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Milestone Report

An Analysis of Hybrid Electric Propulsion Systems for Transit Buses

Milestone Completion Report

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Executive Summary

The future of America's truck and bus industry depends upon its ability to produce cost effective, high quality, environmentally sensitive, and safe vehicles. To spur innovation, agencies of the U.S. Government have partnered with industry for various heavy vehicle programs. The National Renewable Energy Laboratory (NREL) conducted heavy vehicle systems analysis for two such government/industry programs: the 21st Century Truck Program (21CT) and the U.S. Department of Energy (DOE) Advanced Heavy Vehicle Hybrid Propulsion System R & D Program (Heavy Hybrid Program).

Systems analysis work on transit bus platforms for the 21CT Program and Heavy Hybrid Program is presented here. Simulation is conducted using NREL's publicly available vehicle simulation tool, ADVISOR (ADvanced VehIcle SimulatOR) updated and modified for heavy vehicle analysis.

Prior to December 2000, NREL conducted an energy efficiency pathway analysis to include in the *Technology Roadmap for the 21st Century Truck Program*. The pathway analysis investigates the potential to increase fuel economy over a representative baseline vehicle via step-wise advancements in technology. This original study predicted a fuel economy of 2.6 times the baseline transit-bus fuel economy could be reached. The baseline vehicle was chosen using government and industry input and NREL test data. The methodology and data used to choose the baseline are reviewed herein.

The original 21CT pathway is revisited in this report using updated models and assumptions. Using a slightly modified energy pathway based on the original assumptions from the 21CT *Technology Roadmap*, simulation again predicts 2.6 times baseline fuel economy can be achieved. Using further revised assumptions, simulation predicts that 1.7 times baseline fuel economy can be reached. The key difference in assumptions between the two analyses involves the auxiliary load reduction potential assumed. The revised assumptions do not assume as great of an auxiliary load reduction as the original analysis. A summary of the results for the 21CT section of this study appears in Table A. Hybridization, weight reduction, and auxiliary load reduction play key roles in increasing fuel economy for both analyses.

The assumptions made for step-wise technological advancements have a significant effect on final predicted fuel economy for the pathway analysis. Therefore, a set of parametric plots showing variation in fuel economy by key parameter is presented. Key parameters examined include vehicle weight, auxiliary loads, rolling resistance, drive cycle, and aerodynamic drag. Using this data, the reader can estimate the fuel economy resulting from custom assumptions.

The goals of the Heavy Hybrid Program are investigated by performing a pathway analysis similar to the 21CT analysis. At the time of this analysis (October 2001), the Heavy Hybrid Program was focusing on natural gas as a fuel. Therefore, compressed natural gas (CNG) transit bus models were examined. Both a natural-gas-fueled transit bus and a diesel-fueled transit bus were considered for use in defining baseline fuel economy.

Pathway assumptions similar to the revised assumptions from the 21CT program are used in the Heavy Hybrid Program analysis. Under these assumptions, simulation predicts 1.8 times CNG baseline fuel economy is achievable. If a diesel baseline fuel economy is assumed, with a CNG vehicle using revised 21CT program assumptions, only 1.5 times baseline fuel economy is predicted. The predicted fuel economy for both baselines is below the desired program goal of 2 times baseline fuel economy.

If a greater reduction in auxiliary loads is assumed, 2.1 times CNG baseline fuel economy is achievable according to simulation. This reduction in auxiliary loads could be achieved by using non-conventional air-condition technology such as evaporative cooling. If a diesel baseline fuel economy is assumed, only 1.7 times baseline fuel economy is predicted. A summary of Heavy Hybrid Program simulation results is given

in Table B for a CNG baseline. Similar to the diesel buses, parametric plots are given to allow prediction of CNG bus fuel economy based on the reader's assumptions.

Table A. Summary of Energy Efficiency Pathway for Transit Models related to the 21st Century Truck (21CT) Program

Component Energy Utilization	Baseline Conventional Transit Bus		21CT Pathway*		Revised 21CT Pathway	
	Energy over drive cycle (kWh)	Percent Total Energy Use	Energy over drive cycle (kWh)	Percent Total Energy Use	Energy over drive cycle (kWh)	Percent Total Energy Use
Engine losses	14.15	59%	4.78	52%	7.80	55%
Auxiliary loads	4.94	21%	1.83	20%	3.83	27%
Drivetrain losses	2.41	10%	0.24	3%	0.26	2%
Generator losses	NA	NA	0.18	2%	0.19	1%
Energy storage system losses	NA	NA	0.17	2%	0.18	1%
Motor/controller losses	NA	NA	0.47	5%	0.48	3%
Friction braking	1.10	5%	0.63	7%	0.69	5%
Aerodynamic losses	0.24	1%	0.24	3%	0.24	2%
Rolling resistance losses	1.20	5%	0.56	6%	0.62	4%
Regenerative Braking Capture Efficiency	NA		49%		49%	
Powertrain Efficiency	36%		52%		38%	
Transit bus test weight (lbs.)	32006		21710		24021	
Total energy used over CBD-14 (kWh)	24.05		9.11		14.29	
Fuel consumption over CBD-14 (mpg)	3.20		8.46		5.39	
Fuel economy multiplier	1.00		2.64		1.68	

CBD-14 = Central Business District Drive cycle

*Slightly modified to resolve internal inconsistencies and add additional energy-saving steps.

The effect of auxiliary loads on fuel economy is one focus of this study. The baseline transit vehicles are defined as being under high auxiliary load (with air conditioning on). This allows the benefits of auxiliary load reduction to show up in the efficiency process. Two programs at NREL to increase auxiliary load modeling capability are discussed. One program involves a co-simulation to address vehicle electrical loads using Saber ® coupled with ADVISOR. Another program integrates several computer models together to evaluate thermal comfort. Models include a solar loading and window glazing model, a cabin thermal-fluid model, and a transient air conditioning model.

Some concluding observations based on this work are:

- a given increase in auxiliary load (such as from an air conditioner) is observed to have a greater impact on series-hybrid bus fuel economy than conventional bus fuel economy

- a given increase in a key parameter (such as vehicle weight, auxiliary load, rolling resistance, etc.) has a greater impact on a high fuel economy vehicle than a low fuel economy vehicle in terms of miles per gallon

- hybridization, weight reduction, and auxiliary load reduction consistently stand out as key aspects for increasing transit bus fuel economy

Table B. Summary of Modeling Work for the Heavy Hybrid Program (Natural Gas Fuel)

Component Energy Utilization	Baseline CNG Transit Bus		Pathway Similar to 21CT Revised		Pathway Similar to 21CT Revised with Further A/C Load Reduction	
	Energy Lost over drive cycle(kJ)	Percent Energy Lost	Energy Lost over drive cycle(kJ)	Percent Energy Lost	Energy Lost over drive cycle(kJ)	Percent Energy Lost
Engine losses	18.99	66%	9.35	59%	8.41	60%
Auxiliary loads	4.70	16%	3.83	24%	2.79	20%
Drivetrain losses	2.49	9%	0.27	2%	0.27	2%
Generator losses	NA	NA	0.19	1%	0.19	1%
Energy storage system losses	NA	NA	0.17	1%	0.18	1%
Motor/controller losses	NA	NA	0.49	3%	0.49	4%
Friction braking	1.16	4%	0.73	5%	0.73	5%
Aerodynamic losses	0.24	1%	0.24	2%	0.24	2%
Rolling resistance losses	1.26	4%	0.66	4%	0.66	5%
Regenerative Braking Capture Efficiency	NA		49%		49%	
Powertrain Efficiency	38%		40%		47%	
Transit bus test weight (lbs.)	15223		11500		11500	
Total energy used over CBD-14 (kWh)	28.83		15.93		13.96	
Fuel consumption over CBD-14 (mpg)	2.67		4.84		5.52	
Fuel economy multiplier	1.00		1.81		2.07	

CBD-14 = Central Business District drive cycle; Note: fuel economy is reported as miles per gallon equivalent of diesel fuel

- for a series hybrid transit bus optimized under the pathway assumptions, both of the hybrid control strategies examined in this study ("thermostat" or "series power-follower") yield approximately the same fuel economy

- engine downsizing shows dramatic increases in fuel economy under a "series power-following" control strategy but only minimal increases under a "thermostat" control strategy

- series-hybrid transit buses are observed to loose their fuel economy advantage over conventional transit buses when run on high-speed, steady-state duty cycles

- reduction in aerodynamic drag on a transit bus for the purpose of improving fuel economy is not significant for low-speed duty cycles such as the Central Business District cycle (average speed of 12.6 mph), but may be significant for high speed cycles such as the commuter cycle (average speed of 43.8 mph) provided that large reductions in drag coefficient can be achieved

- changes in auxiliary load reduction assumptions during the pathway analysis have a significant effect on final predicted fuel economy

- data for recent transit buses with 5 speed automatic transmissions tend to yield higher fuel economies over the CBD-14 than buses with 3-speed automatic transmissions, especially if ton-mpg units are taken into account

1 Introduction

The future of America's truck and bus industry depends upon its ability to produce cost effective, high quality, environmentally sensitive, and safe vehicles. To spur innovation, agencies of the U.S. Government have partnered with industry for various heavy vehicle projects. Several such partnerships exist and are steadily gaining momentum.

On the 21st of April, 2000, then Vice President Gore announced the 21st Century Truck Program (21CT). As a government-industry partnership, the 21CT Program seeks to improve fuel efficiency, reduce emissions, enhance safety, reduce total owning/operating costs, and maintain or enhance the performance of trucks and transit buses.

Another program, run through the U.S. Department of Energy's Office of Freedom CAR and Vehicle Technologies (OFCVT), is the Advanced Heavy Vehicle Hybrid Propulsion Systems R & D Program (hereafter referred to as the Heavy Hybrid Program). The goal of the current Advanced Heavy Hybrid Program is to develop and demonstrate commercially viable heavy vehicles that achieve up to a 100% increase in fuel economy of existing baseline vehicles by the year 2008. Three teams from industry have been competitively selected for work on the Heavy Hybrid Program.

The National Renewable Energy Laboratory (NREL) located in Golden, Colorado is a national laboratory owned by the U.S. Department of Energy. NREL is dedicated to developing renewable energy and energy efficiency technologies and practices, advancing related science and engineering, and transferring knowledge and innovations to address the nation's energy and environmental goals. As part of this mission, NREL's Center for Transportation Technologies and Systems (CTTS) has been actively involved in both the 21CT and Heavy Hybrid Programs with vehicle systems analysis. Systems analysis provides valuable insight into critical technologies, areas of technical merit, vehicle configurations and control strategies, and fuel economy potentials. This report details NREL's transit bus modeling work related to both the 21CT and Heavy Hybrid Programs.

2 Background on Transit Bus Model Development

In September of 2000, NREL began developing transit bus models for a technical target analysis. An industry peer-reviewed analysis of the potential to triple transit bus fuel economy over a representative baseline was conducted. This analysis appears in the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000).

Transit bus model improvement and development continued after the initial submission for the 21CT Program. Transit bus models were improved to meet real-world performance requirements of acceleration and gradability. In addition, powertrain development was improved to more closely reflect actual energy use and hybrid control strategies. These improved diesel transit bus models, a conventional and series-hybrid-electric, serve as the backbone for this work.

For early phases of the Heavy Hybrid Program, a CNG transit bus analysis was required. The improved diesel transit bus models were modified to reflect modern day CNG transit buses. These modifications included using an 8.1 liter John Deere CNG engine, as well as changes to reflect the added weight of CNG fuel-storage cylinders.

The transit bus models used for the 21st Century Truck and Heavy Hybrid Programs were developed using ADVISOR. ADVISOR (ADvanced VehIcle SimulatOR) is NREL's hybrid vehicle modeling software. ADVISOR is an open-source backward-forward computer model that runs in the MATLAB/Simulink environment. ADVISOR is offered free to the public from NREL's web-site. Details on ADVISOR as well as download information can be obtained from the NREL website (see ADVISOR 2002 and Markel *et. al.* 2002 for detail).

3 Diesel and Diesel Hybrid Bus Models

This section presents the results of a study conducted with conventional and series hybrid diesel transit bus models created in ADVISOR. These models were originally created for work appearing in the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000). The models have since been improved and adjusted. Thus, results presented here will not match those in the *Technology Roadmap* as the models used are slightly different.

The major differences between the models appearing in the *Technology Roadmap* (ibid.) and those presented here are:

- the conventional automatic transmission model has been improved
- gearing has been adjusted, allowing transit bus models to meet real-world performance specifications such as acceleration and gradability
- auxiliary loading has been adjusted to better represent actual auxiliary systems
- the hybrid control strategy has been adjusted

Modeling for the 21CT *Technology Roadmap* was used to set technical targets in response to the 21CT program goals. For the transit bus platform, the program goal is to triple fuel economy over a representative baseline. Simulation from the 21CT *Technology Roadmap* work predicted an achievable technical target of 2.6 times baseline fuel economy (21CT 2000). This same technical target analysis is revisited here using the improved models.

In order to conduct a technical target analysis, three key elements are required. The first is a baseline definition for reference. Secondly, realistic technical information on the extent to which the baseline technologies can be changed and improved is required. Lastly, a means to simulate improvements to the baseline is needed.

The baseline diesel transit bus definition is based on actual vehicle data. The details of baseline selection are presented in Section 3.1. The reader should note that the baseline diesel transit bus specification presented here is exactly the same as that used in the *Technology Roadmap for the 21st Century Truck Program*. The baseline specification is taken from test data. Input from the 21CT industry/government transit bus working group also played a key role in baseline determination. In this way, the baseline specification is a definition of sorts. Thus, it is not necessary to re-evaluate the baseline definition when model improvements are made.

Realistic technical information on the extent to which the baseline technologies can be changed and improved was obtained via industry feedback and input. Much of the input was received as a result of

NREL's participation in the 21st Century Truck Program. This input is applied in the efficiency analysis of Section 3.2.

The means to simulate transit bus potential fuel economy is provided by NREL's ADVISOR software (ADVISOR 2002 and Markel *et. al.2002*).

3.1 Baseline Fuel Economy

The transit-bus technical-target analysis to be included in the *Technology Roadmap for the 21st Century Truck Program* began in 2000. The first step of this process is to determine baseline fuel economy and vehicle configuration. Determination of the baseline can be broken into four areas: duty cycle, vehicle type, operating condition, and corresponding fuel economy.

The central business district cycle with 14 "peaks" (CBD-14) was selected for use in this analysis. The CBD-14 is pictured in Figure 1. There are several reasons for the selection of the CBD-14 as the representative cycle. First, the CBD-14 has a long history of use with transit buses. Because of this, a wealth of fuel economy data exists measured over the CBD-14. Secondly, the CBD-14 is frequently used in technical studies and papers and thus provides a means for comparison. Lastly, the CBD-14 captures the stop-and-go nature of a typical transit bus duty cycle. This last point is important as the benefits of hybridization are lost on relatively constant-speed cycles.

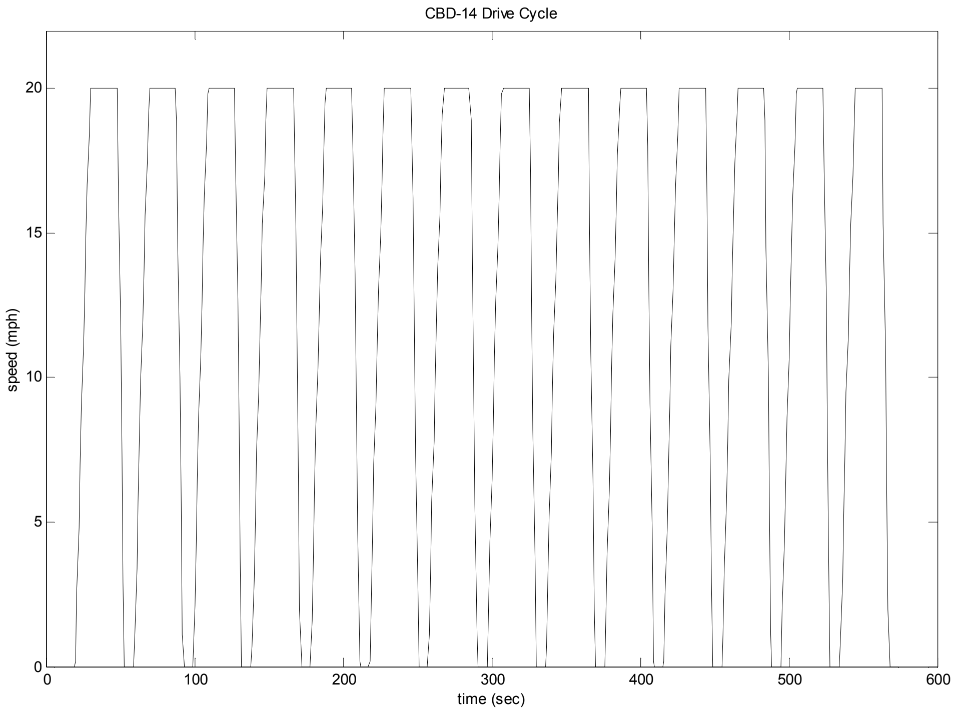


Figure 1 The Central Business District Drive Cycle (CBD-14)—average speed 12.6 mph

From the 21CT program plan, the baseline vehicle type is a 40' urban transit bus typical of year 1999-2000. In order to determine representative vehicle characteristics such as weight, dimensions, and fuel economy, real-world vehicle test data was consulted. NREL has been collecting test data such as fuel economy and emissions for various fleet vehicles for some time now. Many of these vehicles are transit buses tested over the CBD-14 drive cycle with a mobile chassis dynamometer. The mobile chassis dynamometer is operated by West Virginia University (for details, see Bata *et. al.* 1991, 1992; Clark *et. al.* 1995, 1999). These data were used to determine appropriate values for vehicle curb weight, dimensions, and fuel economy. For consistency sake, the vehicle chassis is arbitrarily based upon that of the Orion VI hybrid transit bus.

Fuel economy data by vehicle type from the NREL database appear in Figure 2. The average of all of the fuel economy tests conducted is about 3.5 mpg (diesel) over the CBD-14. The baseline specification is supposed to represent a recent transit bus of the late 1990's to year 2000. However, there is noticeable change in fuel economy over time apparent in the data of Figure 2. In addition, there is a large spread in transit bus model year (1988 to 1999). Therefore, it was decided to use only a subset of the database to determine fuel economy.

Transit bus data over the CBD-14 for model year 1996 and later is used to determine baseline fuel economy. Referencing Figure 2, the average fuel economy of transit buses model year 1996 and later is about 4-mpg diesel. Note that 4 of the 5 transit buses tested with model year 1996 and later employ 5-speed automatic transmissions. The fuel economy averages for these transit buses fall within ±1 standard deviation of 4 mpg (reference tags "O", "P", "Q", and "R" in Figure 2). One data point from the set of buses 1996 and later doesn't fall within ±1 standard deviation of 4 mpg. This point corresponds to tag "S" in Figure 2 and employs a 3-speed automatic transmission.

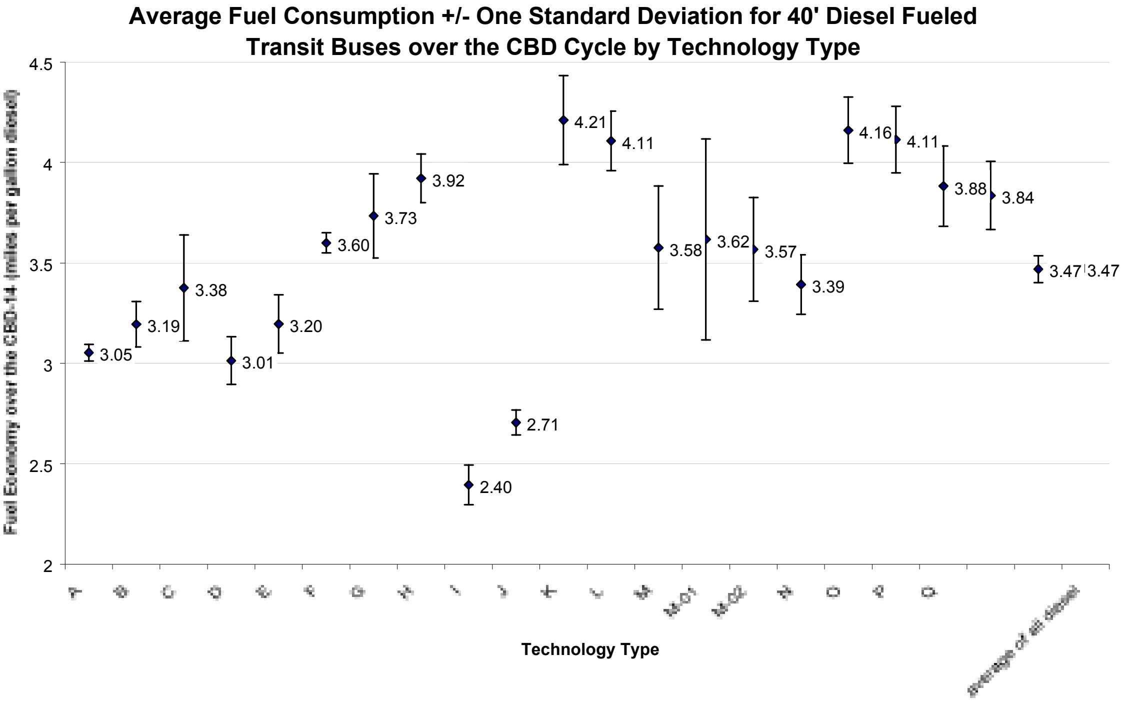
The chosen baseline vehicle type is a 40' diesel transit bus with 5-speed automatic transmission. The vehicle achieves 4 mpg over the CBD-14 drive cycle with air condition off. The chosen test weight for simulation is "half seated load weight". Half seated load weight (½ SLW) is equal to the vehicle curb weight plus the weight of half the seated passengers plus the driver. The baseline vehicle is defined to carry 50 seated passengers—a representative figure for a 40' transit bus. Thus, half seated-load weight is equal to curb weight plus the weight of 26 people (25 passengers plus driver). The standard transit assumption of 150 lbs. (68 kg) per person is assumed.

The chassis characteristics are chosen to be that of the Orion VI. This is done for consistency so that variation in fuel economy due to chassis differences does not appear between models. Rolling resistance and drag coefficient are taken from the settings used on the WVU mobile chassis dynamometer (McKain *et. al.* 2000). These settings are believed representative of real-world transit buses.

Next, the representative operating condition of the vehicle is discussed. Transit bus auxiliary loads have a major impact on fuel economy. This is especially true for "hotel loads" such as air conditioning, which provide for passenger comfort. For this reason, air-conditioning (the largest single auxiliary load) and other typical auxiliary loads are included in the baseline specification. By including the air-conditioning load in the baseline, the benefits of auxiliary load reduction can be observed.

Data on transit bus fuel economy measured with the air conditioning (A/C) on were not available. Therefore, a means of predicting baseline fuel economy with the air conditioning (A/C) engaged was required. A transit bus model *with A/C off* was created in ADVISOR and verified with existing data. Transit bus industry input was obtained for realistic values of auxiliary loading with both the A/C on and A/C off. The model corresponding to *A/C off* was used to predict fuel economy with *A/C on* by increasing the auxiliary load. Note that the details of auxiliary loading assumptions will be presented in Section 3.2.

The resulting final baseline specification is a late 1990's model year 40' diesel transit bus. The bus employs a 5-speed automatic transmission and is tested at half-seated load weight. The vehicle achieves 3.2 mpg over the CBD-14 drive cycle with A/C engaged.



