METRANS
Transportation Center
USC / CSULB

Assessment of Hybrid Configuration and Control Strategies in Planning Future Metropolitan/Urban Transit Systems

FINAL REPORT

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Disclaimer

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Disclosure

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Abstract

Simulation studies are performed to evaluate the potential fuel savings and reduction in emissions from using hybrid powered buses on Long Beach City bus routes. Conventional diesels, diesel-hybrid, and gas turbine-hybrids are considered. The results of these studies are compared with experimental data and are in generally good agreement.

Fuel economy is shown to be dependent on the bus configuration, component sizing as well as the bus route, with a potential fuel economy improvement of as much as 80%. Emissions are also substantially lowered if hybrid buses equipped with diesels or gas turbines are deployed. Depending on the mission, driving patterns, and road conditions, different control strategies demonstrate the best results.

The long-term objective of the project is to investigate the feasibility of utilizing a fleet of small and medium size hybrid passenger vans in metropolitan/urban areas to improve over the overall fuel efficiency, reduce emission, and increase throughput without increasing cost life of the system-- thus allowing additional routes to areas where such services are most needed. This is done by allowing fleets consisting of a mix of vehicles such as hybrids and internal combustion engines to operate. The fuel savings and lower emission over the vehicle life will compensate the higher initial capital costs. The results of this study can be extended to address the transportation problems over large metropolitan areas and facilitate implementation of Air Resource Board (ARB), Metropolitan Transit Authority (MTA), and Caltrans mandates in promoting higher use of high-occupancy vehicles (HOV) and sustainable market demand for ultra low and zero emission vehicles.

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DELIVERABLES

Task 1. Define the Vehicle and Drive System Requirements

Vehicle configurations were selected to simulate Long Beach transit buses. The majority of buses in Long Beach fleet are 40-foot New Flyer Buses with gross weight of 17,962 kg. Engines, transmission, drive train, wheels, and other accessories were simulated. In the analyses it was assumed buses are half full and average weight of each passenger was 150 pounds.

Task 2. Define Driving Cycle

Long Beach Transit currently has over 30 bus routes in service with an average run time of over 30 minutes. For this study, two Long Beach Transit bus routes (Route 1 and Route 192), a Colorado street bus route, and Central Business District (CBD) route were selected. These routes were chosen to represent heavy traffic with a large number of stops and/or traffic lights, or relatively light traffic conditions.

Task 3. Simulate Performance

A comprehensive software program called Advisor developed by NREL was utilized in all simulation studies. Simulation studies include conventional buses, hybrid series and parallel buses, and buses where diesel engines were substituted with comparable gas turbines were considered. When data were available, performance results (fuel efficiency, and emission) were compared with data published by Northeast Advance Vehicle Consortium (NAVC) hybrid-electric vehicles.

Task 4. Prepare a Web-Based Tutorial

A multimedia tutorial on hybrid vehicles design and emission are prepared and is made accessible to CSULB students and auto manufacturers. The website address is *http://front.csulb.edu/~rtoossi/index.htm*. In addition to tutorials, copies of reports, presentations, links to various hybrid vehicle manufacturers, METRANS, and regulatory and government agencies are prepared. The website is still under construction and we expect it to be fully functional by October 2001.

Task 5. Reports

Three interim quarterly progress reports have been prepared and submitted to METRANS. The current report summarizes the comprehensive project results.

CHAPTER 1 □ INTRODUCTION

Background

Internal combustion engines are the major contributors to the air pollution in California. Reducing vehicular emissions and enhancing fuel economy will be effective in improving the air quality. Recent advances in diesel combustion technologies, better afterburners and catalytic oxidizers, and use of alternative fuels such as compressed natural gas (CNG), propane, and methanol have resulted in overall reduction in the emission of particulate matters (PM) and other gaseous emissions such as volatile organic compounds, nitric oxides, and oxides of carbons. In light of increased use of cars and other public transportation, and ever more congested traffics, additional steps must be taken to reduce emissions even further. The advantages and disadvantages of electric vehicles are generally known and accepted. Electric vehicles help the environment by eliminating exhaust emissions and reducing dependency on fossil fuels. However, the disadvantages of limited range and increased vehicle weight limit their use in commercial applications. Hybrid-electric vehicles solve many of the problems plaguing pure electric vehicles such as short range and excessive weight, battery cost and battery life. Commercial hybrids have been in production in Japan and are soon to be introduced in US Market. The Toyota Prius has demonstrated the superiority of these vehicles by getting 60 MPH in city driving and 70 mph in highway driving while at the same time producing emission at one tenth of the legal limits. Honda□s Insight with similar performance is scheduled for release soon.

Buses are extremely well suited to use hybrid propulsion systems since they are capable of carrying the large payload of the batteries and propulsion system. They also work well as hybrids because they operate on predictable routes and can gain back a large portion of energy through regenerative braking. In some cases, it is estimated that as much as 50 to 60 percent of the fuel energy is dissipated as heat in the brakes. Hybrid buses are also currently in production. Orion (a conventional bus manufacturer), and Lockheed Martin Control Systems have jointly developed series hybrid buses for Metropolitan use. Currently, New York City has 15 of these buses in service and is planning to purchase several more. Fuel savings of 40% compared to a conventional diesel buses has been reported. General Motors and New Flyer are also working on manufacturing similar buses. Because series hybrids are simpler and thus are of a lesser investment risk, they have been generally favored by the bus manufacturers. Parallel hybrids however, are expected to offer the best fuel economy because they can recover energy from regenerative braking and can directly use the energy from the fuel converter without the need to convert is first to electricity. No commercial parallel hybrid vehicle is in production, but many manufacturers are investigating their merits.

Unlike the conventional vehicles where engines are directly coupled to drive trains, hybrid vehicles speed is determined by a number of control parameters not directly related to the engine loads. For example, in conventional vehicles, accelerator pedal (load) directly determines the engine speed, and the rate of fuel delivery and gas mileage. Hybrids on the other hand, operate on the principle that the total power delivered by the engine and the battery must be sufficient to satisfy the load requirement while maintaining battery charge power. The power drained out of the engine thus can be changed depending not only on the required motive power, but also to the state of the charge of the batteries.

Compared to conventional buses, hybrid buses offer considerably less emissions. Most of the pollution from a conventional diesel bus is a result of transients, and vary as the power delivered by the engine to the drive axle (generally rear axles). With hybrids, the power delivered by the engine may or may not follow vehicle speed and load. In certain configurations, the engine could be much smaller and even run at a steady speed, thus cutting emissions significantly. Although manufacturers of hybrid vehicles design the system to operate in an optimum performance range, (reduced emission and better fuel economy), situations can be visualized where either one criteria or other are of primary importance.

Whether series or hybrid configurations are considered, these buses cannot be considered optimized for all drive cycles and for all applications. Control strategies are often a simple on/off switch that instructs the vehicle to operate as electric or gasoline vehicle. Thresholds are fixed by the manufacturers irrespective of criteria of interest. For example, a bus that might give a superior gas mileage for a given drive cycle might be quite ineffective in reducing emissions and for a different driving cycle. The air quality problem is of a much greater concern than fuel economy in many of the cities around the world.

The long-term goal of the project is to obtain a set of control parameters that can be used to optimize the operation of vehicles (fuel efficiency, pollution, or both) depending on a particular drive cycle (route), and strategy (minimize pollution or maximize fuel economy). Once such variables are found and each vehicle is tuned for optimal operation, then better routing and scheduling can increase throughput over a given metropolitan district, and by doing so, expand services to remote locations without increasing the overall cost.

In this study, we will review existing hybrid control strategies and simulate typical buses that services Long Beach and other large metropolitan areas on standard drive cycles and actual drive path. Different control strategies as well as hybrid configurations will be simulated and their effect on fuel consumption and emissions will be investigated. To investigate the merits of using turbines as a potential power source, the engine is substituted with two small micro-turbines. The effect of alternative fuels such as methane, methanol, and propane on the overall emission of the buses is also investigated.

The proposed effort will comply with METRANS strategic plans by addressing problems and proposing solutions for delivery of high-quality transit services to disadvantaged populations in *Larger Los Angeles Metropolitan Areas and Alameda*

Corridor. Results of this study can be used in follow up works to develop algorithms for routing and scheduling, to optimize performance, to establish logistics (such as composition of vehicle fleets) for delivery of goods and passengers, and to assess the impact on delivery of mass transit services to disadvantaged populations.

Hybrid Vehicle Technology: An Overview

A hybrid vehicle is a vehicle with multiple distinct energy sources that can be separately or simultaneously used to propel the vehicle. The energy can come from a number of different sources, including batteries, fuel, solar energy, or flywheels. Different energy converters are also used. Generally, electric motors are used with electrical energy from batteries, solar cells, or generators driven by flywheels or heat engines. Fuel energy is converted by a number of different heat engines, including internal combustion engines and gas turbines. The most promising hybrid vehicle today is the hybrid electric vehicle using batteries and an internal combustion engine. This vehicle design makes the best use of existing technology by providing the benefits of both electric and conventional vehicles, while minimizing the shortcomings of each.

Commercial hybrid vehicles are becoming available for purchase to the public. Toyota has been in production of a hybrid 4-door sedan in Japan for over a year. Using a 1.5 Liter 4 cylinder engine, the Prius achieves about 80 MPG with emissions levels at about 10% the legal limit. Honda has also introduced a hybrid vehicle. The Honda Insight is a parallel hybrid two-seater with a 1.0 Liter 3 cylinder engine and weighs about 1,800 pounds. It is recently becoming available in the United States, and is claimed to get 75 MPG in city driving and 70 MPG on the highway.

