5 ¢/kWh.

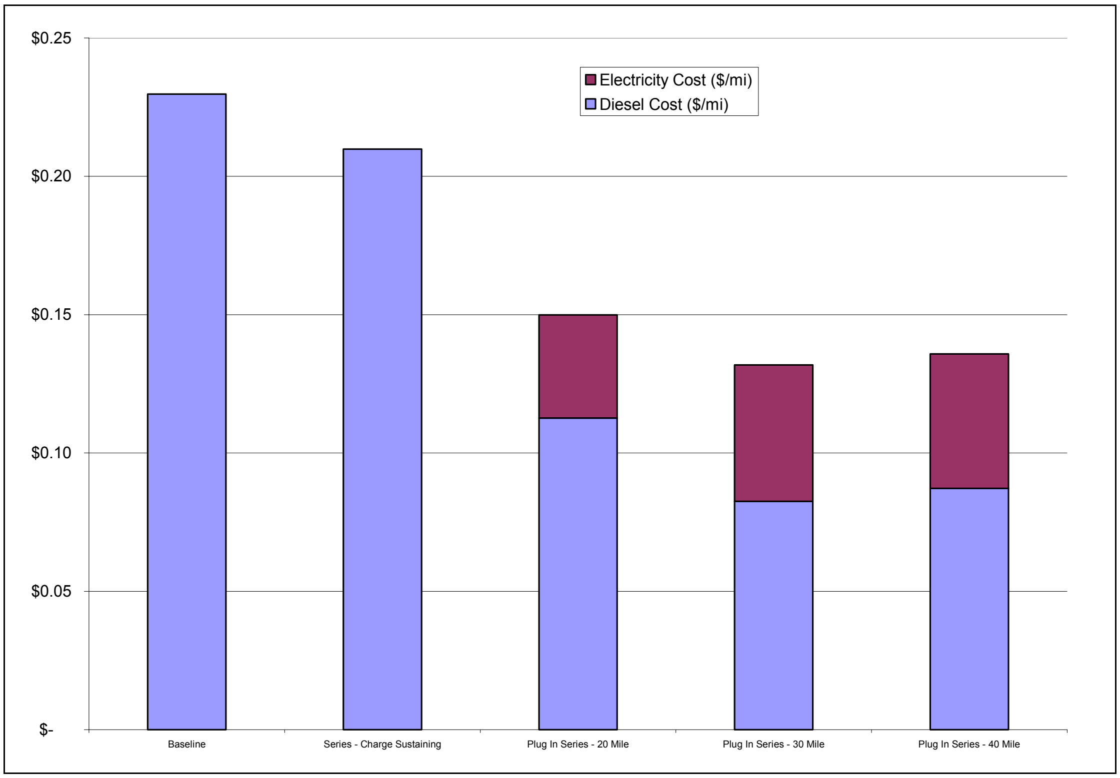


Figure 5.3. Fuel Costs of Selected Series Hybrids

The assumed rate for diesel fuel was $1.70 per gallon, which is the current commercial price for diesel fuel. Based on cost alone, the 30 mile plug-in hybrid would be selected, offering 13¢ per mile versus 23¢ per mile for the baseline. It should be noted that due to the control strategy, the 40 mile plug in hybrid used 33.4 kWh of power, where the 30-mile used slightly more. Changes in the control strategy can likely improve the performance of the 40-mile plug in hybrid. For more information of the power consumed in each model see Table B.1. Battery Pack Usage in the appendix.

5.1.5 Series Hybrid Emissions

NO_x emissions were highly reduced in the series plug-in models, yet the 40 mile plug-in model began to increase emissions. The local power plant emissions are presented in Figure 5.4 as darker colored bars above the three plug-in models. The power plant emissions are shown to be significantly lower that the vehicle emissions per mile yielding over 57% reductions in the 30 mile plug-in hybrid over the conventional vehicle.

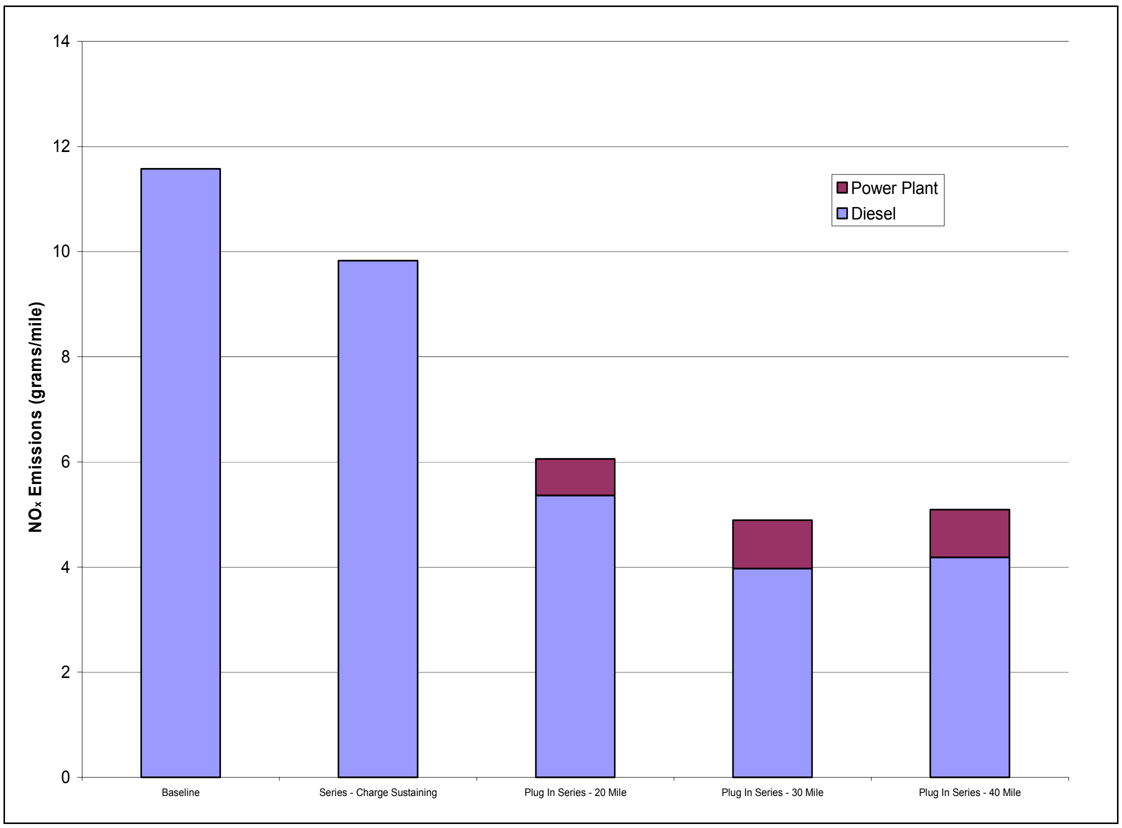


Figure 5.4. NO_x Emissions of Selected Series Models

Because power plant particulate matter emissions are not reported to the EIA, we cannot provide information on the effects of the power plant emitted PM on overall emissions. These emissions are assumed to be much lower than vehicle emissions and are not considered relevant in reporting. Figure 5.5 shows the reductions available through the use of a 30 mile plug-in series hybrid are nearly 85%.

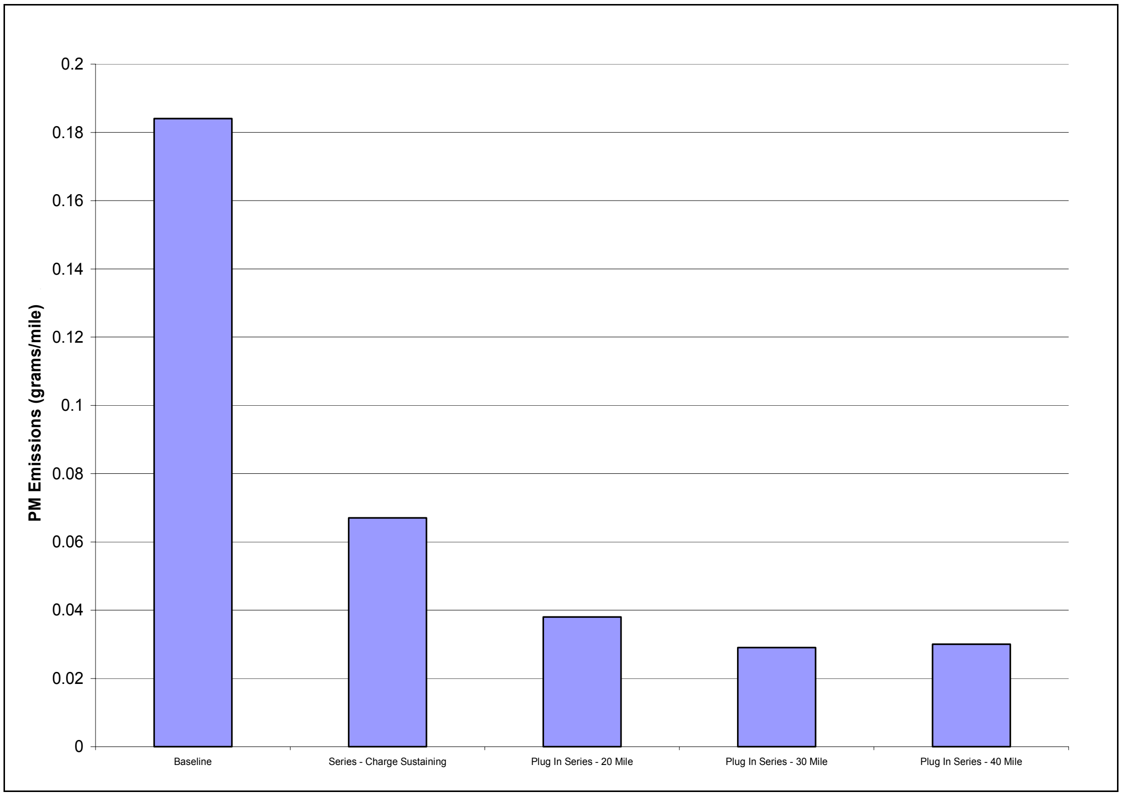


Figure 5.5. Particulate Matter Emissions of Selected Series Hybrids

Carbon dioxide emissions are based on the use of a factor of 9479 grams of CO_2 per gallon of fuel consumed. (Balon 2000). CO_2 emissions reductions are presented in Figure 5.6 where the magnitude of each shows that power plant emissions are slightly lower than vehicle emissions but the greatest efficiency benefit comes from increased efficiency. The 30 mile series plug-in offers a 30% reduction in CO_2 emissions.

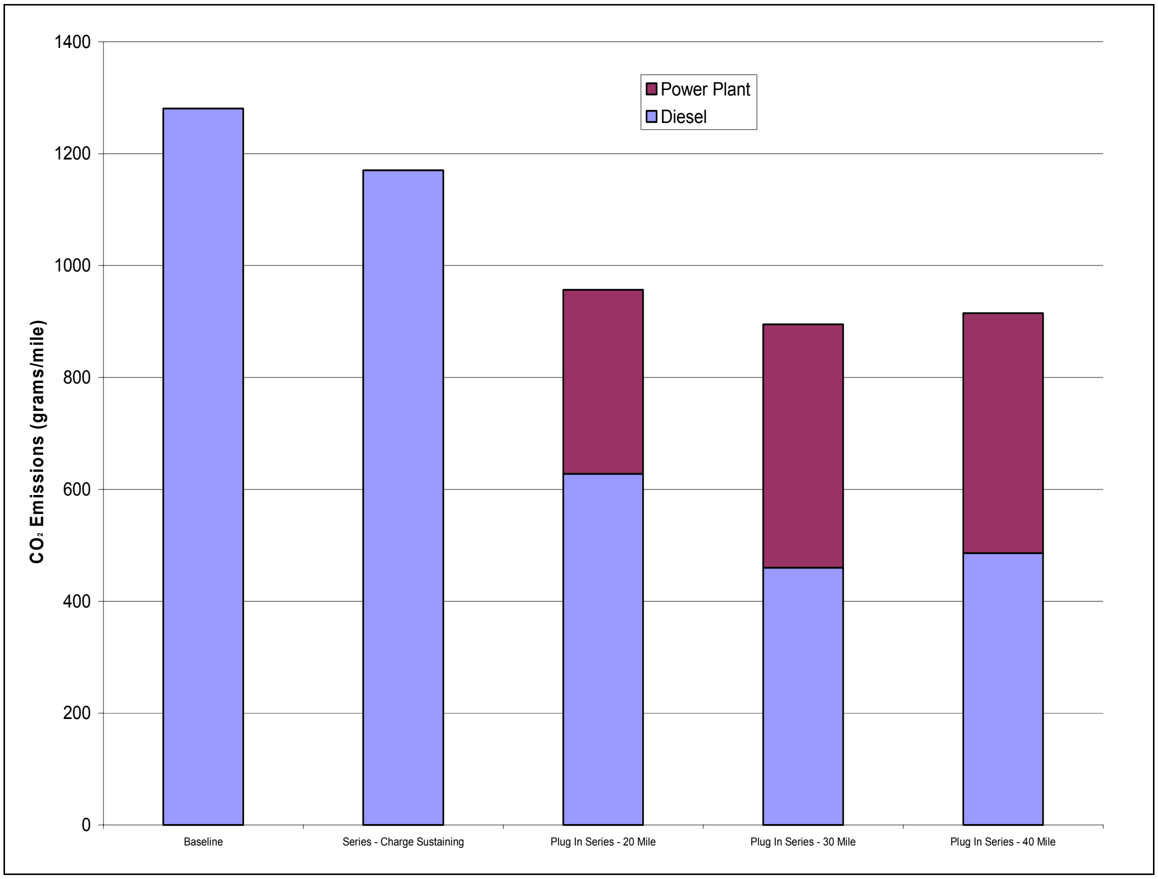


Figure 5.6. Carbon Dioxide Emissions from Selected Series Hybrids

5.1.6 Parallel Hybrid Fuel Economy

As with the series models the direct fuel economy can be misleading because a portion of the fuel economy is based on electricity from the plug. The results for fuel economy for the parallel hybrids reached over 13 miles per gallon for the 40 mile plug-in parallel model, this is in contrast to the 20 miles per gallon seen in the series model. It is assumed that significant improvements can be made to the fuel economy by adding a particulate trap and a catalyst and tuning a smaller engine for fuel economy.

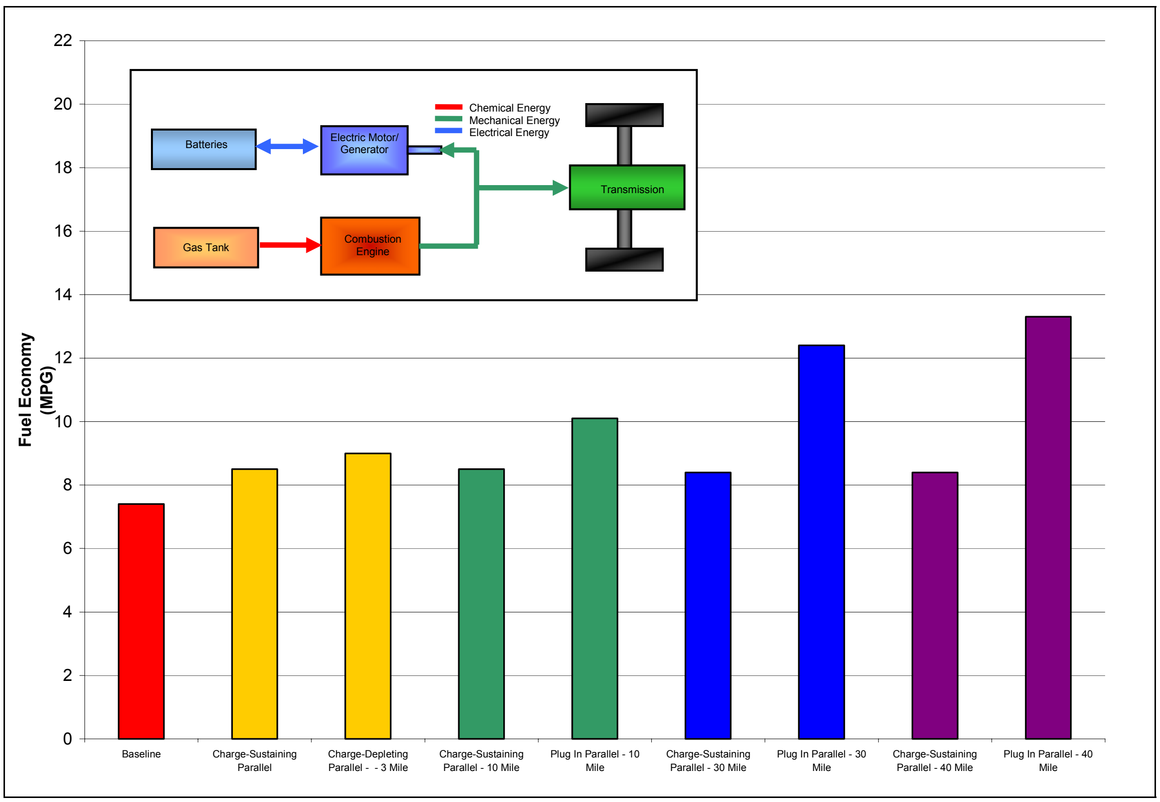


Figure 5.8. Fuel Economy of Parallel Hybrid Models

Figure 5.9 shows the cost per mile for the series hybrids. In the figure, the cost of the added electricity has been included assuming a typical commercial/governmental electricity rate for North Carolina of 6.5 ¢/kWh. The assumed rate for diesel fuel was $1.70 per gallon, which is the current commercial price for diesel fuel. Based on cost alone, the 30 mile plug-in hybrid would be selected, offering 17.5¢ per mile versus 23¢ per mile for the baseline.