Technology Type KEY

GRAPH TAG	Tech Type	Transmission	ave mpg	std dev in mpg	#bus	#tests	ave wt. (lb)	ton-mpg
A	1988 Gillig with 1997 electronically controlled Caterpillar 3126 D2	A4	3.05	0.04	1	3	35820	55
B	1988 FLXIBLE Metro DDC 6V-92TA DDEC I D2	A3	3.19	0.11	4	24	33725	54
C	1988, 1989 FLXIBLE Metro DDC 6V-92TA DDEC II D2	A3	3.38	0.26	4	51	33725	57
D	1990, FLXIBLE Metro DDC 6V-92TA D1	A3	3.01	0.12	4	29	33109	50
E	1988, 1990 FLXIBLE Metro DDC 6V-92TA D2	A3	3.20	0.14	3	15	33432	53
F	1990 FLEXIBLE Metro Cummins L10 D1	A3	3.60	0.05	2	9	33141	60
G	1990, 1992 FLEXIBLE Metro Cummins L10 D2	A4	3.73	0.21	7	38	33469	62
H	1991 BIA Orion Cummins L-10 D2	A4	3.92	0.12	5	42	31902	63
I	1991, 1993 GILLIG Phantom DDC 6V-92TA DDEC II D1	A4	2.40	0.10	10	94	34395	41
J	1991, 1993 GILLIG Phantom DDC 6V-92TA DDEC II D2	A4	2.71	0.06	4	19	33175	45
K	1992 FLXIBLE Metro Cummins L10 280 D2	A3	4.21	0.22	3	21	33690	71
L	1992 FLXIBLE Metro Cummins L10 280G D2	A3	4.11	0.15	2	16	33690	69
M	1993 TMC RTS-06 Detroit Diesel Corp Series 50 (DDEC III) D1	A3	3.58	0.31	5	66	33467	60
M-01	1993 TMC RTS-06 Detroit Diesel Corp Series 50 (DDEC III) D1 (heavy test weight)	A3	3.62	0.50	2	11	42000	76
M-02	1993 TMC RTS-06 Detroit Diesel Corp Series 50 (DDEC III) D1 (light test weight)	A3	3.57	0.26	5	55	31789	57
N	1994 New Flyer DDC Series 50 D2 (model unknown)	A4	3.39	0.15	3	16	32000	54
O	1996 Gillig Cummins M-11-280E+ diesel engine (CPL 2140) D2	A5	4.16	0.17	10	50	33480	70
P	1996 GILLIG Phantom Cummins M11-280E+ D2	A5	4.11	0.17	6	27	33480	69
Q	1996 New Flyer DDC s50 (205 kW) D2	A5	3.88	0.20	8	38	32825	64
R	1998 Nova Cummins M11-280E+ D2	A5	3.84	0.17	5	21	33200	64
S	1999 Nova RTS DDC s50 (205kW) D1	A3	3.47	0.07	3	11	35140	61
averages	average of all Diesel		3.47					
	average of all Diesel 1996 and after		3.98					

Figure 2 Fuel Economy Data by Technology Type for Various Transit Buses from NREL Database

Having a baseline specification defined, the next task is to predict a technical target for potential fuel economy. The pathway to increase energy efficiency will begin with the implementation of a hybrid propulsion system. The initial hybrid model is based upon test data and specifications for the Orion VI series hybrid electric transit bus.

A short discussion follows regarding the initial series-hybrid bus model. Data collected by NREL along with recent reports (NAVC 2000 and TCRP 2000) were used to create a "modern-day" hybrid bus model. This model and data are based upon the Orion VI hybrid transit bus with A/C off. Auxiliary loading was then applied to the ADVISOR model to predict fuel economy with the A/C on. The proper definition of the hybrid model is important. The first step in the efficiency analysis is a change from conventional to hybrid. The remainder of the pathway analysis builds directly on the hybrid model.

A summary of significant fuel economy values mentioned in this section appears in Table 1.

Table 1 Baseline Transit Bus Fuel Economy Values

Transit Bus Platform and Condition	Baseline Fuel Economy (mpg diesel equivalent)	Method of Determination
Conventional Diesel Transit Bus—A/C off	4.00	Based on chassis dynamometer data (fuel economy over CBD-14) for actual transit buses of model year 1996 and later
Conventional Diesel Transit Bus—A/C on —Baseline Fuel Economy—	3.20	Determined by adding best estimate for A/C loading to model with A/C off and simulating with ADVISOR. Consensus obtained for this value from 21CT Program Transit Bus Working Group (including industry and government partners)
Initial Series Hybrid Electric Vehicle—A/C off	4.26	Based on chassis dynamometer and component data for Orion VI series hybrid electric transit bus
Initial Series Hybrid Electric Vehicle—A/C on	3.32	Determined by adding best estimate for A/C loading and simulating with ADVISOR

It is interesting to note the ratios between hybrid and conventional fuel economy values listed in Table 1. The initial hybrid vehicle has 6.5% better fuel economy than the baseline conventional vehicle with the A/C system off. This is equivalent to 0.0153 gallons of diesel fuel saved over the CBD-14 by the hybrid. However, with A/C system on, the hybrid has only 3.75% better fuel economy than the baseline vehicle. This is equivalent to 0.0113 gallons of diesel fuel saved by the hybrid when A/C is on. Thus, the data seem to indicate that a given increase in auxiliary loads will reduce fuel economy in a hybrid vehicle more than in a conventional vehicle.

3.2 Energy Efficiency Analysis using ADVISOR

The model inputs assumed for the baseline conventional transit bus model are presented in Table 2. In Table 3, the inputs for the initial series-hybrid transit-bus model are presented. A breakdown of auxiliary loads assumed for the conventional and series-hybrid models appears in Table 4 and Table 5, respectively.

A note should be made on the determination of auxiliary loads. Representatives from industry and academia provided general power ranges for typical auxiliary systems. Specific power values were chosen within these "valid ranges" when matching the ADVISOR model to fuel economy test data.

Table 2 Model Inputs for Baseline Conventional 40' Transit Bus Model in ADVISOR

Input	Value
Chassis	based upon OBI[1] Orion VI (New York City Transit Configuration)
Simulated Vehicle Weight[2]	~32,000 lbs. (14515 kg)
Auxiliary Load (mechanical, run off of the engine)	31 kW constant with A/C on; 17 kW constant with A/C off
APU	205 kW (275 HP) 8.5 L Detroit Diesel S50, 44% peak efficiency
Transmission	Auto 5 speed
Rolling Resistance Coefficient[3] (RRC_0)	0.00938
Frontal Area	8.0516 m^2
Coefficient of Drag, C_D	0.79
Air Density	1.23 kg/m^3
Acceleration due to Gravity	9.81 m/s^2
Fuel Economy over CBD-14	3.20 mpg diesel with A/C on; 4.0 mpg diesel with A/C off

[1] OBI = Orion Bus Industries

[2] curb weight plus 26 people = ½ SLW [half seated load weight]; one person assumed to weigh 150 lbs.

[3] RRC_0 is independent of vehicle speed. Force due to rolling resistance = RRC_0 x (vehicle weight)

Table 3 Model Inputs for Initial Series Hybrid 40' Transit Bus Model in ADVISOR

Input	Value
Chassis	based upon OBI[4] Orion VI (New York City Transit Configuration)
Simulated Vehicle Weight[1]	35140 lbs. (15940 kg)
Auxiliary Loads	23 kW constant mechanical, 9 kW constant electrical with A/C on 9 kW constant mechanical, 9 kW constant electrical with A/C off
APU	171 kW (~230 HP) 7.3 L Navistar T444E/DDC S30, 44% peak efficiency
Transmission	Single reduction direct drive; final drive ratio of 6.34
Rolling Resistance Coefficient[2] (RRC_0)	0.00938
Frontal Area	8.0516 m^2
Coefficient of Drag, C_D	0.79
Air Density	1.23 kg/m^3
Electric Motor	187 kW AC (92% peak efficiency)
Battery	46 modules (85 Amp hrs ea., weighing 3400 lbs.)
Regenerative Braking Efficiency[3]	~39% over CBD-14
Fuel Economy over CBD-14	3.32 mpg diesel with A/C on; ~4.26 mpg diesel with A/C off

[1] curb weight plus 26 people = ½ SLW [half seated load weight]; one person assumed to weigh 150 lbs.

[2] RRC_0 is independent of vehicle speed. Force due to rolling resistance = RRC_0 x (vehicle weight)

[3] Percent of available braking energy available as electric power from the traction motor

[4] OBI = Orion Bus Industries

Table 4 Breakdown of Auxiliary Loading Assumed for Baseline Conventional Transit Bus Model

Component	Mechanical Load on Engine (kW)	
	Assumed Value	Valid Range
Air Compressor (doors, brakes, suspension, etc.)	1	0.75 to 3
Alternator load on engine	1	0 to ~5
Engine Fan	14	7.5 to 15
HVAC load for Air Conditioning [A/C]	14	~18.5 to ~22.5[1]
Hydraulic Pump/Power Steering	1	0.9 to 1 or higher
Total with A/C	31	
Total without A/C	17	

[1] Note: 12 to 15 kW given by alternate reference (Pesaran *et. al.* 1992)

Table 5 Breakdown of Auxiliary Loading Assumed for Initial Series Hybrid Transit Bus Model

Component	Electrical Load on Power Bus (kW)		Mechanical Load on Engine (kW)	
	Assumed Value	Valid Range	Assumed Value	Valid Range
Air Compressor (doors, brakes, suspension, etc.)	NA	NA	0.75	0.75 to 3
Lights and misc. other low voltage accessories run off of alternator	0	0 to ~5	NA	NA
Hybrid Specific Coolant Pumps (for motor/etc.), Fans for battery compartment, Computers, etc.	9	~9	NA	NA
Engine Fan	NA	NA	7.5	7.5 to 15
HVAC load for Air Conditioning [A/C]	NA	NA	14	~18.5 to ~22.5[1]
Hydraulic Pump/Power Steering	NA	NA	0.75	up to 0.9~1 kW and above
Total with A/C	9		23	
Total without A/C	9		9	

[1] Note: 12 to 15 kW given by alternate reference (Pesaran *et. al.* 1992)

The auxiliary load assumptions and breakdown presented are not based upon actual component data. Instead, they are based upon word-of-mouth. Also, the values used in simulation are static (constant) values. In contrast, actual auxiliary systems are almost always dynamic. The current assumptions are meant to give a “ballpark” representation of the actual system. Future planned activities with industry on dynamic heavy vehicle auxiliary loads and their actual duty cycles may allow for a more detailed analysis to be conducted.

Through NREL’s participation in the 21st Century Truck Program, valuable input regarding future bus technical achievement has been obtained. This input is the basis for the energy efficiency pathway analysis presented here. Various technologies are applied in a step-wise fashion to the baseline ADVISOR heavy vehicle model. The ADVISOR model is then used to compute fuel economy and track energy flow (i.e., an energy audit) at each step for each heavy vehicle configuration.

Depending upon the assumptions made, the final results of the energy pathway analysis can vary significantly. Two slightly different pathway analyses are presented in this section. The first pathway is taken from that presented on page 4-21 of the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000), but slightly modified to resolve internal inconsistencies and add additional energy-saving steps. The second pathway is similar to the first but incorporates some different assumptions such as for auxiliary load reduction. Both pathways incorporate additional steps over and above those presented in the *Technology Roadmap*. The first modified energy-efficiency pathway analysis is presented in Figure 3. The second pathway analysis with slightly different assumptions is presented in Figure 4.

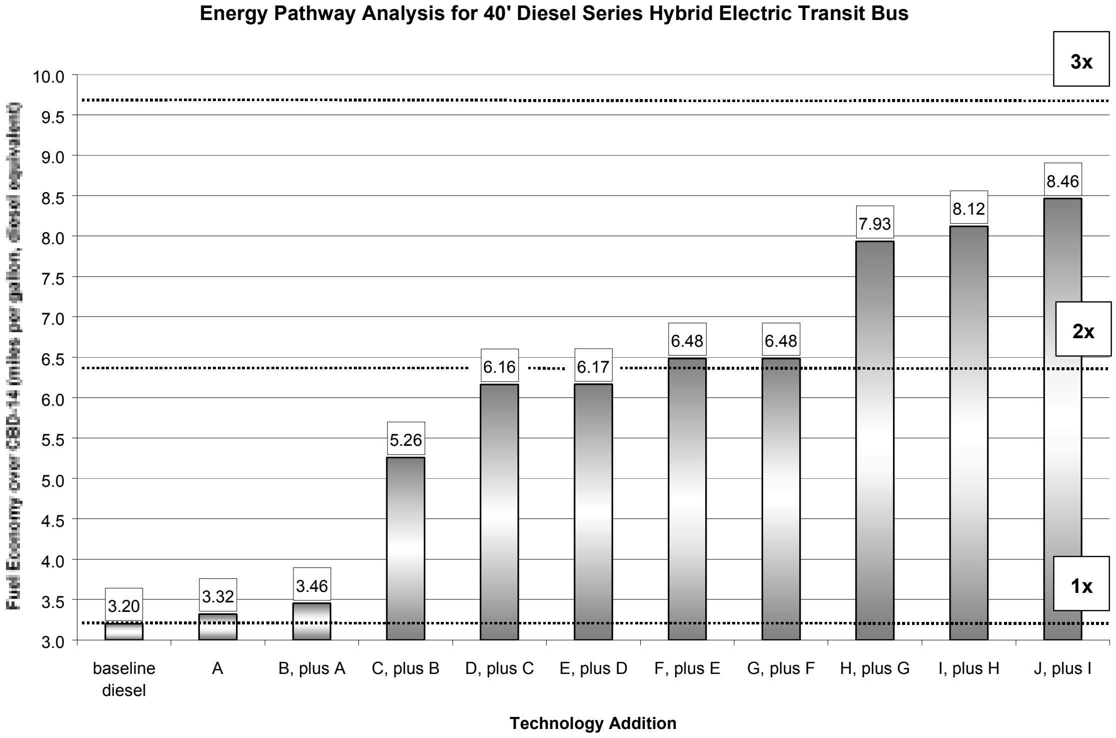
Both pathway analyses show similar trends. Figure 5 and Figure 6 show percentage increase in fuel economy by step-wise technology addition. Figure 5 corresponds to the pathway from the 21CT Program. Figure 6 corresponds to the revised pathway. The most effective technology additions in both figures are hybridization, auxiliary load reduction, and weight reduction. Hybridization allows for regenerative braking, the use of a direct drive transmission, and the ability to perform engine downsizing.

The step-wise technology additions from the two pathways and the reason for their differences are now discussed. The primary focus in the discussion is on the deviations from the pathway analysis presented in the *Technology Roadmap for the 21st Century Truck* (21CT 2000 page 4-21). The reader should refer to the *Technology Roadmap* for more detail on the original pathway analysis.

The technology additions for the pathway analyses presented here are listed in the keys for Figure 3 and Figure 4. Step A, the transition from the baseline transit bus to the initial series hybrid transit bus model, is the same as that used in the *Technology Roadmap* (ibid.). Step B, a reduction in vehicle rolling resistance, is also the same step used in the *Technology Roadmap* (ibid.).

Step C, a reduction in auxiliary loads, is presented in a different manner under the revised pathway analysis. A technical target for transit-bus auxiliary load reduction of 25% is given in the *Technology Roadmap* (21CT 2000 page 4-25 [top]). However, 60% and 30% reductions in electrical and mechanical auxiliary loads were applied to the original 21CT pathway analysis (21CT 2000 page 4-21). The revised pathway shows fuel economy potential for a less-ambitious auxiliary load reduction. Auxiliary load reduction is set to 25%, consistent with the text of the *Technology Roadmap* (21CT 2000 page 4-25 [top]).

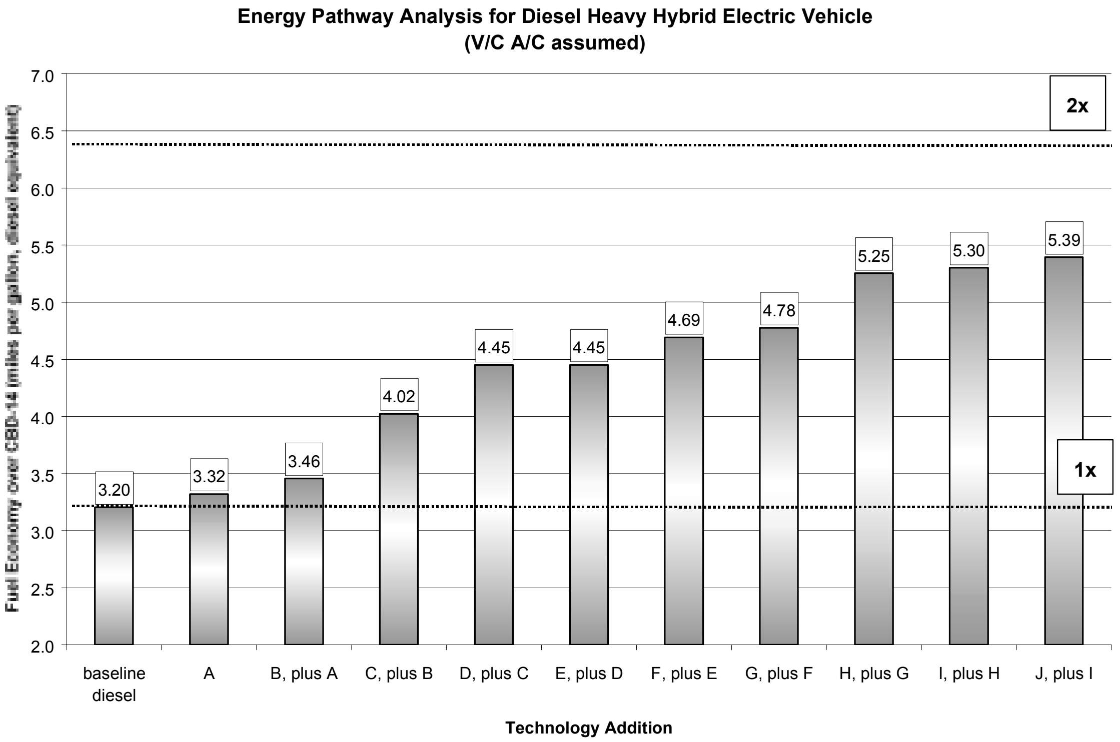
Step D is a weight reduction. The revised weight reduction value assumes a 30% reduction in vehicle curb weight (minus batteries) as opposed to the original assumption of a 30% reduction in overall test weight (which includes passengers and batteries). Thus, the revised weight-reduction of Step D is a more conservative estimate. However, there is evidence that even greater weight reduction potentials are possible. A transit bus weight reduction paper was presented at the 2001 SAE Government/Industry Meeting held in Washington D.C. (Emmons and Blessing 2001). The authors indicate a weight reduction of over 60% (curb weight) has been achieved on a prototype 40’ hybrid bus by using stainless steel (ibid.).



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series Diesel Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. Auxiliary loads reduced from mechanical 23 kW to 5 kW, electrical reduced from 9 kW to 6.5 kW, plus B	**H.** Engine resized to 38 kW from 172 kW, plus G
D. Test mass reduced 30%--test weight changed from 35148 lbs. (15940 kg) to 24603 lbs. (11158 kg), plus C	**I.** Weight reduced by 990-lbs. (450 kg) to represent reduction in engine size, plus H
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J.** Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 21710 lbs.], plus I

NOTE: Steps A through G are based directly on the pathway analysis presented on page 4-21 of the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000). Steps H, I, and J are new steps not seen in the roadmap.

Figure 3 Energy Pathway for a Diesel Transit Bus—Modified Pathway Based on 21st Century Truck Program

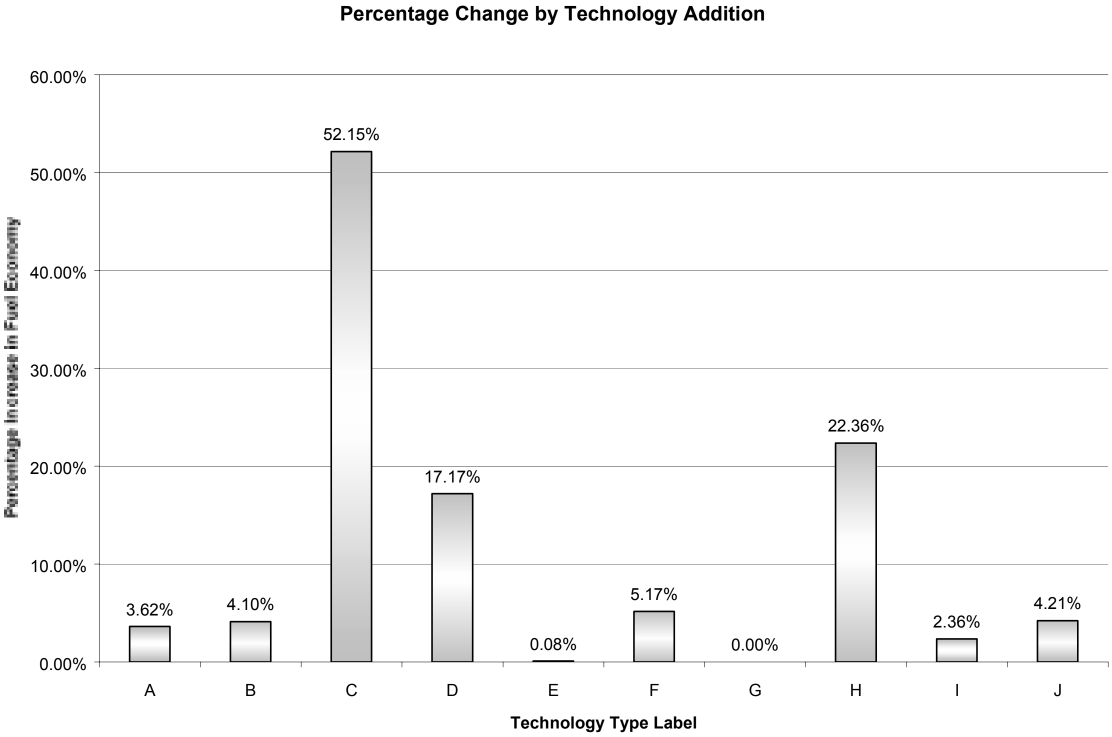


Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series Diesel Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. All Auxiliary loads reduced by 25%: mechanical 23 kW to 17.25 kW, electrical reduced from 9 kW to 6.75 kW, plus B	**H. Engine resized to 58 kW from 172 kW (engine size optimized for fuel economy over CBD-14), plus G**
D. Curb weight minus battery weight reduced 30%--test weight changed from 35148 lbs. (15940 kg) to 26914 lbs. (12206 kg), plus C	**I. Weight reduced by 990 lbs. (450 kg) to represent reduction in engine size, plus H**
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J. Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 24021 lbs.], plus I**

NOTE: Steps different than those used in the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000) are highlighted in bold blue.

NOTE: a Vapor Compression (V/C) unit is assumed in this study. Vehicle curb weight assumed as 31315 lbs. (14202 kg) and battery weight is assumed to be 3400lbs. (1542 kg) for 46 modules.

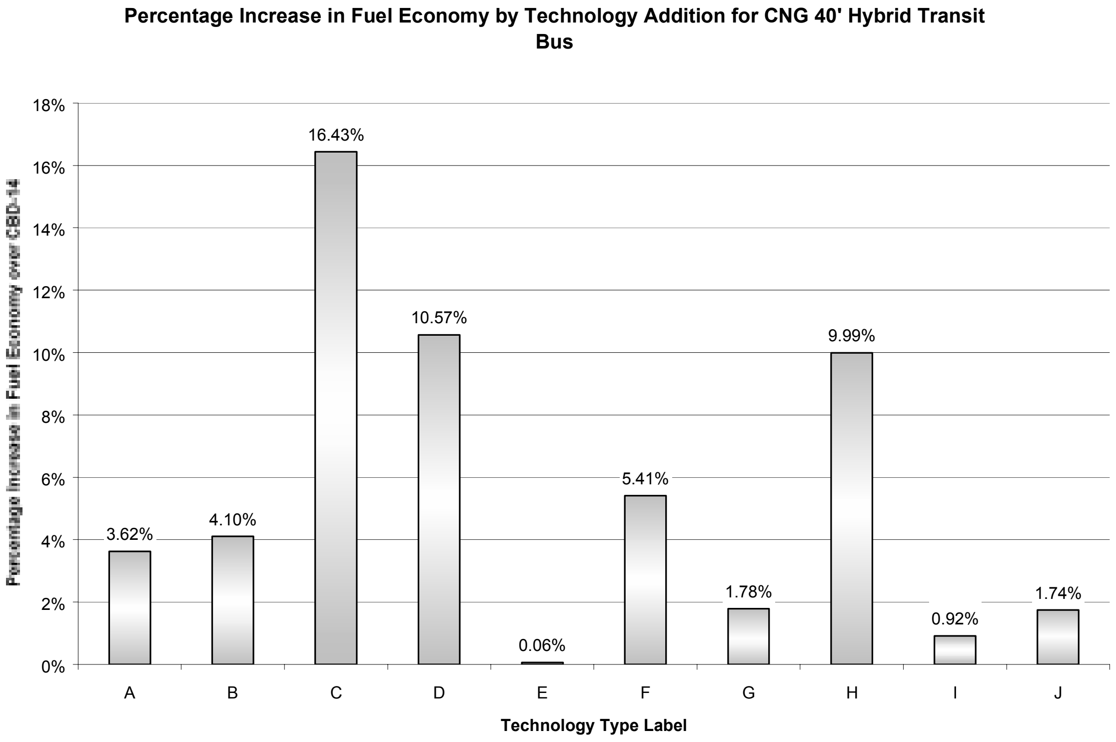
Figure 4 Energy Pathway for a Diesel Transit Bus—Revised Pathway



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series Diesel Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. Auxiliary loads reduced from mechanical 23 kW to 5 kW, electrical reduced from 9 kW to 6.5 kW, plus B	**H.** Engine resized to 38 kW from 172 kW, plus G
D. Test mass reduced 30%--test weight changed from 35148 lbs. (15940 kg) to 24603 lbs. (11158 kg), plus C	**I.** Weight reduced by 450 kg to represent reduction in engine size, plus H
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J.** Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 21710 lbs.], plus I

NOTE: Steps A through G are based directly on the pathway analysis presented on page 4-21 of the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000). Steps H, I, and J are new steps not seen in the roadmap.