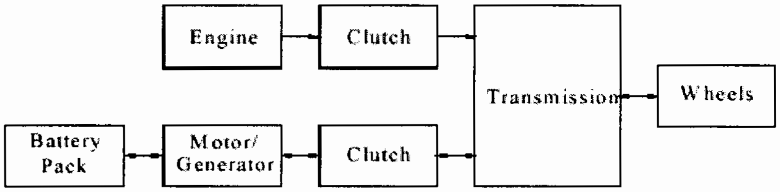
Hybrid buses are also currently in production and the following information about them was obtained from bus manufacturers web sites and sales brochures. Orion, an already well established conventional bus manufacturer, teamed up with Lockheed Martin Control Systems, manufacturer of the HybriDrive diesel-electric hybrid power system, in late 1996 to manufacture series hybrid buses for use in New York City. Currently, New York City has 10 of these buses in service, and another 5 hybrid buses that were made by Nova/Lockheed Martin. General Motors and New Flyer are also working on series hybrid buses. Buses are extremely well suited to use hybrid propulsion systems since they are capable of carrying the large payload of the batteries and propulsion system. They also work well as hybrids because they operate on predictable routes and can gain back a large portion of energy through regenerative braking. In some cases, it is estimated that as much as 50 to 60% of the buses fuel energy is dissipated as heat in the brakes. Orion and Lockheed Martin claim potential fuel savings as high as 40% for their buses compared to a conventional diesel bus. These buses also offer the benefit of reduced emissions. Most of the pollution from a conventional diesel bus is a result of transients. With the series hybrid design, the diesel engine is not only smaller for a comparable size bus, but it also runs at a steady state speed, thereby reducing emissions significantly. Orion and Lockheed Martin report particulate emissions from their hybrids to be comparable to compressed natural gas (CNG) buses with considerable reductions in NOx and CO_2 compared to CNG.

Configurations

The two common configurations of hybrid vehicles are the series and parallel designs, which are shown schematically in Figure 1. Series and parallel refer to the orientation of the two power plants in the propulsion system. In the series hybrid, the engine powers a generator that either supplies power to charge the battery pack, or power the electric drive motor. In the parallel hybrid, the engine supplies mechanical power directly to the propulsion system, while the electric motor is also coupled directly to the propulsion system. The parallel hybrid vehicle can be run on the engine alone, the electric motor alone, or on both engine and electric motor simultaneously, depending on how control is set up.

Series hybrid vehicles are similar to purely electric vehicles except the series hybrid vehicle has an on-board generator system. The internal combustion engine is used to power a generator to generate electricity, which is then used to power the electric drive motor or charge the batteries. The internal combustion engine is typically sized for the vehicle□s high-speed cruise loads. These loads are typically small in comparison to acceleration and hill-climbing loads, so the result is a smaller engine than would be used if the vehicle were conventionally powered. The electric drive motor is then sized to handle the acceleration and hill climbing loads. The series configuration hybrid vehicle results in a relatively simple connection of the electric drive motor to the drive wheels. In most cases, a multiple speed transmission is not required due to the favorable torque and speed properties of electric motors. The vehicle can also be operated for a finite amount of time as a zero emissions vehicle (ZEV) by running off the batteries only. Full vehicle power is also available while running as a ZEV if the battery pack is sized for full vehicle power.

Series Hybrid System



Parallel Hybrid System

Figure 1. Hybrid vehicle system configurations.

However, since the vehicle has on board generator, one could opt for a design with fewer batteries, which saves cost and weight as compared to an electric vehicle. In such a case, engine power is required during peak load conditions. The biggest disadvantage to the series configuration is that all of the engine’s power must be transmitted through the generator and drive motor. Because of the inefficiencies of these two components, some power is lost that is not lost in vehicle designs where the mechanical power of the engine is directly coupled to the wheels. Another disadvantage to the series configuration is that both an electric motor and generator are required, which usually results in a heavier and more costly vehicle as compared to the parallel configuration.

In the parallel hybrid configuration, both the internal combustion engine and the electric motor are mechanically coupled to the drive wheels. Both the engine and the electric motor can supply power to the drive wheels simultaneously, or the electric motor can be used as a generator to charge the batteries. Since the internal combustion engine must be capable of charging the batteries as well as propelling the vehicle at cruise speeds, the engine is larger, and the electric motor is smaller as compared to a series configuration design for a similarly sized vehicle. The internal combustion engine is sized for medium and high speed cruise loads and usually provides slightly better highway fuel economy compared to the series configuration due to optimal loading at those speeds without the added inefficiencies of the generator and electric drive motor. The parallel configuration can also be used ZEV for a limited period of time. However, since the internal combustion engine is required to be on for full vehicle power, full vehicle power is not attainable as a ZEV for a parallel hybrid. The disadvantage of the parallel configuration is that the direct coupling of the internal combustion engine, electric motor and drive wheels often requires an expensive and complex transmission. Also, since the internal combustion engine must operate over a wide range of speed and loads, it can□t be run at optimum efficiency or emissions points all of the time like in the series configuration.

Controllers

Electronic controllers main function is to adjust parameters for the smooth operation of the parts and select the optimum mode of operation at each point. Three types of controllers are often employed.

A ***bang-bang controller*** is essentially an on/off switch, much like a thermostat that controls the temperature a room when it gets cooler or warmer than preset values. When thermostatic controllers are used, the engine continues to run as long as the state of charge of the battery falls below a set value. Once charge in the battery reaches a safe limit, engine shuts off and the hybrid works essentially as a pure electric vehicle. Since most engine emission is during cold start and transient operation, this kind of control does not necessarily reduce emission to the maximum extent possible.

A ***thermostatic controller*** is introduced to minimize the shortcomings of bang-bang controllers. In thermostatic control, the engine operates continuously to provide the steady state (cruising) load demand. This type of hybrid system control typically uses the battery State Of Charge □SOC□ or a filtered battery pack/cell voltage as the control variable to determine the throttle command (Power generation command).

A ***load follower (power follower)*** follows the driver command. When the driver pushes on the accelerator (throttle control), the engine cannot be operated on its optimized operation point (sweet spot). Load follower strategy (such as used in the Prius) allows the power to be modulated either by throttle control or engine speed, and ensuring most efficient engine operation by providing the transient load demand, just enough to maintain the battery□s state of charge.

Energy Management

Flexibility inherent in design of hybrid systems, allows hybrid vehicles to be operated to achieve:

Maximum fuel efficiency
Minimal emissions
Combination of the two

These objectives can be achieved by a combination of proper hardware configuration and a well-designed control algorithm. A proper power control strategy allows controlling the flow of power while assuring adequate energy reserve in the storage devices. Obviously maintaining a reasonable cost and achieving minimum performance and handling is of primary importance.

Hardware configuration and control strategies are designed together to achieve theses objectives. We covered two hardware configurations, parallel and series hybrid. Each configuration can be modified with a variety of control strategies to fit a particular need (Figure 2). Examples are given below:

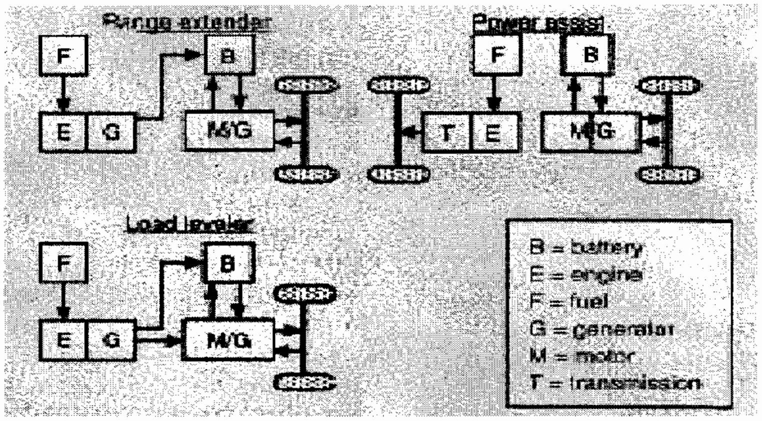


Figure 2. Energy management systems.

Power-assist (Electric-assist) Parallel

A power-assist HEV is driven by an engine, while the electric drive is mostly for starting or high load demands. This allows the APU to operate in a more efficient region and keep emissions low by moving away from the full throttle condition that is normally required for acceleration and steep gradients. Regenerative power can also be used to help boost the efficiency during urban driving. Power-assist configuration uses a large engine with smaller battery pack.

APU-assist Parallel

In this configuration, the electric motor and batteries are used as the main power source, while the APU is turned only on for acceleration, high speed, or steep roads. It operates as zero emission vehicle most of the time when APU is turned off. The drawback is that

APU comes on during high load conditions, where emission is the highest.

For this arrangement, engine is often undersized and operates closer to full load, where it is most efficient. For meeting the vehicle requirement during transients, the electric motor will be available to provide the additional power.

Range-Extender (Genset)

A range-extender HEV (Genset) is essentially an electric vehicle with an on-board charging system. The objective is to allow the battery to deplete the battery to a very low SOC before the APU is turned onto recharge the battery. Once recharged, the APU is turned off again until such needs arise again. Range-extenders have larger battery capacity and a smaller engine. Advantage of this control strategy is that the APU can be set at an operating point (torque and speed) that is most efficient. The APU is off during transients when the highest level of emissions is produced. The disadvantage of this configuration is that batteries are in direct current and need to be converted to alternating current before reaching the traction motor. Because of various elements in series, the overall efficiency is lower than that of some other configurations.

Hybrids using genset (engine/generator) work on an on/off mode, i.e., they are either switched off (zero emission) or operate at a predetermined output where they produce the lowest emission, or achieve the best fuel efficiency (sweet spot). Typically, hybrid gensets are not throttled for variable output, as is the case for conventional engines. Gensets are designed to deliver average power. The battery functions to store the energy from the regenerative braking and to supply peak power during acceleration. The battery is normally downsized and reconfigured for maximum specific power, whereas a BEV is reconfigured for maximum specific energy.

Range-extenders can qualify as zero-emission vehicles when operated only in electric-mode (city driving).

If the engine employs an exhaust catalyst for emissions control, the catalyst can be electronically preheated before the engine is started to minimize startup emission.

Load-Levelers

Although, the propulsive energy is supplied by the fuel tank and the battery concurrently, this configuration is usually considered a series configuration, because all the propulsive power eventually passes to the driving wheels through an electric motor[1].

As with the power-assist, the APU is smaller and sized to meet the average power demand. As with the range-extenders, the engine does not need to follow the transients. Batteries are used to provide additional power during power peaks. In this configuration, the engine continuously runs at a steady state to produce power. If the power exceeds the vehicle□s needs, the excess power is used to charge the battery. In cities, the engine could be shut off, which allows the vehicle to operate as a ZEV for a limited range. The advantage of this strategy is batteries are rather small and it always hovers around a mid-level SOC. The engine is also relatively small. The disadvantage is that engine must change its power output to adjust for changing load. The emissions increase as engine deviates from its □sweet-spot□ operation.

Simulation

To compare the performance of hybrid buses with various control strategies, alternative fuels, and different main power source (diesel or gas turbine) simulation studies were conducted. The results are compared with the experimental data provided by the Northeast Advance Vehicle Consortium (NAVC)[2] and under different standard drive cycles and actual driving paths.