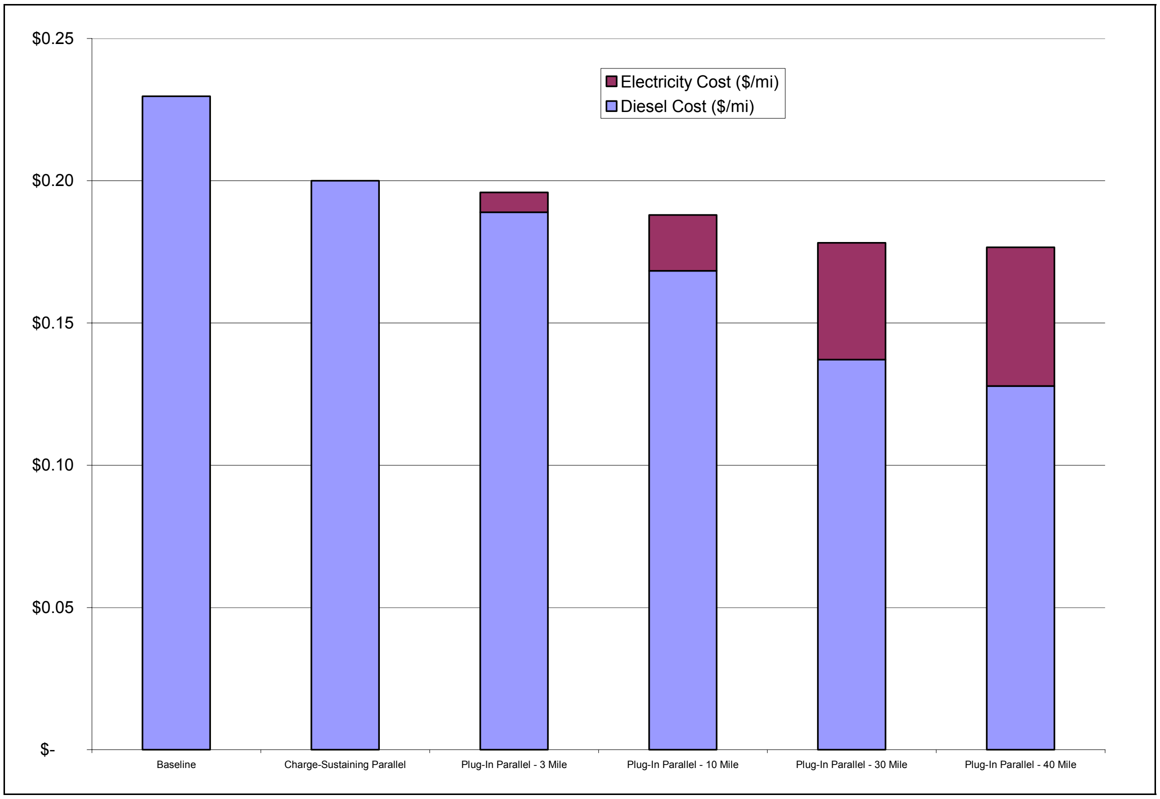


Figure 5.9. Fuel Costs of Parallel Hybrid Models

5.1.7 Parallel Hybrid Emissions

Emissions data show significant reductions in the emission of NO_x can be achieved through the use of plug-in hybrids. Figure 5.10 shows the potential reduction from the baseline to a 40 mile parallel hybrid of 52%. The resulting declines are likely the result of operating the engine at lower speeds allowing the engine to operate at cooler temperatures.

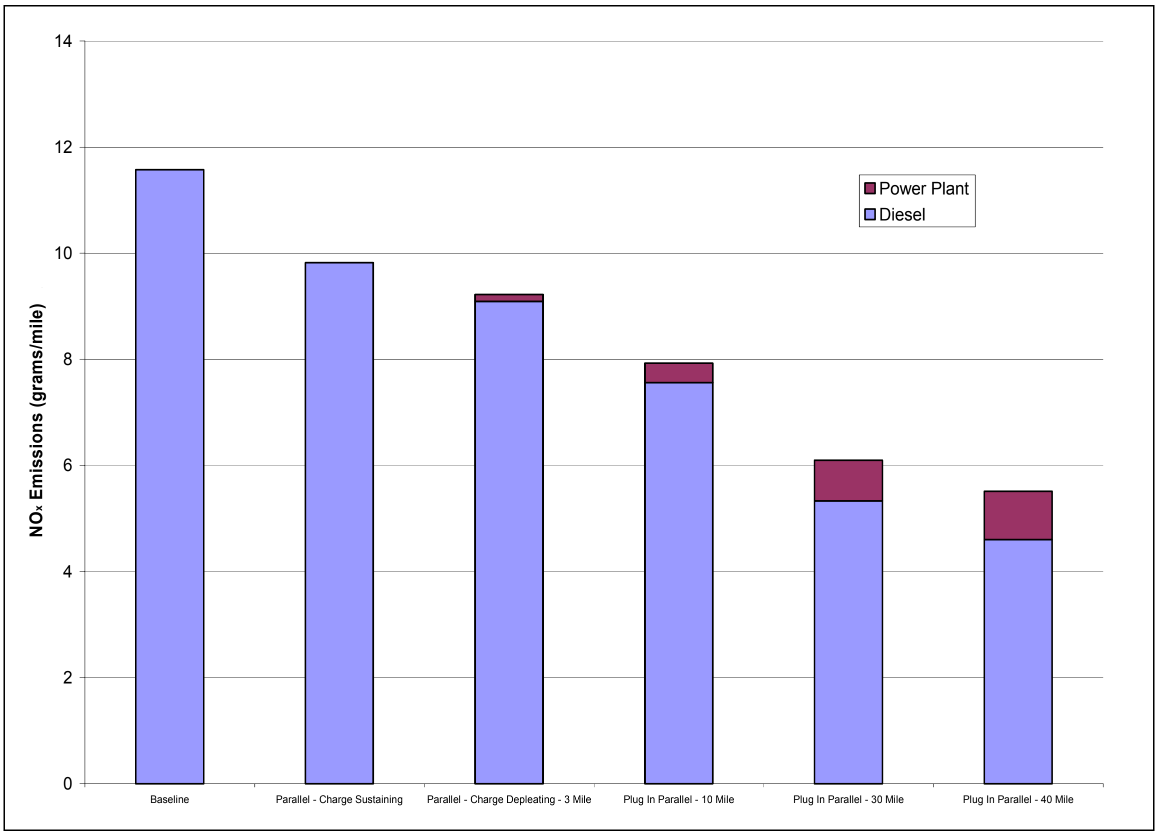


Figure 5.10. NO_x Emissions from Selected Parallel Hybrids

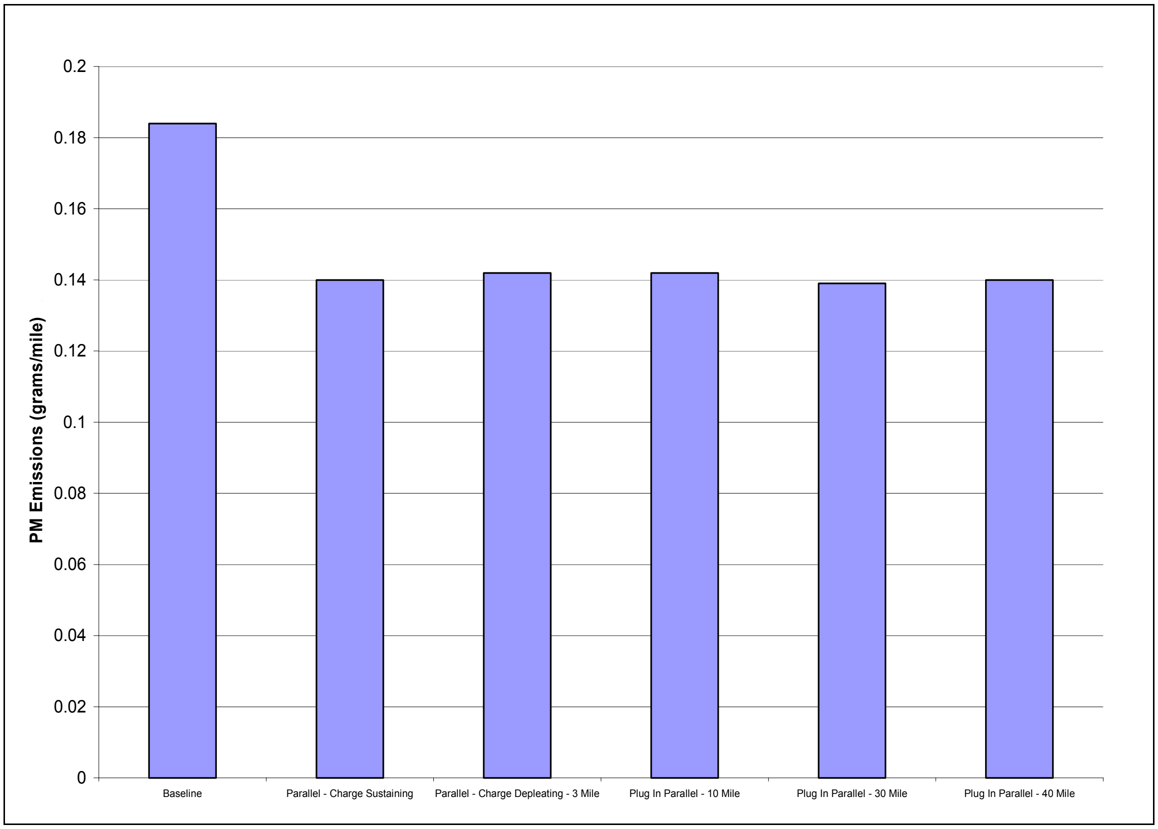


Figure 5.11. Particulate Matter Emissions from Selected Parallel Hybrids

Particulate matter reductions for the parallel hybrids are shown in Figure 5.11. The sharp contrast between the parallel hybrid reductions and the series reductions are primarily base on engine on time. In the case of the parallel models the engine spends a majority of the time on but not being highly utilized. This condition results in high particulate matter emissions. The use of a planetary gearing system can help facilitate the all electric mode The GM/Allison system uses the planetary drivetrain to help increase the use of all electric modes. Operating in all electric mode when able can significantly reduce the emissions of particulate matter.

Similar to the series models, the plug-in models provide little benefit to the emission of CO_2. The resulting CO_2 emissions can be seen in Figure 5.12, where emissions are simply traded between the bus engine and the power plant. A likely solution to this problem is similar to the solution for particulate matter. By keeping the combustion engine off a greater amount of time, the emission of CO_2 can be significantly reduced.

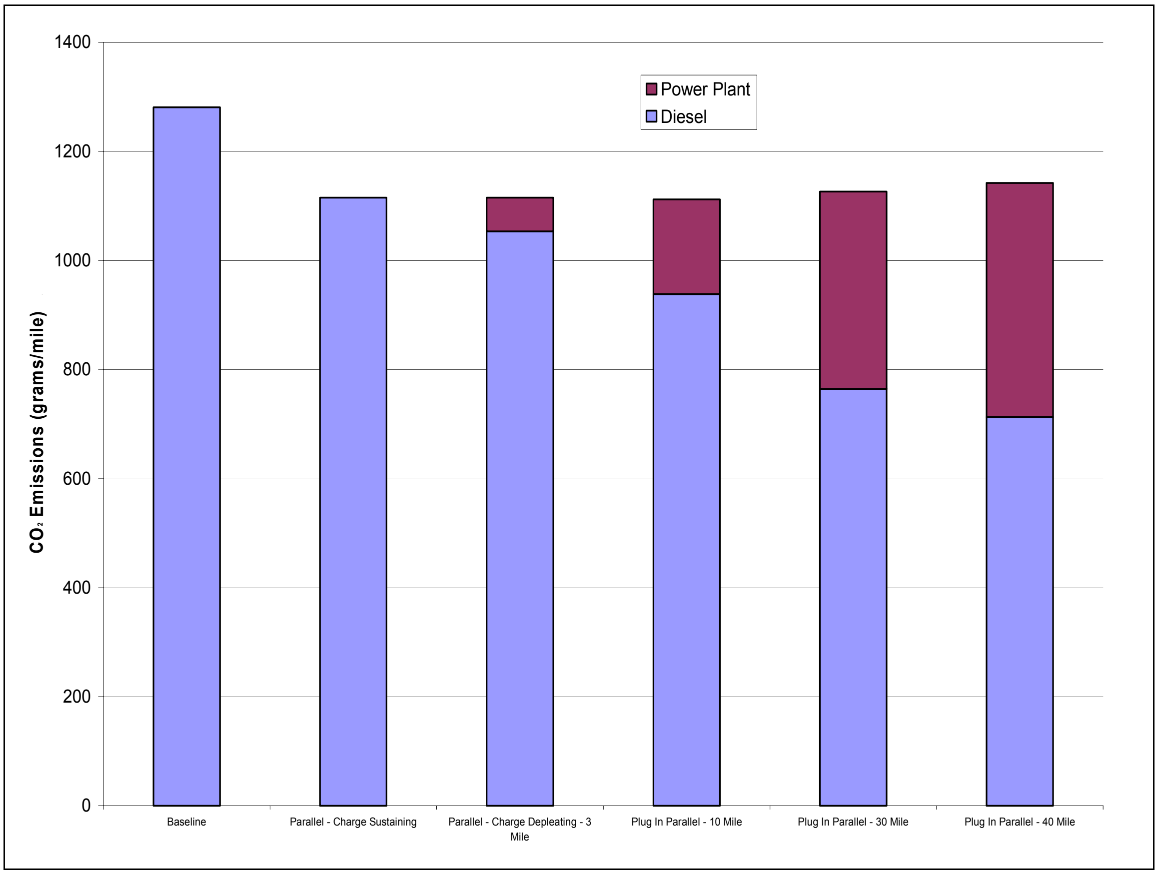


Figure 5.12. Carbon Dioxide Emissions from Selected Parallel Hybrids

6. CONCLUSIONS

The primary goal of this study was to investigate the potential benefits of adding the plug-in capacity to a hybrid electric system and develop a modeling technique to be used to predict the performance of various plug-in hybrid electric school buses. In both parallel and series cases, significant benefits could be seen by adding a plug-in option to a base hybrid without any other system changes. Further benefits can be achieved by increasing the size of the battery pack to accommodate more range. Based on the models tested, the 30 mile series hybrid showed the most benefit with an operating cost of 13¢ per mile versus 23¢ per mile for the baseline and 21¢ per mile for the series hybrid. Each model proved that it can operate as either a plug-in or as a charge-sustaining hybrid with little loss to the charge-sustaining fuel economy. Several anomalies were found as a result of holding variables constant. Most significantly, the use of constant high and low SOC limits likely resulted in the 40 mile series plug-in hybrid utilizing less plug-in load than the 30 mile version. The use of constant component sizes like the electric drive motor, the generator, and the combustion engine resulted in the different plug-in hybrids far exceeding the designed performance characteristics. The systems that exceed the performance will produce higher emissions and lower fuel economy than a correctly designed system.

This study is one piece of a large effort to investigate the use of hybrid electric drivelines in school buses. The results of this study will be used to determine the best path forward and will become the basis for a feasibility study. The results of this work indicate that ADVISOR can be effectively used to predict vehicle emissions from school buses. Data from real world testing helps support the baseline modeling, yet the use of more accurate engine data with complete emissions data will be necessary before the full impact of the hybrid system can be measured. The use of the West Virginia suburban cycle provides reasonable school bus operation data; however, establishing a standard dataset from actual school bus operation would be preferable.

The results of baseline modeling are within reason for a conventional school bus, and validate the basic information used for the hybrid models. The base hybrid electric models show potential improvements over the baseline model, yet future work to investigate the effects of a particulate trap and a catalytic system on the overall emissions is needed. The addition of the exhaust systems will allow for tuning of the combustion engines for performance.

Extra efforts were taken to supply enough information in this study to repeat the work, and build on this study. For the Hybrid Electric School Bus project, this study will be used as the basis for a plug-in hybrid electric bus feasibility study. The feasibility study will lead to the manufacture of prototype buses, and then on to full production capacity for fleet testing.

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APPENDIX A. GLOSSARY

Charge-depleting (CD): A hybrid vehicle mode where the vehicle uses more power than is being generated on board.

Charge-sustaining (CS): A hybrid mode where the vehicle can generate all of its power onboard through the combustion engine.

Parallel hybrid: A hybrid electric drivetrain where only a portion of the final drive power comes from an electric motor, while the other portion comes directly from the combustion engine.

Series hybrid: A hybrid electric drivetrain where all of the final drive power comes from an electric motor, while the combustion engine regenerates the battery pack.

State of charge (SOC): The percentage of power available in a battery pack compared with the maximum power available if the pack were fully charged.