Figure 5 Percentage Increase in Fuel Economy by Energy Pathway Step-Wise Technology Addition Corresponding to 21st Century Truck Pathway



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series Diesel Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. All Auxiliary loads reduced by 25%: mechanical 23 kW to 17.25 kW, electrical reduced from 9 kW to 6.75 kW, plus B	**H. Engine resized to 58 kW from 172 kW (engine size optimized for fuel economy over CBD-14), plus G**
D. Curb weight minus battery weight [31315 lbs. (14202 kg) - 3400lbs. (1542 kg)] reduced 30%--test weight changed from 35148 lbs. (15940 kg) to 26914 lbs. (12206 kg), plus C	**I. Weight reduced by 990 lbs. (450 kg) to represent reduction in engine size, plus H**
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J. Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 24021 lbs.], plus I**

NOTE: Steps different than those used in the *Technology Roadmap for the 21st Century Truck Program* (21CT 2000) are highlighted in bold blue.

Figure 6 Percentage Increase in Fuel Economy by Energy Pathway Step-Wise Technology Addition Corresponding to Revised Pathway

Step E is a change in vehicle gearing (final drive ratios) to better optimize the motor duty cycle. This step is the same as that presented in the *Technology Roadmap* (21CT 2000). However, when revising the initial hybrid model, gear ratios were set to those used in the Orion VI transit bus. This new setting happened to be close to optimum for the CBD-14, given the model component assumptions. Thus, fuel economy increase is almost insignificant because near optimum gearing is already employed.

Step F involves a change in motor peak efficiency representing an advance in motor technology. This step remains the same as that used in the *Technology Roadmap* (ibid.).

Step G is an increase in regenerative braking recovery potential. This step is the same as that used in the *Technology Roadmap* (ibid.). Some readers may be puzzled as to why the contribution to fuel economy from increased regenerative braking is so small. As was presented in Table 3, the initial hybrid's regenerative capture efficiency is about 40%. Thus, the increase to about 50% capture efficiency is only a 10% increase. Furthermore, as of Step G, the transit bus is lighter and there is less kinetic energy available to recover. A good related discussion on batteries and regenerative braking appears in NAVC2 2000 (p 10).

A slight digression is made here on the topic of regenerative braking. Recall that baseline fuel economy is chosen and models are calibrated with chassis dynamometer test data. The initial hybrid bus model (Step A but with A/C off) is compared to Orion VI chassis-dynamometer test data in Table 6. In chassis dynamometer testing, energy dissipation from front-wheel "friction brakes" (i.e., conventional brakes) never comes into play. Only the rear-wheel "friction brakes" are capable of supplementing regenerative braking on a chassis dynamometer. This is due to the fact that the front wheels are not "driven". Thus, more energy may be captured from regenerative braking during a chassis dynamometer test than under normal roadway conditions. This may account for the high initial regenerative capture efficiency of 39% seen in the model. A value of 30% for regenerative capture efficiency is given for real-world heavy-hybrid vehicles from one source (TCRP 2000 page 2). Thus, there may be discrepancy in initial regenerative capture efficiency. That is, initial regenerative capture efficiency may be too high. However, Step G of the pathway analysis is still a valid fuel-economy estimation for 50% regenerative capture efficiency.

Table 6 Comparison of Initial Hybrid Bus Model Predicted Fuel Economy and Regenerative Capture Efficiency to Test Data over CBD-14 (A/C Off)

Regenerative Braking State	Fuel Economy over CBD-14 Predicted by ADVISOR Transit Bus Model (mpg)	Fuel Economy over CBD-14 as Measured from Chassis Dynamometer Testing (Orion VI Transit Bus) (mpg)
Regenerative Braking On	4.27 (39% regenerative capture efficiency)	4.3
Regenerative Braking Off	3.78 (0% regenerative capture efficiency)	3.7

Source: Transit bus chassis-dynamometer fuel-economy results from recent NAVC report (NAVC 2000)

Note: regenerative capture efficiency is the electrical energy available at the motor used as a generator over potential kinetic energy at the wheels (accounting for energy lost to aerodynamic drag and rolling resistance)

Steps H, I, and J are new and were not evaluated in the original *Technology Roadmap* analysis.

Step H involves engine downsizing to a size more appropriate to the new vehicle weight and auxiliary load requirement. Different optimum engine sizes result for the two pathways due to differences in vehicle weight and auxiliary load. Resizing is conducted by linearly scaling engine fuel consumption information.

Step I is the estimated weight reduction associated with the reduction in engine size in Step H. The reader should note that the weight reduction figure used here is only an estimate.

Step J gives an estimate of weight reduction potential for battery storage systems. This step is based upon battery technical targets from the "Heavy Vehicle Hybrid Propulsion Systems R&D Program Plan" (OHVT

2000). However, it is slightly more conservative. Approximately 55% reduction in weight is assumed for equivalent performance.

Differences between fuel economy predicted here and in the *Technology Roadmap* analysis (page 4-21 of 21CT 2000) are now briefly discussed. (Specifically, the differences between Figure 3 of this work and Figure 4.4 of the *Technology Roadmap* (ibid.) are explained.) The source of the differences between the two analyses is caused by differences in the transit bus models. For the *Technology Roadmap*, a fictional "advanced" hybrid bus model was used for Step A. This "advanced" hybrid bus has lower auxiliary loads than the bus used in Step A of the present analysis. A hybrid bus similar to the Orion VI is used for Step A in the present paper. Thus, the initial hybrid bus fuel economy is slightly lower with the present analysis. This fuel economy is believed to better represent the state of recent hybrid buses.

The next major difference lies in hybrid control strategy. The control strategy for the transit bus model used in the *Technology Roadmap* employs an engine on/off control strategy (sometimes referred to as a thermostat control strategy). Major fuel economy advances are achieved by allowing the engine to be "off" for greater percentages of the time. While the engine is off, mechanical auxiliary loads have no impact.

The pathway analysis performed here employs what is thought to be a more realistic control strategy called a power-following control strategy. In a power-following control strategy, the engine-generator (gen. set) adjusts power-output up and down. In this study, the engine is not allowed to turn off. The energy storage system (batteries) is used to level peak demand in energy requirements and to store regenerative braking energy. By more closely matching the road-load demand of the vehicle, battery "round-trip" efficiencies are increased. Major fuel economy savings are obtained through engine downsizing and avoiding excessive battery storage (and associated losses).

Fuel economy increases in the *Technology Roadmap* occur over several steps as the engine is "off" for increased amounts of time. In contrast, the pathway analyses in this report show less drastic increases with each technology addition. This is because the engine must still run, though the load becomes lighter and lighter. A large jump is seen immediately when the engine is resized to the load.

Engine resizing (downsizing) was never conducted for the original 21CT *Technology Roadmap* analysis. Therefore, engine downsizing for a thermostat control strategy was briefly investigated for this report. A fuel benefit occurs due to the associated weight decrease and possible decrease in engine-specific mechanical auxiliary loads. However, simulation results show little benefit to be had from engine downsizing itself using the thermostat control strategy.

The reason for this can be explained by examining the thermostat control strategy. For the models used in this study, scaling does not change efficiency, only output power. The thermostat control strategy allows the battery pack to be dominant. The engine-generator runs at the peak efficiency to recharge the battery pack when battery state-of-charge drops below a given level. Thus, a large powerful engine would run less of the time with a high power output when on. In contrast, a smaller low-power engine will run "on" for longer periods of time but will use less fuel. Overall, the system seems to break even.

Note that final fuel economies predicted in Figure 4.4 of the *Technology Roadmap* analysis and Figure 3 are close. Thus, both control strategies appear to yield similar fuel economy results for models optimized with the given pathway assumptions. It should be noted that a power-following strategy with engine on/off capability has not yet been investigated.

To finish this section, four transit bus model energy audits are presented in Table 7 tracking where all of the chemical energy contained in the fuel is used over the CBD-14 cycle. The first energy audit is for the conventional diesel baseline model. The next energy audit is for the initial hybrid model corresponding to Step A in the pathway analysis. This model is based upon the Orion VI hybrid bus. Next, both versions of the final result from the pathway analyses are presented. These correspond to energy audits of the models at

Step J from Figure 3 and Step J from Figure 4. Energy is broken down by "loss through component". For instance, the energy lost through the engine by the initial series-hybrid transit bus is 13.51 kWh over the CBD-14. Regenerative braking capture efficiency is the percentage of available kinetic energy that is available as electricity to the powertrain. Available kinetic energy is the kinetic energy remaining from a braking/deceleration event after aerodynamic and rolling resistance losses are subtracted. The energy required to move the vehicle is equal to the energy used to overcome rolling resistance and aerodynamic drag. Powertrain efficiency is the energy used to drive the wheels divided by the engine drive-shaft output energy over the cycle. Note that mechanical auxiliary loading is assumed to load directly on the engine drive shaft. By reducing non-driving losses such as auxiliary loading, powertrain efficiency can be increased.

Table 7 Energy Audit for Diesel Transit Bus Models from the Pathway Analysis

Component Energy Utilization	Baseline Conventional Transit Bus		Step A: Initial Series Hybrid Transit Bus Model		Step J from 21CT Pathway		Step J from Revised Pathway	
	Energy over drive cycle (kWh)	Percent Total Energy Use	Energy over drive cycle (kWh)	Percent Total Energy Use	Energy over drive cycle (kWh)	Percent Total Energy Use	Energy over drive cycle (kWh)	Percent Total Energy Use
Engine losses	14.15	59%	13.51	58%	4.78	52%	7.80	55%
Auxiliary loads	4.94	21%	5.10	22%	1.83	20%	3.83	27%
Drivetrain losses	2.41	10%	0.35	2%	0.24	3%	0.26	2%
Generator losses	NA	NA	0.30	1%	0.18	2%	0.19	1%
Energy storage system losses	NA	NA	0.23	1%	0.17	2%	0.18	1%
Motor/controller losses	NA	NA	0.97	4%	0.47	5%	0.48	3%
Friction braking	1.10	5%	1.21	5%	0.63	7%	0.69	5%
Aerodynamic losses	0.24	1%	0.24	1%	0.24	3%	0.24	2%
Rolling resistance losses	1.20	5%	1.32	6%	0.56	6%	0.62	4%
Regenerative Braking Capture Efficiency	NA		39%		49%		49%	
Powertrain Efficiency	36%		40%		52%		38%	
Transit bus test weight (lbs.)	32006		35148		21710		24021	
Total energy used over CBD-14 (kWh)	24.05		23.22		9.11		14.29	
Fuel consumption over CBD-14 (mpg)	3.20		3.32		8.46		5.39	
Fuel economy multiplier	1.00		1.04		2.64		1.68	

NA = Note Applicable

In Table 7, note that a fuel economy multiplier of 2.64x is predicted for the pathway analysis based on that used in the 21st Century Truck Program *Technology Roadmap*. This value is close to the original value of 2.6x given in the *Technology Roadmap*. For the more conservative revised pathway analysis, a fuel economy multiplier of 1.68x is achieved.

3.3 Parametric Analysis

As seen from Section 3.2, predicted fuel economy significantly differs depending upon the assumptions made during the pathway analysis. The reader may desire to predict transit bus fuel economy from a unique, individually chosen pathway different from that assumed here. This section will assist the reader in making quick estimates of transit bus fuel economy over the central business district (CBD-14) drive cycle as a function of key parameters and discuss performance trends derived from a parametric analysis. The diesel conventional and hybrid bus models have been used to create parametric plots of fuel economy versus key parameters. Plots display transit bus fuel economy as a function of the key parameters across a multi-dimensional design space. The reader will be able to interpolate within this design space and extrapolate outside of it to estimate fuel economy. The key parameters of note used in the parametric plots of this section are presented in Table 8**.**

Table 8 Listing of Key Parameters for Parametric Plots

Key Parameter	**Description**
C_D	Coefficient of Drag
Vehicle Weight	Simulated vehicle weight. Curb weight plus weight of half of the seated passengers plus driver (26 people at 150 lbs. per person assumed)
Mechanical Auxiliary Loads	Load on the engine due to mechanical auxiliary systems (constant)
Electrical Auxiliary Loads	Load on the electrical power bus due to electrical auxiliary systems (constant)
Rolling Resistance Coefficient (RRC_0)	"Zeroth" Rolling Resistance Coefficient—independent of vehicle speed. Force due to rolling resistance is RRC_0 times (vehicle weight)

Figure 7 and Figure 8 show a parametric sweep conducted on the baseline conventional transit bus model. Fuel economy contours are a function of vehicle test weight and mechanical auxiliary load for two different rolling resistance coefficients. A trend can be seen in the spacing of fuel economy contour curves. Notice that for high fuel economy, contour lines are closely spaced indicating a steep gradient. In contrast, at lower fuel economy contour lines are farther apart indicating a less severe change. At least part of the reason for this occurrence is believed to lie with the definition of fuel economy.

Fuel economy (miles per gallon) is proportional to the inverse of the energy use over a cycle for constant distance traveled. The rate of change of fuel economy with change in cycle-total energy use can be obtained with a derivative. Let fuel economy equal (k/E) where E is the energy used over a cycle and k is a constant. The change in fuel economy with change in energy use is:

$$\frac{d(k/E)}{dE} = -\frac{k}{E^2}\text{, where k is a constant} \qquad \text{[Eq. 1]}$$

Equation 1 shows that the change in fuel economy per fixed change in total-cycle-energy is greater for a low-energy-use cycle than for a high-energy-use cycle. In fact, the change is inversely proportional to the square of energy use over the cycle according to Equation 1. This explains why the fuel economy of advanced hybrid vehicles can change drastically by simply turning on the air conditioning (see for instance Farrington *et. al.* 1999). This same trend is also seen in the parametric charts in this study. Initially, contour lines are grouped closely together and fuel economy drops off quickly. As the fuel economy becomes lower (i.e., as energy use over the cycle becomes high), fuel economy contours spread out and fuel economy drops more slowly.

Another area to notice is the relative change in fuel economy by parameter. For instance, examine and note the fuel economy for a 21,710 lb. vehicle with no auxiliary load. We observe that adding 5 kW of mechanical load has the same impact as a 3000 lbs. vehicle weight increase.

Figure 9 through Figure13 are parametric sweeps conducted with the "advanced" or "optimized" hybrid bus model. This model corresponds to Step J in the pathway analysis from Figure 3. Note that, although the 38 kW engine works well for its design point, it cannot handle high auxiliary loads. This is especially true when vehicle weight and road load are increased together. Examine the top right-hand side of Figure 14 through Figure 17. The top-right-hand region shows signs that the model is operating in a charge-depleting mode. In this region, the 38 kW engine runs at full power 100% of the time. However, there is not enough power to keep the battery pack from depleting itself. This region of the parametric charts should **not** be used for estimating fuel economy.

Figure 18 through Figure 21 are parametric sweeps conducted with the “advanced” or “optimized” hybrid bus from the revised pathway. This is the model corresponding to Step J from Figure 4. This model has a 58 kW engine instead of a 38 kW engine. The larger engine allows the entire design space to be swept over vehicle weight, rolling resistance, and auxiliary loads. The reader should note that Figure18 through are plotted with contours at every 0.2 mpg instead of 0.1 mpg as is the case for the other figures. This has been done to enhance visual clarity.

Figure 22 and Figure 23 show how varying coefficient of drag (CD) affects fuel economy over several cycles and where drag is relevant to fuel economy. Figure 22 corresponds to the conventional diesel transit bus model. Figure 23 corresponds to the initial series hybrid model (Step A of either pathway analysis). The drive cycles evaluated are the CBD-14 cycle (Central Business Cycle, Figure 1), the Arterial Cycle (Figure 24), and the Commuter Cycle (Figure 25). Each cycle represents a certain type of transit driving. The CBD-14 represents inner city stop-and-go driving. The arterial cycle represents higher speed driving with less stop-and-go typical of arterial streets. The commuter cycle represents high constant speed driving. There is negligible benefit from changing aerodynamic drag over low-speed cycles such as the CBD-14 (average speed of 12.6 mph). Slight benefit can be obtained from drag reduction in medium-speed cycles like the arterial cycle (average speed of 24.8 mph). Some tangible benefit from drag reduction can be obtained for high-speed cycles such as the commuter cycle (average speed of 43.8 mph). Note that the dramatic decreases in aerodynamic drag pictured in Figure 22 and Figure 23 may be technically feasible. A recent paper presented at the SAE Government and Industry meeting discusses dramatic drag improvement via pneumatic air jets (Englar 2001).

One interesting point seen by comparing Figure 22 with Figure 23 involves the difference between conventional and hybrid vehicles. Notice that the hybrid advantage decreases when relatively constant-speed drive cycles are chosen. Both models use the same chassis and thus frontal area (which affects drag). For a given drag coefficient, the hybrid has better fuel economy than the conventional over the CBD-14 and Arterial cycle. However, the conventional vehicle actually has better fuel economy than the hybrid over the commuter cycle. This is because the hybrid is no longer able to capitalize on hybrid features such as regenerative braking. Furthermore, the conventional vehicle is able to run close to maximum efficiency. Thus, the benefit of decoupling the engine from the road demand is nullified for the hybrid. In addition, the hybrid’s added weight and the required powertrain energy conversions work against the hybrid bus in this situation.

Finally, Table 9 displays the predicted fuel economy for models over various drive cycles. Speed-time traces of drive-cycles listed in Table 9 and not pictured in this reported can be found elsewhere (see for example, NAVC 2000). Simulations that slightly deviate from the drive trace are marked with a single asterisk. Simulations with larger deviation (but still deemed acceptable for reporting) are marked with two asterisks. Failure to meet a drive trace is believed to be due to problems with the automatic transmission model. Not meeting a drive trace tends to cause the ADVISOR simulation to under-predict fuel economy. Thus, for cycles such as the Manhattan cycle, the fuel economy multiplier is over-predicted.

Cycles that are listed as “NCS” in Table 9 are “non charge sustaining.” That is, although the hybrid vehicle has no problem driving the requested duty cycle, prolonged driving under this duty cycle would result in depletion of the battery pack charge. Where possible, linear estimates are given to predict what the fuel economy would be if the vehicle were charge-sustaining.

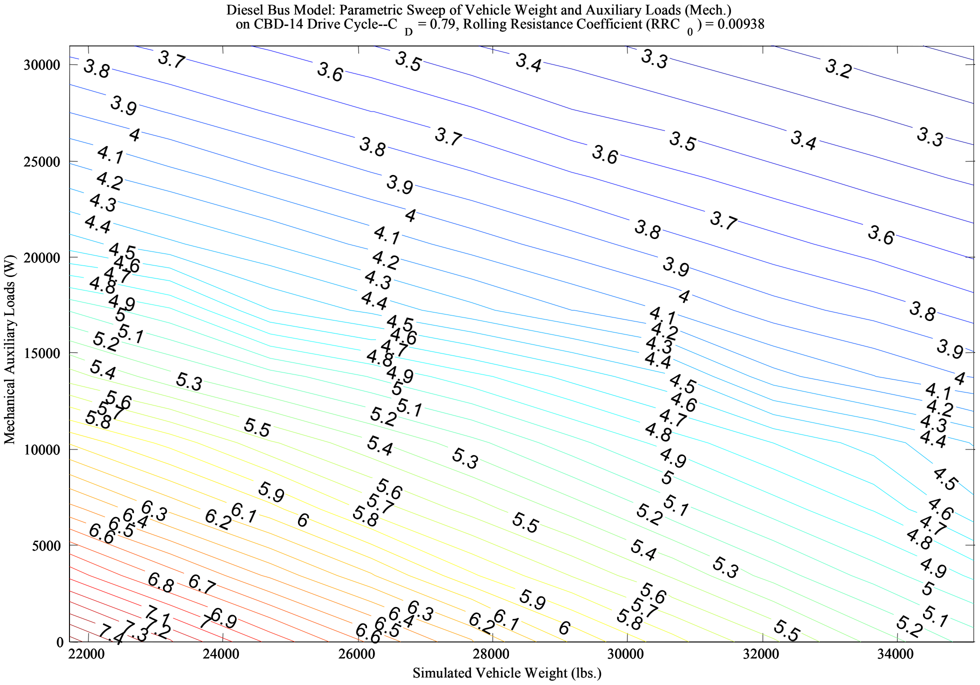


Figure 7 Conventional Diesel Bus Model: Parametric Sweep on Mechanical Auxiliary Load and Vehicle Weight for a Rolling Resistance Coefficient of 0.00938

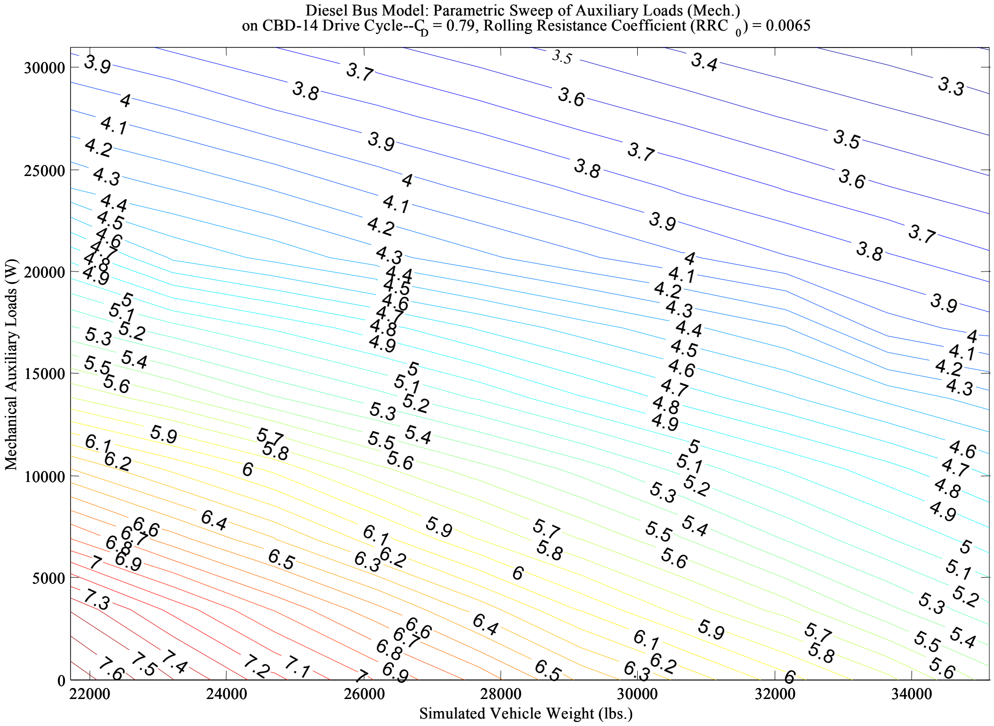


Figure 8 Conventional Diesel Bus Model: Parametric Sweep on Mechanical Auxiliary Loads and Vehicle Weight for a Rolling Resistance Coefficient of 0.0065

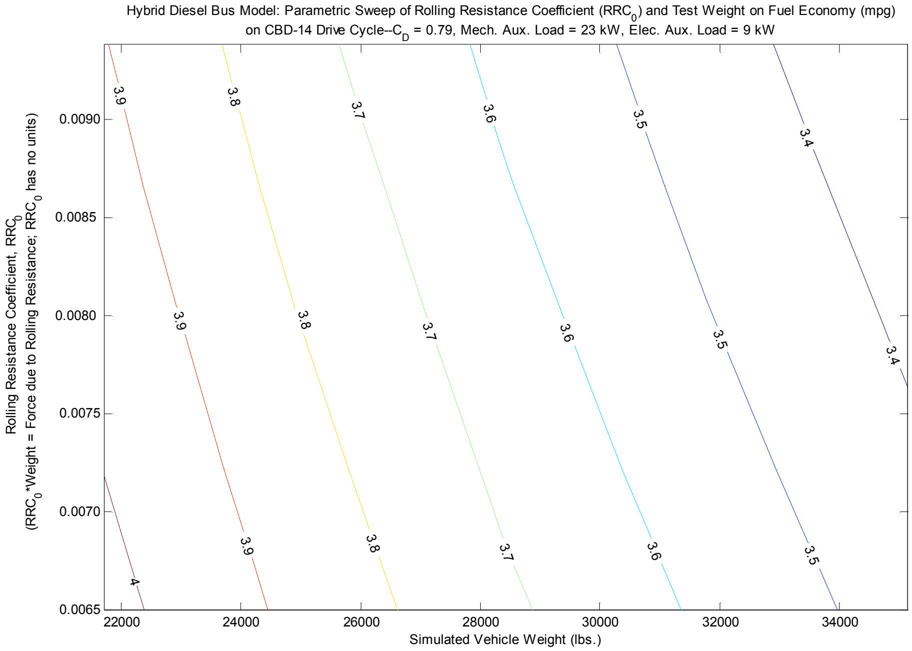


Figure 9 Diesel Series Hybrid Bus Model: Parametric Sweep on Rolling Resistance Coefficient and Vehicle Weight