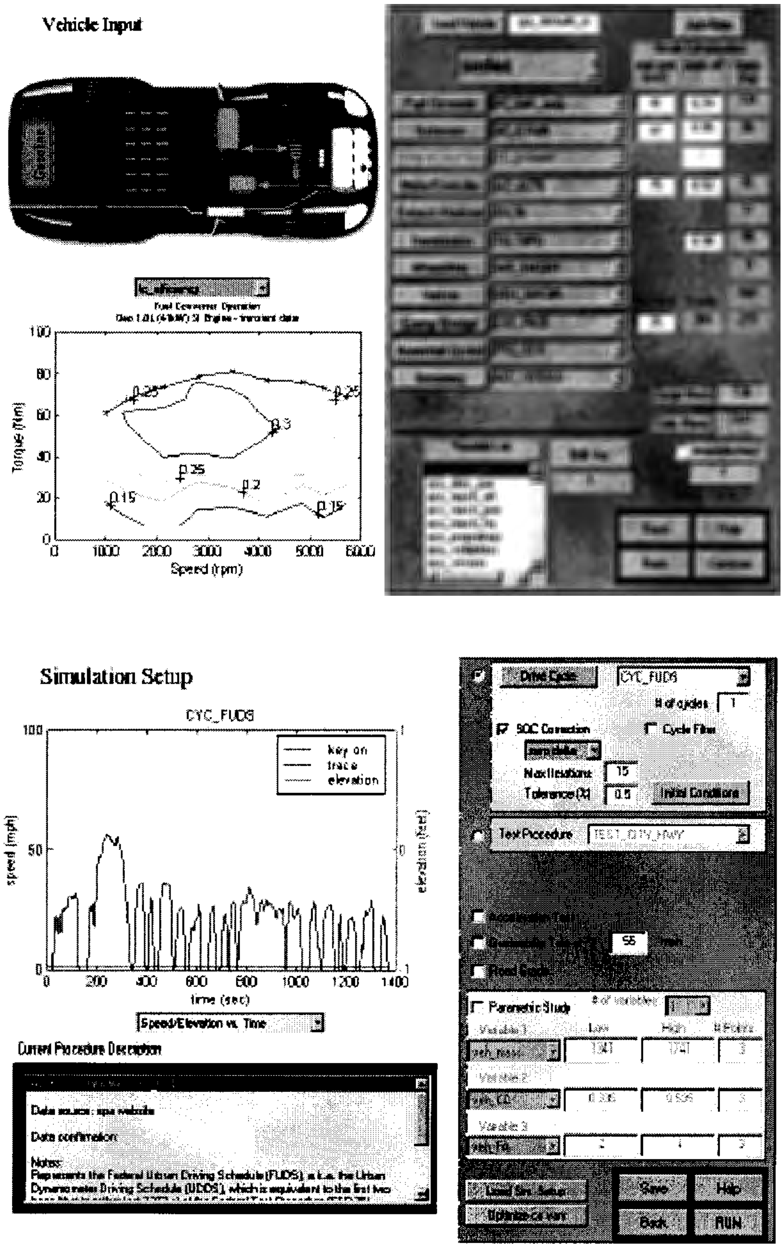
The vehicle simulation program ADVISOR was used for the analysis reported in this study. The software developed by the National Renewable Energy Laboratory (NREL) and is available for download at no cost from the NREL Internet website[3]. ADVISOR operates in the MATLAB/Simulink environment and is set up with a graphical user interface (GUI), which makes it very user friendly and easy to learn. The different components of the vehicle are defined in separate files and the user can pick from a database of input files for each of the vehicle□s components to assemble a custom vehicle. The user can also choose from database of different velocity profiles (drive cycles or traces) for the vehicle to follow, or define own route. Numerous papers have been published which show very good correlation between ADVISOR predictions and actual vehicle test data[4,5]. ADVISOR is made available to the public in its entirety, including all source code so that the user can make modifications for unique applications.

Most vehicle simulation programs use either the forward-facing or backward-facing modeling approach. These programs include SIMPLEV, CarSim, HVEC (Hybrid Vehicle Evaluation Code), CSM HEV and V-Elph. The forward-facing approach works by modeling the input of the driver to develop the appropriate throttle and braking commands to meet the desired vehicle speed. At any instance, torque required to achieve the desired speed is calculated from a map of torque versus rpm inputted for various engines. The torque transmitted from the power plant into the drivetrain and eventually to the wheels is calculated for a desired transmission (gear ratio). Knowing the rotational speed of the axle and wheel radius, the tractive force at the tire/road interface is computed. The major disadvantage of this modeling approach (forward-facing) is the relatively long simulation run time.

The backward-facing approach works by assuming that the vehicle meets the desired velocity profile. From this velocity profile, the tractive effort and associated wheel torque are calculated. The calculation continues backward through the vehicles drivetrain all the way through the power plant. The backward-facing model is fast in comparison to the a forward-facing model, but since the model assumes the velocity profile is already met, it cannot be used for predicting best-effort performance of a given vehicle when the assumed velocity profile exceeds the vehicle capabilities.

ADVISOR uses a combined backward/forward modeling approach similar to the backward-facing approach discussed above. The simulation begins with the desired vehicle profile and follows the backward scheme by calculating the required torque from the driveline through the drivetrain all the way to the engine. The forward-facing algorithm uses available torque, speed, and power forward through the driveline components to ensure that no driveline component has exceeded its capabilities. This gives ADVISOR the capability to handle component performance limits while keeping the computation time relatively fast.

The introduction display shown in Figure 3a is used to specify all vehicle-input data. These include the vehicle configuration (conventional, electric vehicle (EV), series or parallel hybrid, fuel cell, gas turbine, etc.). Also, specified on this screen are various components (transmission, fuel converter, drive train, wheel specs, etc. A comprehensive library of over 85 components is available. If a component with exact power and efficiency is not found, ADVISOR provides the option of scaling data by linearly extrapolating them by the ratio of actual/default power. The second screen shown in Figure 3b, allows the user to select from a list of 17 different driving cycles or define the actual drive cycle that the vehicle will follow during the simulation. Different road grades can also be input into the drive cycle file so that the analysis includes a time varying grade.



Data source: epa website

Data confirmation:

Notes:
Represents the Federal Urban Driving Schedule (FUDS), a.k.a. the Urban Dynamometer Driving Schedule (UDDS), which is equivalent to the first two

☑ Drive Cycle: CYC_FUDS

# of cycles: 1

☑ SOC Correction

Max Iterations: 15

Tolerance (%): 0.5

○ Test Procedure: TEST_CITY_HWY

55 mph

☐ Parametric Study

Variable	Low	High	# Points
veh_mass	1341	1741	3
veh_CD	0.335	0.535	3
veh_FA	2	4	3

Figure 3. ADVISOR Interface Screen. a) vehicle input; b) simulation map

CHAPTER 2 – DRIVE CYCLE

Vehicle fuel economy and emission rates may greatly vary depending on a number of factors such as acceleration, braking time, maximum and average velocities and time the vehicle idles. Selecting the proper driving cycle is therefore critical if a proper assessment of the vehicle performance is to be made. Significant variations can be expected depending on which drive cycle is chosen. Different drive cycles are proposed that vary in their average velocity, maximum velocity, number and frequency of stops, time the vehicle spends behind the traffic lights, and the rate at which vehicle is accelerated, or the distance before a vehicle comes to a complete stop. To evaluate the hybrid effectiveness under different driving conditions, the following drive cycles were considered in this study:

Central Business District (CBD)

The CBD cycle shown in Figure 4 was proposed by the Society of Automotive Engineers (SAE) and is typically used to evaluate transit buses. It covers a distance of 2.0 miles over 10 minutes. It is made of a 14 identical sections, each consisted of acceleration to 20 mph, a cruise at this velocity, braking to a complete stop followed by a short dwelling before the cycle is repeated. Critics of this driving pattern point to the fact that the acceleration is twice as fast as the rate of deceleration (4.5 seconds versus 9.0 seconds, which is not typical of actual in-use driving. Furthermore, the cycle average velocity is 12.6 mph, which is faster than most transit operations.

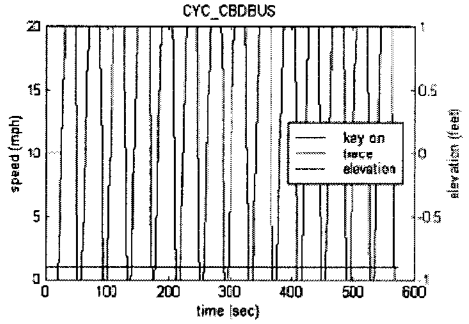


Figure 4. CBD bus drive cycle.

New York

Several drive cycles were proposed for NY City driving. The differences are in cycle duration, maximum and average speed. These are:

NY Bus Cycle: New York bus cycle represents the real life data for heavy-duty trucks in New York City. Similar to CBD, the NY bus cycle lasts for 571 seconds, but the total distance traveled is only 0.6 miles and the average speed is 3.7 mph.

Manhattan: Manhattan cycle was designed to better reflect driving condition in NYC metropolitan areas. It is similar to NY Bus cycle, except the average speed is 6.9 mph, which is more consistent with average speed of buses operating in NYC metropolitan areas.

NY Composite: The NY Composite represents a mix of inner city and urban transit bus uses. The average speed is 8.8 mph.

Route 77 and Route 22: These two cycles represent the service routes to Logan International Airport in Boston, Massachusetts. The maximum speed reached on these routes reach as high as 30 mph. The average speeds for these routes are 16.8 and 13.9 mph.

Long Beach

For designing strategies for planning future transit systems for a particular region it is best to analysis the performance on the actual route on which the buses are to be used. As a part of this study, we investigated several routes for Long Beach Transit buses. Two bus routes were chosen which typified the routes most commonly followed by Long Beach commuters. Since such data were not available, we collected our own data by following buses operating on these two routes. The Enova System provides one of its experimental electric cars that had an onboard computer capable of logging the car's velocity at 1-second intervals. A computer logs the wheel speed versus time, from which, the subject vehicle□s speed, acceleration, and distance traveled can be determined. When following the bus careful attention was paid to matching its velocity profile. This included matching acceleration, deceleration and stopping durations. The car was also stopped behind the bus every time the bus stopped for any reason.