APPENDIX B. MODEL RESULTS

Table B.1. Battery Pack Usage

Energy use (kWh)			
Model	**SOC Initial**	**SOC Final**	**Elec Use**
Baseline	NA	NA	NA
Series - charge-sustaining	32.45%	32.17%	0.00
Plug-in Series - 20 Mile	100.00%	28.21%	25.63
Charge-sustaining Series - 30 Mile	36.04%	36.02%	0.00
Plug-in Series - 30 Mile	100.00%	30.82%	33.87
Charge-sustaining Series - 40 Mile	26.80%	26.17%	0.00
Plug-in Series - 40 Mile	100.00%	45.43%	33.40
Parallel - Charge-sustaining	30.96%	30.96%	0.00
Plug-in parallel - 3 Mile	100.00%	30.96%	4.83
Charge-sustaining Parallel - 10 Mile	30.96%	30.96%	0.00
Plug-in parallel - 10 Mile	100.00%	31.15%	13.50
Charge-sustaining parallel - 30 Mile	30.00%	30.49%	0.00
Plug-in parallel - 30 Mile	100.00%	36.79%	28.21
Charge-sustaining parallel - 40 Mile	30.00%	30.21%	0.00
Plug-in parallel - 40 Mile	100.00%	41.30%	33.49

Table B.2. Acceleration Results

Performance (seconds)										
Model	**0-10**	**Imp**	**0-20**	**Imp**	**0-30**	**Imp**	**0-40**	**Imp**	**0-50**	**Imp**
Baseline	3.2		7.2		12.5		20.5		31.7	
CS Series	2.3	28.1%	4.7	34.7%	8.2	34.4%	13.6	33.7%	22.0	30.6%
Series - 20 Mile	2.3	28.1%	4.7	34.7%	8.2	34.4%	13.6	33.7%	22.0	30.6%
CS Series - 30 Mile	2.4	25.0%	4.8	33.3%	8.3	33.6%	13.5	34.1%	21.0	33.8%
CD Series - 30 Mile	2.4	25.0%	4.8	33.3%	8.3	33.6%	13.5	34.1%	21.0	33.8%
CS Series - 40 Mile	2.5	21.9%	5	30.6%	8.5	32.0%	13.9	32.2%	21.7	31.5%
CD Series - 40 Mile	2.5	21.9%	5	30.6%	8.5	32.0%	13.9	32.2%	21.7	31.5%
CS Parallel	1.4	56.3%	4.2	41.7%	8.1	35.2%	13.8	32.7%	21.4	32.5%
CD Parallel - 3 Mile	1.4	56.3%	4.2	41.7%	8.1	35.2%	13.8	32.7%	21.4	32.5%
CS Parallel - 10 Mile	0.9	71.9%	2.6	63.9%	5.1	59.2%	8.8	57.1%	13.5	57.4%
CD Parallel - 10 Mile	0.9	71.9%	2.6	63.9%	5.1	59.2%	8.8	57.1%	13.5	57.4%
CS Parallel - 30 Mile	0.9	71.9%	2.7	62.5%	5.4	56.8%	9.3	54.6%	14.4	54.6%
CD Parallel - 30 Mile	0.9	71.9%	2.7	62.5%	5.4	56.8%	9.3	54.6%	14.4	54.6%
CS Parallel - 40 Mile	0.9	71.9%	2.7	62.5%	5.5	56.0%	9.6	53.2%	14.8	53.3%
CD Parallel - 40 Mile	0.9	71.9%	2.7	62.5%	5.5	56.0%	9.6	53.2%	14.8	53.3%

Table B.3. Additional Performance Results

Performance (continued)							
Model	25 mph Grad. (%)	55 mph Grad (%)	Max Acc. (ft/s^2)	5 Sec (ft)	1/4 Mi (Sec)	Max Spd. (mph)
Baseline	10.9	1.9	5.2	58.8	29.6	71.1
CS Series	11.4	3.2	6.6	80.1	25.7	65.6
Series - 20 Mile	11.4	3.2	6.6	80.1	25.7	65.6
CS Series - 30 Mile	11	3	6.4	77.6	25.5	65.6
CD Series - 30 Mile	11	3	6.4	77.6	25.5	65.6
CS Series - 40 Mile	10.6	2.9	6.2	75.3	25.8	65.6
CD Series - 40 Mile	10.6	2.9	6.2	75.3	25.8	65.6
CS Parallel	14.6	3.7	17.9	102.2	25.2	72.9
CD Parallel - 3 Mile	14.6	3.7	17.9	102.2	25.2	72.9
CS Parallel - 10 Mile	22	7.1	17.9	137.4	21.6	72.7
CD Parallel - 10 Mile	22	7.1	17.9	137.4	21.6	72.7
CS Parallel - 30 Mile	20.9	6.7	17.9	134.1	22.1	72.8
CD Parallel - 30 Mile	20.9	6.7	17.9	134.1	22.1	72.8
CS Parallel - 40 Mile	20.3	6.5	17.9	132.6	22.3	72.8
CD Parallel - 40 Mile	20.3	6.5	17.9	132.6	22.3	72.8

Table B.4. Fuel Economy and Emission Results

Fuel economy and emissions								
Model	Fuel Econ. (MPG)	PM (g/mi)	NO_x Diesel	NO_x Power Plant (g/mi)	Total NO_x (g/mi)	CO_2 Diesel (g/mi)	CO_2 Power Plant (g/mi)	Total CO_2 (g/mi)
Baseline	7.4	0.184	11.578	NA	11.578	1280.95	NA	1280.95
CS Series	8.1	0.067	9.826	NA	9.826	1170.25	NA	1170.25
Series - 20 Mile	15.1	0.038	5.362	0.695	6.057	627.75	328.97	956.72
CS Series - 30 Mile	7.8	0.070	10.202	NA	10.202	1215.26	NA	1215.26
CD Series - 30 Mile	20.6	0.029	3.972	0.918	4.890	460.15	434.76	894.91
CS Series - 40 Mile	7.8	0.070	10.214	NA	10.214	1215.26	NA	1215.26
CD Series - 40 Mile	19.5	0.030	4.184	0.905	5.089	486.10	428.70	914.80
CS Parallel	8.5	0.140	9.821	NA	9.821	1115.18	NA	1115.18
CD Parallel - 3 Mile	9	0.142	9.092	0.131	9.223	1053.22	62.04	1115.26
CS Parallel - 10 Mile	8.5	0.141	9.801	NA	9.801	1115.18	NA	1115.18
CD Parallel - 10 Mile	10.1	0.142	7.563	0.366	7.929	938.51	173.23	1111.74
CS Parallel - 30 Mile	8.4	0.140	10.144	NA	10.144	1128.45	NA	1128.45
CD Parallel - 30 Mile	12.4	0.139	5.335	0.765	6.100	764.44	362.07	1126.50
CS Parallel - 40 Mile	8.4	0.141	10.306	NA	10.306	1128.46	NA	1128.45
CD Parallel - 40 Mile	13.3	0.140	4.604	0.908	5.512	712.71	429.80	1142.55

Table B.5. Fuel Cost Chart

Fuel cost data				
Model	**Diesel Cost ($/mi)**	**Electricity Cost ($/mi)**	**Total Cost ($/Mile)**	**% Improvement**
Baseline	$ 0.23	$ -	$ 0.23	
CS Series	$ 0.21	$ -	$ 0.21	8.6%
Series - 20 Mile	$ 0.11	$ 0.04	$ 0.15	34.7%
CS Series - 30 Mile	$ 0.22	$ -	$ 0.22	5.1%
CD Series - 30 Mile	$ 0.08	$ 0.05	$ 0.13	42.6%
CS Series - 40 Mile	$ 0.22	$ -	$ 0.22	5.1%
CD Series - 40 Mile	$ 0.09	$ 0.05	$ 0.14	40.9%
CS Parallel	$ 0.20	$ -	$ 0.20	12.9%
CD Parallel - 3 Mile	$ 0.19	$ 0.01	$ 0.20	14.7%
CS Parallel - 10 Mile	$ 0.20	$ -	$ 0.20	12.9%
CD Parallel - 10 Mile	$ 0.17	$ 0.02	$ 0.19	18.2%
CS Parallel - 30 Mile	$ 0.20	$ -	$ 0.20	11.9%
CD Parallel - 30 Mile	$ 0.14	$ 0.04	$ 0.18	22.4%
CS Parallel - 40 Mile	$ 0.20	$ -	$ 0.20	11.9%
CD Parallel - 40 Mile	$ 0.13	$ 0.05	$ 0.18	23.1%