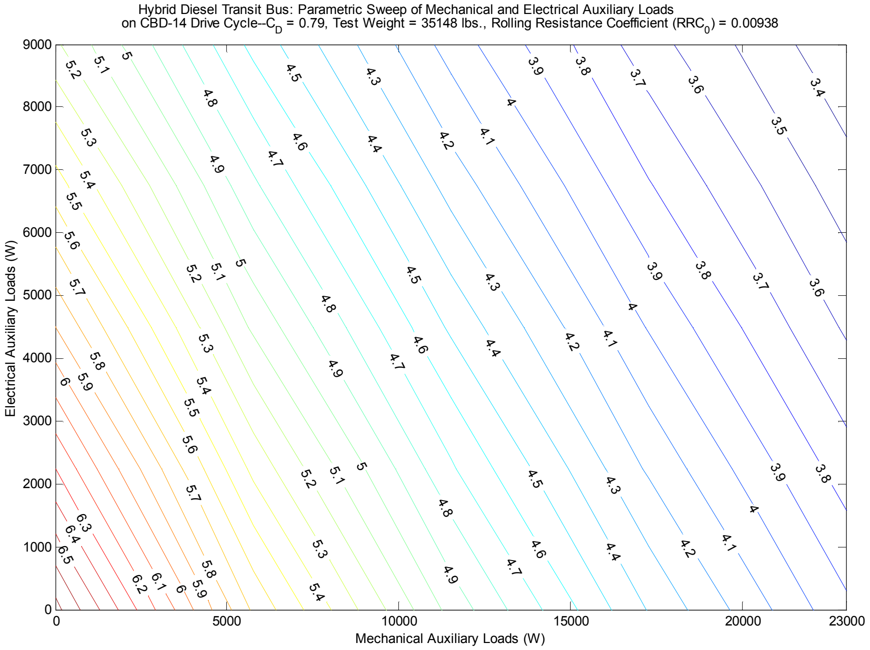


Figure 10 Diesel Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 35148 lbs. (15940 kg)

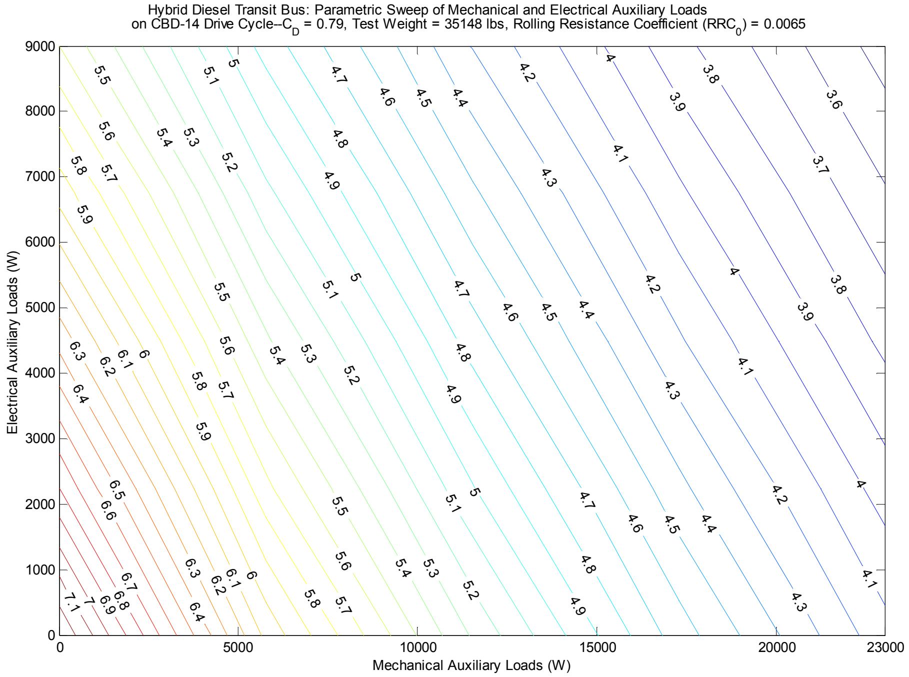


Figure 11 Diesel Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 35148 lbs. (15940 kg)

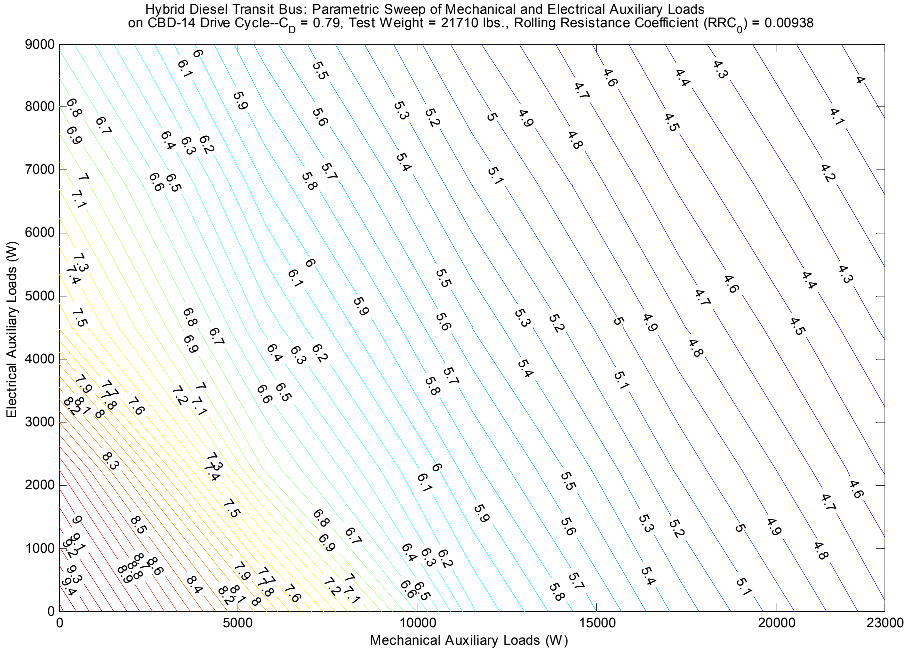


Figure 12 Diesel Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 21710 lbs. (9846 kg)

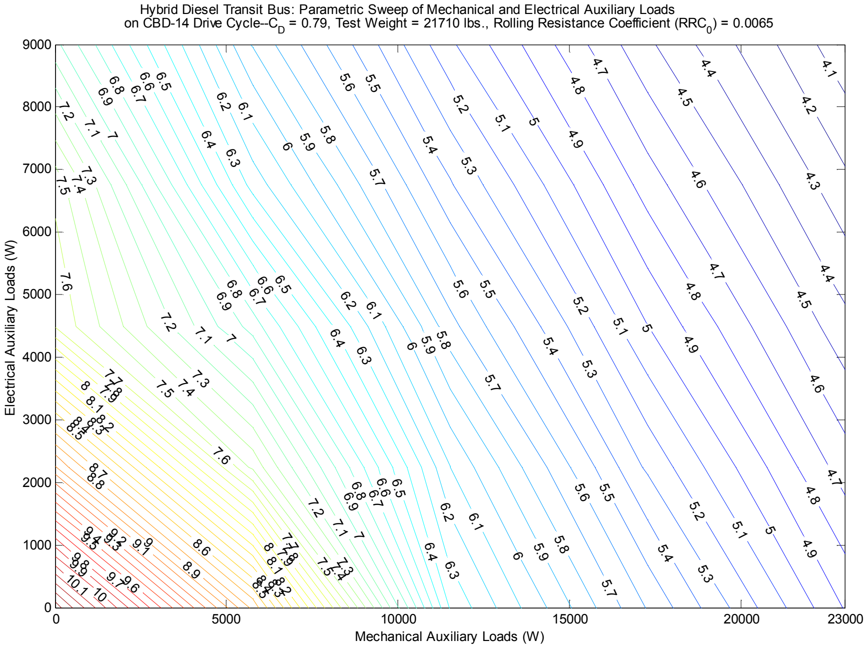


Figure 13 Diesel Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 21710 lbs. (9846 kg)

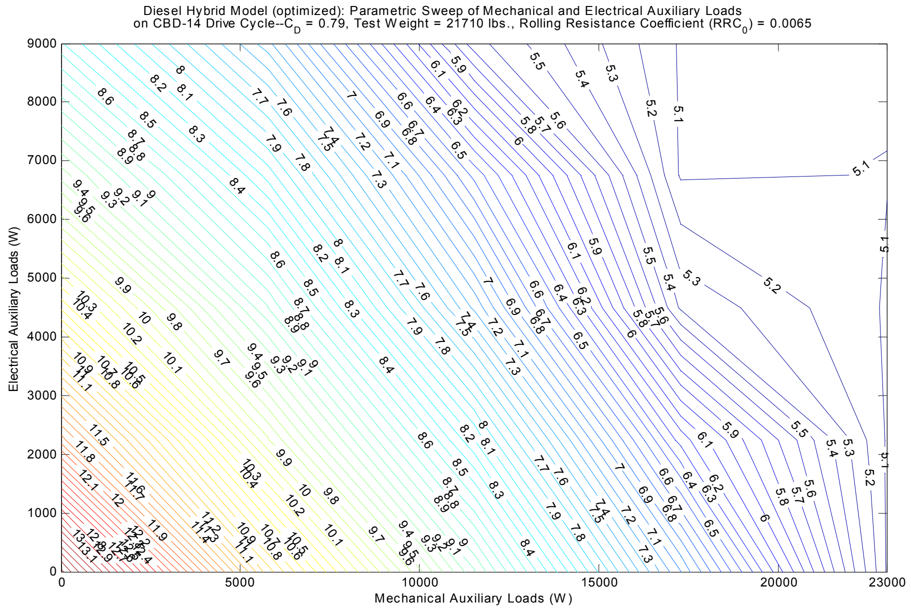
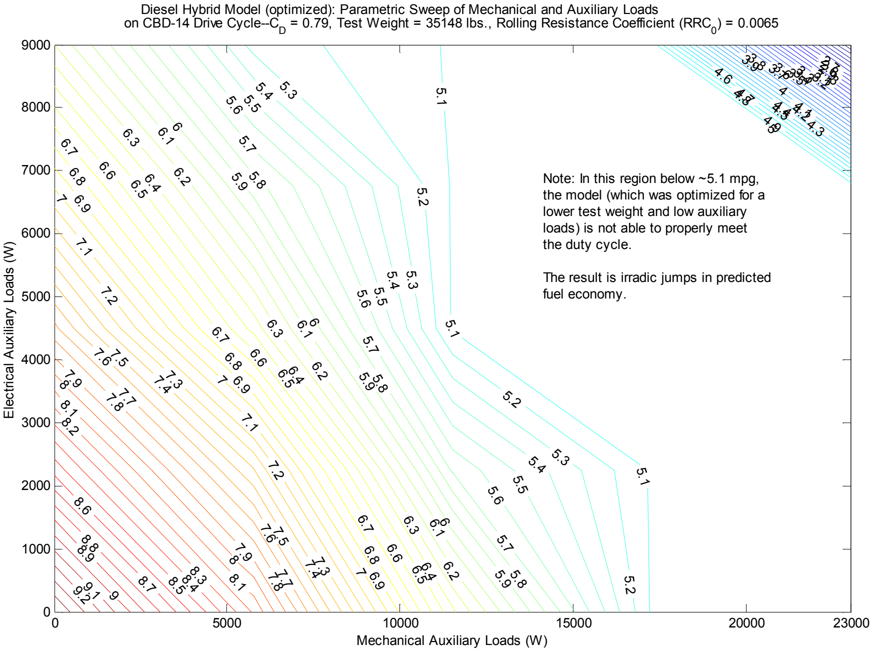


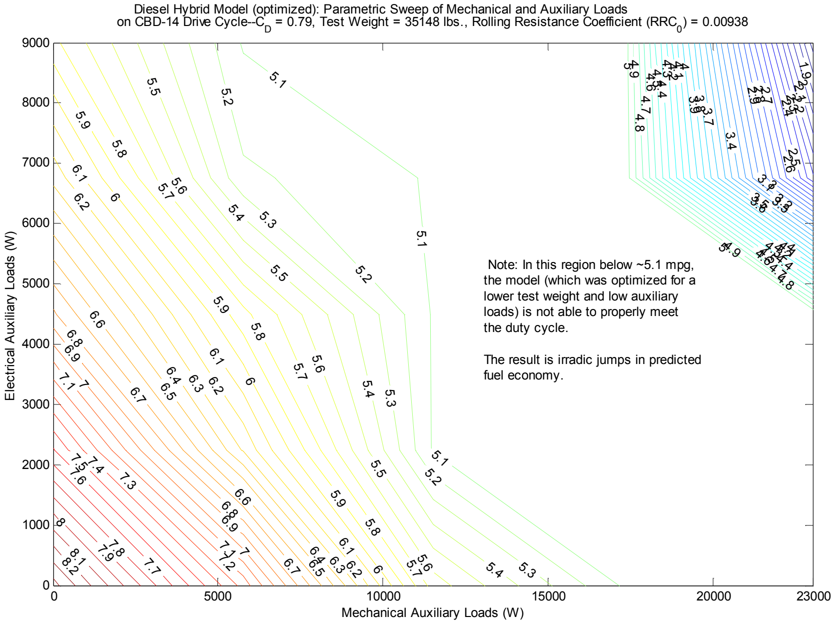
Figure 14 Advanced Diesel Series Hybrid Bus Model (38 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 21710 (9846 kg)



Note: In this region below ~5.1 mpg, the model (which was optimized for a lower test weight and low auxiliary loads) is not able to properly meet the duty cycle.

The result is irradic jumps in predicted fuel economy.

Figure 15 Advanced Diesel Series Hybrid Bus Model (38 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 35148 lbs. (15940 kg)



Note: In this region below ~5.1 mpg, the model (which was optimized for a lower test weight and low auxiliary loads) is not able to properly meet the duty cycle.

The result is irradic jumps in predicted fuel economy.

Figure 16 Advanced Diesel Series Hybrid Bus Model (38 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 35148 lbs. (15940 kg)

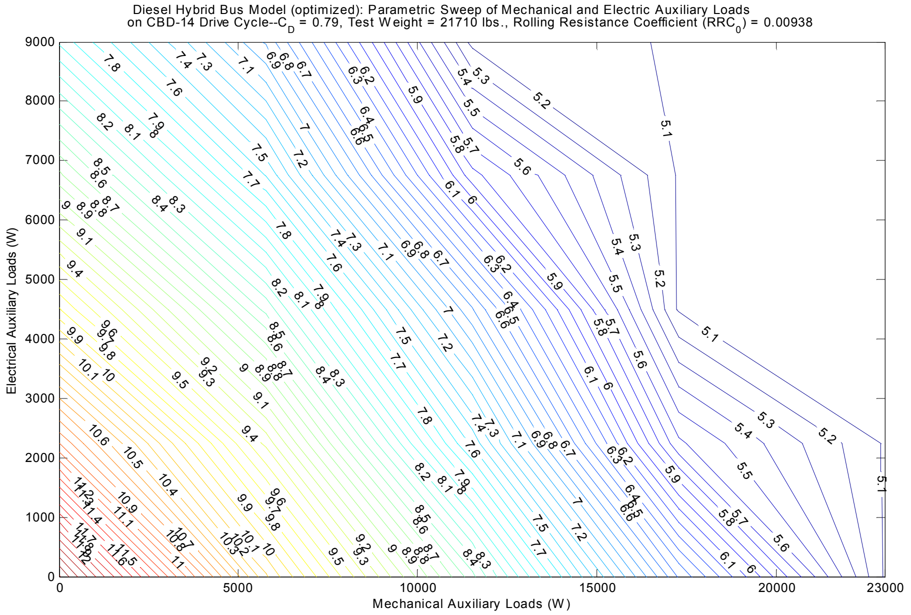


Figure 17 Advanced Diesel Series Hybrid Bus Model (38 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 21710 lbs. (9846 kg)

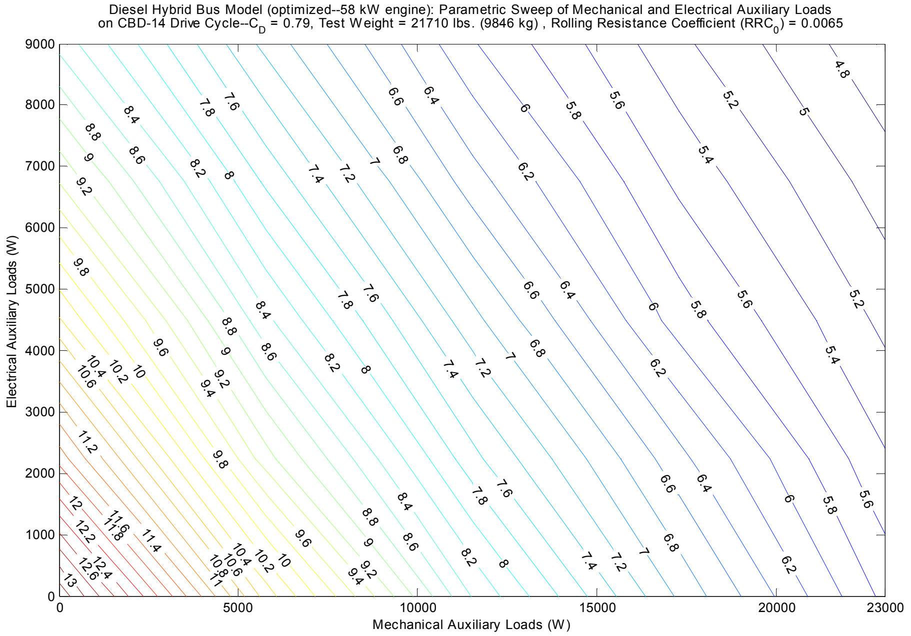


Figure 18 Advanced Diesel Series Hybrid Bus Model (58 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 21710 lbs. (9846 kg)

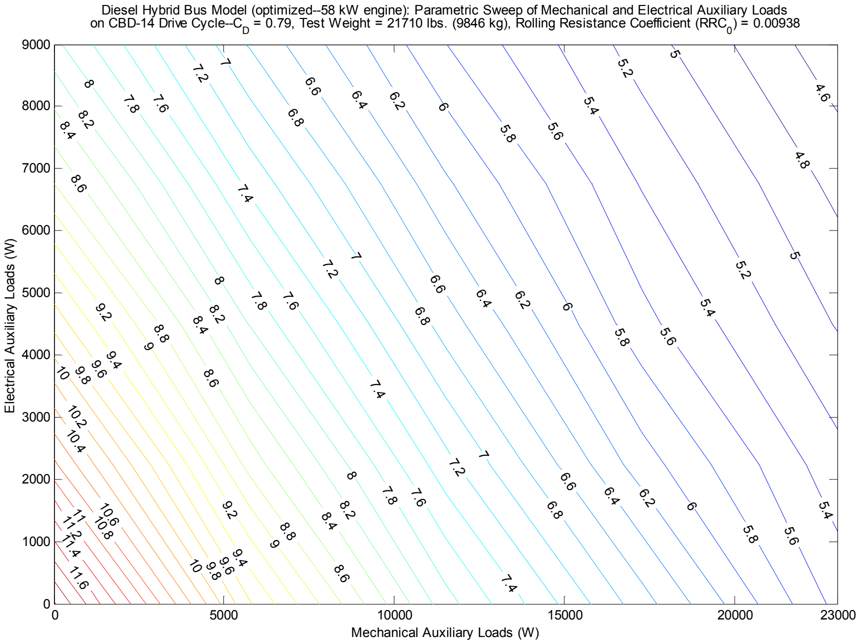


Figure 19 Advanced Diesel Series Hybrid Bus Model (58 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 21710 lbs. (9846 kg)

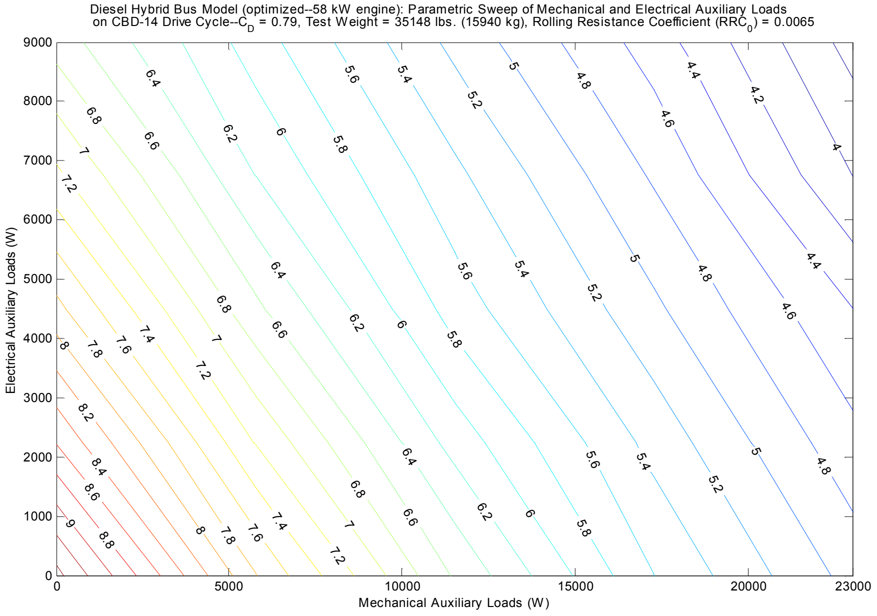


Figure 20 Advanced Diesel Series Hybrid Bus Model (58 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 35148 lbs. (15940 kg)

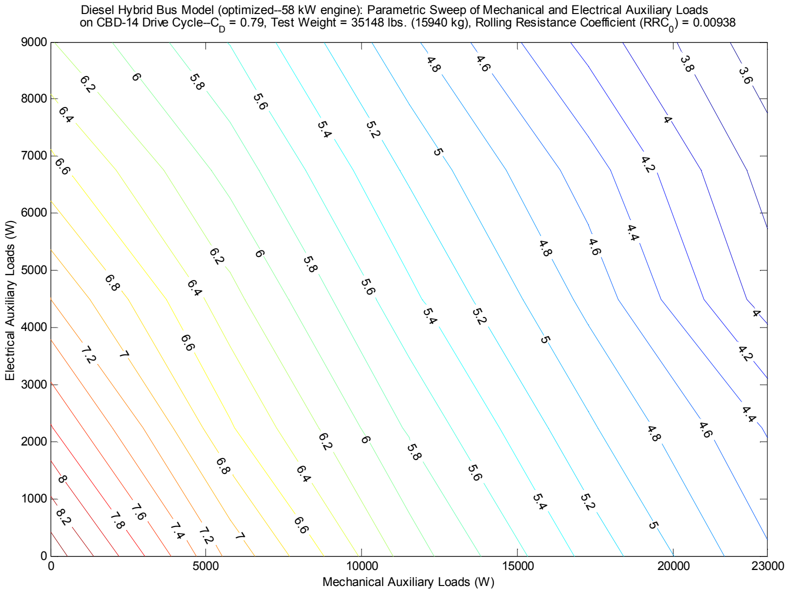


Figure 21 Advanced Diesel Series Hybrid Bus Model (58 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 35148 lbs. (15940 kg)