Long Beach Transit currently has over 30 bus routes in service with an average run time of over 30 minutes. Even with the use of the electric vehicle described above, taking data for all of the bus routes in Long Beach would be a very ambitious task. For this study, three representative bus routes were selected using existing available data of the cities bus routes. Data included route length and number of stops per route. Routes through the downtown area were of particular interest since they served a high volume of riders. Routes with many stops were also given emphasis because a hybrid bus should show the most benefit on this type of route. The routes chosen were Route 1, Route 172, and Route 192.

Route-1 operated between the intersection of Wardlow and Magnolia in one end, and Broadway and Long Beach Boulevard near the Transit Mall, at the other end. Route □192 operated between the Transit Mall, and intersection of Del Amo and Norwalk. Figures 5 and 6 are taken from the Long Beach bus schedule, and show the routes described above. Data obtained from velocity-time history, V(t) are used to obtain the Drive cycles for Routes 1 and 192 are shown in Figure 7 and Figure 8 respectively.

Colorado

In addition to the two Long Beach Bus Routes described above, a bus route drive cycle provided with ADVISOR was also used in the forthcoming analysis. The drive cycle represents a 16th Street Mall bus from Denver Colorado. This cycle was chosen because it has 28 starts and stops over its 1.65-mile route, and therefore represents an extreme case of a low speed stop and go route. A plot of this drive cycle is shown in Figure 9. Table 1 is a summary of the drive cycles and associated average

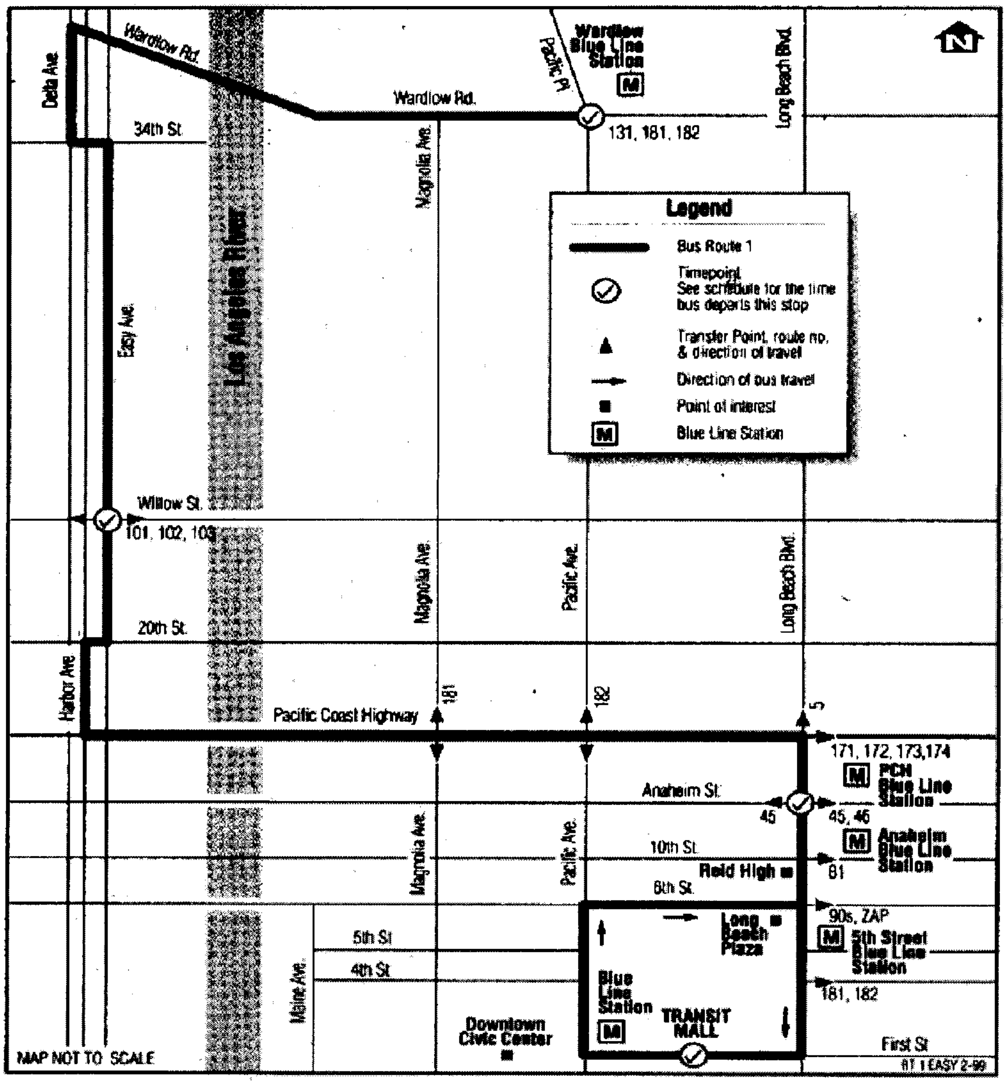


Figure 5. Long Beach Route 1.

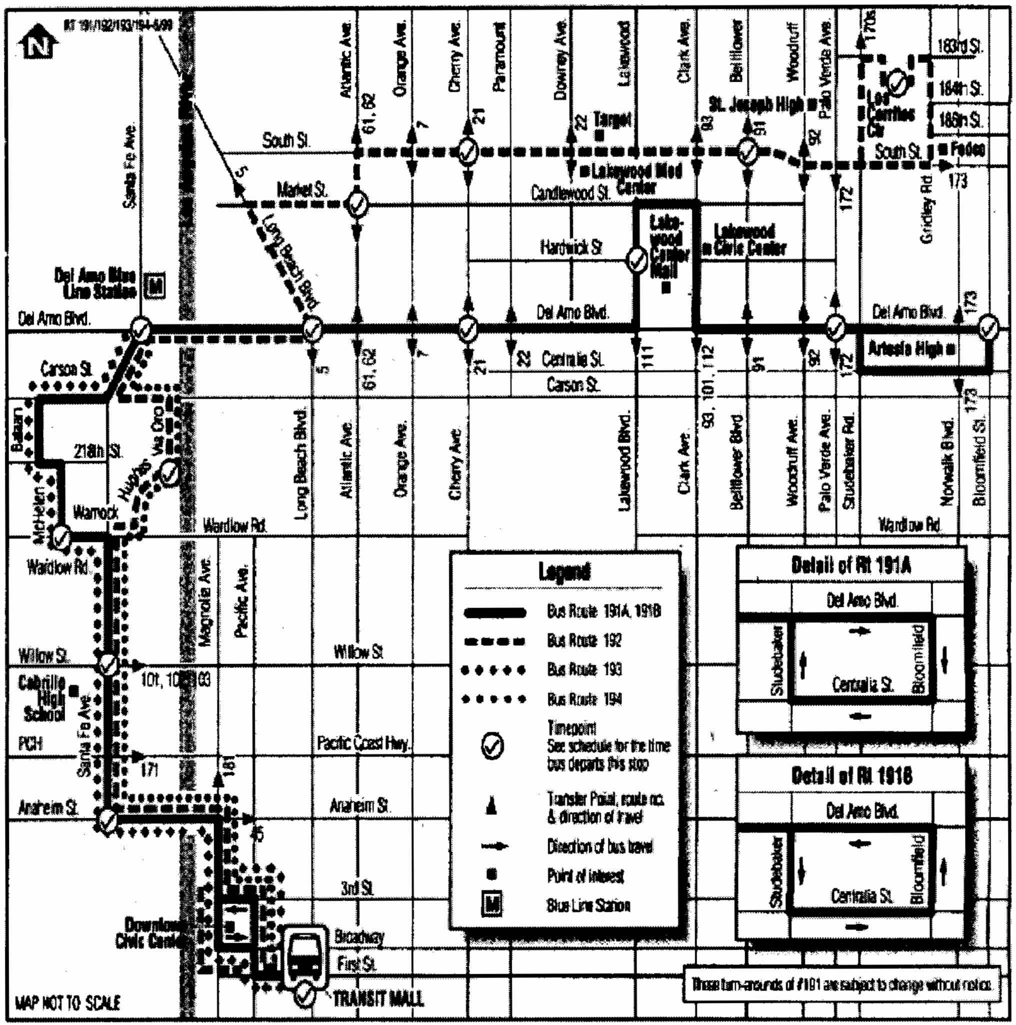


Figure 6. Long Beach Route 192.

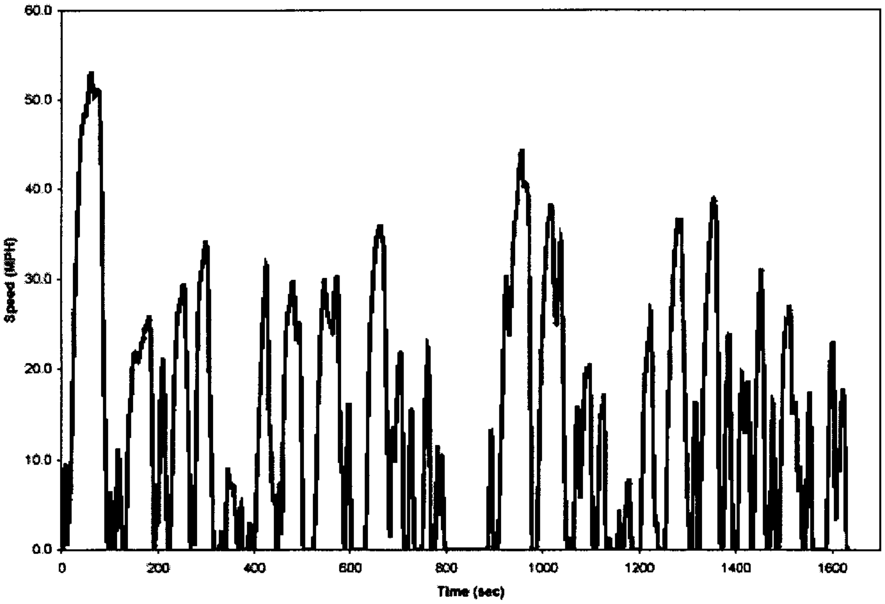
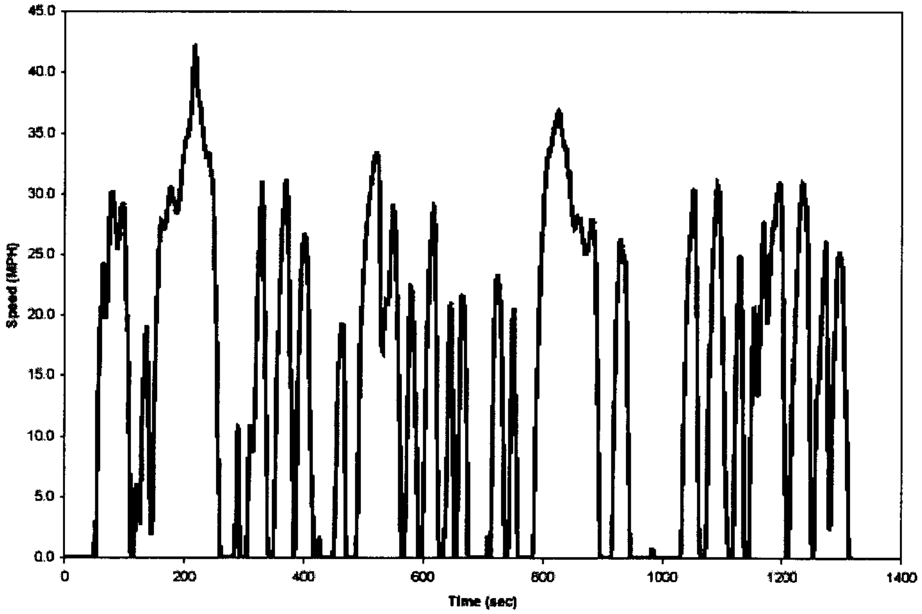