APPENDIX C. MODEL DATA FILES

School Bus Chassis Data File

Navistar T444-230 HP Engine Data File

Allison 2000 Transmission Data File

Michelin ZXE-11R22.5 Tire Data

Exhaust System with No Catalyst Data File

Conventional Control File

Series Control File

Parallel Control File

Accessories File

Series Definition File

Parallel Definition File

75 kW AC Induction Motor/Controller File

95 kW DC Generator/Controller File

Nickel Metal Hybride Battery File

Lead Acid Battery File

```
% ADVISOR Data file: ClassCSchoolBus.M
%
%
% Data source: Ewan Pritchard, P.E. Advanced Energy
%
% Data confidence level: {provide details as to how well the data
% represents the source data.}
%
% Notes: {include any other comments pertaining to the data or use
% the data}
%
% Created on: 7/14/2003
% By: Ewan Pritchard, P.E. Advanced Energy Corporation,
%       North Carolina State University, epritcha@advancedenergy.org
%
% Revision history at end of file.
%
% References:
% Gattis, J.L. and Howard, Micheal D. "Large School Bus Design Vehicle
Dimensions", Sept. 1998, Mack Blackwell National Rural Transportation
Study Center.
% North Carolina Department of Public Instruction, "North Carolina
School Bus & Activity Bus Specifications", Jan. 2002, Raleigh, North
Carolina.
% Florida Department of Education, "Florida School Bus Specifications",
Feb. 2003, Tallahassee, FL.
% South Carolina Department of Education, "South Carolina 2001 Minimum
Specifications for Type A, C & D School Buses", May 2001, Columbia, SC.
% North Carolina Department of Public Instruction,
"BusWeightChart.xls", Nov. 2001, Raleigh, North Carolina.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
veh_description='Class C, 65 Passenger School Bus - configured for
emission tests', % one line descriptor identifying the vehicle
veh_version=2002, % version of ADVISOR for which the file was generated
veh_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
veh_validation=0, % 0=> no validation, 1=> data agrees with source
data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: ClassCSchoolBus.m - ',veh_description]),

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PHYSICAL CONSTANTS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
veh_gravity=9.81,  % m/s^2
veh_air_density=1.23, % kg/m^3

% Vehicle data
veh_CD=0.55, % for a school bus (Fl. II-5)
%veh_CD=0.605, % for a school bus (+10% for sensitivity analysis)
%veh_CD=0.495, % for a school bus (-10% for sensitivity analysis)
veh_FA=7.432,     % (m^2) 120" height(Fl II-5), 96" Width (Gattis 3)
veh_cg_height=1.1176, % (m) 44" (Thomas Built Representative)
```

```
veh_front_wt_frac=0.65, % (SC 89 - This is actually the rear fraction
for drive purposes)
veh_wheelbase=6.4516, % (m) 254" (Fl II-10)
%veh_glider_mass = 7079.66, % (kg) 17,000 lb - 330 lb transmission &
1062 lb engine = 15,608 lb (Fl, Allison, Navistar)
veh_glider_mass = 7760.06, % (kg) 18,500 lb - 330 lb transmission &
1062 lb engine = 17,108 lb (Thomas Built)
%veh_glider_mass = 6921, % (kg) 16,650 lb - 330 lb transmission & 1062
lb engine = 15,258 lb (-10% for sensitivity analysis)
%veh_glider_mass = 8599, % (kg) 20,350 lb - 330 lb transmission & 1062
lb engine = 18,958 lb (+10% for sensitivity analysis)
veh_cargo_mass=792.88, % (kg) Loaded - 1748 lb. (North Carolina Weight
Chart - 44 HS Students), Assuming 25% Loaded with driver.
%veh_cargo_mass=158.76, % (kg) Unloaded with driver and 1 passenger 350
lb (Fl II-5) - Used in performance runs.



%revision history
% 7/14/2003 (ep) file created
% 1/19/2004 (ep) Corrected most values to match specifications and
documented.
% 2/08/2004 (ep) Changed glider mass to match Thomas Built specs.
```

```
% ADVISOR Data file: FC_CI163_emis_d2_poly.m
%
% Data source: Engine datafile for the Navistar T444/ Powerstroke 7.3L
engines tested on No. 2 Diesel Fuel
% Data from John Orban of Batelle through contract to do data
collection and analysis.
% These data were collected under the DECSE program and the engines
were tested on the OICA test matrix.
%
% Useful links,
%
% DECSE program site
% http://www.ott.doe.gov//decse/
%
% APBF program site (formerly DECSE)
% http://www.ott.doe.gov/advanced_petroleum.shtml
%
% OICA test details
% http://www.dieselnet.com/standards/cycles/esc.html
%
% Data confidence level:
%
% Notes:
% File created by engmodel using mat file: p_stroke_d2.mat,
% Points outside of data points extrapolated based on the following
algorithm: polynomial,
% Map: fc_fuel_map,
% Average error (%): 2.5262,
% Maximum error (g/s): 0.11076,
% max error at speed (rpm): 1600,
% max error at torque (Nm): 202.4,
% Map: fc_nox_map,
% Average error (%): 3.6687,
% Maximum error (g/s): -0.0057435,
% max error at speed (rpm): 1350,
% max error at torque (Nm): 348.5,
% Map: fc_pm_map,
% Average error (%): 7.185,
% Maximum error (g/s): 0.00013088,
% max error at speed (rpm): 1350,
% max error at torque (Nm): 348.5
%
% Created on: 01-Aug-2000 09:16:19
% By: Tony Markel, NREL, tony_markel@nrel.gov
%
% Revision history at end of file.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_description='Powerstroke 7.3L Diesel Engine tested at Ricardo
(Diesel Fuel)',
fc_version=2002,                    % version of ADVISOR for which the
file was generated
fc_proprietary=1,       % 0=> non-proprietary, 1=> proprietary, do not
distribute
```

```
fc_validation=0,        % 1=> no validation, 1=> data agrees with
source data,
                                            % 2=> data matches source
data and data collection methods have been verified
fc_fuel_type='Diesel',
fc_disp=7.3,                  % (L), engine displacement
fc_emis=1,                          % boolean 0=no emis data, 1=emis
data
fc_cold=0,   % boolean 0=no cold data, 1=cold data exists
disp(['Data loaded: FC_CI163_emis_d2_poly.m - ',fc_description]),

% Use EGR? 1==> yes, 0==> no
fc_egr_bool=1,

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (rad/s), speed range of the engine
fc_map_spd=[73.3 99.48 125.7 151.8 178 204.2 230.4 256.6 282.7],

% (N*m), torque range of the engine
fc_map_trq=[15 55 95 135 175 215 255 295 335 375 415 455 495 535 575
615 655],


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUEL USE AND EMISSIONS MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (g/s), fuel use map indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_fuel_map=[0.2909 0.4727 0.6704 0.8814 1.104 1.336 1.578 1.828 2.087,
0.3674 0.6447 0.799 0.9946 1.266 1.566 1.893 2.248 2.628,
0.5643 0.872 1.026 1.329 1.766 2.203 2.64 2.787 3.29,
0.8118 1.118 1.254 1.604 2.031 2.468 2.905 3.342 4.003,
1.085 1.243 1.525 1.889 2.296 2.736 3.389 4.042 4.742,
1.372 1.523 1.814 2.178 2.785 3.438 4.091 4.744 5.494,
1.664 1.809 2.113 2.476 3.251 4.14 4.793 5.446 6.251,
1.955 2.094 2.377 2.793 3.697 4.602 5.495 6.148 7.007,
2.242 2.375 2.671 3.239 4.143 5.048 5.952 6.85 7.76,
2.522 2.649 2.956 3.759 4.657 5.555 6.453 7.351 8.504,
2.792 2.912 3.232 3.749 5.219 6.117 7.015 7.913 9.24,
3.05 3.164 3.497 4.044 4.805 6.68 7.578 8.476 9.963,
3.295 3.403 3.748 4.326 5.136 7.242 8.14 9.038 10.67,
3.526 3.628 3.984 4.593 5.452 6.56 8.702 9.6 11.37,
3.741 3.836 4.205 4.844 5.752 6.928 9.264 10.16 12.05,
3.939 4.028 4.409 5.079 6.036 7.279 8.806 10.72 12.71,
4.119 4.203 4.596 5.297 6.303 7.612 9.225 11.14 13.36]',


% (g/s), engine out HC emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_hc_map=zeros(size(fc_fuel_map)),

% (g/s), engine out CO emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_co_map=zeros(size(fc_fuel_map)),
```

```
% (g/s), engine out NOx emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_nox_map =[0.006818 0.004369 0.002369 0.00155 0.002388 0.005214
0.01028 0.01777 0.02784,
0.005126 0.0127 0.0141 0.01574 0.01879 0.02228 0.02647 0.03154 0.03766,
0.0007549 0.0176 0.01899 0.02827 0.03094 0.03361 0.03629 0.04264
0.0448,
2.22e-016 0.02417 0.02389 0.03917 0.04367 0.04635 0.04902 0.05169
0.05128,
2.22e-016 0.01564 0.03192 0.04816 0.05641 0.05906 0.06028 0.0615
0.05781,
2.22e-016 0.01793 0.04197 0.05821 0.06763 0.06886 0.07008 0.0713
0.06478,
2.22e-016 0.02089 0.05434 0.07058 0.07631 0.07865 0.07987 0.08109
0.07241,
2.22e-016 0.02466 0.05972 0.08247 0.08489 0.0873 0.08966 0.09089
0.08087,
2.22e-016 0.02938 0.06973 0.09105 0.09347 0.09588 0.0983 0.1007
0.09027,
2.22e-016 0.03513 0.08077 0.107 0.1087 0.1105 0.1123 0.1141 0.1007,
2.22e-016 0.04197 0.0929 0.1296 0.1288 0.1306 0.1324 0.1341 0.1122,
2.22e-016 0.04996 0.1062 0.1466 0.1718 0.1506 0.1524 0.1542 0.1249,
2.22e-016 0.05915 0.1207 0.1649 0.1922 0.1707 0.1724 0.1742 0.1387,
2.22e-016 0.06957 0.1364 0.1843 0.2139 0.2254 0.1925 0.1943 0.1538,
2.22e-016 0.08126 0.1534 0.2051 0.2368 0.249 0.2125 0.2143 0.1702,
2.22e-016 0.09425 0.1716 0.2271 0.2611 0.2739 0.2659 0.2343 0.1879,
0.001638 0.1086 0.1912 0.2505 0.2866 0.3002 0.2913 0.2601 0.2069]',

% (g/s), engine out PM emissions indexed vertically by fc_map_spd and
% horizontally by fc_map_trq
fc_pm_map=[0.0001543 0.000259 0.0003907 0.0005294 0.0006623 0.00078
0.000876 0.0009449 0.0009827,
0.0007622 0.0005509 0.0007765 0.000945 0.001058 0.001178 0.001299
0.001415 0.001521,
0.001067 0.0006367 0.0008622 0.0009394 0.001122 0.001304 0.001487
0.001582 0.001757,
0.001246 0.0006823 0.000948 0.0009169 0.001068 0.00125 0.001433
0.001615 0.001866,
0.001359 0.001119 0.0009758 0.0009269 0.001014 0.001197 0.001402
0.001606 0.001911,
0.001441 0.001114 0.0009465 0.0008976 0.0009836 0.001188 0.001393
0.001598 0.001923,
0.001511 0.001098 0.0008317 0.0007828 0.0009482 0.00118 0.001384
0.001589 0.001924,
0.001583 0.001084 0.0007666 0.0006775 0.0009106 0.001144 0.001375
0.00158 0.001927,
0.001667 0.001082 0.0007006 0.0006398 0.0008729 0.001106 0.001339
0.001571 0.001942,
0.001772 0.0011 0.0006544 0.0006738 0.0009007 0.001128 0.001354
0.001581 0.001977,
0.001901 0.001143 0.0006339 0.0003535 0.0009748 0.001202 0.001429
0.001655 0.002038,
0.002062 0.001218 0.0006441 0.0003217 0.0002374 0.001276 0.001503
0.00173 0.002129,
0.002257 0.001326 0.0006889 0.0003246 0.0002205 0.00135 0.001577
0.001804 0.002255,
```

```
0.00249 0.001473 0.0007716 0.0003654 0.0002415 0.000391 0.001651
0.001878 0.002419,
0.002764 0.001661 0.0008951 0.0004469 0.0003033 0.0004552 0.001725
0.001952 0.002623,
0.003081 0.001892 0.001062 0.0005716 0.0004083 0.0005626 0.001028
0.002026 0.002871,
0.003443 0.002168 0.001274 0.0007416 0.0005585 0.0007153 0.001205
0.002023 0.003164]',


% create BS** maps for plotting purposes
[T,w]=meshgrid(fc_map_trq,fc_map_spd),
fc_map_kW=T.*w/1000,
fc_fuel_map_gpkWh=fc_fuel_map./fc_map_kW*3600,
fc_co_map_gpkWh=fc_co_map./fc_map_kW*3600,
fc_hc_map_gpkWh=fc_hc_map./fc_map_kW*3600,
fc_nox_map_gpkWh=fc_nox_map./fc_map_kW*3600,
fc_pm_map_gpkWh=fc_pm_map./fc_map_kW*3600,

% build basic egr map
if fc_egr_bool
  egr_spd_percent_index=[0 50 55 60 65 70 75 80 85 90 95 100],
  egr_load_percent_index=[0 10 20 30 40 50 60 70 80 90 100],
  egr_def_map=[30 30 30 26.1 20.7 15.8 12.1 9.96 7.74 6 6.25,
   30 30 30 26.1 20.7 15.8 12.1 9.96 7.74 6 6.25,
   30 30 30 26.22 20.93 16.06 12.33 10.12 7.926 6.164 6.224,
   30 30 30 26.17 20.93 16.34 12.93 10.79 9.179 7.297 6.308,
   30 30 30 26.02 21.29 17.01 14.16 12.23 10.72 9.187 8.31,
   30 30 29.9 25.88 21.56 18.06 15.7 13.88 12.38 11.16 10.32,
   30 30 29.18 25.98 22.38 19.22 17.4 15.97 14.73 13.64 12.7,
   30 30 28.85 26.27 23.17 20.59 19 18.03 17.13 16.27 15.7,
   30 30 28.74 26.5 23.91 21.66 20.21 19.45 18.92 18.61 18.35,
   29.9 29.9 28.44 26.52 24.59 22.67 21.39 20.79 20.43 20.2 20.2,
   29.3 29.3 28.43 26.99 25.29 23.79 22.8 22.3 22.3 22.3 22.3,
   29.3 29.3 28.47 27.06 25.38 23.9 22.86 22.3 22.3 22.3 22.3],
  fc_egr_map=interp2(egr_spd_percent_index, egr_load_percent_index,
egr_def_map', (fc_map_spd./max(fc_map_spd)*100)',
fc_map_trq./max(fc_map_trq)*100)',
else
  fc_egr_map=zeros(size(fc_fuel_map)),
end
clear egr_spd_percent_index egr_load_percent_index egr_def_map


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (N*m), max torque curve of the engine indexed by fc_map_spd
spd=[500 1000 1500 2000 2500 3000]*pi/30, % Ford Website
trq=[300 400 500 490 475 400]*1.35671, % Ford Website
fc_max_trq=interp1(spd,trq,fc_map_spd),

% (N*m), closed throttle torque of the engine (max torque that can be
absorbed)
% indexed by fc_map_spd -- correlation from JDMA
fc_ct_trq=4.448/3.281*(-fc_disp)*61.02/24 * ...
```

```
  (9*(fc_map_spd/max(fc_map_spd)).^2 + 14 *
(fc_map_spd/max(fc_map_spd))),

fc_ct_trq=interp1([0 100],[0.11
0.18],fc_map_spd/max(fc_map_spd)*100).*fc_max_trq*(-1),

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), used to scale fc_map_spd to simulate a faster or slower running
engine
fc_spd_scale=1.0,
% (--), used to scale fc_map_trq to simulate a higher or lower torque
engine
fc_trq_scale=1.0,
fc_pwr_scale=fc_spd_scale*fc_trq_scale,  % -- scale fc power

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% STUFF THAT SCALES WITH TRQ & SPD SCALES (MASS AND INERTIA)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%fc_inertia=0.1*fc_pwr_scale,      % (kg*m^2), rotational inertia of
the engine
fc_max_pwr=(max(fc_map_spd.*fc_max_trq)/1000)*fc_pwr_scale, % kW   peak
engine power
fc_base_mass=2.8*fc_max_pwr,        % (kg), mass of the engine block
and head (base engine)
                                           % mass penalty of 1.8 kg/kW
from 1994 OTA report, Table 3
fc_acc_mass=1.0*fc_max_pwr,         % kg  engine accy's, electrics,
cntrl's - assumes mass penalty of 0.8 kg/kW (from OTA report)
fc_fuel_mass=0.6*fc_max_pwr,        % kg  mass of fuel and fuel tank
fc_mass=fc_base_mass+fc_acc_mass+fc_fuel_mass,       % kg total
engine/fuel system mass
fc_ext_sarea=0.3*(fc_max_pwr/100)^0.67,              % m^2  exterior
surface area of engine

fc_inertia=fc_base_mass*(1/3+1/3*2/3)*(0.08^2),
% assumes 1/3 purely rotating mass, 1/3 purely oscillating, and 1/3
stationary
% and crank radius of 0.08m, 2/3 of oscilatting mass included in
rotational inertia calc
% correlation from Bosch handbook p.379

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_fuel_den=843,                          % (g/l), density of the fuel
fc_fuel_lhv=43000,                                          % (J/g),
lower heating value of the fuel

fc_tstat=96,                        % C   engine coolant thermostat set
temperature (typically 95 +/- 5 C)
fc_cp=500,                    % J/kgK ave cp of engine (iron=500, Al or
Mg = 1000)
fc_h_cp=500,                  % J/kgK ave cp of hood & engine
compartment (iron=500, Al or Mg = 1000)
```

```
fc_hood_sarea=1.5,                  % m^2  surface area of hood/eng
compt.
fc_emisv=.8,                  %    emissivity of engine ext
surface/hood int surface
fc_hood_emisv=.9,                   %    emissivity hood ext
fc_h_air_flow=0,              % kg/s  heater air flow rate (140
cfm=0.07)
fc_cl2h_eff=.7,               % --   ave cabin heater HX eff (based on
air side)
fc_c2i_th_cond=500,                 % W/K  conductance btwn engine cyl
& int
fc_i2x_th_cond=500,                 % W/K  conductance btwn engine int
& ext
fc_h2x_th_cond=10,                  % W/K  conductance btwn engine &
engine compartment

% calculate "predicted" exh gas flow rate and engine-out (EO) temp
fc_ex_pwr_frac=[0.40 0.30],             % --  frac of waste heat that
goes to exhaust as func of engine speed
fc_ex_pwr_frac=[0.50 0.40],             % --  frac of waste heat that
goes to exhaust as func of engine speed

% build basic af map
if 1
  af_spd_percent_index=[0 50 100],
  af_load_percent_index=[0 50 100],
  af_def_map=[50 34 16, 42 28 16, 34 22 16],
  fc_af_map=interp2(af_spd_percent_index, af_load_percent_index,
af_def_map', (fc_map_spd./max(fc_map_spd)*100)',
fc_map_trq./max(fc_map_trq)*100)',
  fc_exflow_map=fc_fuel_map.*(1+fc_af_map),
else
  %fc_exflow_map=fc_fuel_map*(1+14.5),         % g/s ex gas flow map:
for SI engines, exflow=(fuel use)*[1 + (stoic A/F ratio)]
  fc_exflow_map=fc_fuel_map*(1+18*2),         % g/s ex gas flow map:
for CI engines, exflow=(fuel use)*[1 + (stoic A/F ratio)*2]

                               % *2 to account for generally lean
operation, A/F typically ~18:1 at high load and ~50:1 at low load
end
clear af_spd_percent_index af_load_percent_index af_def_map

fc_waste_pwr_map=fc_fuel_map*fc_fuel_lhv - T.*w,  % W  tot FC waste
heat = (fuel pwr) - (mech out pwr)
spd=fc_map_spd,
fc_ex_pwr_map=zeros(size(fc_waste_pwr_map)),    % W  initialize size of
ex pwr map
for i=1:length(spd)
 fc_ex_pwr_map(i,:)=fc_waste_pwr_map(i,:)*interp1([min(spd)
max(spd)],fc_ex_pwr_frac,spd(i)), % W trq-spd map of waste heat to exh
end
fc_extmp_map=fc_ex_pwr_map./(fc_exflow_map*1089/1000) + 20,  % W  EO ex
gas temp = Q/(MF*cp) + Tamb (assumes engine tested ~20 C)

%the following variable is not used directly in modelling and should
always be equal to one
%it's used for initialization purposes
```

```
fc_eff_scale=1,

% clean up workspace
clear T w fc_waste_pwr_map fc_ex_pwr_map spd fc_map_kW

% Begin added by ADVISOR 3.2 converter: 14-Dec-2001
fc_cold_tmp=21.1,

fc_exflow_map_cold=fc_exflow_map,

fc_extmp_map_cold=fc_extmp_map,

fc_fuel_map_cold=fc_fuel_map,

fc_hc_map_cold=fc_hc_map,

fc_co_map_cold=zeros(size(fc_fuel_map)),

fc_pm_map_cold=fc_pm_map,

fc_nox_map_cold=fc_nox_map,

fc_o2_map=zeros(size(fc_fuel_map)),

% Process cold maps
names={'fc_fuel_map', 'fc_hc_map', 'fc_co_map', 'fc_nox_map',
'fc_pm_map'},
for i=1:length(names)
  %cold to hot raio, e.g. fc_fuel_map_c2h = fc_fuel_map_cold ./
fc_fuel_map
  eval([names{i},'_c2h=',names{i},'_cold./(',names{i},'+eps),'])
end

fc_mass_scale_fun=inline('(x(1)*fc_trq_scale+x(2))*(x(3)*fc_spd_scale+x
(4))*(fc_base_mass+fc_acc_mass)+fc_fuel_mass','x','fc_spd_scale','fc_tr
q_scale','fc_base_mass','fc_acc_mass','fc_fuel_mass'),
fc_mass_scale_coef=[1 0 1 0],
% End added by ADVISOR 3.2 converter: 14-Dec-2001

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% YYYY-MMM-DD
% 2000-Aug-01 09:16:19: file created using engmodel
% 2000-Sep-01: automatically updated to version 3
% 2002-Jan-02: [mpo] updated file for ADVISOR 3.2
```

```
% ADVISOR data file: TX_ALL2000.m
%
% Data source:
%
http://www.allisontransmission.com/product/series/2000series_specificat
ionsheets.jsp
%   Net input power 300 hp (224 kW)
%   Net input torque 520 lb-ft (705 N-m)
%   Net turbine torque 850 lb-ft (1152 N-m)
%   GVW 30,000 lbs (13,600 kg)
%   GCW 30,000 lbs (13,600 kg)
%   N/V Ratio2 38-62 rpm/mph (24-38 rpm/kMph)