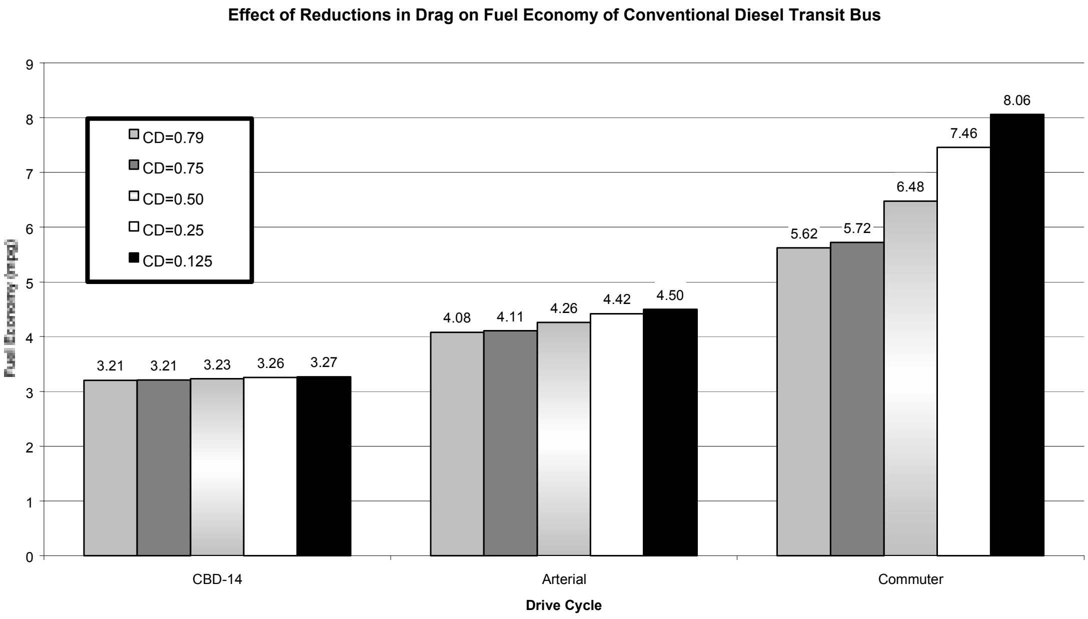


Figure 22 Effect of Reductions in Drag Coefficient (C_D) on Fuel Economy of Conventional Diesel Bus over Various Drive Cycles

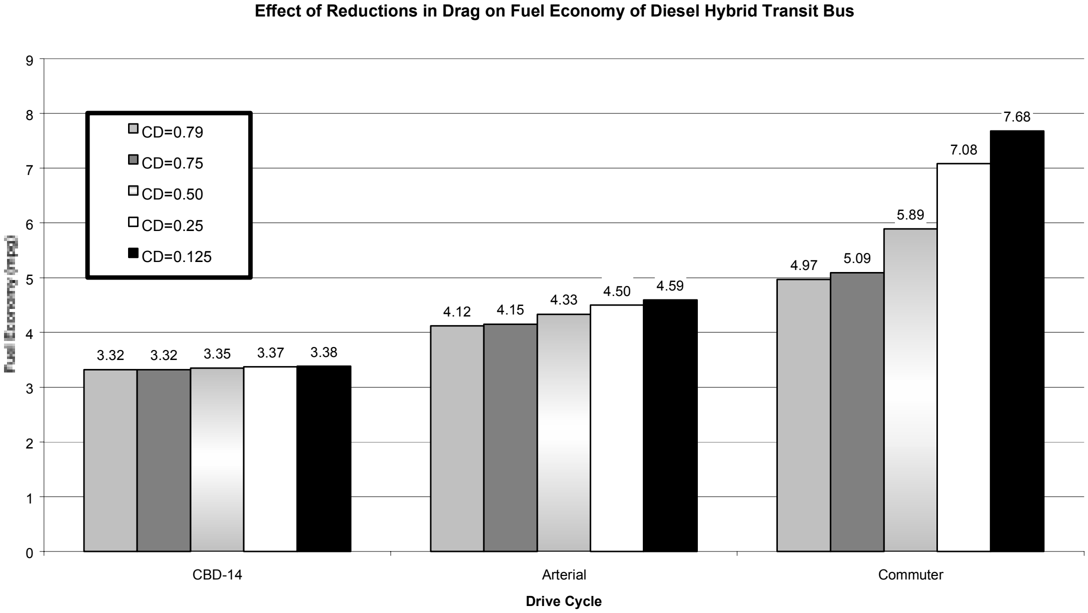


Figure 23 Effect of Reductions in Drag Coefficient (C_D) on Fuel Economy of Initial Hybrid Diesel Bus over Various Drive Cycles

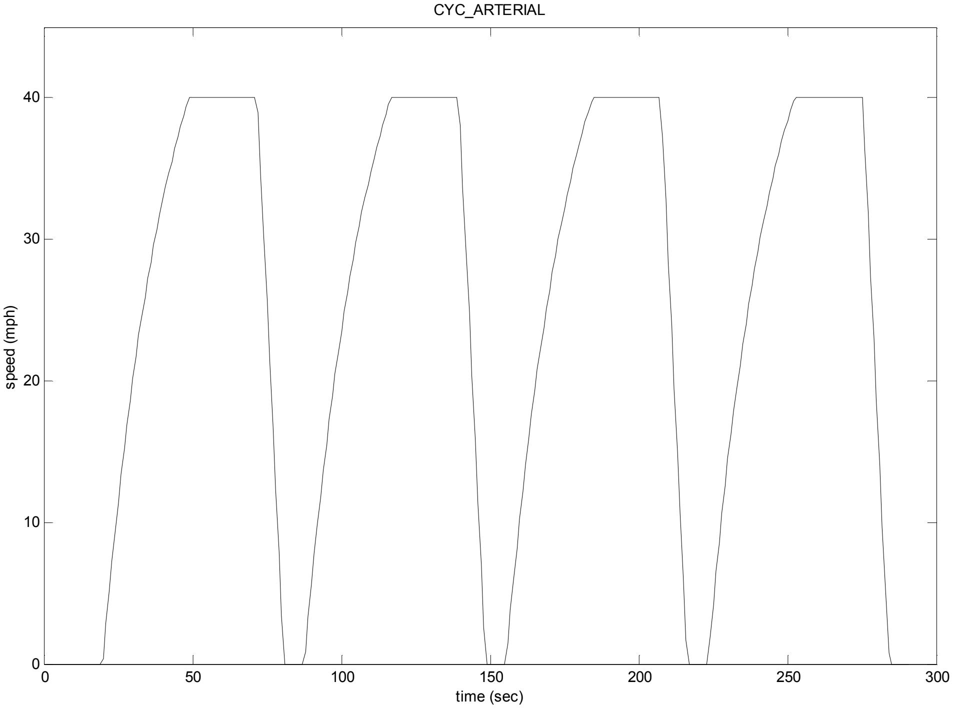


Figure 24 The Arterial Drive Cycle—average speed 24.8 mph

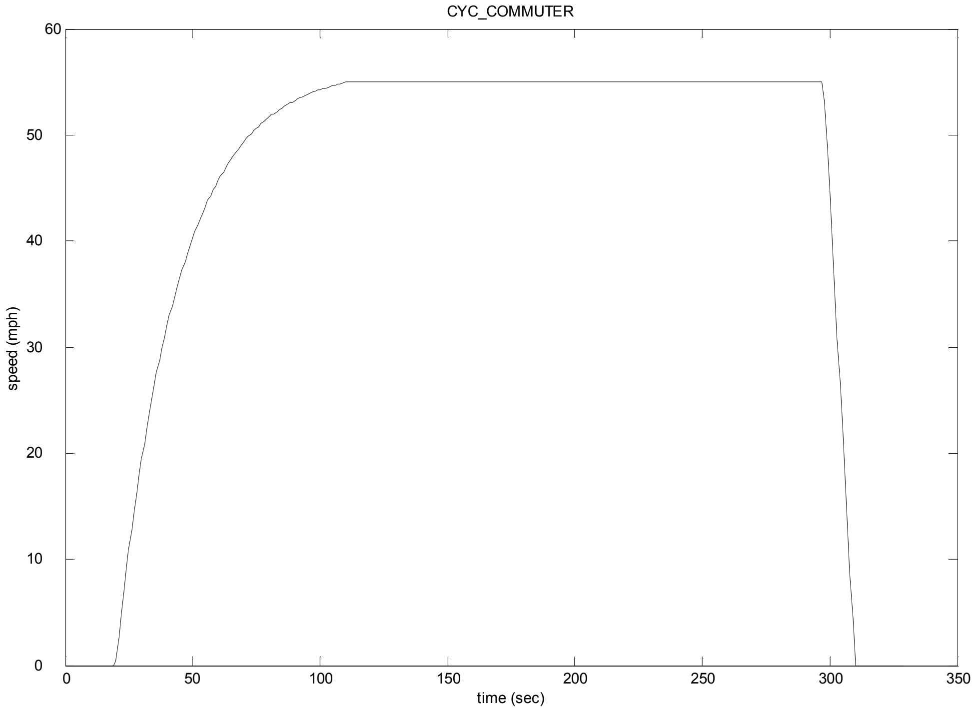


Figure 25 The Commuter Drive Cycle—average speed 43.8 mph

Table 9 Fuel Economy Predictions for Models over Various Drive Cycles

Drive Cycle	Baseline Conventional Diesel Model Fuel Economy (mpg)	Advanced Hybrid Diesel Model Fuel Economy—21CT Pathway (mpg)	Advanced Hybrid Diesel Model Fuel Economy—Revised Pathway (mpg)
CBD	3.20	8.46 (2.64x)	5.39 (1.68x)
Arterial	4.08	NCS: 5.05 (1.24x)	NCS: 6.01 (1.47x)
Commuter	5.62	NCS	NCS
Manhattan	1.85*	5.61 (3.03x)	3.33 (1.80x)
New York Bus	1.17*	3.51 (3.00x)	1.95 (1.67x)
New York Composite	2.52*	6.62 (2.63x)	4.08 (1.62x)

* Slight trace miss (deviation from intended drive cycle) was experienced by the models shown. Average absolute difference in speed less than 0.3 mph.

** Trace miss with absolute average difference greater than 0.3 mph but less than 0.5 mph experienced

NCS = Not Charge Sustaining, if a number appears in this column, it was obtained via linear estimation

4 Natural Gas and Natural-Gas-Hybrid Bus Models

To investigate the goals of the OFCVT's prior Heavy Hybrid Program, CNG transit bus modeling was conducted. The study presented here is similar in methodology to that presented in Section 3. ADVISOR was used with CNG transit bus models to predict technical targets and fuel economy potential. Conventional CNG and hybrid CNG bus models were developed for this purpose. The previous Heavy Hybrid Program goal was to achieve a nominal doubling of fuel economy of a comparable 1999 baseline vehicle, while the new advanced heavy hybrid propulsion system goal is to achieve up to a nominal doubling of fuel economy in a comparable Class 3 – 8 vehicle. This goal was evaluated with the models presented in this section.

The CNG transit bus models (conventional and hybrid) are derived from the diesel transit bus models of Section 3. The main differences between the diesel transit bus models and the CNG models are as follows:

- The CNG transit bus models use a CNG engine based on the John Deere PowerTech 8.1 L natural gas engine
- The CNG transit bus model vehicle weight is increased over their diesel counterparts to account for the weight of CNG tanks

The strategy for choosing the baseline fuel economy and baseline CNG vehicle is similar to that presented in Section 3.1. Details on the determination of the CNG baseline specification are presented in Section 4.1.

Fuel economy reported in this section is given as "miles per gallon equivalent of diesel fuel" based upon energy equivalency. That is, fuel economy is calculated as "miles traveled per amount of vehicle fuel that is equivalent energy-wise to one gallon of diesel fuel." These units are used to allow quick comparison to the diesel-fueled transit buses from this and other reports. Based upon a representative lower heating value and density for diesel fuel, it is assumed that there are 138,365 kJ of energy per each gallon of diesel fuel.

4.1 Baseline Fuel Economy

For the reasons discussion in Section 3.1, the baseline CNG transit bus fuel economy is defined over the Central Business District (CBD-14) drive cycle, with air conditioning engaged. The CNG baseline models use the same chassis (Orion VI) as the diesel transit bus models of Section 3. This is done to maximize comparability and to isolate the unique differences that natural gas brings to the study. As was the case for the diesel bus models, test weight is half seated load weight (½ SLW—see Section 3.1).

Auxiliary loads are one of the largest energy sinks on a transit bus (second only to losses from fuel combustion). These auxiliary loads (i.e., the so-called "hotel loads") are often employed while in revenue service. Auxiliary loads also represent prime territory for the application of more efficient techniques. For these reasons, the baseline specification is defined for high accessory loading (air conditioning engaged). In this way, the potential for improvements in fuel economy by auxiliary load reduction can be examined.

Chassis dynamometer fuel economy test data for CNG transit buses are used in defining the baseline fuel economy. Fuel economy data for CNG and LNG 40' transit buses appear in Figure 26. These data are used to determine baseline fuel economy for a CNG 40' transit bus with air conditioning (A/C) off. This value is 3.14 mpg over the CBD-14 (diesel equivalent gallons). The baseline specification is chosen to have a 5-speed automatic transmission. The automatic 5-speed transmission (A5) is chosen because 2 of the 3 CNG buses model year 1996 and later use A5s (see "G", "H", and "I" in Figure 26). Moreover, the use of a 5-speed automatic allows consistent comparison to the conventional diesel bus models (see Section 3). Note that bus "H" in Figure 26 uses an A4 transmission and has a higher fuel economy than both of the buses "G" and "I" with A5 transmissions. However, if differences in curb-weight are accounted for using "ton-mpg," the A5 buses are seen to have better fuel economy.

An ADVISOR transit bus model corresponding to the CNG baseline with air conditioning (A/C) off was created. Fuel economy with air conditioning engaged was estimated by applying A/C loads to this initial model. Industry and academia provided (through the 21CT Program) representative ranges for power consumption of auxiliary loads including the A/C. Details regarding the auxiliary load values assumed are given in Section 4.2. A fuel economy with air conditioning engaged of 2.67 mpg (diesel equivalent) over the CBD-14 drive cycle is predicted. A comparison to data for a CNG transit bus tested with A/C "on" and "off" is given in Table 10. These data provide a sense of the validity behind A/C load assumptions.

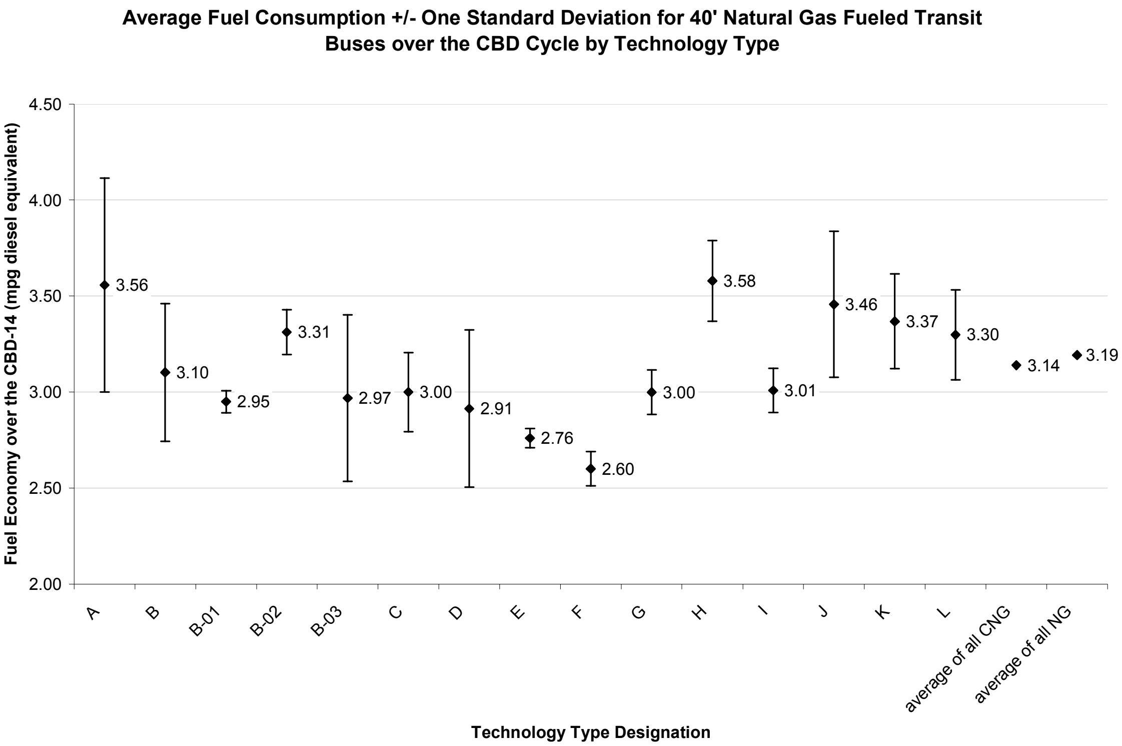
The data given in Table 10 correspond to chassis dynamometer testing of a 40' CNG transit bus over the CBD-14. As a condition for using these data, details on the transit bus are kept anonymous. Without air conditioning engaged, this transit bus's fuel economy averages 3.4 mpg (diesel equivalent). With air conditioning engaged, fuel economy averages 2.8 mpg (diesel equivalent). Based upon the fuel economy difference, the air conditioning adds a penalty of 17 MJ of fuel energy over the CBD-14. This is equal to about 0.12 additional gallons of diesel fuel use over the cycle. If the individual data points from Table 10 are taken separately, a range of fuel penalties can be determined. The range of additional fuel-energy required for the air conditioning is from 11.8 to 21.7 MJ. This is certainly equal to the energy of about 0.085 to 0.157 additional gallons of diesel fuel.

The baseline model with A/C load engaged predicts a fuel economy of 2.67-mpg (diesel equivalent) over the CBD-14. This is equivalent to a 15.4 MJ fuel penalty (0.11 gallons of diesel fuel). This is certainly within the range of A/C load energy penalties seen from the data in Table 10.

Summarizing, the baseline specification is for a 40' compressed natural gas transit bus. The bus uses a 5-speed automatic transmission, composite tank storage, and a natural gas IC engine. The baseline bus is to be tested at half-seated load weight. The bus will achieve 2.67 mpg (diesel equivalent) over the CBD-14 drive cycle with the A/C engaged. The bus chassis is assumed similar to the Orion VI.

Initially, there was some question as to what the baseline fuel economy for the prior Heavy Hybrid Program should be. The program goal states only that the baseline vehicle should be a "comparable 1999 vehicle." As has been detailed above, a CNG baseline fuel economy was chosen and is used in this study. However, the diesel baseline fuel economy from Section 3.1 was also considered. Simulation indicates that the program goal of doubling the fuel economy in a CNG-baseline vehicle is possible. This aspect is discussed in more detail in Section 4.2.

Having the baseline defined, the next step is to evaluate an energy pathway analysis. Series hybridization is the first step along this energy pathway. The initial hybrid model is briefly discussed here. Orion VI hybrid bus test data aided in setting up and validating the initial hybrid model in Section 3.2. However, there are no corresponding test data available for the natural gas series-hybrid bus model. Therefore, the CNG hybrid model is based on the "Orion VI" diesel hybrid model. Slight changes have been made that are appropriate for natural gas. Changes include the use of a natural gas (NG) engine and appropriate weight (to account for NG cylinders). The initial series hybrid model predicts 3.53 mpg (diesel equivalent) over the CBD-14 with the A/C off. With the A/C on, a value of 2.87 mpg (diesel equivalent) is predicted. For comparison with Table 10, the A/C fuel energy penalty for the CNG-hybrid model is 18.0 MJ on the CBD-14. A listing of the notable fuel economy values mentioned in this section is given in Table 11.



Technology Type KEY

GRAPH TAG	Tech Type	Transmission	ave mpg	std dev in mpg	ave wt. (lb)	fuel	ton-mpg
A	1991, 1992 FLXIBLE Metro Cummins L10 G CNG	A3	3.56	0.56	35506	CNG	63
B	1991 FLXIBLE Metro Cummins L10 240G CNG	A3	3.10	0.36	35704	CNG	55
B-01	1991, 1993 FLXIBLE Metro Cummins L10 240G CNG (light test weight)	A3	2.95	0.06	33875	CNG	50
B-02	1991, 1993 FLXIBLE Metro Cummins L10 240G CNG (medium test weight)	A3	3.31	0.12	35110	CNG	58
B-03	1991, 1993 FLXIBLE Metro Cummins L10 240G CNG (heavy test weight)	A3	2.97	0.43	36495	CNG	54
C	1992 BIA Orion Cummins L-10 240G CNG	A4	3.00	0.21	35700	CNG	54
D	1993 TMC RTS-06 Cummins L-10 240G CNG	A5	2.91	0.41	34694	CNG	51
E	1994 OBI Orion V Cummins L-10-240G CNG	A4	2.76	0.05	35700	CNG	49
F	1994 OBI Orion V Cummins L-10-260G CNG	A4	2.60	0.09	35700	CNG	46
G	1996 OBI 5.501 Cummins GL-10-300E+ CNG	A5	3.00	0.12	35820	CNG	54
H	1996 Thomas Built Safe-T-Liner Cummins C8.3-250G CNG	A4	3.58	0.21	28531	CNG	51
I	1996,1997 Orion Cummins GL-10-300E+ (CPL 2190) CNG	A5	3.01	0.12	35820	CNG	54
J	1991, 1993 FLXIBLE Metro Cummins L10 240G LNG	A3	3.46	0.38	36330	LNG	63
K	1993 FLXIBLE Metro Cummins L10 280 LNG	A3	3.37	0.25	36330	LNG	61
L	1998 Nova Cummins L10-280G LNG	A5	3.30	0.23	33200	LNG	55
	average of all CNG		3.14				
	average of all NG		3.19				

Figure 26 Fuel Economy Data for 40’ Natural Gas Transit Buses Run on the CBD-14

Notice that the data in Table 11 show the same trend that was observed in Table 1 from Section 3.1. A given increase in auxiliary loads has a greater impact on hybrid vehicle fuel economy than conventional vehicle fuel economy. The fuel economy benefit due to hybridization is 12.4% with the A/C off. This is equivalent to a saving of 0.0352 gallons equivalent of diesel fuel over the CBD-14 cycle. With the air condition (A/C) engaged, however, the benefit due to hybridization is only 7.5%. This is equivalent to a saving of 0.0261 gallons of diesel fuel over the CBD-14. Note that the same mechanical A/C load value is added to each model (conventional and hybrid) to simulate A/C "on."

Table 10 Fuel Economy for a 40' CNG Transit Bus Tested With and Without A/C Engaged

Test Number	Fuel Economy with A/C Off	Test Number	Fuel Economy with A/C On
1	3.497	4	2.746
2	3.373	5	2.849
3	3.241	6	2.784
Average	3.37	average	2.79

Table 11 Fuel Economy Values of Note from CNG Transit Bus Baseline Determination

Transit Bus Platform and Condition	Baseline Fuel Economy (mpg diesel equivalent)	Method of Determination
Conventional CNG Transit Bus—A/C off	3.14	Based on chassis dynamometer data (fuel economy over CBD-14) for actual transit buses from approximately 1991 to 1998
Conventional CNG Transit Bus Model—A/C on —Baseline Fuel Economy—	2.67	Determined by adding best estimate for A/C loading and simulated with ADVISOR; results compared with actual data for CNG transit bus tested with and without A/C
Initial Series Hybrid CNG Transit Bus—A/C off	3.53	Based on 21CT hybrid model but with weight and engine changed for CNG application
Initial Series Hybrid CNG Transit Bus—A/C on	2.87	Determined by adding best estimate for A/C loading; Matches somewhat with single test data point for a CNG bus tested with A/C on and A/C off

4.2 Energy Efficiency Analysis using ADVISOR

An energy pathway analysis is carried out here to assess the potential fuel economy resulting from step-wise advancements in technology. These step-wise technology additions are the energy efficiency pathway. The pathway presented here is nearly identical to that used in Figure 4 of Section 3.2. There is one exception. The engine is resized to a different value optimized for the circumstances of the CNG pathway (Step H). The energy pathway is based upon the pathway analysis from the Technology Roadmap for the 21st Century Truck Program (21CT 2000 page 4-21). However, the energy pathway has been revised to reflect knowledge gained since the 21CT Roadmap activity. For details and discussion as to the changes made and why, refer to Section 3.2 of this report.

Inputs to the baseline CNG conventional and initial hybrid bus models are presented in Table 12 and Table 13, respectively. Auxiliary load values assumed for the baseline conventional and initial-hybrid bus models are given in Table 14 and Table 15, respectively.

The pathway analysis for the Heavy Hybrid Program appears in Figure 27. The relative contributions of step-wise technology additions to fuel economy are displayed in Figure 28. Similar to Section 3.2, hybridization, weight reduction, and auxiliary loads reduction are key parameters for increasing fuel economy. Hybridization allows for regenerative braking, engine resizing, and use of an electric powertrain. Reduction in rolling resistance also plays a significant role for the CNG bus. This is primarily due to the increased weight of the vehicle over its diesel counterpart. The heavier a vehicle is, the more effect rolling resistance will have on fuel economy.

As can be seen from Table 16, the prior Heavy Hybrid Program goal to double fuel economy is not achieved. Simulation only supports an increase to approximately 1.8 times the baseline fuel economy. However, other potential pathways may be possible that will allow the program goals to be met.