Figure 7. Route 1 drive cycle. Length = 6.1 miles, Average Speed = 13.6 MPH,



Maximum Speed = 53.0 MPH, Maximum Acceleration = 6.5 ft/s^2.

Figure 8. Route 192 Drive Cycle. Length = 5.2 miles, Average Speed = 14.3 MPH, Maximum Speed = 42.3 MPH, Maximum Acceleration = 6.2 ft/s

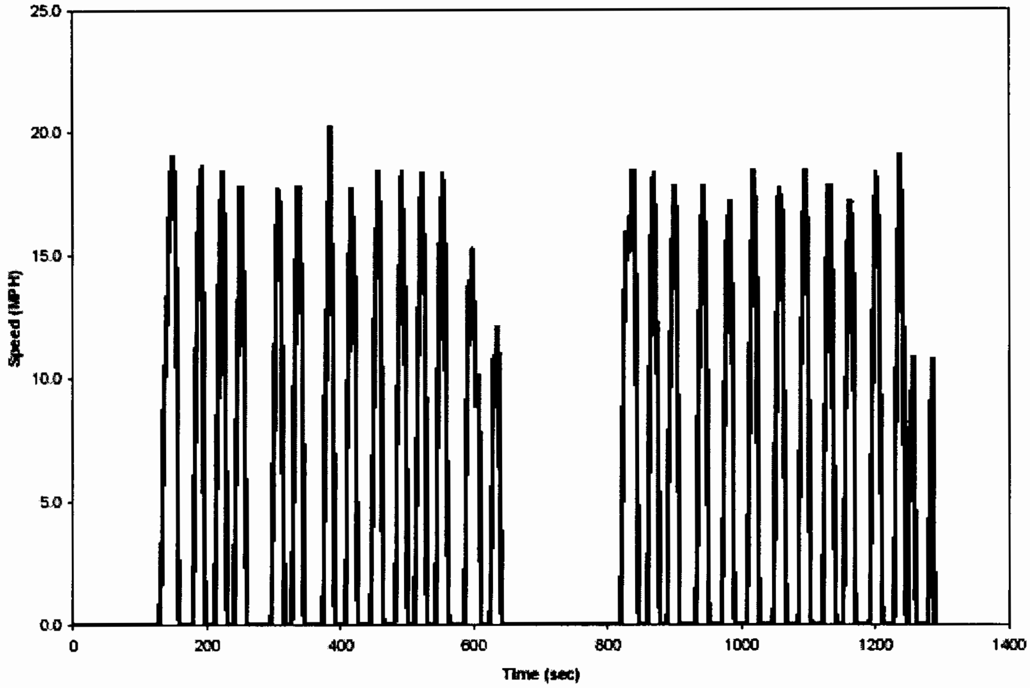


Figure 9. Colorado 16th Street Mall bus drive cycle.

Table 1. Drive cycles and average speeds

Cycle	Average Speed, MPH
NY Bus Cycle	3.7
Colorado	4.5
Manhattan	6.9
NY Composite	8.8
CBD	12.6
Route 22	13.9
LB Route 192	14.3
Route 77	16.8

CHAPTER 3 — RESULTS

Conventional Bus at a Constant Speed: Cummins M11-330

A simple model of a 246 kW conventional diesel bus (Cummins M11-330) operating at a constant velocity of 40 MPH and on a flat road was used to validate the ADVISOR. It was furthermore assumed all accessory loads to be negligible. The simulation time was varied until the effect of initial acceleration on vehicle performance could be safely ignored. Various loads on the engine (aerodynamic drags and rolling resistances) were computed and found to be in close agreement with analytical results presented in Chapter 2.

These loads were then used to calculate the required wheel torque and speed. For a given transmission gear ratio, the required torque and speed of the engine was calculated. Using engine's fuel efficiency map (Figure 10), the fuel consumption rate (lbm/s) was determined. The gas mileage of the bus was calculated assuming a fuel density of 0.86 g/ml. As can be seen from the data presented in Table 2, good agreement is seen between calculated and predicted results. The differences could easily be accounted for the rounding errors and the assumed fuel density used in the gas mileage calculations.

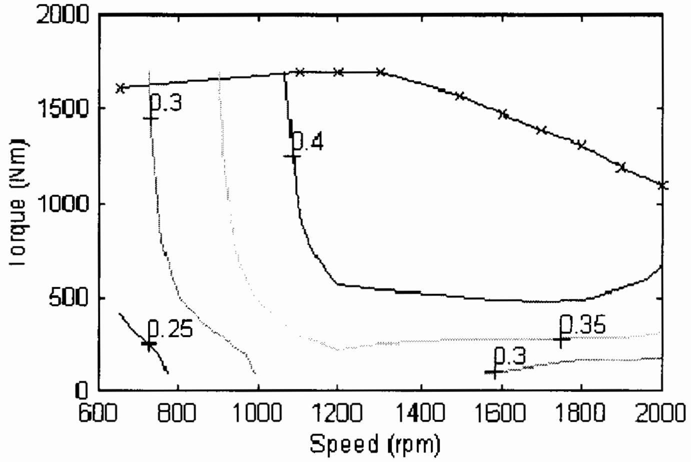


Figure 10. Fuel Converter, Cummins M11-330- 246 kW engine.

Table 2. Validation Study Results

Parameter	Analytical	Simulation	Difference
Vehicle Force, N	2371	2370	0.0%
Wheel Torque, Nm	1185.1	1186	0.08%
Engine Torque, Nm	326	327	0.31%
Wheel Speed, RPM	342	342	0.0%
Engine Speed, RPM	1366	1370	0.29%
Gas Mileage Diesel, MPG	12.0	11.7	2.56%

Conventional Diesel Bus: New Flyer

Long Beach Transit deploys a large fleet of 40-ft New Flyer buses in different routes around the city. Buses seat 40 passengers. The peak power output of the diesel engines on these buses is 275 HP (205 kW). The data used to model the vehicle were obtained directly from the manufacturer or from the Long Beach Transit. The gross weight of the vehicles are 39600 pounds (17,962 kg) which includes vehicle mass, passengers masses, fuel, oil, coolant, etc. Other parameters used in the simulations are given in Table 3.

The simulation was made for buses operating on Long Beach routes 1 and 192 as well as Colorado 16th street. The results are given in Table 4, which show very good agreement with the average fuel consumption rates of about 4 MPG reported by Long Beach Transit fleet operators for all routes. The dependence on cycle runs (1 vs. 10) shows the effect of the initial cold start on the overall fuel efficiency. After the first cycle (25 minutes), engines have reached steady state operation and the fuel efficiency is increasing considerably. Efficiencies drop for as much as 20% during the cold operation. We anticipate even more serious emission consequences, however such data are not available and cannot be verified at this time.

Investigating the results we observed that for a short time at the beginning of the drive cycle, buses operate on Route 1 cannot follow the velocity profile accurately and may miss it by more than 2 mph. This happens only at the beginning when rapid acceleration to 55 MPH is required (See Figure 7). Increasing power to 245 kW removed this problem and bus was able to accurately trace the drive cycle. The results also show that conventional buses will have lower efficiencies by as much as 50%, when they are operated in busy traffic such as is common on Colorado's 16th street.

Table 3. Long Beach New Flyer bus parameters

Parameter	Value	Source of Data
Bus Width	2.6 m	New Flyer
Bus Height	2.83 m	New Flyer
Clearance Height	0.37 m	New Flyer
C_d	0.79 m	Estimated
Frontal Area	6.4 m_2	Calculated
Wheel Base	7.44 m	New Flyer
Height of CG	0.8 m Rear Drive	Estimated
Fraction of Weight on Drive Wheel	0.65	Estimated
Vehicle Mass	13900 kg	Estimated
Engine Mass (210KW)	882	Estimated
Engine Mass (245KW)	1029	Estimated
Transmission Mass	280	Estimated
Passenger Mass	1360 kg	Estimated
Total Mass (210KW)	16422	Estimated
Total Mass (245KW)	16569	Estimated
Gear Ratios (1st to 5th)	3.49, 1.86, 1.41, 1.00, 0.75	LB Transit
Rear Axle Ratio	4.04	LB Transit
Engine Peak Power	275 HP	LB Transit
Rolling resistance 1st Coefficient	0.008	Estimated

Rolling resistance 2nd Coefficient	0.0	Estimated

Table 4. Conventional bus fuel economy

Bus Route	**210 kW Bus**		**245 kW Bus**	
	1 Cycle	10 Cycles	1 Cycle	10 Cycles
LB Route 1	3.6 MPG*	4.0 MPG*	3.5 MPG	3.9 MPG
LB Route 192	4.1 MPG	4.5 MPG	3.9 MPG	4.4 MPG
Colorado Route	2.0 MPG	2.4 MPG	1.9 MPG	2.2 MPG

*Bus missed trace by more than

Series Hybrids

Conventional bus data was modified to simulate hybrid operation. For series configuration, all the motive force was provided by the electric motor, therefore no transmission was necessary. The power transmitted to the wheel however depends on the final drive gear ratio. A higher gear ratio gives a lower required motor torque and a higher motor speed – which limits the vehicle's top speed. A lower gear ratio gives a lower motor speed, but requires higher torque from the motor. In our simulation, we used the final drive gear ratio of 20:1 for a top speed of 60 MPH.