%
%  TORQUE CONVERTER STALL TORQUE RATIO Kp-FACTOR* AT STALL
%  TC-210      2.05        118.2 (101.6)
%  TC-211      2.00        111.3 (95.6)
%  TC-221      1.73        97.8 (84.0)
%  TC-222      1.58        85.2 (73.2)
%
%  Includes standard integral damper which is operational in lockup
%  *Kp-Factor defines torque converter capacity. Kp = the ratio of
converter pump
%  speed [rpm] divided by the square root of the pump torque [lb-ft (N-
m)].
%
%  MECHANICAL RATIOS (RANGE)*
%  First 3.51:1
%  Second 1.90:1
%  Third 1.44:1
%  Fourth 1.00:1
%  Fifth 0.74:1
%  Reverse -5.09:1
%
%  RATIO COVERAGE
%  Forward 4.74
%
%  *Gear ratios do not include torque converter multiplication.
%  Weight (dry) 330 lbs (150 kg)
%
% Data confirmation: Not confirmed
%
% Notes:
% A constant 96.13% efficiency for the system is assumed based on
Florida testing specifications.
% This file was Adapted from TX_ZF4HP590.m
%
% Created/Adapted on: August 24, 2003
% By: Ewan Pritchard, Advanced Energy, epritcha@advancedenergy.org
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

%Description of type of transmission
```

```
%(important in determining what block diagram to run in
gui_run_simulation)
tx_type='auto 5 speed',
% automatic which behaves more like a manual (BD_CONV is selected)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% INITIALIZE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
gb_ratio=[3.51 1.90 1.44 1.00 0.74], % without final drive ratios
gb_gears_num=5, % number of gears


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tx_description='GM/Allison 2000 Series 5-speed automatic trans.
(Conventional School Bus)',
tx_version=2002, % version of ADVISOR for which the file was generated
tx_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
tx_validation=0,
% 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been
verified

disp(['Data loaded: TX_ALL2000 - ',tx_description]),

gb_version=2002,
gb_description1=['Allison 2000 - ',num2str(gb_gears_num),'- speed '],
gb_description2=' constant 96.13% efficiency gearbox ',
gb_description=[gb_description1 gb_description2],
gb_proprietary=0, % 0=> public data, 1=> restricted access, see
comments above
gb_validated=0,  % 0=> no validation, 1=> confirmed agreement with
source data,
% 2=> agrees with source data, and data collection methods have been
verified
clear gb_description1 gb_description2


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GEARBOX
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSSES AND EFFICIENCIES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 96.13% efficient gearbox - Florida test specifications
 tx_map_spd=[0 10000], % speed of transmission shaft output (wheel-side
of transmission) in rad/s
 tx_map_trq=[-10000 10000], % torque of transmission shaft output
(wheel-side of transmission) in Nm
 tx_eff_map=[0.9613 0.9613,0.9613 0.9613], % transmission efficiency,
row index is tx_map_spd, col index is tx_map_trq
 %tx_eff_map=[0.9513 0.9513,0.9513 0.9513], % transmission efficiency -
1% for sensitivity analysis
```

```
 %tx_eff_map=[0.9713 0.9713,0.9713 0.9713], % transmission efficiency
+1% for sensitivity analysis

gb_inertia=0,     % (kg*m^2), gearbox rotational inertia measured at
input,

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%the following variable is not used directly in modelling and should
always
%be equal to one, it's used for initialization purposes
gb_eff_scale=1,
gb_spd_scale=1,
gb_trq_scale=1,


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FINAL DRIVE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSSES AND EFFICIENCIES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fd_loss=0,  % (Nm), constant torque loss in final drive, measured at
input


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fd_ratio=6.14,  % Florida Specs (Spicer 19060S)
%fd_ratio=6.754,  % +10% for sensitivity analysis
%fd_ratio=5.526,  % -10% for sensitivity analysis
%fd_ratio=7.17,  % North Carolina Specs
fd_inertia=0, % (kg*m^2), rotational inertia of final drive, measured
at input

gb_mass=150, % (kg), mass of the gearbox listed by Allison (330 lb)
fd_mass=0, % (kg), mass of final drive estimated

tx_mass=gb_mass+fd_mass,% (kg), mass of the gearbox + final
drive=(transmission)

% user definable mass scaling relationship

tx_mass_scale_fun=inline('(x(1)*gb_trq_scale+x(2))*(x(3)*gb_spd_scale+x
(4))*(fd_mass+gb_mass)','x','gb_spd_scale','gb_trq_scale','fd_mass','gb
_mass'),
tx_mass_scale_coef=[1 0 1 0], % coefficients for mass scaling
relationship

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 18-Jan-2004: automatically updated to version 2002
```

```
% 08-Feb-2004: (ep)Changed final drive ratio to Florida Spec.
% 08-Feb-2004: (ep)Corrected transmission mass to kg not lb.
```

```
% ADVISOR data file: WH_CSCHBUS.m
%
% Data source:
%    2002 North Carolina School Bus Specifications
%    Michelin Specifications
%
% Data confirmation:
%
% Notes:
% Defines tire, wheel, and axle assembly parameters for use with
ADVISOR 2, for
% modeling of a school bus.
%
% Created on: 9/6/03
% By: Ewan Pritchard, Advanced Energy and North Carolina State
University
%       epritcha@advancedenergy.org
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_description='Wheel/axle assembly for class C school bus',
wh_version=2002, % version of ADVISOR for which the file was generated
wh_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
wh_validation=0, % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: WH_CSCHBUS - ',wh_description])


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FORCE AND MASS RANGES over which data is defined
% taken from WH_HEAVY.m file
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% vehicle test mass vector used in tandem with "wh_axle_loss_trq" to
estimate
% wheel and axle bearing and brake drag
wh_axle_loss_mass=[0 5000 10000 15000 30000],  % (kg)
% (tractive force on the front tires)/(weight on front axle), used in
tandem
% with "wh_slip" to estimate tire slip at any time
wh_slip_force_coeff=[0 0.3913 0.6715 0.8540 0.9616 1.0212], % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% drag torque applied at the front (drive) axle, used with
"wh_axle_loss_mass"
%wh_axle_loss_trq=[4 24 48 72 144]*.4,  % (Nm)
wh_axle_loss_trq=[0 500 1000 1500 3000]*0.03,  % (Nm)
% slip=(omega * r)/v -1, used with "wh_slip_force_coeff"
```

```
wh_slip=[0.0 0.025 0.050 0.075 0.10 0.125], % (--)


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wh_radius=0.5271,  % (m), rolling radius of Michelin XZE 11R22.5 (41.5
inch diameter)
% rotational inertia of all wheels, tires, and axles
% below uses OTA's '94 estimate of Taurus wheel, tire & tool mass as
mass of
% solid cylinders of radius wh_radius, rotating at wheel speed in this
vehicle
wh_inertia=181*2/2.205*wh_radius^2/2, % (kg*m^2)
%wh_inertia=0, % (kg*m^2)
% fraction of braking done by driveline, indexed by wh_fa_dl_brake_mph
wh_fa_dl_brake_frac=[0 0 0.5 0.8 0.8], % (--)
% (--), fraction of braking done by front friction brakes,
% indexed by wh_fa_fric_brake_mph
wh_fa_fric_brake_frac=[0.8 0.8 0.4 0.1 0.1], % (--)
wh_fa_dl_brake_mph=[-1 0 10 60 1000],  % (mph)
wh_fa_fric_brake_mph=wh_fa_dl_brake_mph, % (mph)

wh_1st_rrc=0.00938, % (--), rolling resistance coefficient
wh_2nd_rrc=0, % (s/m)

wh_mass=0,

%%%%%%%%%%%%%%%%%
% Error checking
%%%%%%%%%%%%%%%%%
% dl+fa_fric must add up to <= 1 for all speeds. Give user warning if
in error
temp_total_braking=wh_fa_dl_brake_frac+wh_fa_fric_brake_frac,
if any(temp_total_braking>1)
  disp('Warning: Driveline and Front Friction Braking need to add to
less than or equal to 1 for')
  disp('     all speeds. Please edit either wh_fa_dl_brake_frac or
wh_fa_fric_brake_frac'),
  disp('     in WH_*.m. See Chapter 3.2.4, Braking of the documentation
for more info.'),
end
clear temp_total_braking


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 9/6/03 ep: file created from WH_HEAVY.m

% 18-Jan-2004: automatically updated to version 2002
```

```
% ADVISOR data file: EX_CI_NoCat.m
%
% Data source: ORNL testing
%
% Data confirmation:
%
% Masses, areas, etc. are scaled based on engine peak power
(fc_pwr_max)
%
% Created on: February, 5 2004
% By: EP, Ewan Pritchard, Advanced Energy Corporation, North Carolina
State University
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_description='Diesel Exhaust, No Catalyst',
ex_version=2003, % version of ADVISOR for which the file was generated
ex_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
ex_validation=0, % 1=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: EX_CI_NoCat - ',ex_description])

ex_calc=1,     % 0=> skip ex sys calc (if fc has no emis maps or no cat
info avail)
          % 1=> perform ex sys calcs including tailpipe emis
ex_ornl_bool=1,              %1->Use efficiencies from ORNL data
                                        %0->Use basic ADVISOR removal
efficiencies

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CAT EFF VS TEMPERATURE catalyst's temperature-dependent
% conversion efficiencies indexed by ex_cat_tmp_range
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_tmp_range=[-100 1200], % (deg. C)
% The HC, CO, and NOx removal efficiencies are hard-coded in the
lib_exhaust for
% the NOx Absorber
ex_cat_hc_frac=zeros(size(ex_cat_tmp_range)),
ex_cat_co_frac=zeros(size(ex_cat_tmp_range)),
ex_cat_nox_frac=zeros(size(ex_cat_tmp_range)),
ex_cat_pm_frac=[0 0],

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CAT "BREAKTHROUGH" LIMITS (MAX g/s for each pollutant)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_lim= [1.25 17.0 2.0 0.4]',   % g/s "break-thru" limit of
converter (HC, CO, NOx, PM)
                   % assumed to be ~5X the Tier 1 g/mi limits

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% NEW CONVERTER, ETC DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CONVENTIONAL CONVERTER
ex_mass=0.3*fc_max_pwr/fc_pwr_scale,       % kg   mass of exhaust
system assumes mass penalty of 0.3 kg/kW)
%ex_mass=0.3*fc_max_pwr,       % kg   mass of exhaust system assumes
mass penalty of 0.3 kg/kW)
                   %    (vs 0.26 for SI from 1994 OTA report, Table 3)
 ex_cat_mass=ex_mass*0.36,      % kg   mass of catalytic converter
(from 1994 OTA report, Table 3)
 ex_cat_mon_mass=ex_cat_mass*0.22,  % kg   mass of cat monolith
(ceramic)
 ex_cat_int_mass=ex_cat_mass*0.33,  % kg   mass of cat internal SS
shell
 ex_cat_pipe_mass=ex_cat_mass*0.17, % kg   mass of cat inlet/outlet
pipes
 ex_cat_ext_mass=ex_cat_mass*0.28,  % kg   mass of cat ext shell
(shield)
 ex_manif_mass=ex_mass*0.20,     % kg   mass of engine manifold &
downpipe, turbo (if applicable)
 ex_muf_mass=ex_mass-ex_cat_mass-ex_manif_mass, % kg   mass of muffler
and other pipes downstream of cat

ex_cat_pcm_mass=0,         % kg   mass of cat phase change mat'l heat
storage
ex_mass=ex_mass+ex_cat_pcm_mass,  % kg   add mass of PCM (if any) to ex
sys mass

ex_cat_mon_cp=1070,    % J/kgK ave cp of cat mon: CERAMIC SAE #880282)
%ex_cat_mon_cp=636,    % J/kgK ave cp of cat mon: METAL (SAE #890798)
ex_cat_int_cp=460,     % J/kgK ave cp of cat int: SS (SAE #890798)
ex_cat_pipe_cp=460,    % J/kgK ave sens heat cap of cat i/o pipes (SAE
#890798)
ex_cat_ext_cp=460,     % J/kgK ave sens heat cap of cat ext (SAE
#890798)
ex_manif_cp=460,      % J/kgK ave sens heat cap of manifold & dwnpipe
(SAE #890798)
ex_gas_cp=1089,      % J/kgK ave sens heat cap of exh gas (SAE #890798)
ex_cat_pcm_tmp=[-100 1200], % C  temp range for cat pcm ecp vec
ex_cat_pcm_ecp=[0 0],   % J/kgK ave eff heat cap of pcm (latent + sens)

ex_cat_mon_sarea=0.1*(fc_max_pwr/100)^0.67,    % m^2 outer surface area
of cat monolith (approx. 0.1 m^2/100 kW)
ex_cat_monf_sarea=ex_cat_mon_sarea/4,  % m^2 surface area of cat
monolith front face
ex_cat_moni_sarea=ex_cat_mon_sarea*50,  % m^2 inner (honeycomb) surf
area of cat monolith
ex_cat_int_sarea=ex_cat_mon_sarea*1.3,  % m^2 surface area of cat
interior
ex_cat_pipe_sarea=ex_cat_mon_sarea/2,  % m^2 surface area of cat i/o
pipes
ex_cat_ext_sarea=ex_cat_mon_sarea*1.4,  % m^2 surface area of cat ext
shield
ex_man2cat_length=0.7,          % m  length of exhaust pipe between
manifold and cat conv
ex_manif_sarea=(fc_max_pwr/600)*(0.3+ex_man2cat_length),  % m^2 surface
area of manif & downpipe: pi*D*L
```

```
ex_cat_m2p_emisv=0.1,    %    emissivity x view factor from cat
monolith to cat pipes
ex_cat_i2x_emisv=0.5,    %    emissivity from cat int to cat ext shield
ex_cat_pipe_emisv=0.7,   %    emissivity of cat i/o pipe
ex_cat_ext_emisv=0.7,    %    emissivity of cat ext shield
ex_manif_emisv=0.7,     %    emissivity of manif & dwnpipe

ex_cat_m2i_th_cond=[0.7 1.3 2.65 6.5]*0.1/0.003 , % W/K  cond btwn
CERAMIC mono & int (from SAE#880282)
ex_cat_m2i_tmp=[-40 97 344 1200],        % C   corresponding
temperature vector
ex_cat_i2x_th_cond  =1.0,            % W/K  conductance btwn cat int &
ext
ex_cat_i2p_th_cond  =0.2,            % W/K  conductance btwn cat int &
pipe
ex_cat_p2x_th_cond  =0.02,            % W/K  conductance btwn cat pipe
& ext

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% STUFF FOR OLD CAT TEMP APPROACH
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ex_cat_max_tmp=400,               % deg. C, maximum catalyst
temperature

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% user definable mass scaling function
ex_mass_scale_fun=inline('(x(1)*fc_pwr_scale+x(2))*ex_mass','x','fc_pwr
_scale','ex_mass'),
ex_mass_scale_coef=[1 0], % mass scaling function coefficients

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 02/26/01: vhj file created from EX_CI, added ex_abs_bool
% 02/27/01: vhj repalced NOx Abs with OxCat
% 02/28/01: vhj changed ex_abs_bool to ex_ornl_bool
% 7/30/01:tm added mass scaling relationship
mass=f(ex_mass,fc_pwr_scale)
```

```
% ADVISOR data file: PTC_CONVAT.m
%
% Data source:
%
% Data confirmation:
%
% Notes:
% Defines all powertrain control parameters, including gearbox, clutch,
% and engine controls, for an advanced conventional vehicle using a 4-
spd
% gearbox.
%
% Created on: 7-Oct-1998
% By: MRC, NREL, matthew_cuddy@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ptc_description='4-spd AT control',
ptc_version=2002, % version of ADVISOR for which the file was generated
ptc_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
ptc_validation=0, % 1=> no validation, 1=> data agrees with source
data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: PTC_CONVAT - ',ptc_description])


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLUTCH & ENGINE CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% compute idle speed such that
% fc_max_trq(vc_idle_spd) >= 2 * accessory_torque(vc_idle_spd) AND
% vc_idle_spd >= 800 rpm
fc_max_pwr_vec=fc_map_spd.*fc_max_trq,
last_index=min(find(diff(fc_max_pwr_vec)<=0)),%ss added '=' in '<='
spot on 7/9/99
if isempty(last_index)
  last_index=length(fc_max_pwr_vec),
end
temp=interp1(fc_max_pwr_vec(1:last_index),fc_map_spd(1:last_index),2*ac
c_mech_pwr),
if isnan(temp) % if 2*accessory power is off the map (too low)...
  vc_idle_spd=800*2*pi/60, % (rad/s), engine's idle speed
else
  vc_idle_spd=max(temp,800*2*pi/60),
end

% 1=> idling allowed, 0=> engine shuts down rather than
vc_idle_bool=1, % (--)
```

```
% 1=> disengaged clutch when req'd engine torque <=0, 0=> clutch
remains engaged
vc_clutch_bool=0, % (--)
% speed at which engine spins while clutch slips during launch
vc_launch_spd=max(max(fc_map_spd)/5,1.5*vc_idle_spd), % (rad/s)


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GEARBOX CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if 1 % use new shift map
  % fractional engine load {=(torque)/(max torque at speed)} above
which a
  % downshift is called for, indexed by gb_gearN_dnshift_spd
  gb_gear1_dnshift_load=[0 0.6 0.9 1], % (--)
  gb_gear2_dnshift_load=gb_gear1_dnshift_load, % (--)
  gb_gear3_dnshift_load=gb_gear1_dnshift_load, % (--)
  gb_gear4_dnshift_load=gb_gear1_dnshift_load, % (--)
  gb_gear5_dnshift_load=gb_gear1_dnshift_load, % (--)
  % fractional engine load {=(torque)/(max torque at speed)} below
which an
  % upshift is called for, indexed by gb_gearN_upshift_spd
  gb_gear1_upshift_load=[0 0.3 1], % (--)
  gb_gear2_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear3_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear4_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear5_upshift_load=gb_gear1_upshift_load, % (--)
  %gb_gear1_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.20
0.25]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
  gb_gear1_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10
0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
  gb_gear2_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear3_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear4_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear5_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  %gb_gear1_upshift_spd=min(fc_map_spd)+[0.30 0.42
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
  gb_gear1_upshift_spd=min(fc_map_spd)+[0.27 0.42
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
  % 0.98 rather than 1 because engine may not be able to reach the max
speed
  % under certain conditions due to speed estimation method
  % this setting allows the vehicle to shift before it gets to the max
engine speed (tm:11/11/99)
  gb_gear2_upshift_spd=min(fc_map_spd)+[0.35 0.47
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale,, % (rad/s)
  gb_gear3_upshift_spd=min(fc_map_spd)+[0.37 0.47
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
  gb_gear4_upshift_spd=min(fc_map_spd)+[0.35 0.47
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
  gb_gear5_upshift_spd=min(fc_map_spd)+[0.35 0.47
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale, % (rad/s)
else % use v3.1 shift map
  % fractional engine load {=(torque)/(max torque at speed)} above
which a
  % downshift is called for, indexed by gb_gearN_dnshift_spd
  gb_gear1_dnshift_load=[0 0.6 0.9 1], % (--)
```

```
  gb_gear2_dnshift_load=gb_gear1_dnshift_load, % (--)
  gb_gear3_dnshift_load=gb_gear1_dnshift_load, % (--)
  gb_gear4_dnshift_load=gb_gear1_dnshift_load, % (--)
  gb_gear5_dnshift_load=gb_gear1_dnshift_load, % (--)
  % fractional engine load {=(torque)/(max torque at speed)} below
which an