Auxiliary load reduction from the pathway analysis is assumed to be a straight 25% reduction in all components (see top of page 4-25 of 21CT 2000). The auxiliary load reduction step assumes a common vapor compression (V/C) air conditioning (A/C) system is optimized for energy reduction (see Cullimore and Hendricks 2001 or Hendricks 2001 for more information on this topic). Another possibility that could allow a greater than 25% reduction involves the use of different air conditioning (A/C) technology. Several promising technologies have been studied for efficient cooling of vehicles. These technologies include evaporative cooling (E/C) systems, electrically driven V/C systems, and thermal storage systems. In addition to normal E/C systems, E/C systems with desiccant absorption have been examined. The desiccant system allows the E/C system to work even in humid areas by drawing moisture from the air. The use of an evaporative cooling (E/C) system is further explored here. Information on heavy vehicle applications of some of the other systems mentioned above is available from recent sources (see, for example, Kampf and Schmadl 2001 or Pippione *et. al.* 2001).

The E/C system was chosen for further evaluation due to the availability of data from a previous NREL study (Pesaran 1991, 1992). In addition, E/C systems have been employed on transit buses in the past (see VehiCool 2001). Also, these systems appear to have great potential to reduce the A/C load for a given amount of cooling. However, to this author's knowledge, a desiccant equipped E/C system has not been used in any commercial vehicle application. Thus, a practical E/C system may be limited by climate considerations.

A modified version of the pathway analysis that assumes a switch to an E/C system is presented in Figure 29. A representative load of 4 kW is assumed for the E/C system (Pesaran 1991). This is in contrast to the value of 14 kW assumed for an operating V/C (vapor compression) system. As can be seen from Figure 29, with the additional reduction in auxiliary load, a fuel economy greater than double the baseline is predicted. From Table 16, we see that this value is 2.07 times baseline fuel economy. The intention of evaluating an E/C system is to show the potential fuel economy benefit from a reduced A/C load. However, this author does not intend to advocate or reject E/C technology. The technical challenges, pros, and cons of such a system are not addressed here with sufficient depth for meaningful evaluation.

A note should be made regarding the modeling of A/C auxiliary loads in this report. The transit bus models presented here are for constant auxiliary loading only. Thus, the A/C load is simulated as either a constant "on" or a constant "off." A/C control strategy, A/C transient operation, and cabin state (e.g., temperature and humidity) are not modeled at this time. Because of these limitations, designs that reduce cabin heating (see for example, Rugh *et. al.* 2001), and thus the need for A/C use, are not considered. Instead, the transit bus models simulate a "snapshot" in time when the A/C is 100% engaged. Comparisons are made on the basis of this "snapshot."

The choice of baseline fuel economy for the prior Heavy Hybrid Program is discussed next. The previous Heavy Hybrid Program goal statement supports the interpretation of either a CNG baseline vehicle or a diesel baseline vehicle (OHVT 2000). In a sense, there is no right or wrong answer regarding this matter—it is a matter of definition. However, the energy pathway results indicate doubling the fuel economy of a CNG baseline is more plausible than doubling relative to a diesel baseline. Figure 30 reprints the information from the pathway analysis displayed in Figure 29, but with demarcations for a diesel baseline. Even assuming a switch to an E/C system, the model is unable to reach double diesel baseline fuel economy. A value of approximately 1.7 times the baseline diesel fuel economy is achieved instead.

Table 12 Model Inputs for Baseline Conventional CNG 40' Transit Bus Model in ADVISOR

Input	Value
Chassis	based upon OBI Orion VI (New York City Transit Configuration)
Simulated Vehicle Weight[1]	33,567 lbs. (15,223 kg)
Auxiliary Load (mechanical, run off of the engine)	29.5 kW constant with A/C on; 15.5 kW constant with A/C off
APU	based on 209 kW (280 HP) John Deere PowerTech 8.1 L CNG engine, 39% peak efficiency
Transmission	Auto 5 speed
Rolling Resistance Coefficient[2] (RRC_0)	0.00938
Frontal Area	8.0516 m^2
Coefficient of Drag, C_D	0.79
Air Density	1.23 kg/m^3
Acceleration due to Gravity	9.81 m/s^2
Fuel Economy over CBD-14	2.67 mpg diesel equivalent with A/C on; 3.14 mpg diesel equivalent with A/C off

[1] curb weight plus 26 people = ½ SLW [half seated load weight]; one person assumed to weigh 150 lbs.

[2] RRC_0 is independent of vehicle speed. Force due to rolling resistance = RRC_0 x (vehicle weight)

Table 13 Models Values for Initial Series Hybrid CNG 40' Transit Bus Model in ADVISOR

Input	Value
Chassis	based upon OBI Orion VI (New York City Transit Configuration)
Simulated Vehicle Weight[1]	36625 lbs. (16610 kg)
Auxiliary Loads	23 kW constant mechanical, 9 kW constant electrical with A/C on 9 kW constant mechanical, 9 kW constant electrical with A/C off
APU	based on 189 kW (250 HP) John Deere PowerTech 8.1 L CNG engine, 39% peak efficiency
Transmission	Single reduction direct drive; final drive ratio of 6.34
Rolling Resistance Coefficient[2] (RRC_0)	0.00938
Frontal Area	8.0516 m^2
Coefficient of Drag, C_D	0.79
Air Density	1.23 kg/m^3
Electric Motor	187 kW AC (92% peak efficiency)
Battery	46 modules (85 Amp hrs ea., weighing 3400 lbs.)
Regenerative Braking Efficiency[3]	~39% over CBD-14
Fuel Economy over CBD-14	2.87 mpg diesel with A/C on; 3.53 mpg diesel with A/C off

[1] curb weight plus 26 people = ½ SLW [half seated load weight]; one person assumed to weigh 150 lbs.

[2] RRC_0 is independent of vehicle speed. Force due to rolling resistance = RRC_0 x (vehicle weight)

[3] Percent of available braking energy available as electric power from the traction motor

Table 14 Breakdown of Auxiliary Loading Assumed for Baseline CNG Conventional Bus Model

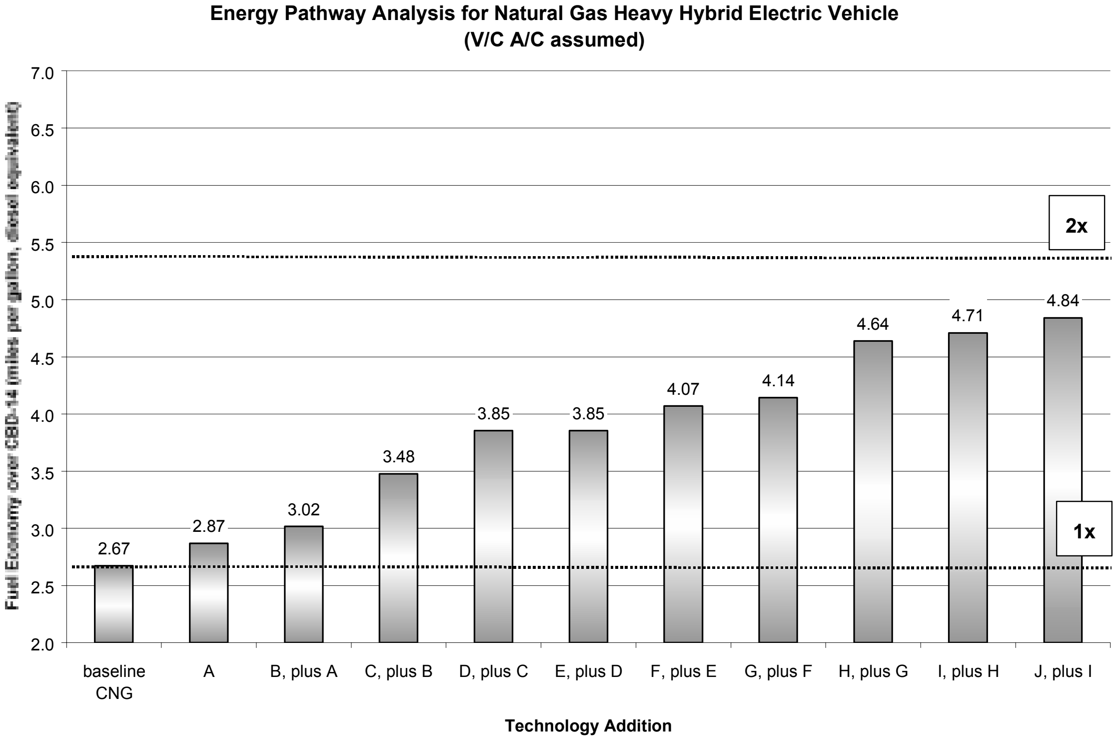
Component	**Mechanical Load on Engine (kW)**	
	Assumed Value	**Valid Range**
Air Compressor (doors, brakes, suspension, etc.)	1	0.75 to 3
Alternator load on engine	1	0 to ~5
Engine Fan	12.5	7.5 to 15
HVAC load for Air Conditioning [A/C]	14	~18.5 to ~22.5[1]
Hydraulic Pump/Power Steering	1	0.9 to 1 or higher
Total with A/C	29.5	
Total without A/C	15.5	

[1] Note: 12 to 15 kW given by alternate reference (Pesaran *et. al.* 1992)

Table 15 Breakdown of Auxiliary Loading Assumed for Initial CNG Series Hybrid Bus Model

Component	**Electrical Load on Power Bus (kW)**		**Mechanical Load on Engine (kW)**	
	Assumed Value	**Valid Range**	**Assumed Value**	**Valid Range**
Air Compressor (doors, brakes, suspension, etc.)	NA	NA	0.75	0.75 to 3
Lights and misc. other low voltage accessories run off of alternator	0	0 to ~5	NA	NA
Hybrid Specific Coolant Pumps (for motor/etc.), Fans for battery compartment, Computers, etc.	9	~9	NA	NA
Engine Fan	NA	NA	7.5	7.5 to 15
HVAC load for Air Conditioning [A/C]	NA	NA	14	~18.5 to ~22.5[1]
Hydraulic Pump/Power Steering	NA	NA	0.75	up to 0.9~1 kW and above
Total with A/C	9		23	
Total without A/C	9		9	

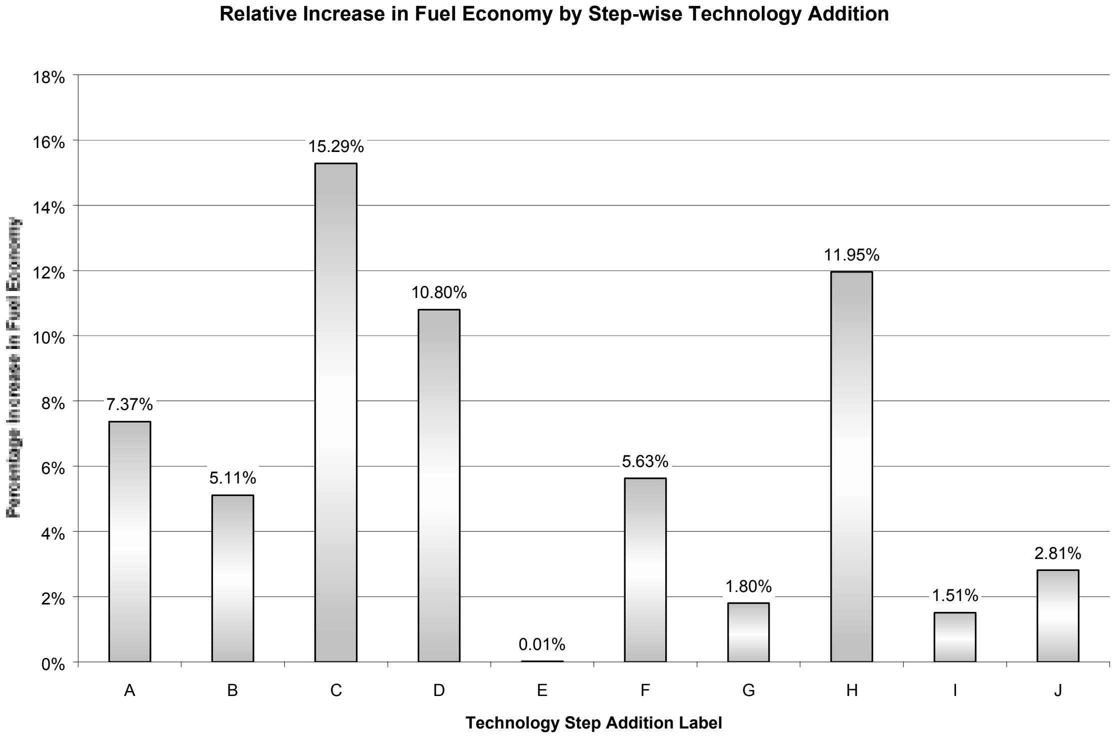
[1] Note: 12 to 15 kW given by alternate reference (Pesaran *et. al.* 1992)



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series CNG Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. All Auxiliary loads reduced by 25%: mechanical 23 kW to 17.25 kW, electrical reduced from 9 kW to 6.75 kW, plus B	**H.** Engine resized to 85 kW from 189 kW (engine size optimized for fuel economy over CBD-14), plus G
D. Curb weight minus battery weight and CNG tank weight reduced 30%--test weight changed from 36625 lbs. (16610 kg) to 28250 lbs. (12812 kg), plus C	**I.** Weight reduced by 990 lbs. (450 kg) to represent reduction in engine size, plus H
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J.** Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 24021 lbs.], plus I

NOTE: a Vapor Compression (V/C) air condition (A/C) unit is assumed in this study. Battery pack weight is assumed to be 3400lbs. (1542 kg) for 46 modules and CNG tank weight is assumed to be 1410 lbs. (640 kg) for 6 tanks

Figure 27 Energy Pathway Analysis for 40’ CNG Transit Bus—Assuming Vapor Compression Air Condition System Used Throughout



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series CNG Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. All Auxiliary loads reduced by 25%: mechanical 23 kW to 17.25 kW, electrical reduced from 9 kW to 6.75 kW, plus B	**H.** Engine resized to 85 kW from 189 kW (engine size optimized for fuel economy over CBD-14), plus G
D. Curb weight minus battery weight and CNG tank weight reduced 30%--test weight changed from 36625 lbs. (16610 kg) to 28250 lbs. (12812 kg), plus C	**I.** Weight reduced by 990 lbs. (450 kg) to represent reduction in engine size, plus H
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J.** Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 24021 lbs.], plus I

NOTE: a Vapor Compression (V/C) air condition (A/C) unit is assumed in this study. Battery pack weight is assumed to be 3400lbs. (1542 kg) for 46 modules and CNG tank weight is assumed to be 1410 lbs. (640 kg) for 6 tanks

Figure 28 Relative Percent Increases in Fuel Economy by Technology Step Addition for CNG Bus

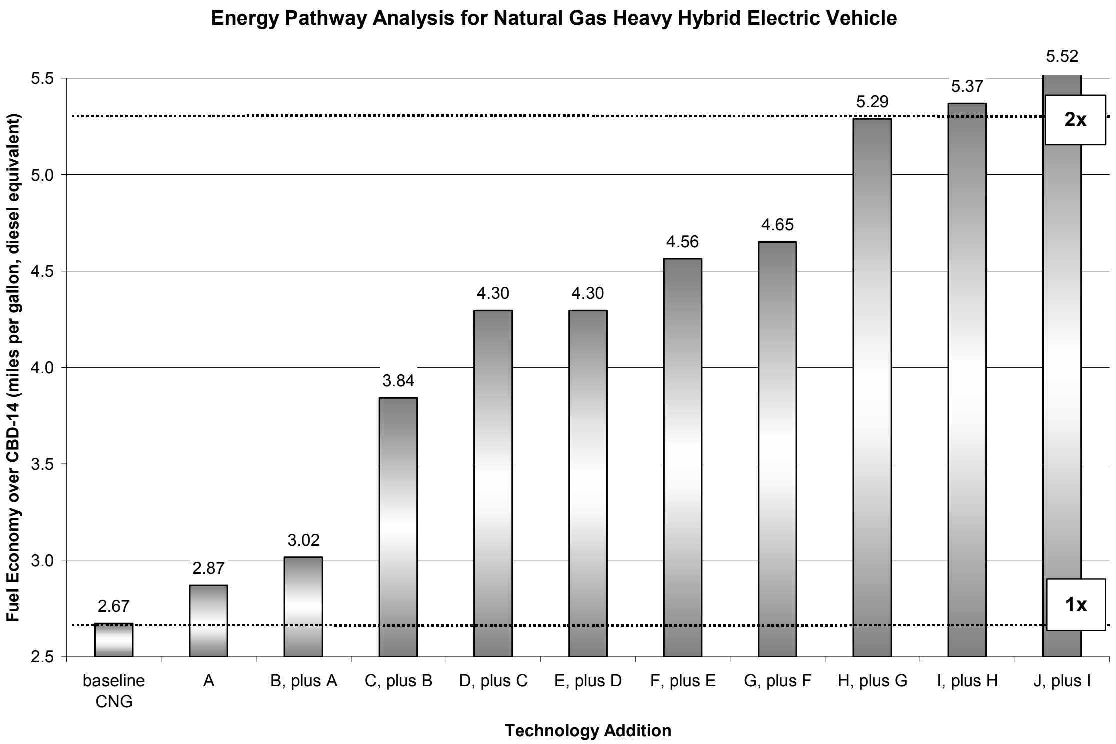
Table 16 Energy Audit of Natural Gas Transit Bus Models

Component Energy Utilization	Baseline CNG Transit Bus		Step A. Initial Series CNG Hybrid Transit Bus Model		Step J. from Pathway Analysis--V/C A/C Used Throughout		Step J. from Pathway Analysis--V/C A/C changed to E/C A/C	
	Energy Lost over drive cycle(kJ)	Percent Energy Lost	Energy Lost over drive cycle(kJ)	Percent Energy Lost	Energy Lost over drive cycle(kJ)	Percent Energy Lost	Energy Lost over drive cycle(kJ)	Percent Energy Lost
Engine losses	18.99	66%	16.97	63%	9.35	59%	8.41	60%
Auxiliary loads	4.70	16%	5.10	19%	3.83	24%	2.79	20%
Drivetrain losses	2.49	9%	0.35	1%	0.27	2%	0.27	2%
Generator losses	NA	NA	0.31	1%	0.19	1%	0.19	1%
Energy storage system losses	NA	NA	0.27	1%	0.17	1%	0.18	1%
Motor/controller losses	NA	NA	0.99	4%	0.49	3%	0.49	4%
Friction braking	1.16	4%	1.26	5%	0.73	5%	0.73	5%
Aerodynamic losses	0.24	1%	0.24	1%	0.24	2%	0.24	2%
Rolling resistance losses	1.26	4%	1.37	5%	0.66	4%	0.66	5%
Regenerative Braking Capture Efficiency	NA		39%		49%		49%	
Powertrain Efficiency	38%		41%		40%		47%	
Transit bus test weight (lbs.)	15223		16610		11500		11500	
Total energy used over CBD-14 (kWh)	28.83		26.87		15.93		13.96	
Fuel consumption over CBD-14 (mpg)	2.67		2.87		4.84		5.52	
Fuel economy multiplier	1.00		1.07		1.81		2.07	

V/C = vapor compression

A/C = air conditioning

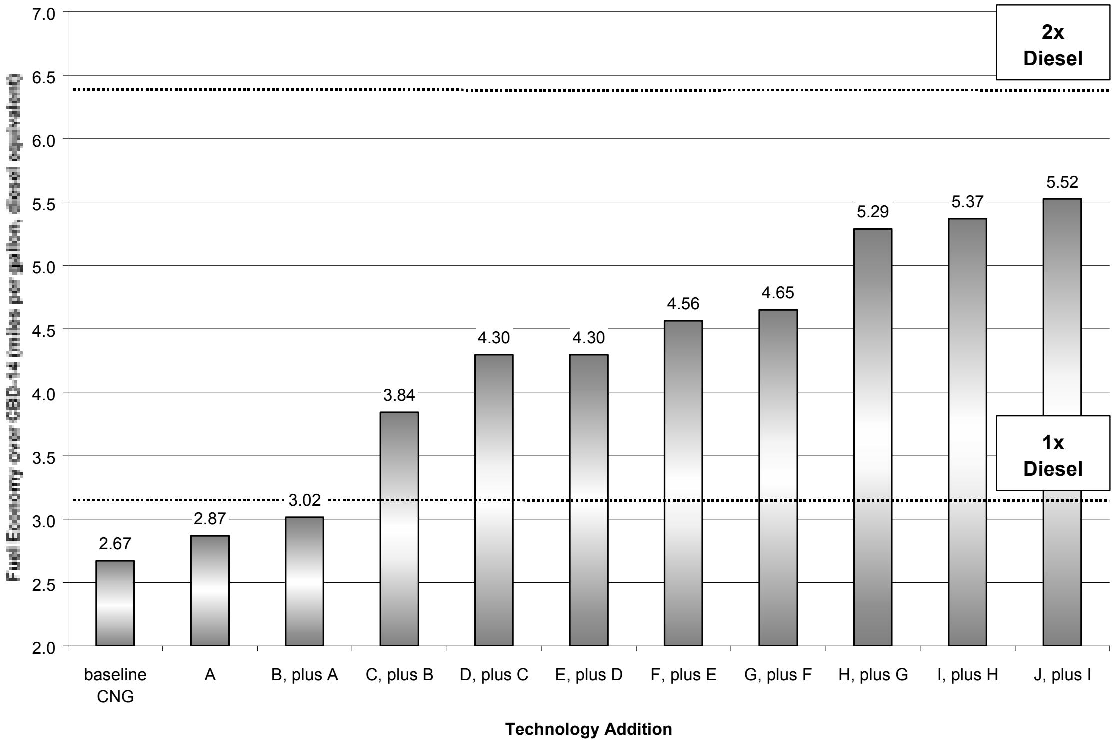
E/C = evaporative cooled



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series CNG Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. All auxiliary loads reduced by 25% except A/C which is reduced ~71% to simulate switch from Vapor Compression (V/C at 14 kW mechanical) to Desiccant Assisted Evaporative Cooled (E/C at 4 kW mechanical) A/C. Accessory load moves from 23 kW mechanical to 10.75 kW mechanical and 9 kW electrical to 6.75 kW electrical, plus B	**H.** Engine resized to 85 kW from 189 kW (engine size optimized for fuel economy over CBD-14), plus G
D. Curb weight minus battery weight and CNG tank weight reduced 30%--test weight changed from 36625 lbs. (16610 kg) to 28250 lbs. (12812 kg), plus C	**I.** Weight reduced by 990 lbs. (450 kg) to represent reduction in engine size, plus H
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J.** Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 24021 lbs. (11500 kg)], plus I

NOTE: a change from Vapor Compression (V/C) air condition (A/C) to Evaporative Cooled (E/C) A/C is assumed in this study. Battery pack weight is assumed to be 3400lbs. (1542 kg) for 46 modules and CNG tank weight is assumed to be 1410 lbs. (640 kg) for 6 tanks

Figure 29 Energy Pathway Analysis for 40' CNG Transit Bus—Assuming a Change from Vapor Compression Air Condition System to Evaporative Cooled Air Condition System



Key to Energy Pathway Step-Wise Technology Addition	
A. Initial Series CNG Hybrid Transit Bus Model	**F.** Peak Motor efficiency increased to 96% from 92%, plus E
B. Rolling resistance coefficient reduced from 0.00938 to 0.0065, plus A	**G.** Regenerative Braking schedule changed such that 50% of available brake energy captured, plus F
C. All auxiliary loads reduced by 25% except A/C which is reduced ~71% to simulate switch from Vapor Compression (V/C at 14 kW mechanical) to Desiccant Assisted Evaporative Cooled (E/C at 4 kW mechanical) A/C. Accessory load moves from 23 kW mechanical to 10.75 kW mechanical and 9 kW electrical to 6.75 kW electrical, plus B	**H.** Engine resized to 85 kW from 189 kW (engine size optimized for fuel economy over CBD-14), plus G
D. Curb weight minus battery weight and CNG tank weight reduced 30%--test weight changed from 36625 lbs. (16610 kg) to 28250 lbs. (12812 kg), plus C	**I.** Weight reduced by 990 lbs. (450 kg) to represent reduction in engine size, plus H
E. Final drive gearing and motor operation points optimized for current drive cycle, plus D	**J.** Battery weight reduced by 1900 lbs. (~56% reduction) [test weight is 24021 lbs. (11500 kg)], plus I

NOTE: a change from Vapor Compression (V/C) air condition (A/C) to Evaporative Cooled (E/C) A/C is assumed in this study. Battery pack weight is assumed to be 3400lbs. (1542 kg) for 46 modules and CNG tank weight is assumed to be 1410 lbs. (640 kg) for 6 tanks

Figure 30 Energy Pathway Analysis for 40' CNG Transit Bus with Diesel Baseline Displayed—Assuming a Change from Vapor Compression Air Condition System to Evaporative Cooling System

4.3 Parametric Analysis

The parametric analysis in this section displays "carpet plots" of predicted transit bus fuel economy. This is accomplished by making parametric sweeps on fuel economy with several key parameters using ADVISOR. The organization of this section is the same as that found in Section 3.3. For a listing of the key parameters used for the parametric sweep analysis, refer to Table 8 in Section 3.3.