Another important factor in series hybrid operation is the stable and sustained temperature of the catalytic converter system. Long transients common in series operation result in fluctuations in the catalytic converter temperature, which reduces its operational life, and results in excessive tailpipe emissions. We simulated the series hybrid with both thermostatic and power follower control strategies to see the effect of control strategy on the bus operation.

With power followers, the fuel converter operates on an optimum torque-speed curve, i.e. adjust the torque to minimize the fuel consumption rates at a given speeds. At any time, the engine speed is adjusted such that sufficient torque is provided to enable the vehicle to follow the required drive path. A representation of the fuel converter operation for bus operating on Route 192 is shown in Figure 11. Notice that the fuel converter output torque (fc_trq_out_a, [Nm]) and output speed (fc_spd_out_a, [rad/s]) vary throughout the run based on the power demand of the bus.

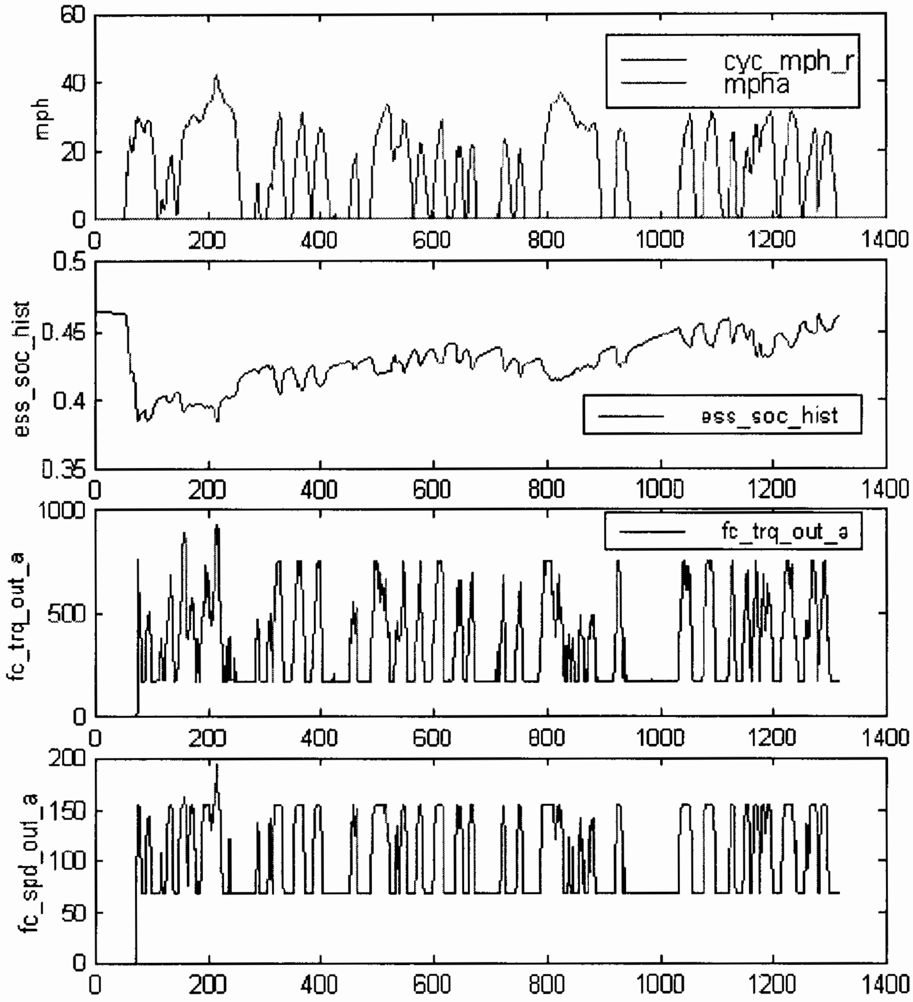


Figure 11. Series hybrid bus with power follower control, 1 Cycle on Route 192

Another point to remember with this control strategy is that the current required by motor to follow the path may exceed what can be provided by the battery. In these instances, additional batteries might be necessary. In fact, when bus operates on Route 1, we found that a minimum of 61 batteries was needed to meet the large transients in the early times. Only 38 batteries were sufficient to assure Route 192 is traced accurately. With 38 batteries, the traces were missed only during the first minute into the drive cycle, and therefore simulation was considered adequate. Fuel economy results for the three routes using the series hybrid bus model with power follower control and 38 battery modules are shown in Table 5.

Table 5. Fuel Economy--Series hybrid bus with power follower control

Drive Cycle	**1 Cycle**	**10 Cycles**
Route 1	4.3 MPG*	4.9 MPG*
Route 192	4.8 MPG	5.6 MPG
Colorado Route	2.8 MPG	3.6 MPG

The differences across different number of cycling can be explained by not only the effect of cold start, but also by the fact that controllers are designed to assure the stae of the charge is maintained after each simulation run.

With thermostatic control, the controller is governed by the battery state of charge or the processed battery pack/module voltage. The fuel converter operates at an optimum point where maximum fuel efficiency (minimum brake specific consumption, BSFC) can be obtained. For the diesel engine used in this simulation, this (sweet spot) occurs at the speed of 1600 RPM and engine torque of 80 Nm (See Figure 12).

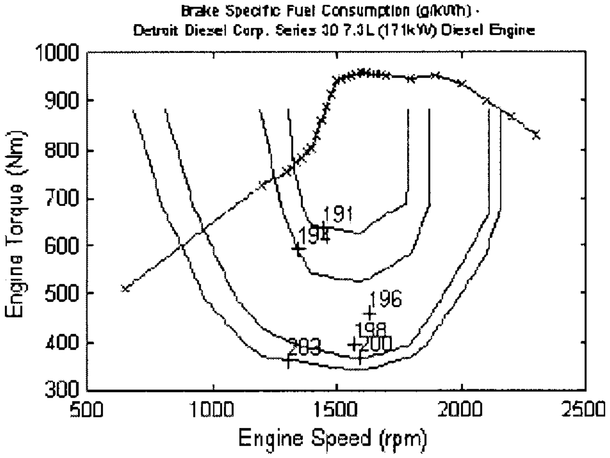


Figure 12. BSFC for series hybrid bus fuel converter.

Figure 13 shows the output for a single run on Route 192 with thermostatic control. Notice that the fuel converter toggles on and off when the SOC reaches 0.4 and 0.8 receptively. Also notice, that unlike the power follower control, when the fuel converter is on, it only operates at speed of 154 rad/s (about 1,500 RPM), and a torque of 649 Nm. Plotting this point on the BSFC map shown in Figure 12 shows that the fuel converter is operating in the lowest BSFC portion of the map corresponding to 191 g/kWh. Fuel economy results for the three routes using thermostatic control are shown in Table 6.

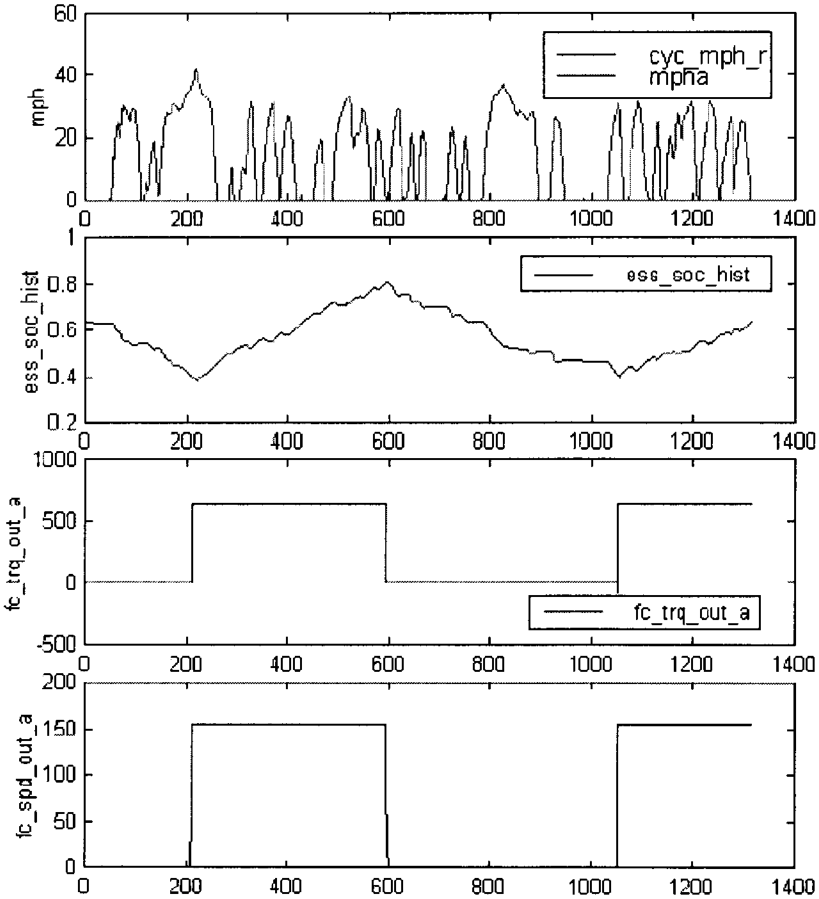


Figure 13. Series hybrid bus with "thermostatic" control, Route 192.

Table 6. Fuel Economy--Series hybrid bus with thermostatic control

Drive Cycle	1 Cycle	10 Cycles
Route 1	3.7 MPG*	4.2 MPG*
Route 192	4.1 MPG	4.7 MPG
Colorado Route	2.4 MPG	3.2 MPG

*Bus missed trace by more than 2 MPH

Gas Turbines

Gas turbines are attractive to hybrid vehicle manufacturers because of their inherently lower emission, which results from ultra-lean combustion. To see the potential advantages of turbine propulsion over diesels, it was assumed that New Flyer buses were equipped with two 30-kW Capstone MicroTurbines[6] (Model 330 HEV) using CNG, propane and diesel fuels in a thermostatic series configuration. It was further assumed that turbines operated near their maximum efficiency, and close to their maximum speeds of 92000-96000 RPM. The manufacturer's data gives an efficiency of 26-28%. Torque provided by the turbines was calculated from the power delivered and the speed ($T=P/\omega$). Knowing the fuel flow rates (8.5kg/hr for CNG, 8.6 kg/hr for propane, and 10.0 kg/hr for diesel fuel), the fuel consumption rates (g/kW.h) were calculated, and were substituted the ADVISOR fuel efficiency map. Results showed that the power plant could supply the demand for CBD, Long Beach Route 192, and Colorado route, but power was not sufficient to allow bus to closely trace Route 1. The fuel consumption rates of about 3.0-3.1 MPG are expected for all the cycles considered—which is lower by as much as 43% as compared to conventional and hybrid diesels. All fuel economy data are reported as "diesel-equivalent." CNG and propane fuel rates are scaled by the ratios of their lower heating values (LHV).