  % upshift is called for, indexed by gb_gearN_upshift_spd
  gb_gear1_upshift_load=[0 0.3 1], % (--)
  gb_gear2_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear3_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear4_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear5_upshift_load=gb_gear1_upshift_load, % (--)
  gb_gear1_dnshift_spd=[799.9*pi/30 800*pi/30
0.5*max(fc_map_spd)*fc_spd_scale ...
     0.501*max(fc_map_spd)*fc_spd_scale], % (rad/s)
  gb_gear2_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear3_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear4_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear5_dnshift_spd=gb_gear1_dnshift_spd, % (rad/s)
  gb_gear1_upshift_spd=[1499.9*pi/30      1500*pi/30
0.98*max(fc_map_spd)*fc_spd_scale],
  % 0.98* because engine may not be able to reach the max speed
  % under certain conditions due to speed estimation method
  % this setting allows the vehicle to shift before it gets to the max
engine speed (tm:11/11/99)
  gb_gear2_upshift_spd=gb_gear1_upshift_spd, % (rad/s)
  gb_gear3_upshift_spd=gb_gear1_upshift_spd, % (rad/s)
  gb_gear4_upshift_spd=gb_gear1_upshift_spd, % (rad/s)
  gb_gear5_upshift_spd=gb_gear1_upshift_spd, % (rad/s)
end

% duration of shift during which no torque can be transmitted
gb_shift_delay=0, % (s)

% convert old shift commands to new shift commands
gb_upshift_spd={gb_gear1_upshift_spd, ...
   gb_gear2_upshift_spd,...
   gb_gear3_upshift_spd,...
   gb_gear4_upshift_spd,...
   gb_gear5_upshift_spd}, % (rad/s)

gb_upshift_load={gb_gear1_upshift_load, ...
   gb_gear2_upshift_load,...
   gb_gear3_upshift_load,...
   gb_gear4_upshift_load,...
   gb_gear5_upshift_load}, % (--)

gb_dnshift_spd={gb_gear1_dnshift_spd, ...
   gb_gear2_dnshift_spd,...
   gb_gear3_dnshift_spd,...
   gb_gear4_dnshift_spd,...
   gb_gear5_dnshift_spd}, % (rad/s)

gb_dnshift_load={gb_gear1_dnshift_load, ...
   gb_gear2_dnshift_load,...
   gb_gear3_dnshift_load,...
   gb_gear4_dnshift_load,...
```

```
   gb_gear5_dnshift_load}, % (--)

clear gb_gear*shift* % remove unnecessary data

% fixes the difference between number of shift vectors and gears in
gearbox
if length(gb_upshift_spd)<length(gb_ratio)
  start_pt=length(gb_upshift_spd),
  for x=1:length(gb_ratio)-length(gb_upshift_spd)
   gb_upshift_spd{x+start_pt}=gb_upshift_spd{1},
   gb_upshift_load{x+start_pt}=gb_upshift_load{1},
   gb_dnshift_spd{x+start_pt}=gb_dnshift_spd{1},
   gb_dnshift_load{x+start_pt}=gb_dnshift_load{1},
  end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HYDRAULIC TORQUE CONVERTER CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
htc_lockup=[0 0 0 1], % (--), htc_lockup(i)=='when in gear i, lock up
HTC'


%%%%%%%%%%%%%%% START OF SPEED DEPENDENT SHIFTING INFORMATION
%%%%%%%%%%%%%

% Data specific for SPEED DEPENDENT SHIFTING in the (PRE_TX) GEARBOX
CONTROL
% BLOCK in VEHICLE CONTROLS <vc>
% --implemented for all powertrains except CVT versions and Toyota
Prius (JPN)
%
tx_speed_dep=0,   % Value for the switch in the gearbox control
%                 If tx_speed_dep=1, the speed dependent gearbox is
chosen
%                 If tx_speed_dep=0, the engine load dependent gearbox
is chosen
%
% Vehicle speed (m/s) where the gearbox has to shift
%tx_1_2_spd=24/3.6,     % converting from km/hr to m/s

%tx_2_3_spd=40/3.6,
%tx_3_4_spd=64/3.6,
%tx_4_5_spd=75/3.6,
%tx_5_4_spd=75/3.6,
%tx_4_3_spd=64/3.6,
%tx_3_2_spd=40/3.6,
%tx_2_1_spd=tx_1_2_spd,

% first column is speed in m/s, second column is gear number
% note: lookup data should be specified as a step function
% ..... this can be done by repeating values of x (first column, speed)
% ..... for differing values of y (second column, )
% note: division by 3.6 to change from km/hr to m/s

% speeds to use for upshift transition (shifting while accelerating)
tx_spd_dep_upshift = [
```

```
  0/3.6, 1
  24/3.6, 1
  24/3.6, 2
  40/3.6, 2
  40/3.6, 3
  64/3.6, 3
  64/3.6, 4
  75/3.6, 4
  75/3.6, 5
  1000/3.6, 5],

% speeds to use for downshift transition (shifting while decelerating)
tx_spd_dep_dnshift = [
  0/3.6, 1
  24/3.6, 1
  24/3.6, 2
  40/3.6, 2
  40/3.6, 3
  64/3.6, 3
  64/3.6, 4
  75/3.6, 4
  75/3.6, 5
  1000/3.6, 5],
%%%%%%%%%%%%%%% END OF SPEED DEPENDENT SHIFTING %%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLEAN UP
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 7/9/99:ss added calculation of idle speed
% 10/6/99:mc added fc_spd_scale to definition of shift speeds
% 11/03/99:ss updated version from 2.2 to 2.21
% 7/30/01:tm updated version from 3.1 to 3.2
% 7/30/01:tm added new auto scaled shift map
% 7/31/01:mpo added variables for speed dependent shifting
```

```
% ADVISOR data file:  PTC_SER.m
%
% Data source:
%
% Data confirmation:
%
% Notes:
% Defines all powertrain control parameters, including gearbox, clutch,
hybrid
% and engine controls, for a series hybrid using a thermostat control
strategy.
% To ensure proper operation, this file must be reloaded every time the
FC or
% GC is rescaled.
%
% Created on: 2-Sep-1998
% By:  MRC, NREL, matthew_cuddy@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

if ~exist('update_cs_flag')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ptc_description='Powertrain control for series hybrid w/ pure
thermostat cs';
ptc_version=2002; % version of ADVISOR for which the file was generated
ptc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not
distribute
ptc_validation=0; % 1=> no validation, 1=> data agrees with source
data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: PTC_SER - ',ptc_description])


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLUTCH & ENGINE CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
vc_idle_spd=0;  % (rad/s), engine's idle speed


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GEARBOX CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% fractional engine load {=(torque)/(max torque at speed)} above which
a
% downshift is called for, indexed by gb_gearN_dnshift_spd
gb_gear1_dnshift_load=[2 2];  % (--)
gb_gear2_dnshift_load=[2 2];  % (--)
% fractional engine load {=(torque)/(max torque at speed)} below which
an
% upshift is called for, indexed by gb_gearN_upshift_spd
gb_gear1_upshift_load=[-1 -1];  % (--)
```

```
gb_gear2_upshift_load=[-1 -1];  % (--)
gb_gear1_dnshift_spd=[0 1000];  % (rad/s)
gb_gear2_dnshift_spd=[0 1000];  % (rad/s)
gb_gear1_upshift_spd=[0 1000];  % (rad/s)
gb_gear2_upshift_spd=[0 1000];  % (rad/s)

% convert old shift commands to new shift commands
gb_upshift_spd={gb_gear1_upshift_spd; ...
      gb_gear2_upshift_spd};  % (rad/s)
gb_upshift_load={gb_gear1_upshift_load; ...
      gb_gear2_upshift_load};  % (--)
gb_dnshift_spd={gb_gear1_dnshift_spd; ...
      gb_gear2_dnshift_spd};  % (rad/s)
gb_dnshift_load={gb_gear1_dnshift_load; ...
      gb_gear2_dnshift_load};  % (--)

clear gb_gear*shift* % remove unnecessary data

% fixes the difference between number of shift vectors and gears in
gearbox
if length(gb_upshift_spd)<length(gb_ratio)
   start_pt=length(gb_upshift_spd);
   for x=1:length(gb_ratio)-length(gb_upshift_spd)
      gb_upshift_spd{x+start_pt}=gb_upshift_spd{1};
      gb_upshift_load{x+start_pt}=gb_upshift_load{1};
      gb_dnshift_spd{x+start_pt}=gb_dnshift_spd{1};
      gb_dnshift_load{x+start_pt}=gb_dnshift_load{1};
   end
end

% duration of shift during which no torque can be transmitted
gb_shift_delay=0;  % (s), no delay since no shifts; this is a 1-spd


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% HYBRID CONTROL STRATEGY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%ess_init_soc=0.7;  % (--), initial battery SOC;  now this is inputed
from the simulation screen

cs_hi_soc=0.8;  % (--), highest desired battery state of charge
cs_lo_soc=0.2;  % (--), lowest desired battery state of charge
cs_fc_init_state=0;  % (--), initial FC state; 1=> on, 0=> off
% (W), minimum operating power for genset
% pure thermostat:set it to operating power
cs_min_pwr=max(fc_max_trq.*fc_map_spd)*.35;
% (W), maximum operating power for genset (exceeded only if
SOC<cs_lo_soc)
% pure thermostat:set it to operating power
%cs_max_pwr=max(fc_max_trq.*fc_map_spd)*.6;
cs_max_pwr=max(fc_max_trq.*fc_map_spd)*.75;
% (W), extra power output by genset when (cs_lo_soc+cs_hi_soc)/2-SOC=1
% pure thermostat:set it to zero to make genset power output
independent of SOC
cs_charge_pwr=0;
% (s), minimum time genset remains off, enforced unless SOC<=cs_lo_soc
```

```
% pure thermostat:set it to inf s.t. genset won't come on until
SOC<=cs_lo_soc
cs_min_off_time=inf;
% (W/s), maximum rate of increase of genset power
% pure thermostat:set it to zero s.t. power is constant whenever on
cs_max_pwr_rise_rate=0;
% (W/s), maximum rate of decrease of genset power
% pure thermostat:set it to zero s.t. power is constant whenever on
cs_max_pwr_fall_rate=0;

cs_charge_deplete_bool=1; % boolean 1=> use charge deplete strategy,
0=> use charge sustaining strategy

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% compute locus of best efficiency points
%
if ~exist('fc_fuel_map_gpkWh')
   %
   % compute engine efficiency map for use in genset control
   %
   [T,w]=meshgrid(fc_map_trq,fc_map_spd);
   fc_outpwr_map_kW=T.*w/1000;
   fc_fuel_map_gpkWh=fc_fuel_map./(fc_outpwr_map_kW+eps)*3600;
   % if zero speed is in map, replace associated data with nearest
BSFC*4
   if min(fc_map_spd)<eps
      fc_fuel_map_gpkWh(1,:)=fc_fuel_map_gpkWh(2,:)*4;
   end
   % if zero torque is in map, replace associated data with nearest
BSFC*4
   if min(fc_map_trq)<eps
      fc_fuel_map_gpkWh(:,1)=fc_fuel_map_gpkWh(:,2)*4;
   end
end

%
% compute allowable genset torques and speeds
% (these are limited by the max torque envelopes of the FC and GC, and
by the
% extents of their maps)
%
temp1=min([max(fc_map_trq)*fc_trq_scale max(gc_map_trq)*gc_trq_scale]);
temp2=max([min(fc_map_trq)*fc_trq_scale min(gc_map_trq)*gc_trq_scale]);
genset_map_trq=[temp2:(temp1-temp2)/10:temp1];

temp1=min([max(fc_map_spd)*fc_spd_scale max(gc_map_spd)*gc_spd_scale]);
temp2=max([min(fc_map_spd)*fc_spd_scale min(gc_map_spd)*gc_spd_scale]);
genset_map_spd=[temp2:(temp1-temp2)/10:temp1];

temp1=interp1(fc_map_spd*fc_spd_scale,fc_max_trq*fc_trq_scale,genset_ma
p_spd);
temp2=interp1(gc_map_spd*gc_spd_scale,gc_max_trq*gc_trq_scale,genset_ma
p_spd);
genset_max_trq=min([temp1;temp2]);
```

```
% compute genset BSFC map
temp1=interp2(gc_map_trq*gc_trq_scale,gc_map_spd'*gc_spd_scale,gc_eff_m
ap,...
   genset_map_trq,genset_map_spd');
temp2=interp2(fc_map_trq*fc_trq_scale,fc_map_spd'*fc_spd_scale,...
   fc_fuel_map_gpkWh,genset_map_trq,genset_map_spd');
genset_BSFC_map=temp2./(temp1+eps);

% Define power vector
genset_max_pwr=max(genset_map_spd.*...

(min([genset_max_trq;ones(size(genset_max_trq))*max(genset_map_trq)])))
;
%genset_max_pwr=min(max(genset_map_spd.*genset_max_trq),...
  % max(genset_map_spd)*max(genset_map_trq));
genset_min_pwr=min(genset_map_spd)*min(genset_map_trq);
cs_pwr=[genset_min_pwr:(genset_max_pwr-
genset_min_pwr)/10:genset_max_pwr];

% Loop on power
for pwr_index=2:length(cs_pwr-1)

   % consider every integer speed in the map
   spds=[ceil(min(genset_map_spd)):floor(max(genset_map_spd))];

   % determine corresponding torque to produce the current power
   trqs1=cs_pwr(pwr_index)./(spds+eps);

   % make sure all torques are on the map
   trqs2=min(trqs1,max(genset_map_trq));
   trqs2=max(trqs2,min(genset_map_trq));

   % compute BSFCs corresponding to spd/trq points

BSFCs=interp2(genset_map_spd,genset_map_trq,genset_BSFC_map',spds,trqs2
);

   % correct BSFCs to disallow points beyond the engine's or
generator's
   % (continuous) operating range
   BSFCs=BSFCs + (trqs1 > interp1(fc_map_spd*fc_spd_scale,...
      fc_max_trq*fc_trq_scale,spds)) * 10000 ...
      + (trqs1 >
interp1(gc_map_spd*gc_spd_scale,gc_max_trq*gc_trq_scale,...
      spds)) * 10000;

   if any(isnan(BSFCs))
      error('Error in PTC_SERFO: couldn''t compute genset eff. map')
   end

   % pick index of best BSFC (choose minimum so that lowest speed will
be
   % chosen for given power, leading to reduced losses in other
components)
   best_index=min(find(min(BSFCs)==BSFCs));

   cs_spd(pwr_index)=spds(best_index);
```

```
end % for pwr_index=...

% make cvt_locus_spd=0 if cvt_locus_pwr=0
zero_indices=find(abs(cs_pwr)<1e-3);
if ~isempty(zero_indices)
   cs_spd(zero_indices)=zeros(size(zero_indices));
end

% insert max power point as last value
cs_pwr(length(cs_pwr))=genset_max_pwr;
if genset_max_pwr==max(genset_map_spd.*genset_max_trq)
   cs_spd(length(cs_pwr))=genset_map_spd(find...
      ((genset_map_spd.*genset_max_trq)==genset_max_pwr));
else
   cs_spd(length(cs_pwr))=max(genset_map_spd);
end

% insert min power point as first value
cs_pwr(1)=min(genset_map_spd)*min(genset_map_trq);
cs_spd(1)=min(genset_map_spd);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLOT RESULTS OF LOCUS FINDING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if 0

c=contour(genset_map_spd*30/pi,genset_map_trq,genset_BSFC_map',[200:20:
400]);
   hold on
   plot(genset_map_spd*30/pi,genset_max_trq,'rx')
   plot(cs_spd*30/pi,cs_pwr./cs_spd,'.')
   plot(fc_map_spd*fc_spd_scale*30/pi,fc_max_trq*fc_trq_scale,'r')
   plot(gc_map_spd*gc_spd_scale*30/pi,gc_max_trq*gc_trq_scale)
   set(gca,'Ylim',[min(genset_map_trq) ...
         max([gc_max_trq*gc_trq_scale fc_max_trq*fc_trq_scale])])
end

%%%%%%%%%%%%%%% START OF SPEED DEPENDENT SHIFTING INFORMATION
%%%%%%%%%%%%%

% Data specific for SPEED DEPENDENT SHIFTING in the (PRE_TX) GEARBOX
CONTROL
% BLOCK in VEHICLE CONTROLS <vc>
% --implemented for all powertrains except CVT versions and Toyota
Prius (JPN)
%
tx_speed_dep=0;   % Value for the switch in the gearbox control
%                  If tx_speed_dep=1, the speed dependent gearbox is
chosen
%                  If tx_speed_dep=0, the engine load dependent gearbox
is chosen
%
% Vehicle speed (m/s) where the gearbox has to shift
%tx_1_2_spd=24/3.6;     % converting from km/hr to m/s

%tx_2_3_spd=40/3.6;
```

```
%tx_3_4_spd=64/3.6;
%tx_4_5_spd=75/3.6;
%tx_5_4_spd=75/3.6;
%tx_4_3_spd=64/3.6;
%tx_3_2_spd=40/3.6;
%tx_2_1_spd=tx_1_2_spd;

% first column is speed in m/s, second column is gear number
% note: lookup data should be specified as a step function
% ..... this can be done by repeating values of x (first column, speed)
% ..... for differing values of y (second column, )
% note: division by 3.6 to change from km/hr to m/s

% speeds to use for upshift transition (shifting while accelerating)
tx_spd_dep_upshift = [
   0/3.6, 1
   24/3.6, 1
   24/3.6, 2
   40/3.6, 2
   40/3.6, 3
   64/3.6, 3
   64/3.6, 4
   75/3.6, 4
   75/3.6, 5
   1000/3.6, 5];

% speeds to use for downshift transition (shifting while decelerating)
tx_spd_dep_dnshift = [
   0/3.6, 1
   24/3.6, 1
   24/3.6, 2
   40/3.6, 2
   40/3.6, 3
   64/3.6, 3
   64/3.6, 4
   75/3.6, 4
   75/3.6, 5
   1000/3.6, 5];
%%%%%%%%%%%%%%% END OF SPEED DEPENDENT SHIFTING %%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLEAN UP
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear T w fc_outpwr_map best_at_each_trq best_trq_index
clear best_at_each_spd best_spd_index
clear genset_max_pwr genset_max_trq genset_map_spd genset_map_trq
clear temp1 temp2 first_index last_index genset_BSFC_map

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 09/14/98:MC set cs_fc_init_state to 0 (off)
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/03/99:ss updated version from 2.2 to 2.21
% 1/12/00:tm introduced cs_charge_deplete_bool
% 7/31/01:mpo added variables for speed dependent shifting
```

```
% ADVISOR data file:  PTC_PAR.m
%
% Data source:    NREL
%
% Data confirmation:
%
% Notes:
% Defines all powertrain control parameters, including gearbox, clutch,
hybrid
% and engine controls, for a parallel hybrid using a multi-spd gearbox.
%
% Created on: 30-Jun-1998
% By:  MRC, NREL, matthew_cuddy@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

if ~exist('update_cs_flag')

   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   % FILE ID INFO
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   ptc_description='multi-spd parallel electric-assist hybrid w/
electric launch';
   ptc_version=2002; % version of ADVISOR for which the file was
generated
   ptc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not
distribute
   ptc_validation=0; % 1=> no validation, 1=> data agrees with source
data,
   % 2=> data matches source data and data collection methods have been
verified
   disp(['Data loaded: PTC_PAR - ',ptc_description])


   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   % CLUTCH & ENGINE CONTROL
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   % engine idle speed
   vc_idle_spd=0;  % (rad/s)
   % 1=> idling allowed; 0=> engine shuts down rather than
   vc_idle_bool=0;  % (--)
   % 1=> disengaged clutch when req'd engine torque <=0; 0=> clutch
remains engaged
   vc_clutch_bool=1; % (--)
   % speed at which engine spins while clutch slips during launch
   vc_launch_spd=max(fc_map_spd)/6; % (rad/s)
   % fraction of engine thermostat temperature below which the engine
will stay on once it is on
   vc_fc_warm_tmp_frac=0.85; % (--)

   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   % GEARBOX CONTROL
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   if 1 % use new auto scaled shift maps
```

```
      % fractional engine load {=(torque)/(max torque at speed)} above
which a
      % downshift is called for, indexed by gb_gearN_dnshift_spd
      gb_gear1_dnshift_load=[0 0.6 0.9 1];  % (--)
      gb_gear2_dnshift_load=gb_gear1_dnshift_load;  % (--)
      gb_gear3_dnshift_load=gb_gear1_dnshift_load;  % (--)
      gb_gear4_dnshift_load=gb_gear1_dnshift_load;  % (--)
      gb_gear5_dnshift_load=gb_gear1_dnshift_load;  % (--)
      % fractional engine load {=(torque)/(max torque at speed)} below
which an
      % upshift is called for, indexed by gb_gearN_upshift_spd
      gb_gear1_upshift_load=[0 0.3 1];  % (--)
      gb_gear2_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear3_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear4_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear5_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear1_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10
0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
      gb_gear2_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10