Figure 31 and Figure 32 show the variation of conventional CNG bus fuel economy with weight and mechanical auxiliary load for two different rolling resistances. Note how fuel economy falls off much faster from points of high fuel economy than low. That is, contour lines are closer together at high fuel economy than low fuel economy. Refer to Section 3.3 for details on this observation.

Figure 33 through Figure 37 show initial series-hybrid model fuel economy by weight, rolling resistance, and auxiliary loads. This bus model corresponds to Step A of the energy pathway analysis (see Figure 27 or Figure 29).

Figure 38 through Figure 41 show the "advanced" bus model's fuel economy by weight, rolling resistance, and auxiliary load. This bus model corresponds to Step J of either of the two energy-pathway analyses presented in Section 4. This is because the two pathway analyses presented here only differ by the assumed value of auxiliary load reduction. Since auxiliary loads are parameterized in the charts, the differences in pathway assumptions are eliminated as well.

Figure 42 and Figure 43 show the effect variation in aerodynamic drag has on fuel economy over several cycles. Figure 42 corresponds to the conventional CNG transit bus model. Figure 43 corresponds to the initial series hybrid model (Step A). The drive cycles evaluated are the CBD-14 cycle (Central Business Cycle, Figure 1), the Arterial Cycle (Figure 24), and the Commuter Cycle (Figure 25). Each cycle represents a certain type of transit bus driving. The CBD-14 represents intense inner city stop-and-go driving. The arterial cycle represents slightly less stop-and-go with higher speed. The commuter cycle represents high constant-speed driving. Several conclusions can be drawn from Figure 42 and Figure 43. It is apparent that there is little benefit to aerodynamic drag reduction on low-speed cycles such as the CBD-14 (average speed of 12.6 mph). There is some benefit for drag reduction on medium speed cycles such as the arterial cycle (average speed of 24.8 mph). Significant benefit can be obtained for drag reduction on high-speed cycles such as the commuter cycle (average speed of 43.8 mph).

Figure 42 and Figure 43 together show the difference between conventional and hybrid vehicles. Notice that the hybrid advantage decreases when relatively high constant-speed drive cycles are chosen. The hybrid receives better gas mileage than the conventional vehicle over the CBD-14 and Arterial cycles. However, the conventional vehicle has better gas mileage for the higher constant-speed commuter cycle. This is because the hybrid is no longer able to capitalize on hybrid features such as regenerative braking. Furthermore, the conventional vehicle is able to run close to maximum efficiency. Thus, the benefit of decoupling the engine from the road demand is nullified. The hybrid's added weight and multiple energy conversions work against the hybrid bus as well, in this situation.

Finally, Table 17 displays the predicted fuel economy for models over various drive cycles. Descriptions of drive cycles listed in Table 17 but not described in this report are available from other sources (see for example, NAVC 2000). Simulations that slightly deviate from the drive trace are marked with a single asterisk. Simulations with larger deviation (but still deemed acceptable for reporting) are marked with two asterisks. Failure to meet a drive trace is believed to be due to problems with the automatic transmission model. Not meeting a drive trace tends to cause the ADVISOR simulation to under-predict fuel economy. Thus, for cycles such as the Manhattan cycle, the fuel economy multiplier is over-predicted.

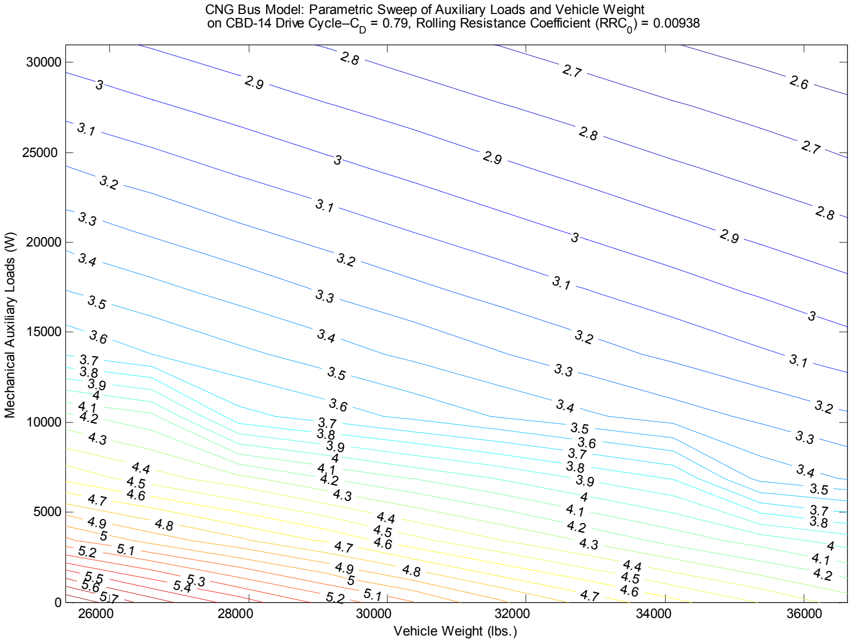


Figure 31 Conventional CNG Bus Model: Parametric Sweep on Mechanical Auxiliary Load and Vehicle Weight for a Rolling Resistance Coefficient of 0.00938

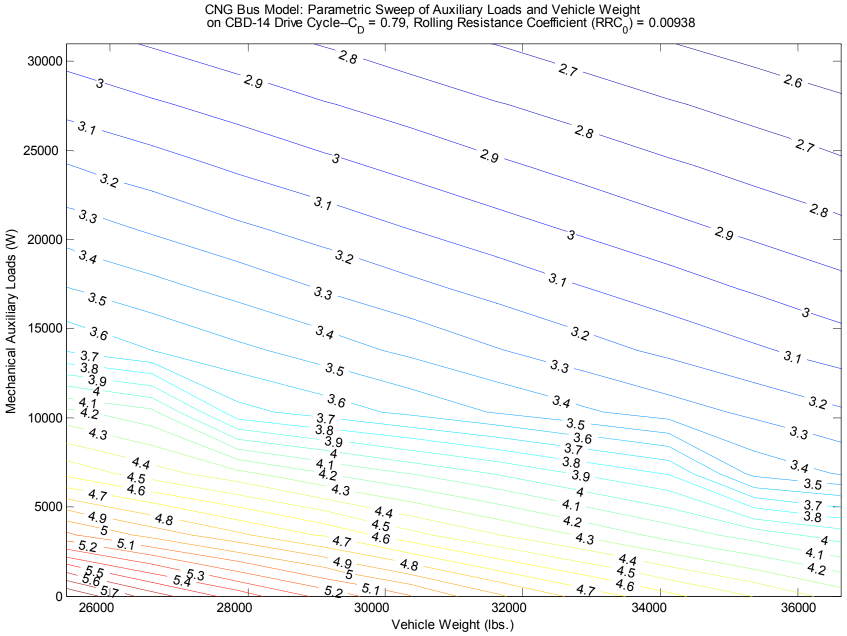


Figure 32 Conventional CNG Bus Model: Parametric Sweep on Mechanical Auxiliary Loads and Vehicle Weight for a Rolling Resistance Coefficient of 0.0065

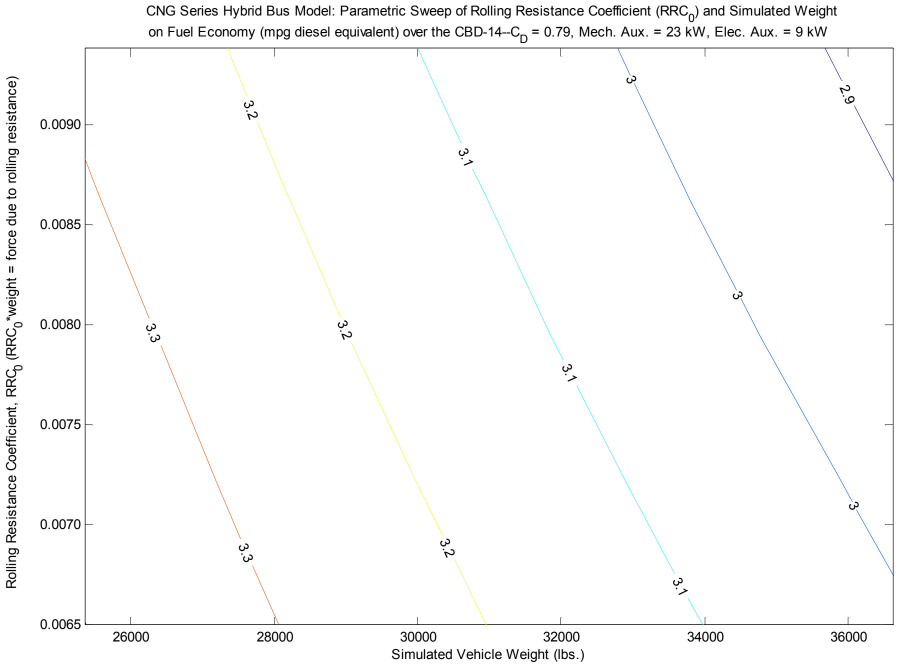


Figure 33 CNG Series Hybrid Bus Model: Parametric Sweep on Rolling Resistance Coefficient and Vehicle Weight

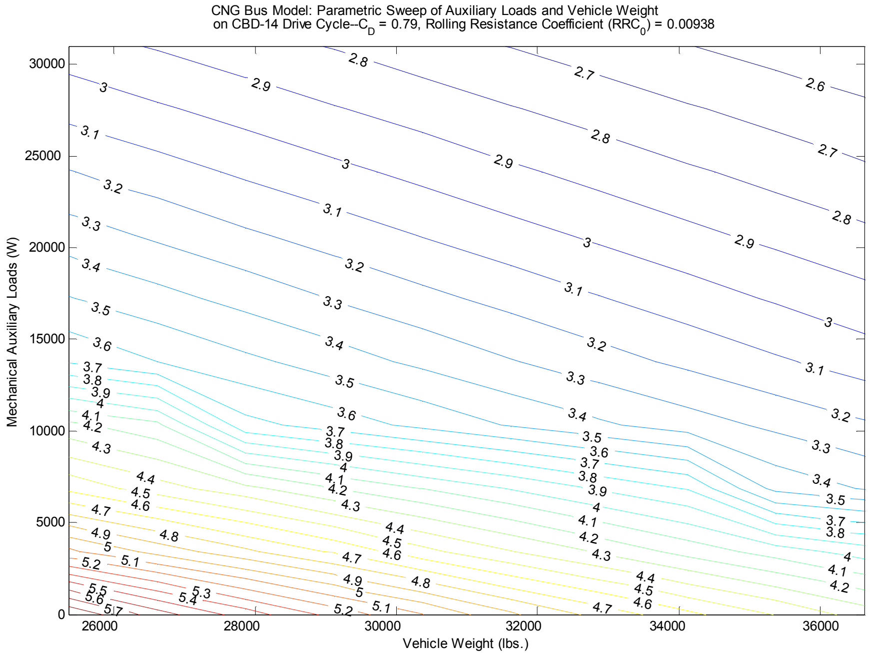


Figure 34 CNG Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 36625 lbs. (16610 kg)

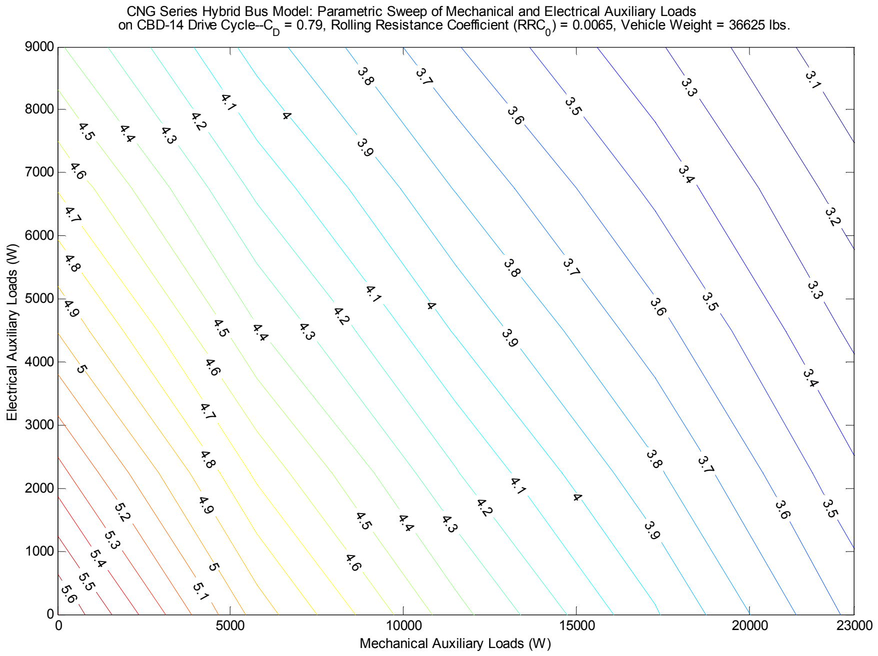


Figure 35 CNG Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 36625 lbs. (16610 kg)

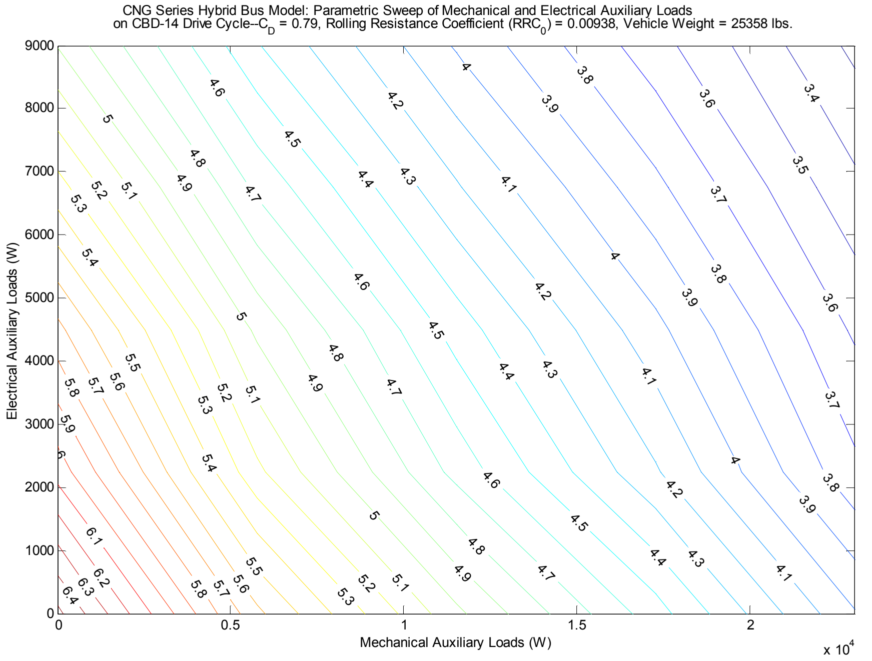


Figure 36 CNG Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 25358 lbs. (11500 kg)

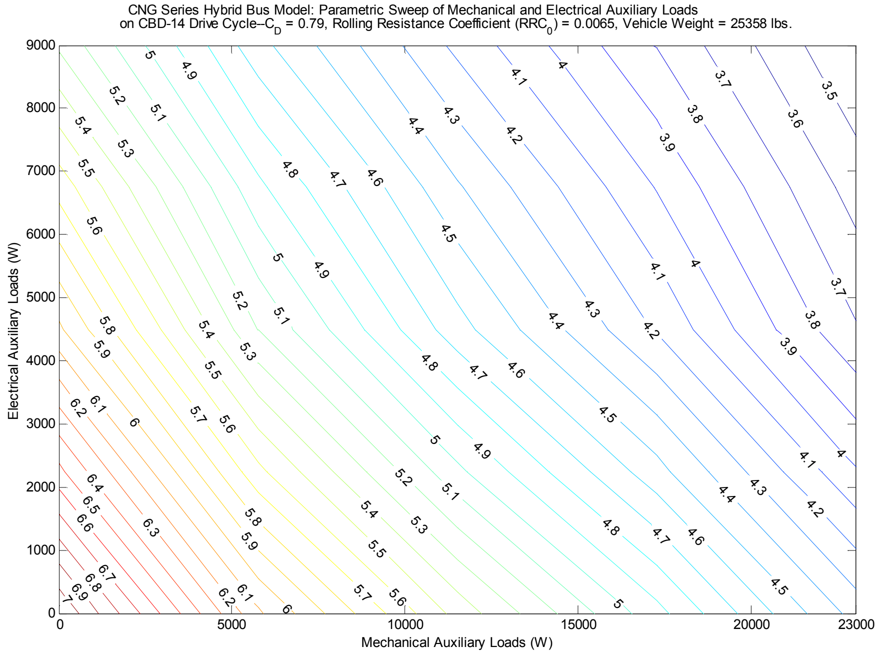


Figure 37 CNG Series Hybrid Bus Model: Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 25358 lbs. (11500 kg)

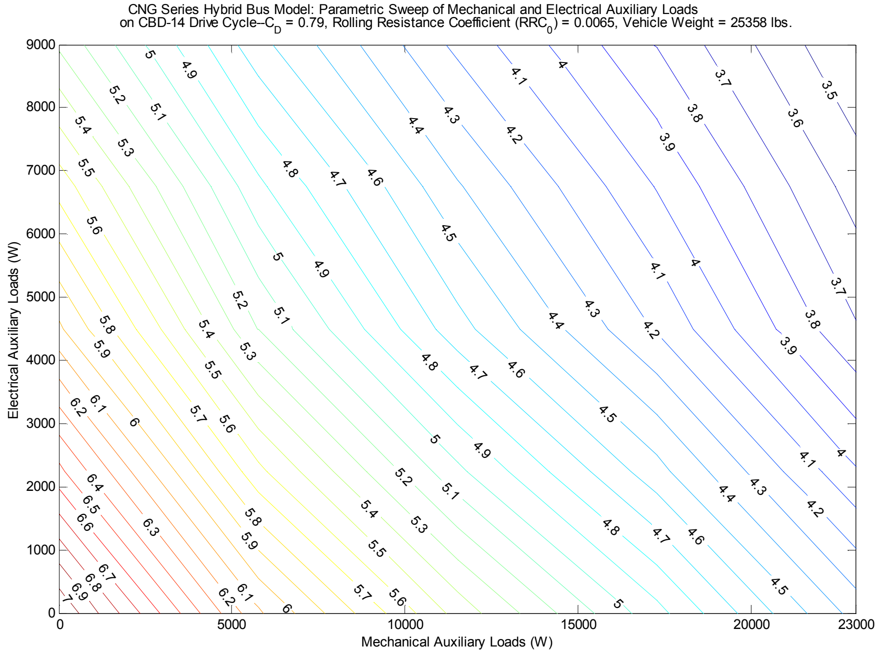


Figure 38 Advanced CNG Series Hybrid Bus Model (85 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 25358 (11500 kg)

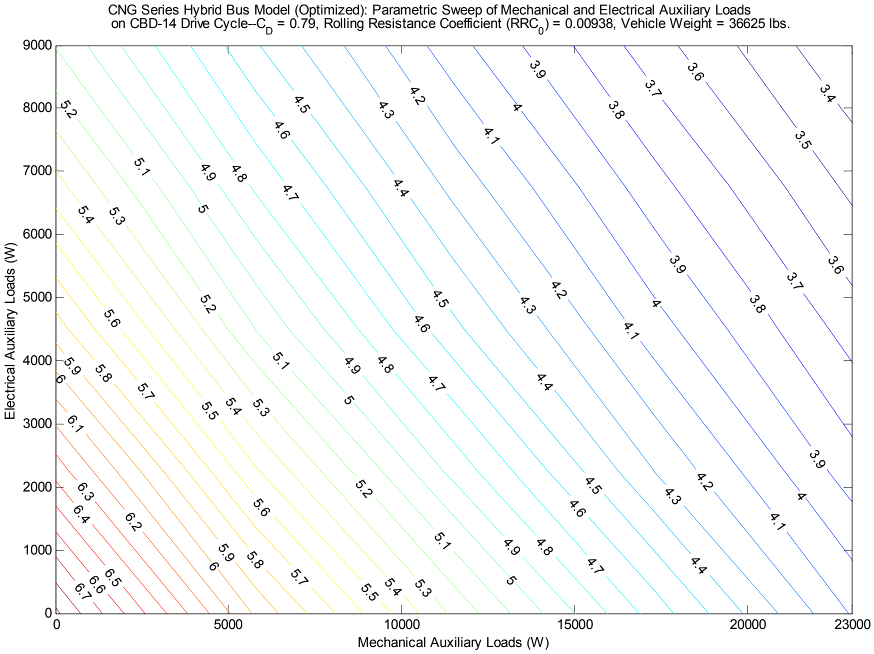


Figure 39 Advanced CNG Series Hybrid Bus Model (85 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 36625 lbs. (16610 kg)

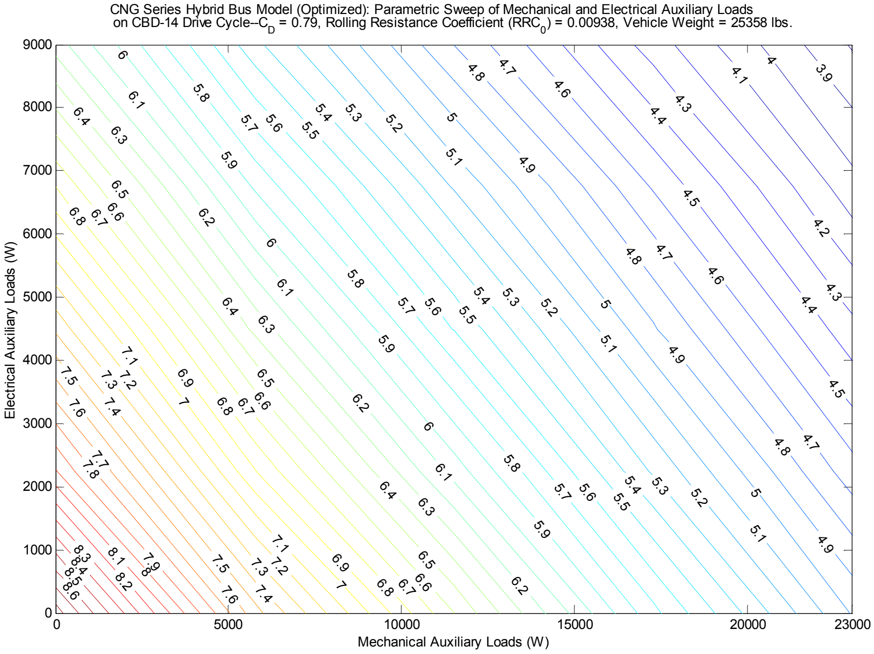


Figure 40 Advanced CNG Series Hybrid Bus Model (85 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.00938 and Vehicle Weight of 25358 lbs. (11500 kg)

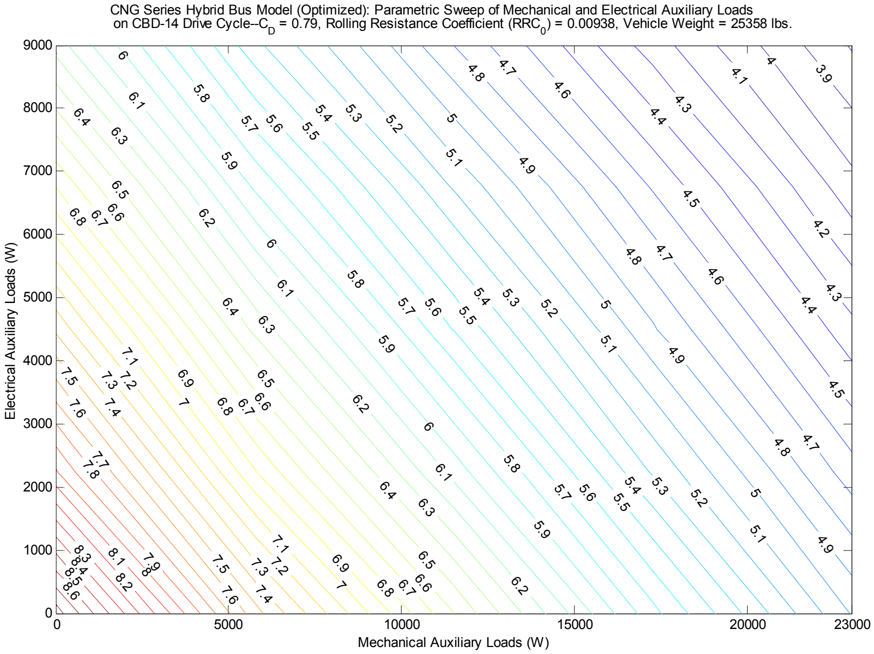


Figure 41 Advanced CNG Series Hybrid Bus Model (85 kW engine): Parametric Sweep of Mechanical and Electrical Auxiliary Loads for Rolling Resistance Coefficient of 0.0065 and Vehicle Weight of 36625 lbs. (16610 kg)