Since the power was essentially constant throughout the turbine operation, the emission data were calculated by multiplying the actual test data (Table 7) by the fraction of time that turbine was operating during each cycles. The most significant advantages of the turbine system is when reduction in emission (especially when using diesel fuel) is of primary concern.

Table 7. Gas turbine emissions

Emissions	CNG*	Propane*	Diesel**
	g/bhp.h		
NOX	0.26	0.53	0.75
HC	0.42	0.42	0.80

CO	0.41	0.18	0.56
PM	0.0041	.0041	--

Parallel Hybrids

For parallel hybrids, components were sized such that most of the buses' power would be supplied by the engine, with the electric motor used for only supplemental power during high load situations. Numerous runs were then performed to optimize the size of each of the components. Inspection of the vehicle's components reveals that the bus is very similar to the conventional bus modeled previously, except the fuel converter is slightly smaller (205 kW verses 210 kW). Also notice that the motor is much smaller than the motor used in the series hybrid (100 kW vs.210 kW), and the number of battery modules is much lower (15 verses 38). Table 8 shows the fuel economy results for the parallel hybrid bus.

Table 8. Parallel hybrid bus fuel economy

Drive Cycle	1 Cycle	10 Cycles
Route 1	5.0 MPG	5.7 MPG
Route 192	5.7 MPG	6.7 MPG
Colorado Route	3.3 MPG	4.3 MPG

Correction for the State of Charge: Unlike conventional engines where enough energy is expended (and thus produced by the engine) to meet the load demand, hybrid vehicles operate to assure the batteries are always sufficiently charged. To be able to compare the relative merits of different hybrid configurations, and/or control strategies, the batteries must remain at the same state of charge before and after the drive-cycle is completed. The default tolerance of 0.5% was used for all of the runs in this study. The effect of such variations in overall efficiency, we compared the energy stored in the battery to the energy consumed by the fuel converter. If the energy stored in the battery were positive, then better fuel efficiency could be achieved compared to those that were predicted by the model. Negative energy storage, means additional fuel must have been used to provide sufficient energy to charge the battery. The correction factor is:

$$\mathrm{BSFC}_{\mathrm{Nominal}} = \mathrm{BSFC}_{\mathrm{measured}} \cdot \frac{E_{\mathrm{tot}}}{E_{\mathrm{tot}} + \Delta E_{\mathrm{Battery}} / \eta_{fc}\eta_{gen}}$$

Where E_{tot} is total fuel energy consumed, and ç_{fc} and ç_{gen} are efficiencies of fuel converter and generator respectively. For example if the energy depleted from the battery is 393 kJ during the run, and if the generator and the fuel converter have efficiencies of 95% and35%, then 393/(.35 x.95)=1182 kJ of additional fuel should have been used. If the actual fuel used were 150,322 kJ then the fuel efficiency would be smaller by 1-50,322/(150,322+1182)= 0.008 or 0.8%. All data were corrected, and results are shown in Figure 14.

Table 9. Fuel economy improvement of hybrid compared to conventional buses.

	Series-Hybrid Bus with Power Follower Control		Series-Hybrid Bus with Thermostatic Control		Parallel-Hybrid Bus	
	1 Cycle	10 Cycles	1 Cycle	10 Cycles	1 Cycle	10 Cycles
LB Route 1	19%	23%	3%	5%	39%	43%
LB Route 192	17%	24%	0%	4%	39%	49%
Colorado Route	40%	50%	20%	33%	65%	79%

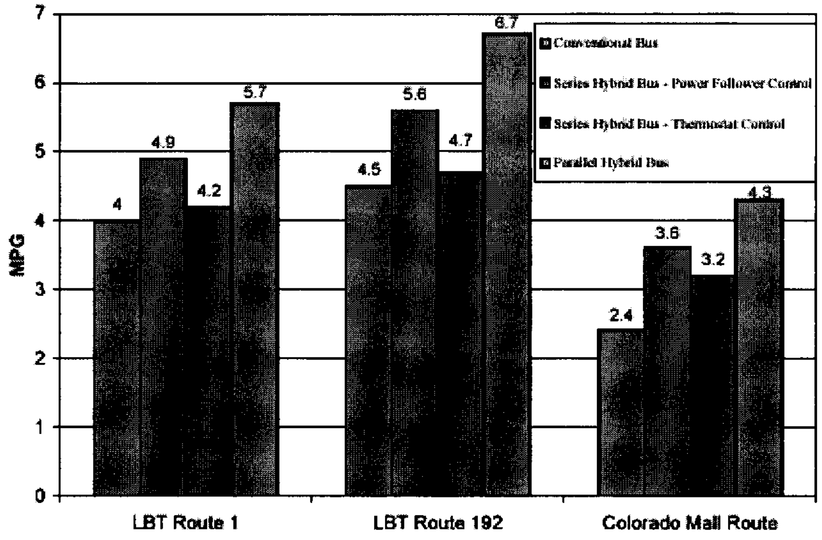


Figure 14. Fuel economy comparison between different routes.

Regenerative Braking: The effect of regenerative braking on fuel efficiency was investigated by taking inventory of the energy recovered and supplied back into the generator. It was concluded that regenerative braking could be responsible for a significant reduction in the fuel consumption in hybrid buses. The actual percentage however depends to a large part to the driver habits and the drive path it is being operated. For example, if vehicle deceleration is fast (short braking distance), a lower percentage of the kinetic energy can be recovered. This is mainly due to limited storage capacities of batteries and their ability to accept charges. Acceleration on the other hand is limited by the engine power and in the case of a hybrid vehicle, drive system power. Regenerative braking allows, a portion of the energy lost to be recovered. Higher efficiencies of smaller engines and lower idling time (for all-electric operation during the stops) will also help to improve the fuel efficiencies.

Operating Map: Figures 15-18 illustrate the operating points of the fuel converter on the engine efficiency map for the conventional, parallel, and series hybrid buses when operated along Route 192. The higher concentrations of the data points show the larger fraction of the time that the engine operates in that speed. For conventional and parallel hybrids, the engine is directly coupled to the wheels, and its speed is directly follows the load. The operating points are seen to scatter all over the map.

In contrast, in the series bus configuration, the engines speed is independent of the vehicle speed. As seen in Figure 18, the thermostatically controlled series bus engine operates in the optimum location of the efficiency map during most of the run. With power follower control (Figure 17), the control operates the engine on an optimized design curve. This configuration showed the best fuel efficiency, as is expected.