0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
      gb_gear3_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10
0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
      gb_gear4_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10
0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale; % (rad/s)
      gb_gear5_dnshift_spd=min(fc_map_spd)+[0.01 0.05 0.10
0.15]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)

      gb_gear1_upshift_spd=min(fc_map_spd)+[0.20 0.3
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
      % 0.98 rather than 1 because engine may not be able to reach the
max speed
      % under certain conditions due to speed estimation method
      % this setting allows the vehicle to shift before it gets to the
max engine speed (tm:11/11/99)
      gb_gear2_upshift_spd=min(fc_map_spd)+[0.20 0.30
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;% (rad/s)
      gb_gear3_upshift_spd=min(fc_map_spd)+[0.20 0.30
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
      gb_gear4_upshift_spd=min(fc_map_spd)+[0.20 0.30
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
      gb_gear5_upshift_spd=min(fc_map_spd)+[0.20 0.30
0.98]*(max(fc_map_spd)-min(fc_map_spd))*fc_spd_scale;  % (rad/s)
   else % use v3.1 shift maps
      % fractional engine load {=(torque)/(max torque at speed)} above
which a
      % downshift is called for, indexed by gb_gearN_dnshift_spd
      gb_gear1_dnshift_load=[0 0.6 0.9 1];  % (--)
      gb_gear2_dnshift_load=gb_gear1_dnshift_load;  % (--)
      gb_gear3_dnshift_load=gb_gear1_dnshift_load;  % (--)
      gb_gear4_dnshift_load=gb_gear1_dnshift_load;  % (--)
      gb_gear5_dnshift_load=gb_gear1_dnshift_load;  % (--)
      % fractional engine load {=(torque)/(max torque at speed)} below
which an
      % upshift is called for, indexed by gb_gearN_upshift_spd
      gb_gear1_upshift_load=[0 0.3 1];  % (--)
      gb_gear2_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear3_upshift_load=gb_gear1_upshift_load;  % (--)
```

```
      gb_gear4_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear5_upshift_load=gb_gear1_upshift_load;  % (--)
      gb_gear1_dnshift_spd=[0.1399 0.14 0.3
0.3001]*max(fc_map_spd)*fc_spd_scale;  % (rad/s)
      gb_gear2_dnshift_spd=gb_gear1_dnshift_spd;  % (rad/s)
      gb_gear3_dnshift_spd=gb_gear1_dnshift_spd;  % (rad/s)
      gb_gear4_dnshift_spd=gb_gear1_dnshift_spd;  % (rad/s)
      gb_gear5_dnshift_spd=gb_gear1_dnshift_spd;  % (rad/s)
      gb_gear1_upshift_spd=[0.2631 0.2632
0.98]*max(fc_map_spd)*fc_spd_scale;  % (rad/s)
      % 0.98 rather than 1 because engine may not be able to reach the
max speed
      % under certain conditions due to speed estimation method
      % this setting allows the vehicle to shift before it gets to the
max engine speed (tm:11/11/99)
      gb_gear2_upshift_spd=gb_gear1_upshift_spd;  % (rad/s)
      gb_gear3_upshift_spd=gb_gear1_upshift_spd;  % (rad/s)
      gb_gear4_upshift_spd=gb_gear1_upshift_spd;  % (rad/s)
      gb_gear5_upshift_spd=gb_gear1_upshift_spd;  % (rad/s)
   end

   % convert old shift commands to new shift commands
   gb_upshift_spd={gb_gear1_upshift_spd; ...
         gb_gear2_upshift_spd;...
         gb_gear3_upshift_spd;...
         gb_gear4_upshift_spd;...
         gb_gear5_upshift_spd};  % (rad/s)

   gb_upshift_load={gb_gear1_upshift_load; ...
         gb_gear2_upshift_load;...
         gb_gear3_upshift_load;...
         gb_gear4_upshift_load;...
         gb_gear5_upshift_load};  % (--)

   gb_dnshift_spd={gb_gear1_dnshift_spd; ...
         gb_gear2_dnshift_spd;...
         gb_gear3_dnshift_spd;...
         gb_gear4_dnshift_spd;...
         gb_gear5_dnshift_spd};  % (rad/s)

   gb_dnshift_load={gb_gear1_dnshift_load; ...
         gb_gear2_dnshift_load;...
         gb_gear3_dnshift_load;...
         gb_gear4_dnshift_load;...
         gb_gear5_dnshift_load};  % (--)

   clear gb_gear*shift* % remove unnecessary data

   % fixes the difference between number of shift vectors and gears in
gearbox
   if length(gb_upshift_spd)<length(gb_ratio)
      start_pt=length(gb_upshift_spd);
      for x=1:length(gb_ratio)-length(gb_upshift_spd)
         gb_upshift_spd{x+start_pt}=gb_upshift_spd{1};
         gb_upshift_load{x+start_pt}=gb_upshift_load{1};
         gb_dnshift_spd{x+start_pt}=gb_dnshift_spd{1};
         gb_dnshift_load{x+start_pt}=gb_dnshift_load{1};
```

```
      end
   end

   % duration of shift during which no torque can be transmitted
   gb_shift_delay=0;  % (s)


   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   % HYBRID CONTROL STRATEGY
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   % highest desired battery state of charge
   cs_hi_soc=0.8;  % (--)
   % lowest desired battery state of charge
   cs_lo_soc=0.2;  % (--)
   % vehicle speed below which vehicle operates as ZEV
   % at low SOC
   cs_electric_launch_spd_lo=0;  % (m/s)
   % at and above high SOC
   cs_electric_launch_spd_hi=0;  % (m/s)
   % req'd torque as a fraction of max trq (at speed)
   % below which engine shuts off, when SOC > cs_lo_soc
   cs_off_trq_frac=0;
   % torque as a fraction of max trq (at speed) that engine
   % puts out when req'd is below this value, when SOC < cs_lo_soc
   cs_min_trq_frac=0.4;
   % accessory-like torque load on engine that
   % goes to recharging the batteries whenever the engine is
   % on cs_charge_trq*(mean(cs_lo_soc cs_hi_soc)-SOC)/(cs_hi_soc-
cs_lo_soc)=additional torque
   cs_charge_trq=0.25*min(fc_max_trq);
   % charge depleting hybrid strategy flag, 1=> use charge
   % deplete strategy, 0=> use charge sustaining strategy
   cs_charge_deplete_bool=0; % boolean
   % speed above which no engine shut down occurs due to low torque
requests
   cs_electric_decel_spd=0;  % (m/s)

%%%%%%%%%%%%%%%% START OF SPEED DEPENDENT SHIFTING INFORMATION
%%%%%%%%%%%%%%

% Data specific for SPEED DEPENDENT SHIFTING in the (PRE_TX) GEARBOX
CONTROL
% BLOCK in VEHICLE CONTROLS <vc>
% --implemented for all powertrains except CVT versions and Toyota
Prius (JPN)
%
tx_speed_dep=0;   % Value for the switch in the gearbox control
%                 If tx_speed_dep=1, the speed dependent gearbox is
chosen
%                 If tx_speed_dep=0, the engine load dependent gearbox
is chosen
%
% Vehicle speed (m/s) where the gearbox has to shift
%tx_1_2_spd=24/3.6;     % converting from km/hr to m/s

%tx_2_3_spd=40/3.6;
%tx_3_4_spd=64/3.6;
```

```
%tx_4_5_spd=75/3.6;
%tx_5_4_spd=75/3.6;
%tx_4_3_spd=64/3.6;
%tx_3_2_spd=40/3.6;
%tx_2_1_spd=tx_1_2_spd;

% first column is speed in m/s, second column is gear number
% note: lookup data should be specified as a step function
% ..... this can be done by repeating values of x (first column, speed)
% ..... for differing values of y (second column, )
% note: division by 3.6 to change from km/hr to m/s

% speeds to use for upshift transition (shifting while accelerating)
tx_spd_dep_upshift = [
   0/3.6, 1
   24/3.6, 1
   24/3.6, 2
   40/3.6, 2
   40/3.6, 3
   64/3.6, 3
   64/3.6, 4
   75/3.6, 4
   75/3.6, 5
   1000/3.6, 5];

% speeds to use for downshift transition (shifting while decelerating)
tx_spd_dep_dnshift = [
   0/3.6, 1
   24/3.6, 1
   24/3.6, 2
   40/3.6, 2
   40/3.6, 3
   64/3.6, 3
   64/3.6, 4
   75/3.6, 4
   75/3.6, 5
   1000/3.6, 5];
%%%%%%%%%%%%%%% END OF SPEED DEPENDENT SHIFTING %%%%%%%%%%%%%

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%8/12/98,vh, cs_charge_trq,initialy =0, set to 20
%8/17/98,vh, changed behavior of cs_charge_trq in block diagram:  only
adds this
%            additional torque when SOC < cs_lo_soc
%8/26/98,vh changed behavior of cs_charge_trq in block diagram: now,
cscharge_trq*(cs_lo_soc-SOC)=additional torque
%09/15/98:MC set gb_shift_delay=0 for reasonable trace following
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 10/7/99:tm added *fc_spd_scale to shift speed definitions
%10/25/99:mc updated cs_electric_launch_spd and cs_off_trq_frac to
improve FE and reduce engine cycling
% 11/03/99:ss updated version from 2.2 to 2.21
% 1/12/00:tm introduced cs_charge_deplete_bool
```

```
% 8/9/00:tm updated default value of cs_charge_trq due to block diagram
revision
% 8/16/00:tm removed cs_offset_soc - no longer used in block diagram
% 8/16/00:tm introduced cs_electric_launch_spd_lo and _hi to replace
cs_electric_launch_spd
% 8/16/00:tm introduced vc_fc_warm_tmp_frac to control engine on state
based on coolant temperature
% 11/1/00:tm introduced cs_electric_decel_spd to prevent engine
shutdown at high speeds
% 7/30/01:tm updated version from 3.1 to 3.2
% 7/30/01:tm added new auto scaled shift map
% 7/31/01:mpo added variables for speed dependent shifting
```

```
% ADVISOR data file: ACC_CONV_SCHOOL_BUS.m
%
% Data source: estimates
%
% Data confirmation: none
%
% Notes:
% Defines standard accessory load data for a conventional school bus--
default
% values are for A/C off but values with A/C on are given (commented
out).
%
% Created on: 27 September 2003
% By: EGDP, Ewan Pritchard, Advanced Energy Corp., NCSU,
epritcha@advancedenergy.org
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
acc_description='Conventional school bus vehicle accessory loads',
acc_version=2002, % version of ADVISOR for which the file was generated
acc_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
acc_validation=0, % 0=> no validation, 1=> data agrees with source
data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: ACC_CONV_SCHOOL_BUS - ',acc_description])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% load breakdown (mechanical): aux. load breakdown assumed for school
bus
% alternator load =     ~ 500 W (Without HVAC Blowers)
% engine fan =       ~ 7450 W (20 HP, from SAE Handbook, on 50% of the
time)
% HVAC Compressors =    ~ 5200 W (From Carrier)
% HVAC Blowers =      ~ 800 W (From Carrier)
% Water Pump =       ~ 2000 W (Estimate)
% Hydraulic Steering Pump = ~ 1500 W (2 HP, from SAE Handbook)

acc_mech_pwr=         11450, % (W) without Air Conditioning
%acc_mech_pwr=        17450, % (W) with Air Conditioning
%acc_mech_pwr=        24900, % (W) with Air Conditioning and full fan
power

% load breakdown (electrical): 15 Aug 2001 [mpo] assumed to be taken
care of in mechanical alternator
% --assuming daytime running with minimal lighting/electrical load
```

```
acc_elec_pwr=0, % (W), electrical acc. load, drawn from the
voltage/power bus--accounted for w/alternator above
acc_mech_eff=1, % efficiency of accessory
acc_elec_eff=1, %
acc_mech_trq=0, % (Nm), constant torque load on engine

vinf.AuxLoads=load('Default_aux.mat'),
vinf.AuxLoadsOn=0,

clear acc_air_comp_pwr acc_alternator_pwr acc_cooling_fan_pwr
acc_air_cond_pwr

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 9/27/2003: (ep) Created from ACC_CONV_BUS.m
% 2/08/2004: (ep) updated load breakdown


% Begin added by ADVISOR 2002 converter: 18-Jan-2004
vinf.AuxLoads=load('Default_aux.mat'),vinf.AuxLoadsOn=0,

% End added by ADVISOR 2002 converter: 18-Jan-2004
```

```
% SchoolBus_ser_in.m ADVISOR 2002 input file created: 21-Mar-2004
12:50:26

global vinf

vinf.name='SchoolBus_ser_in',
vinf.drivetrain.name='series',
vinf.fuel_converter.name='FC_CI163_emis_d2_poly',
vinf.fuel_converter.ver='ic',
vinf.fuel_converter.type='ci',
vinf.generator.name='GC_ETA95',
vinf.generator.ver='reg',
vinf.generator.type='reg',
vinf.motor_controller.name='MC_AC75',
vinf.energy_storage.name='ESS_PB85',
vinf.energy_storage.ver='rint',
vinf.energy_storage.type='pb',
vinf.transmission.name='TX_1SPD',
vinf.transmission.ver='man',
vinf.transmission.type='man',
vinf.wheel_axle.name='WH_CSCHBUS',
vinf.wheel_axle.ver='Crr',
vinf.wheel_axle.type='Crr',
vinf.vehicle.name='VEH_ClassCSchoolBus',
vinf.exhaust_aftertreat.name='EX_CI_NOCAT',
vinf.powertrain_control.name='PTC_SER_NPISchoolBus',
vinf.powertrain_control.ver='ser',
vinf.powertrain_control.type='man',
vinf.accessory.name='ACC_CONV_SCHOOL_BUS',
vinf.accessory.ver='Const',
vinf.accessory.type='Const',
vinf.variables.name{1}='gc_spd_scale',
vinf.variables.value(1)=0.35,
vinf.variables.default(1)=1,
vinf.variables.name{2}='gc_trq_scale',
vinf.variables.value(2)=1.7734,
vinf.variables.default(2)=1,
vinf.variables.name{3}='wh_1st_rrc',
vinf.variables.value(3)=0.00938,
vinf.variables.default(3)=0.008,
vinf.variables.name{4}='mc_trq_scale',
vinf.variables.value(4)=1.8893,
vinf.variables.default(4)=1,
vinf.variables.name{5}='mc_overtrq_factor',
vinf.variables.value(5)=1.2,
vinf.variables.default(5)=1.8,
vinf.variables.name{6}='ess_module_num',
vinf.variables.value(6)=60,
vinf.variables.default(6)=0,
vinf.variables.name{7}='fc_trq_scale',
vinf.variables.value(7)=0.76743,
vinf.variables.default(7)=1,
```

```
% SchoolBus_par_in.m ADVISOR 2002 input file created: 22-Mar-2004
20:54:35

global vinf

vinf.name='SchoolBus_par_in',
vinf.drivetrain.name='parallel',
vinf.fuel_converter.name='FC_CI163_emis_d2_poly',
vinf.fuel_converter.ver='ic',
vinf.fuel_converter.type='ci',
vinf.torque_coupling.name='TC_DUMMY',
vinf.motor_controller.name='MC_AC75',
vinf.energy_storage.name='ESS_AnnexVII_SHEV_NIMH28',
vinf.energy_storage.ver='rint',
vinf.energy_storage.type='nimh',
vinf.transmission.name='TX_ALL2000',
vinf.transmission.ver='man',
vinf.transmission.type='man',
vinf.wheel_axle.name='WH_CSCHBUS',
vinf.wheel_axle.ver='Crr',
vinf.wheel_axle.type='Crr',
vinf.vehicle.name='VEH_ClassCSchoolBus_PERF',
vinf.exhaust_aftertreat.name='EX_CI_NOCAT',
vinf.powertrain_control.name='PTC_PAR',
vinf.powertrain_control.ver='par',
vinf.powertrain_control.type='man',
vinf.accessory.name='ACC_CONV_SCHOOL_BUS_PERF',
vinf.accessory.ver='Const',
vinf.accessory.type='Const',
vinf.variables.name{1}='fc_trq_scale',
vinf.variables.value(1)=0.83187,
vinf.variables.default(1)=1,
vinf.variables.name{2}='mc_trq_scale',
vinf.variables.value(2)=1.0049,
vinf.variables.default(2)=1,
vinf.variables.name{3}='ess_module_num',
vinf.variables.value(3)=40,
vinf.variables.default(3)=0,
```

```
% ADVISOR Data file: MC_AC75.m
%
% Data source:
% Lester, L.E., et al., "An Induction Motor Power Train for EVs--The
Right
% Power at the Right Price," reprinted in Proceedings: Advanced
Components for
% Electric and Hybrid Electric Vehicles, 10/27-28/93, Gaithersburg, MD.
% Mr. Lester was employed with Westinghouse in Maryland at that time,
and may
% be still.
%
% Data confidence level: Good: data from a published paper
%
% Notes: This is a Westinghouse, 75 kW, AC Induction motor
%     Efficiency/loss data appropriate for a 320 V system.
%
% Created on: 6/15/98
% By: MRC & KW
%
% Revision history at end of file.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mc_description='Westinghouse 75-kW (continuous) AC induction
motor/inverter',
mc_version=2002, % version of ADVISOR for which the file was generated
mc_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
mc_validation=0, % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: MC_AC75 - ',mc_description]),


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (rad/s), speed range of the motor
mc_map_spd=[0 1000 2000 3000 4000 5000 6000 7000 8000 9000
10000]*(2*pi/60),
% Note: the above conversion from rpm to rad/s was fixed 6/16/98

% (N*m), torque range of the motor
mc_map_trq=[-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 ...
      0 20 40 60 80 100 120 140 160 180 200]*4.448/3.281,


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EFFICIENCY AND INPUT POWER MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), efficiency map indexed vertically by mc_map_spd and
% horizontally by mc_map_trq
mc_eff_map=[...
0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7
      0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7   0.7
```

```
0.78  0.78  0.79  0.8   0.81  0.82  0.82  0.82  0.81  0.77  0.7   0.77
      0.81  0.82  0.82  0.82  0.81  0.8   0.79  0.78  0.78
0.85  0.86  0.86  0.86  0.87  0.88  0.87  0.86  0.85  0.82  0.7   0.82
      0.85  0.86  0.87  0.88  0.87  0.86  0.86  0.86  0.85
0.86  0.87  0.88  0.89  0.9   0.9   0.9   0.9   0.89  0.87  0.7   0.87
      0.89  0.9   0.9   0.9   0.9   0.89  0.88  0.87  0.86
0.81  0.82  0.85  0.87  0.88  0.9   0.91  0.91  0.91  0.88  0.7   0.88
      0.91  0.91  0.91  0.9   0.88  0.87  0.85  0.82  0.81
0.82  0.82  0.82  0.82  0.85  0.87  0.9   0.91  0.91  0.89  0.7   0.89
      0.91  0.91  0.9   0.87  0.85  0.82  0.82  0.82  0.82
0.79  0.79  0.79  0.78  0.79  0.82  0.86  0.9   0.91  0.9   0.7   0.9
      0.91  0.9   0.86  0.82  0.79  0.78  0.79  0.79  0.79
0.78  0.78  0.78  0.78  0.78  0.78  0.8   0.88  0.91  0.91  0.7   0.91
      0.91  0.88  0.8   0.78  0.78  0.78  0.78  0.78  0.78
0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.8   0.9   0.92  0.7   0.92
      0.9   0.8   0.78  0.78  0.78  0.78  0.78  0.78  0.78
0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.88  0.92  0.7   0.92
      0.88  0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.78
0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.8   0.92  0.7   0.92
      0.8   0.78  0.78  0.78  0.78  0.78  0.78  0.78  0.78],

%if ~exist('mc_inpwr_map')
 % disp('Converting: MC_AC75 motor map efficiency data --> power loss
data')
      %% find indices of well-defined efficiencies (where speed and
torque > 0)
      pos_trqs=find(mc_map_trq>0),
      pos_spds=find(mc_map_spd>0),

      %% compute losses in well-defined efficiency area
      [T1,w1]=meshgrid(mc_map_trq(pos_trqs),mc_map_spd(pos_spds)),
      mc_outpwr1_map=T1.*w1,
      mc_losspwr_map=(1./mc_eff_map(pos_spds,pos_trqs)-
1).*mc_outpwr1_map,

      %% to compute losses in entire operating range
      %% ASSUME that losses are symmetric about zero-torque axis, and
   %% ASSUME that losses at zero torque are the same as those at the
lowest
   %% positive torque, and
   %% ASSUME that losses at zero speed are the same as those at the
lowest
   %% positive speed
      mc_losspwr_map=[fliplr(mc_losspwr_map) mc_losspwr_map(:,1)
mc_losspwr_map],
      mc_losspwr_map=[mc_losspwr_map(1,:),mc_losspwr_map],

      %% compute input power (power req'd at electrical side of
motor/inverter set)
      [T,w]=meshgrid(mc_map_trq,mc_map_spd),
      mc_outpwr_map=T.*w,
      mc_inpwr_map=mc_outpwr_map+mc_losspwr_map,
%end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% max torque curve of the motor indexed by mc_map_spd
mc_max_trq=[200 200 200 175.2 131.4 105.1 87.6 75.1 65.7 58.4 52.5]*...
      4.448/3.281, % (N*m)