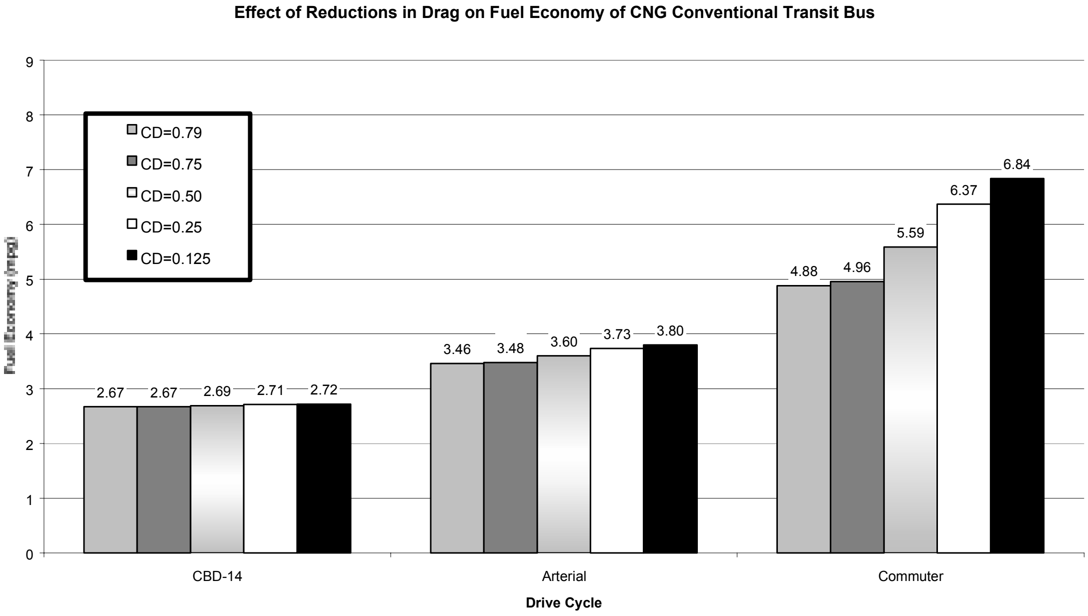


Figure 42 Effect of Reductions in Drag Coefficient (C_D) on Fuel Economy of Conventional CNG Transit Bus

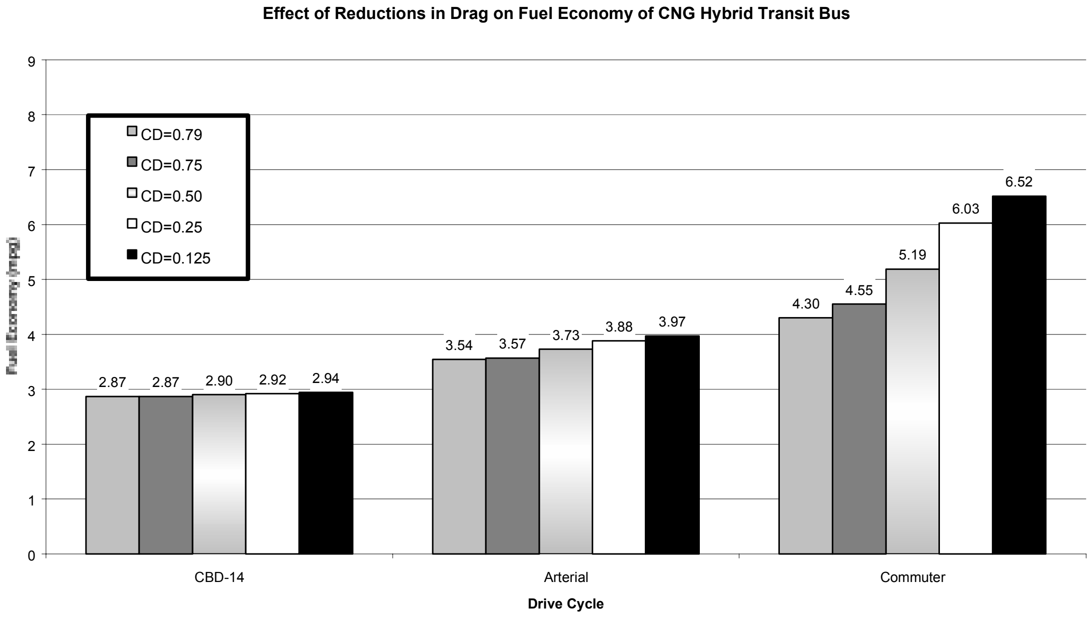


Figure 43 Effect of Reductions in Drag Coefficient (C_D) on Fuel Economy of Initial CNG Hybrid Transit Bus

Table 17 Fuel Economy Predictions for Models over Various Drive Cycles

Drive Cycle	Baseline Conventional CNG Model Fuel Economy (mpg)	Advanced Hybrid CNG Model Fuel Economy—V/C (mpg)	Advanced Hybrid CNG Model Fuel Economy—V/C to E/C (mpg)
CBD	2.67	4.84 (1.81x)	5.52 (2.07x)
Arterial	3.46	5.60 (1.62x)	6.27 (1.81x)
Commuter	4.88	NCS: 3.56 (0.73x)	NCS: 6.03 (1.24x)
Manhattan	1.59*	3.16 (1.99x)	3.65 (2.30x)
New York Bus	0.79**	1.94 (2.46x)	2.26 (2.86x)
New York Composite	2.12*	3.81 (1.80x)	4.38 (2.07x)

* Slight trace miss (deviation from intended drive cycle) was experienced by the models shown. Average absolute difference in speed less than 0.3 mph.

** Trace miss with absolute average difference greater than 0.3 mph but less than 0.5 mph experienced

NCS = Not Charge Sustaining, if a number appears in this column, it was obtained via linear estimation

5 Planned Auxiliary Loads Modeling Enhancements

The overall objective to maximize vehicle fuel economy is constrained by requirement to address certain needs with auxiliary loads. An auxiliary load is defined here as an energy demand on the powertrain not directly related to the vehicle's mission(s). The primary mission of most vehicles is the transport of people and/or goods. An increased focus on vehicle auxiliary loads reduction is justified due to their importance in increasing fuel economy. In this section, modeling techniques being developed at NREL to address auxiliary loads are presented and discussed.

An auxiliary load is placed upon the powertrain by an auxiliary device that addresses some need. For example, a belt-driven compressor places a load on the engine to run the A/C system. The A/C system addresses the need for occupant thermal comfort. Some auxiliary loads satisfy critical needs that must be addressed for sustained vehicle operation. For example, the engine cooling-fan and water-pump convect damaging heat away from the engine. Other auxiliary loads are required to address the need for safe operation of a vehicle. For example, external lights and windshield-wipers allow a driver to safely operate a vehicle in adverse conditions. Thus, often the needs addressed by auxiliary devices cannot be ignored. At the same time, the energy used by auxiliary loads can be significant. This is especially true for heavy vehicles such as transit buses where auxiliary loads can be upwards of 30 kW (approximately 15% of typical engine peak-power). Thus the potential fuel savings that could result from auxiliary load reduction is high.

Currently, ADVISOR only supports the specification of lumped constant mechanical and/or electrical auxiliary loads. However, NREL researchers are developing better auxiliary load models. The basic elements in an auxiliary load model are presented in Figure .

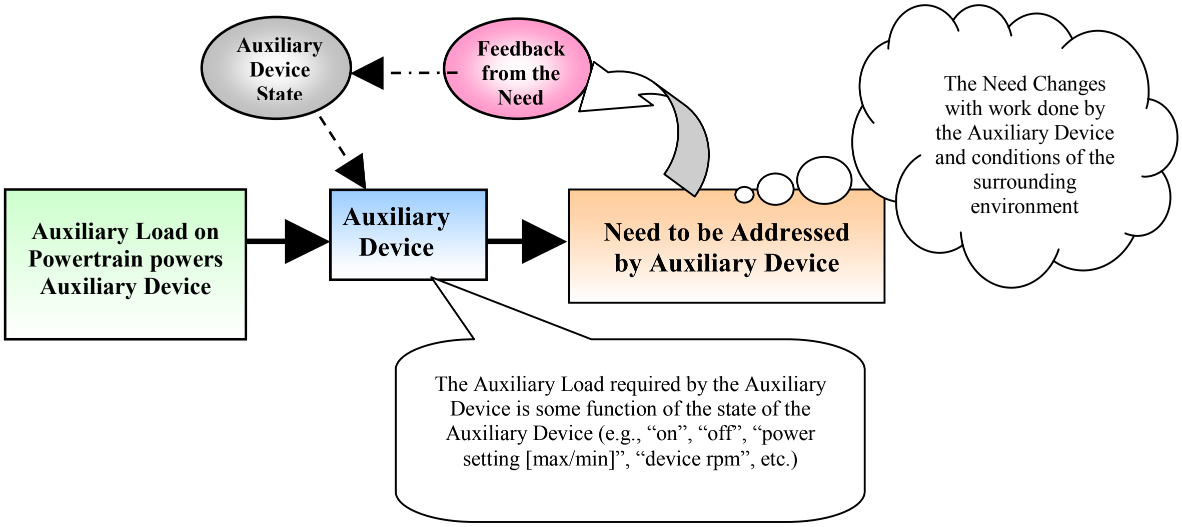


Figure 44 Generic Model of an Auxiliary Load, Device, and Need.

As can be seen from Figure 44, there are different aspects to an auxiliary load model. The detail with which an auxiliary load is modeled depends upon the situation and modeling objective. The simplest model is a constant auxiliary loading. This is currently implemented in ADVISOR. This simple model may be appropriate for some systems. A more detailed model would specify auxiliary loading versus time. This strategy requires prior knowledge of the duty cycle of an auxiliary device.

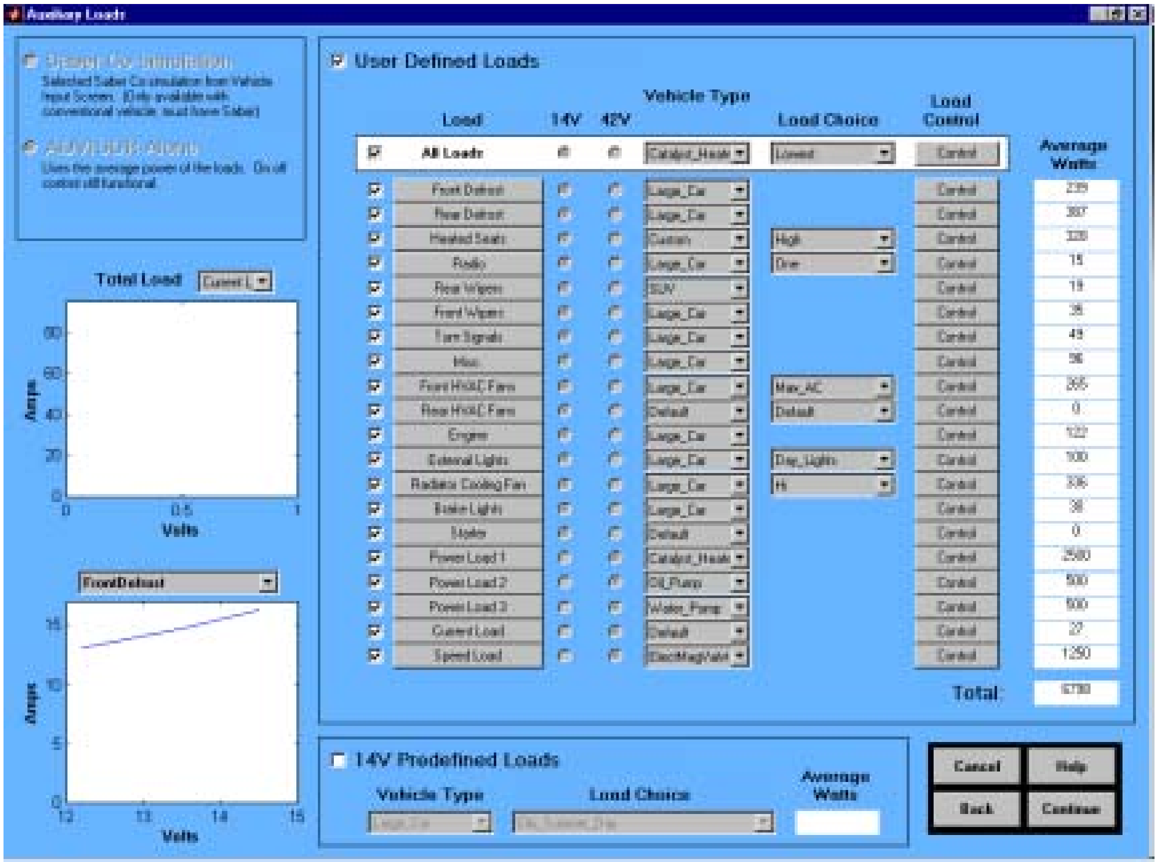
Another level of modeling detail would take into account the auxiliary device and auxiliary device's state. For instance, the performance of a belt-driven device often changes with shaft rpm or external environment conditions. Fuel transient A/C models have been developed at NREL to capture sophisticated dynamics within an A/C system and, thereby, more accurately simulate realistic operation and driving conditions. Simple controls can be implemented by specifying such things as "on" or "off" vs. time. This level of modeling creates quasi-realistic loading on the powertrain to better estimate fuel economy and emissions. The major effects of many devices can be sufficiently captured with this level of detail. Brake lights and power steering pumps could be good candidates for this type of model. The final level of detail models the need itself. The interaction of the need, the surrounding environment, and the auxiliary device are modeled. This level of modeling requires the most effort to create, but is necessary for effective auxiliary-load reduction.

An effective auxiliary-load reduction strategy starts with the "need" first. After the need has been minimized, the distribution system and auxiliary device technology can be addressed. A perfect example of this is vehicle climate control. Consider a need to cool a vehicle cabin for occupant thermal comfort. By applying reflective paints, insulation, and reflective window glazings, the need to cool the vehicle cabin can be reduced significantly (see for example, Farrington *et. al.* 1999). Thus, the A/C load is reduced because the A/C unit no longer has to work as long or as hard. Two projects related to auxiliary loads modeling and currently in progress at NREL are discussed below.

5.1 The Modeling of Auxiliary Loads through Co-simulation with Saber

Saber is a software tool for mixed-signal and mixed-technology simulation and modeling. Saber offers the ability to evaluate electrical systems and circuit, module, and electrical component designs on a detailed level. Coupled with ADVISOR, which evaluates propulsion and energy management system efficiency, the entire electromechanical system can be modeled.

Currently, single voltage (14 V) and dual voltage (14 and 42 V) ADVISOR/Saber co-simulations are possible on conventional vehicle powertrains. The vehicle's generator, regulator, battery, and auxiliary loads (on the voltage bus) are modeled in the Saber environment. The auxiliary load models are represented as current draws (varying with battery voltage or engine speed) or power draws. Figure 455 shows the auxiliary load GUI with multiple pre-defined loads, all of which may also be user-defined. The user may also specify on/off control operation, where applicable.



☑ User Defined Loads

	Load	Vehicle Type	Load Choice	Load Control	Average Watts
☑	All Loads	Catalyst_Heat	Lowest	Control	
☑	Front Defrost	Large_Car		Control	239
☑	Rear Defrost	Large_Car		Control	387
☑	Heated Seats	Custom	High	Control	320
☑	Radio	Large_Car	Drive	Control	15
☑	Rear Wipers	SUV		Control	19
☑	Front Wipers	Large_Car		Control	35
☑	Turn Signals	Large_Car		Control	49
☑	Misc	Large_Car		Control	56
☑	Front HVAC Fans	Large_Car	Max_AC	Control	265
☑	Rear HVAC Fans	Default	Default	Control	0
☑	Engine	Large_Car		Control	122
☑	External Lights	Large_Car	Day_Lights	Control	100
☑	Radiator Cooling Fan	Large_Car	Hi	Control	336
☑	Brake Lights	Large_Car		Control	38
☑	Starter	Default		Control	0
☑	Power Load 1	Catalyst_Heat		Control	2580
☑	Power Load 2	Oil_Pump		Control	500
☑	Power Load 3	Water_Pump		Control	500
☑	Current Load	Default		Control	27
☑	Speed Load	ElectMagValv		Control	1250
				Total:	6730

☐ 14V Predefined Loads

Vehicle Type: Large_Car

Load Choice: [illegible]

Average Watts:

Figure 45 Saber Co-simulation Setup Screen in ADVISOR

Co-simulation is conducted through the reading and writing of files between ADVISOR and Saber. Information is transferred back and forth at the end of each simulation time step. The setup of single-voltage and dual-voltage templates for a simulation can be done from within ADVISOR. Custom Saber models can be created and called as well.

To extend the functionality of ADVISOR/Saber co-simulation, the series-hybrid powertrain is planned to incorporate Saber co-simulation by December of 2001. The parallel hybrid powertrain is slated for June of 2002.

5.2 Modeling for Vehicle Climate Control

The NREL Vehicle Auxiliary Loads Reduction team is working on a total climate-control systems modeling approach. As mentioned earlier, a key strategy for auxiliary load reduction is to focus on reducing the need first. An integrated modeling approach uses this strategy to study occupant thermal comfort and climate-control system issues. The Vehicle Auxiliary Loads Reduction team works with various industry partners to reduce the cabin cooling need. Various diverse backgrounds and computer models are being brought to bear on the problem. Using NREL's experience with predicting solar energy flux, a solar radiation model has been created. A CAD model and window-glazing model have also been created. Together, these models feed into a cabin thermal-fluid model to define the cabin thermal state. The cabin thermal-fluid model is used to help assess occupant thermal comfort. A thermal manikin is being created to help with testing and validation-work in this area (see McGuffin 2001). The conditions experienced in the cabin thermal model are supplemented by a transient air conditioning (A/C) model written in SINDA/FLUINT. This A/C model in turn calculates the auxiliary load upon the vehicle's engine, which affects fuel economy and emissions. The fuel economy and emissions are predicted with ADVISOR (a vehicle energy model).

A schematic depicting the integrated modeling approach described above is given in Figure 46.

With this coupled climate-system model, the benefit of reducing the cooling need can be assessed. Details on this coupled modeling approach can be found in several recent papers authored by NREL engineers (see for example Farrington *et. al.* 2001; Rugh *et. al.* 2001; Hendricks 2001; McGuffin 2001; Cullimore and Hendricks 2001).

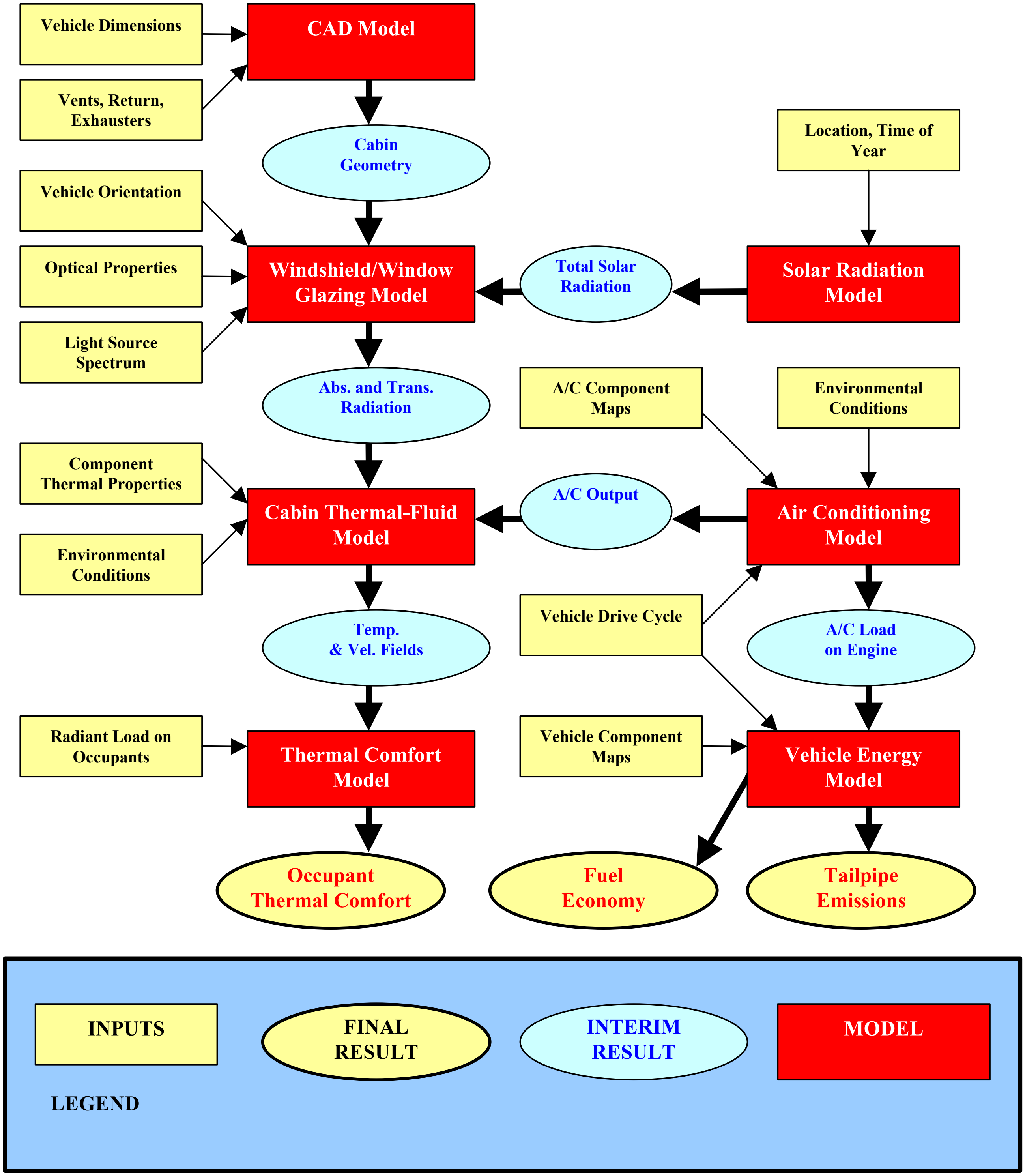


Figure 46 Integrated Modeling for a Vehicular Thermal Comfort System

Source: Farrington *et. al.* 2001

6 Conclusion

Several conclusions are drawn from this study and presented here. Note that these conclusions are largely based on simulation results.

Concluding remarks are:

- a given increase in auxiliary load (such as from an air conditioner) is observed to have a greater impact on series-hybrid bus fuel economy than conventional bus fuel economy

- a given increase in a key parameter (such as vehicle weight, auxiliary load, rolling resistance, etc.) has a greater impact on a high fuel economy vehicle than a low fuel economy vehicle in terms of miles per gallon

- hybridization, weight reduction, and auxiliary load reduction consistently stand out as key aspects for increasing transit bus fuel economy

- for a series hybrid transit bus optimized under the pathway assumptions, both of the hybrid control strategies examined in this study (“thermostat” or “series power-follower”) yield approximately the same fuel economy

- engine downsizing shows dramatic increases in fuel economy under a “series power-following” control strategy, but only minimal increases under a “thermostat” control strategy

- series-hybrid transit buses are observed to loose their fuel economy advantage over conventional transit buses when run on high-speed, steady-state duty cycles

- reduction in aerodynamic drag on a transit bus for the purpose of improving fuel economy is not significant for low-speed duty cycles such as the Central Business District cycle (average speed of 12.6 mph), but may be significant for high speed cycles such as the commuter cycle (average speed of 43.8 mph) provided that large reductions in drag coefficient can be achieved

- changes in auxiliary load reduction assumptions during the pathway analysis have significant effect on final predicted fuel economy

- data for recent transit buses with 5 speed automatic transmissions tend to yield higher fuel economies over the CBD-14 than buses with 3-speed automatic transmissions, especially if ton-mpg units are taken into account

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The future of America's truck and bus industry depends upon its ability to produce cost effective, high quality, environmentally sensitive, and safe vehicles. To spur innovation, agencies of the U.S. Government have partnered with industry for various heavy vehicle programs. This work presents systems analysis work on transit bus platforms for the 21CT Program and Heavy Hybrid Program. Simulation was conducted using NREL's vehicle simulation tool, ADVISOR.

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