mc_max_gen_trq=-1*[200 200 200 175.2 131.4 105.1 87.6 75.1 65.7 58.4
52.5]*...
      4.448/3.281, % (N*m), estimate

% maximum overtorque capability (not continuous, because the motor
would overheat)
mc_overtrq_factor=1.8, % (--), estimated

mc_max_crrnt=480, % (A), maximum current allowed by the controller and
motor
mc_min_volts=120, % (V), minimum voltage allowed by the controller and
motor


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), used to scale mc_map_spd to simulate a faster or slower running
motor
mc_spd_scale=1.0,

% (--), used to scale mc_map_trq to simulate a higher or lower torque
motor
mc_trq_scale=1.0,


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mc_inertia=0, % (kg*m^2), rotor inertia, unknown
mc_mass=91, % (kg), mass of motor and controller



% user definable mass scaling function
mc_mass_scale_fun=inline('(x(1)*mc_trq_scale+x(2))*(x(3)*mc_spd_scale+x
(4))*mc_mass','x','mc_spd_scale','mc_trq_scale','mc_mass'),
mc_mass_scale_coef=[1 0 1 0], % mass scaling function coefficients


% motor/controller thermal model
mc_th_calc=1,               % --   0=no mc thermal calculations, 1=do
calc's
mc_cp=430,                % J/kgK ave heat capacity of motor/controller
(estimate: ave of SS & Cu)
mc_tstat=45,               % C   thermostat temp of motor/controler
when cooling pump comes on
mc_area_scale=(mc_mass/91)^0.7,      % --   if motor dimensions are
unknown, assume rectang shape and scale vs AC75
mc_sarea=0.4*mc_area_scale,        % m^2  total module surface area
exposed to cooling fluid (typ rectang module)
```

```
%the following variable is not used directly in modelling and should
always be equal to one
%it's used for initialization purposes
mc_eff_scale=1,

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLEAN UP
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear T w mc_outpwr1_map mc_outpwr_map mc_losspwr_map T1 w1 pos_spds
pos_trqs


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 6/12/98 (KW): converted data from A1.2.1 into A2 (as
MC_WESTINGHOUSE), have not yet verified
% 6/15/98 (KW): combined with MRC's MC_AC75.m and replaced both with
new one
% 6/16/98 (KW): speed vector multiplier from rpm to rad/s was correctly
inverted
% 6/23/98 (MC): disabled existence check preceding computation of input
power map
% 6/30/98 (MC): cosmetic changes
% 2/3/99 (SB): added thermal model variables
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/03/99:ss updated version from 2.2 to 2.21
% 11/1/00:tm added max gen trq placeholder data
% 7/30/01:tm added mass scaling function mass=f(mc_spd_scale,
mc_trq_scale, mc_mass)
%
% 30-Jul-2001: automatically updated to version 3.2
```

```
% ADVISOR data file:  GC_ETA95.m
%
% Data source:
%
% Data confirmation:
%
% Notes:
% Speed- and torque-independent efficiency=95%.
%
% Created on: 23-Jun-1998
% By:  MRC, NREL, matthew_cuddy@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
gc_description='Sample generator/controller file, 95% efficient';
gc_version=2002; % version of ADVISOR for which the file was generated
gc_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not
distribute
gc_validation=0; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: GC_ETA95 - ',gc_description])


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (N*m), torque vector corresponding to columns of efficiency & loss
maps
% this is INPUT torque (>0 => running as a generator)
gc_map_trq=[0:5:200];

% (rad/s), speed vector corresponding to rows of efficiency & loss maps
gc_map_spd=[0:250:7000]*(2*pi)/60;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSSES AND EFFICIENCIES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
gc_eff_map=ones(length(gc_map_spd),length(gc_map_trq))*0.95;  % (--)

% CONVERT EFFICIENCY MAP TO OUTPUT POWER MAP
[T1,w1]=meshgrid(gc_map_trq,gc_map_spd);
gc_inpwr_map=T1.*w1;
% (W), output power map indexed vertically by gc_map_spd and
horizontally
% by gc_map_trq
gc_outpwr_map=gc_inpwr_map.*gc_eff_map;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
gc_max_crrnt=480; % maximum current draw for motor/controller set, A
gc_min_volts=120; % minimum voltage for motor/controller set, V
% maximum continuous torque corresponding to speeds in mc_map_spd
gc_max_trq=200*ones(size(gc_map_spd));  % (N*m)


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFAULT SCALING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (--), used to scale fc_map_spd to simulate a faster or slower running
engine
gc_spd_scale=1.0;
% (--), used to scale fc_map_trq to simulate a higher or lower torque
engine
gc_trq_scale=1.0;

% user definable mass scaling relationship
gc_mass_scale_fun=inline('(x(1)*gc_trq_scale+x(2))*(x(3)*gc_spd_scale+x
(4))*gc_mass','x','gc_spd_scale','gc_trq_scale','gc_mass');
gc_mass_scale_coef=[1 0 1 0]; % mass scaling coefficiencts

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

gc_inertia=0.01;  % (kg*m^2), rotor's rotational inertia


% mass of generator and controller based on the specific mass of
GC_PM32 (0.8663 kW/kg)
gc_mass=max(gc_map_spd.*gc_max_trq)*gc_trq_scale*gc_spd_scale/1000/0.86
63;  % (kg)
% factor by which motor torque can exceed maximum continuous torque for
short
% periods of time
gc_overtrq_factor=1;  % (--)


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CLEAN UP
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear T1 w1 gc_inpwr_map


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 09/14/98:MC adjusted map torques to extend all the way up to max
torques
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 11/03/99:ss updated version from 2.2 to 2.21
% 7/30/01:tm updated version from 3.1 to 3.2
% 7/30/01:tm added mass scaling relationship
mass=f(gc_spd_scale,gc_trq_scale, gc_mass)
% 30-Jul-2001: automatically updated to version 3.2
```

```
% ADVISOR data file: ESS_AnnexVII_SerHyb_NIMH28_OVONIC.m
%
% Data source:
% Dennis Corrigan, Vice President of EV Battery Systems, Ovonic
%
% Data confirmation:
% Data provided by manufacturer.
%
% Notes: These are designed to be a high power, intermediate energy
battery.
% Cell type = M70
% Nominal Voltage = 6V
% Nominal Capacity (C/3) = 28Ah
% Dimensions (L * W * H) = 195mm X 102mm X 81mm
% Weight = 3.6kg
% Volume (modules only) = 1.6L
% Nominal Energy (C/3) = 175 Wh
% Peak Power (10s pulse @ 50%DOD @ 35 deg. C) = 1.6kW
%
% Created on: 4/7/00
% By: TM, NREL, tony_markel@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_description='Ovonic 28Ah NiMH HEV battery',
ess_version=2002, % version of ADVISOR for which the file was generated
ess_proprietary=0, % 0=> non-proprietary, 1=> proprietary, do not
distribute
ess_validation=1, % 0=> no validation, 1=> data agrees with source
data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: ESS_AnnexVII_SerHyb_NIMH28_OVONIC.m -
',ess_description])


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SOC RANGE over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_soc=[0:.1:1], % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Temperature range over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_tmp=[0 22 40], % (C)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS AND EFFICIENCY parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Parameters vary by SOC horizontally, and temperature vertically

ess_max_ah_cap=[
```

```
  28
  28
  28
],    % (A*h), max. capacity at C/5 rate, indexed by ess_tmp

% average coulombic (a.k.a. amp-hour) efficiency below, indexed by
ess_tmp
ess_coulombic_eff=[
  1
  1
  1
]*0.99, % (--),

% module's resistance to being discharged, indexed by ess_soc and
ess_tmp
ess_r_dis=[0.01266 0.00685    0.00644     0.00599     0.00587
      0.00575     0.00568     0.00581     0.00623     0.00667 0.00635
             0.01266 0.00685  0.00644     0.00599     0.00587
      0.00575     0.00568     0.00581     0.00623     0.00667 0.00635
      0.01266 0.00685   0.00644     0.00599     0.00587     0.00575
      0.00568     0.00581     0.00623     0.00667 0.00635
    ], % (ohm)

% module's resistance to being charged, indexed by ess_soc and ess_tmp
ess_r_chg=ess_r_dis,% (ohm), no other data available

% module's open-circuit (a.k.a. no-load) voltage, indexed by ess_soc
and ess_tmp
%ess_voc=[11.9 12.3 12.6 12.8 12.9 12.9 13 13.1 13.2 13.4 13.7,
%  11.9 12.3 12.6 12.8 12.9 12.9 13 13.1 13.2 13.4 13.7,
%  11.9 12.3 12.6 12.8 12.9 12.9 13 13.1 13.2 13.4 13.7]/10*5, % (V),
Source: Ovonic Charge-decreasing
ess_voc=[12.5 12.8 13.1 13.3 13.4 13.4 13.5 13.6 13.7 13.9 14.2,
  12.5 12.8 13.1 13.3 13.4 13.4 13.5 13.6 13.7 13.9 14.2,
  12.5 12.8 13.1 13.3 13.4 13.4 13.5 13.6 13.7 13.9 14.2]/10*5, % (V),
Source: Ovonic Charge-sustaining
%ess_voc=[12.8 13.2 13.5 13.7 13.8 13.8 13.9 14 14.1 14.3 14.6,
%  12.8 13.2 13.5 13.7 13.8 13.8 13.9 14 14.1 14.3 14.6,
%  12.8 13.2 13.5 13.7 13.8 13.8 13.9 14 14.1 14.3 14.6]/10*5, % (V),
Source: Ovonic Charge-increasing

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_min_volts=0.87*1.05*5, % (V), 0.87*105% safety factor volts time 5
cells
ess_max_volts=1.65*0.95*5,% (V), 1.65*95% safety factor volts times 5
cells



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_module_mass=3.6, % (kg), mass of a single ~6 V module
ess_module_volume=0.195*0.102*0.081, % (m^3), length X width X height
ess_module_num=65, %a default value for number of modules
```

```
% battery thermal model
ess_th_calc=1,                % --   0=no ess thermal calculations, 1=do
calc's
ess_mod_cp=830,               % J/kgK ave heat capacity of module
(estimated for NiMH)
ess_set_tmp=35,               % C   thermostat temp of module when
cooling fan comes on
ess_area_scale=1.6*(ess_module_mass/11)^0.7,  % --   if module
dimensions are unknown, assume rectang shape and scale vs PB25
%tm:3/24/00 ess_mod_sarea=0.2*ess_area_scale,     % m^2  total module
surface area exposed to cooling air (typ rectang module)
ess_mod_sarea=2*(0.195*0.081+0.102*0.081),     % m^2  total module
surface area exposed to cooling air (typ rectang module)
ess_mod_airflow=0.01,           % kg/s  cooling air mass flow rate
across module (20 cfm=0.01 kg/s at 20 C)
%tm:3/24/00 ess_mod_flow_area=0.005*ess_area_scale,  % m^2  cross-sec
flow area for cooling air per module (assumes 10-mm gap btwn mods)
ess_mod_flow_area=0.005*2*(0.195+0.102),  % m^2  cross-sec flow area
for cooling air per module (assumes 10-mm gap btwn mods)
ess_mod_case_thk=2/1000,          % m   thickness of module case (typ
from Optima)
ess_mod_case_th_cond=0.20,         % W/mK  thermal conductivity of
module case material (typ polyprop plastic - Optima)
ess_air_vel=ess_mod_airflow/(1.16*ess_mod_flow_area), % m/s ave
velocity of cooling air
ess_air_htcoef=30*(ess_air_vel/5)^0.8,   % W/m^2K cooling air heat
transfer coef.
ess_th_res_on=((1/ess_air_htcoef)+(ess_mod_case_thk/ess_mod_case_th_con
d))/ess_mod_sarea, % K/W tot thermal res key on
ess_th_res_off=((1/4)+(ess_mod_case_thk/ess_mod_case_th_cond))/ess_mod_
sarea, % K/W tot thermal res key off (cold soak)
% set bounds on flow rate and thermal resistance
ess_mod_airflow=max(ess_mod_airflow,0.001),
ess_th_res_on=min(ess_th_res_on,ess_th_res_off),
clear ess_mod_sarea ess_mod_flow_area ess_mod_case_thk
ess_mod_case_th_cond ess_air_vel ess_air_htcoef ess_area_scale


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 4/7/00:tm file created
% 9/7/00:tm updated OCV data and removed fliplr from charge resistance
definition
% Begin added by ADVISOR 2002 converter: 17-Apr-2002
ess_cap_scale=1,

ess_mass_scale_coef=[1 0 1 0],


ess_res_scale_coef=[1 0 1 0],


ess_mass_scale_fun=inline('(x(1)*ess_module_num+x(2))*(x(3)*ess_cap_sca
le+x(4))*(ess_module_mass)','x','ess_module_num','ess_cap_scale','ess_m
odule_mass'),
```

```
ess_res_scale_fun=inline('(x(1)*ess_module_num+x(2))/(x(3)*ess_cap_scal
e+x(4))','x','ess_module_num','ess_cap_scale'),
% End added by ADVISOR 2002 converter: 17-Apr-2002
```

```
% ADVISOR data file:  ESS_PB85.m    where 85 is c/5-rate capacity
%
% Data source:
% File created from ESS_PB91.m
%
% Data confirmation:
% Not confirmed
%
% Notes:
% This battery model has been created in attempt to model lead acid
batteries
% used in Orion VI series hybrid transit bus. ess_voc, ess_max_ah_cap,
and
% ess_module_num have been changed from their values in ESS_PB91. All
other
% values have been left as is.
%
% Created on: Oct-2000
% By:  mpo, NREL, Michael_O'Keefe@nrel.gov
%
% Revision history at end of file.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_description='Horizon 12N85 lead-acid battery';
ess_version=2002; % version of ADVISOR for which the file was generated
ess_proprietary=0; % 0=> non-proprietary, 1=> proprietary, do not
distribute
ess_validation=0; % 0=> no validation, 1=> data agrees with source
data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: ESS_PB85 - ',ess_description])


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SOC RANGE over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_soc=[0:.1:1];  % (--)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Temperature range over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_tmp=[0 22 40];  % (C)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOSS AND EFFICIENCY parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Parameters vary by SOC horizontally, and temperature vertically
ess_max_ah_cap=[
   85
   85
   85
```

```
];    % (A*h), max. capacity at C/5 rate, indexed by ess_tmp, changed
from 91 by mpo Oct-2000
% average coulombic (a.k.a. amp-hour) efficiency below, indexed by
ess_tmp
ess_coulombic_eff=[
   .9
   .9
   .9
];  % (--);
% module's resistance to being discharged, indexed by ess_soc and
ess_tmp
ess_r_dis=[
   4.57 2.686 2.226 1.970 1.843 1.747 1.711 1.685 1.697 1.756 1.769
   4.57 2.686 2.226 1.970 1.843 1.747 1.711 1.685 1.697 1.756 1.769
   4.57 2.686 2.226 1.970 1.843 1.747 1.711 1.685 1.697 1.756 1.769
]/1000; % (ohm)
% module's resistance to being charged, indexed by ess_soc and ess_tmp
%ess_r_chg=ess_r_dis; % (ohm), no other data available
ess_r_chg=fliplr(ess_r_dis); % (ohm), no other data available tm:022800
% module's open-circuit (a.k.a. no-load) voltage, indexed by ess_soc
and ess_tmp
ess_voc=[
   11.406 11.73 11.904 12.096 12.216 12.384 12.492 12.636 12.75 12.918
12.99
   11.406 11.73 11.904 12.096 12.216 12.384 12.492 12.636 12.75 12.918
12.99
   11.406 11.73 11.904 12.096 12.216 12.384 12.492 12.636 12.75 12.918
12.99
]*12/12.384; % (V) Voltages changed slightly for better modeling fit
mpo, oct 2000


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LIMITS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_min_volts=9.5;
ess_max_volts=16.5;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OTHER DATA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_module_mass=24.9;  % (kg), mass of a single ~12 V module

ess_module_num=46;  %a default value for number of modules; corresponds
to default number of modules in Orion VI transit bus

ess_cap_scale=1; % scale factor for module max ah capacity

% user definable mass scaling relationship
ess_mass_scale_fun=inline('(x(1)*ess_module_num+x(2))*(x(3)*ess_cap_sca
le+x(4))*(ess_module_mass)','x','ess_module_num','ess_cap_scale','ess_m
odule_mass');
ess_mass_scale_coef=[1 0 1 0]; % coefficients in ess_mass_scale_fun

% user definable resistance scaling relationship
```

```
ess_res_scale_fun=inline('(x(1)*ess_module_num+x(2))/(x(3)*ess_cap_scal
e+x(4))','x','ess_module_num','ess_cap_scale');
ess_res_scale_coef=[1 0 1 0]; % coefficients in ess_res_scale_fun

% battery thermal model
ess_th_calc=1;                             % --     0=no ess thermal
calculations, 1=do calc's
ess_mod_cp=660;                            % J/kgK  ave heat capacity
of module (typical Pb bat - from Optima)
ess_set_tmp=35;                            % C      thermostat temp of
module when cooling fan comes on
ess_area_scale=(ess_module_mass/11)^0.7;   % --     if module
dimensions are unknown, assume rectang shape and scale vs PB25
ess_mod_sarea=0.2*ess_area_scale;          % m^2    total module
surface area exposed to cooling air (typ rectang module)
ess_mod_airflow=0.01;                      % kg/s   cooling air mass
flow rate across module (20 cfm=0.01 kg/s at 20 C)
ess_mod_flow_area=0.005*ess_area_scale;    % m^2    cross-sec flow area
for cooling air per module (assumes 10-mm gap btwn mods)
ess_mod_case_thk=2/1000;                   % m      thickness of module
case (typ from Optima)
ess_mod_case_th_cond=0.20;                 % W/mK   thermal
conductivity of module case material (typ polyprop plastic - Optima)
ess_air_vel=ess_mod_airflow/(1.16*ess_mod_flow_area); % m/s  ave
velocity of cooling air
ess_air_htcoef=30*(ess_air_vel/5)^0.8;      % W/m^2K cooling air heat
transfer coef.
ess_th_res_on=((1/ess_air_htcoef)+(ess_mod_case_thk/ess_mod_case_th_con
d))/ess_mod_sarea; % K/W  tot thermal res key on
ess_th_res_off=((1/4)+(ess_mod_case_thk/ess_mod_case_th_cond))/ess_mod_
sarea; % K/W  tot thermal res key off (cold soak)
% set bounds on flow rate and thermal resistance
ess_mod_airflow=max(ess_mod_airflow,0.001);
ess_th_res_on=min(ess_th_res_on,ess_th_res_off);
clear ess_mod_sarea ess_mod_flow_area ess_mod_case_thk
ess_mod_case_th_cond ess_air_vel ess_air_htcoef ess_area_scale


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% REVISION HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 6/30/98 (MC): converted from E_H12N85.M
% 10/13/98:mc recomputed ess_max_ah_cap and renamed file (from
ESS_PB85)
%             for consistency with other files
% 02/09/99 (SDB):  added thermal model inputs
% 2/4/99 ss: added ess_module_num=25;
% 3/15/99:ss updated *_version to 2.1 from 2.0
% 8/5/99:ss deleted all peukert coefficient and data(no longer needed
in advisor model)
%           added limits 'ess_max_volt' and 'ess_min_volt'
%9/9/99: vhj changed variables to include thermal modeling (matrices,
not vector), added ess_tmp

% 11/03/99:ss updated version from 2.2 to 2.21
% 3/15/00 tm added fliplr to ess_r_chg to more realistically represnt
the expected charge resistance trend
```

```
% 01-Oct-2000 mpo: created ESS_PB85.m file from ESS_PB91.m
% 19-Jan-2001 mpo: updated version from 3.0 to 3.1
% 7/30/01:tm added user defineable scaling functions for
mass=f(ess_module_num,ess_cap_scale,ess_module_mass)
%            and
resistance=f(ess_module_num,ess_cap_scale)*base_resistance
```