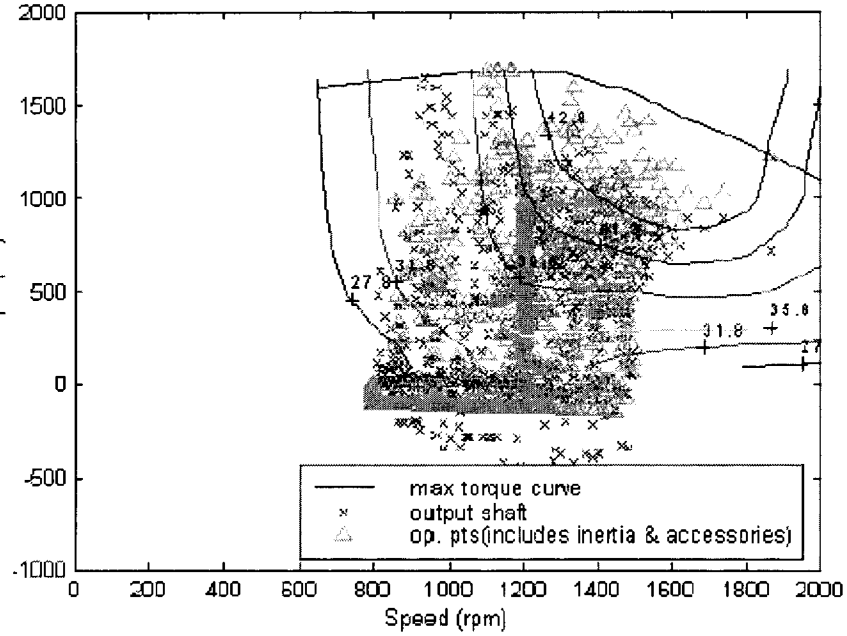


Figure 15. Fuel converter operating points for the conventional bus

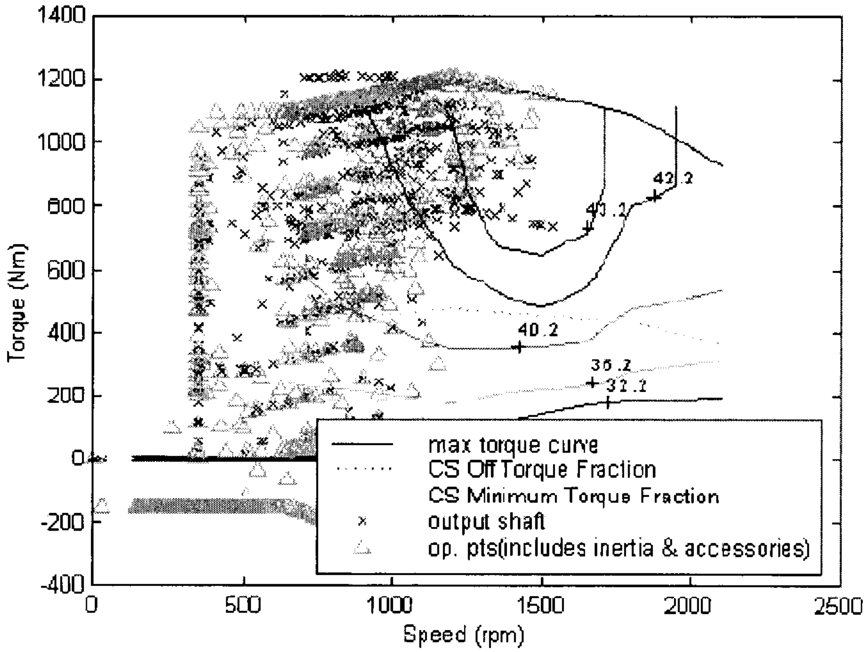


Figure 16. Fuel converter operating points for the parallel hybrid bus

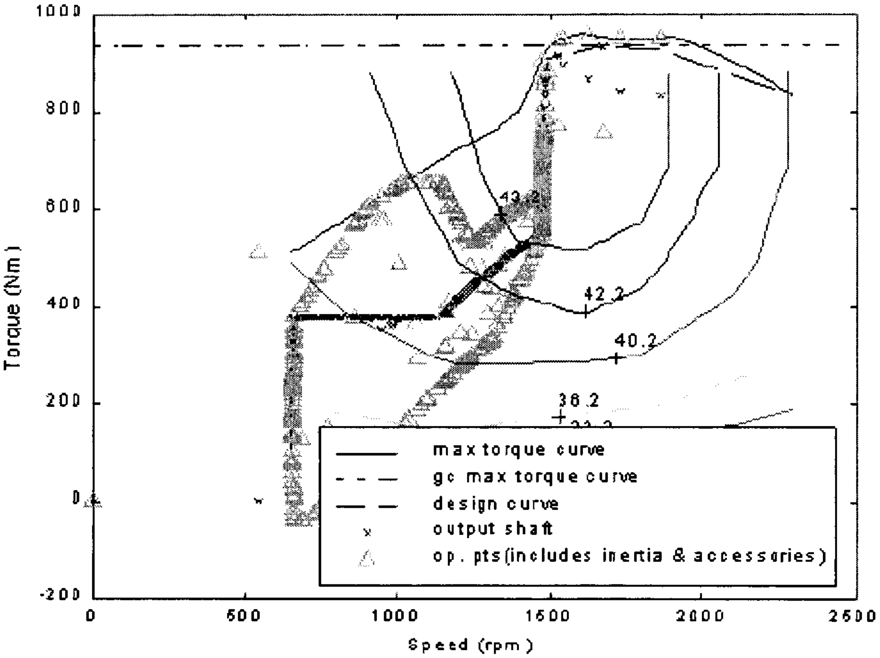


Figure 17. Fuel converter operating points for the series hybrid bus with power follower control.

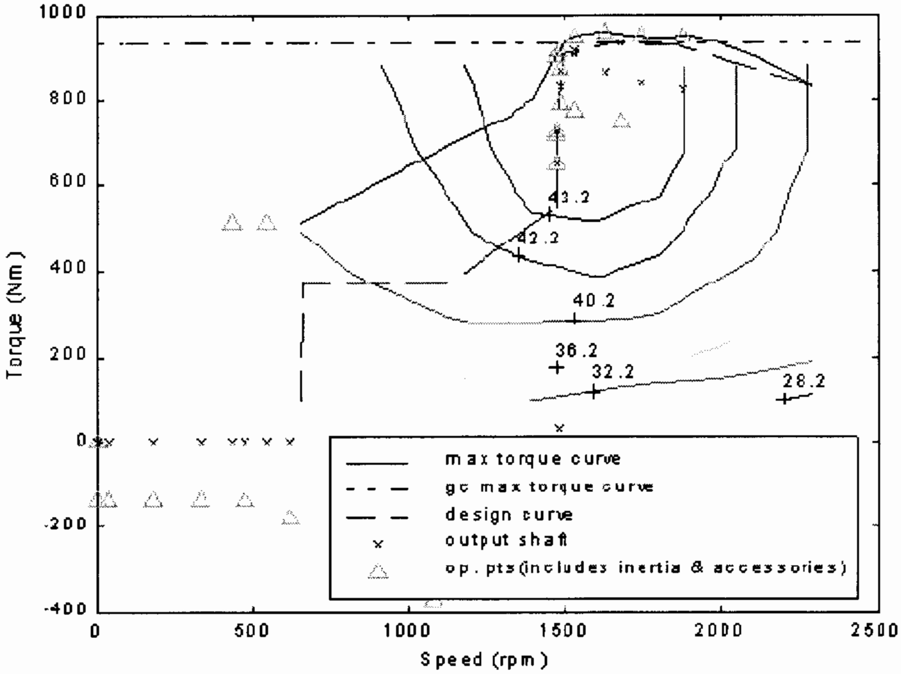


Figure 18. Fuel converter operating points for the series hybrid bus with thermostatic control.

Comparison with Other Data

The predicted results presented in this study were compared to the experimental studies carried by the Northeast Advanced Vehicle Consortium (NAVC). The NAVC is a public-private partnership of companies, public agencies, and university and federal laboratories formed to promote advanced vehicle technologies in Northeast United States.

Under a grant from Defense Advanced Research Project Agency (DARPA), NAVC initiated the testing of hybrid-electric buses to evaluate the state of the art in hybrid-electric technology and assess their impact on fuel efficiency and emission released to the atmosphere. The experiments were conducted in the laboratories of West Virginia University, which is equipped with the state-of-the-art heavy-duty chassis dynamometer and other emission monitoring instrumentations. The studies were conducted on a number of 1997-1999 model 40-ft buses (Orion, Neoplan, New Flyer, and NovaBUS), for a variety of conventional and alternative fuels (Diesel, CNG, and propane), and several drive cycles. The details of the experiments are reported elsewhere. Table 10 summarizes the emission and fuel economy data for several buses and associated drive cycles when operated in CBD drive cycle.

Table 10. Comparison of fuel economy and emission between various conventional, diesel hybrid, and gas turbine (CBD Cycle)

Bus Description	**Configuration**	**Fuel**	**Data Source**	**NOx**	**HC***	**CO**	**PM**	**Fuel Econ.**
				g/mile	g/mil	g/mil	g/mil	MPG
Orion-LMCS Hybrid Diesel	Series Hybrid	Diesel	NAVC	19.20	0.08	0.10	0.12	4.3
Nova-Allison Hybrid Diesel	Series Hybrid	Diesel	NAVC	27.70	bdl	0.40	bdl	3.9
NovaBUS Diesel Series 50	Conventional	Diesel	NAVC	30.10	0.14	3.00	0.24	3.5
Neoplan AN440T L10-280G	Conventional	CNG	NAVC	25.00	0.60	0.60	0.02	3.1
New Flyer C40LF Series 50G	Conventional	CNG	NAVC	14.90	3.15	12.70	0.02	3.1
Orion Series 50G	Conventional	CNG	NAVC	9.70	2.36	10.80	0.02	2.6
Turbine Hybrid**	Series Hybrid	CNG	ADVISOR	1.31	2.11	2.06	0.02	3.1
Turbine Hybrid**	Series Hybrid	Propane	ADVISOR	2.66	2.11	0.9	0.02	3.1
Turbine Hybrid**	Series Hybrid	Diesel	ADVISOR	3.77	1.51	2.01	0.05	3.0
New Flyer 40' bus**	Conventional	Diesel	ADVISOR					3.7
Hybrid Diesel **	Series Hybrid	Diesel	ADVISOR					4.2

* NMOC for data obtained from NAVC report
** ADVISOR Simulation
bdl - Below detectable levels

Fuel Economy

Figure 19 compares the fuel economy data with those predicted from the simulation runs made for conventional (◊) and hybrid (□) diesels. The predicted results are in excellent agreement with the test data.

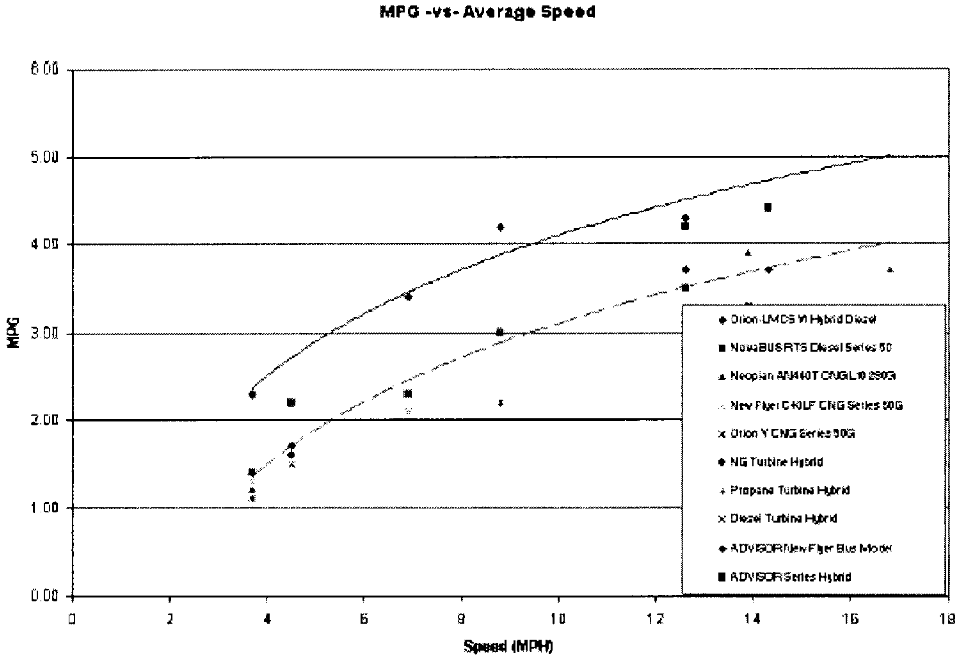


Figure 19. Fuel economy for several buses. The horizontal axis represents the average speed for different drive cycles. The predicted results show excellent agreement with experimental data for hybrid (solid line) and conventional (dashed line).

Emission

Exhaust emissions are closely linked to combustion regime and the matter in which combustion parameters (temperature, pressure, residence time, and fuel/air mixture) are affected. Hybrid vehicles would necessarily produce lower emissions by taking advantage of operating in higher combustion efficiency regions, and spending at least part of the transient time on electric drive. Different drive cycles have different mixes of cruising and transients, and vary widely in average speeds. Gas turbine combustion is very different from diesel combustion as they use higher air/fuel ratios and much lower average temperatures.

Natural gas vehicles are usually associated with significant amount of CO and NOx conventional buses (Figures 21 and 22). When buses are fueled with CNG and propane, particulate emission can drop by another factor of 2-3. Gas turbines offer the best performance for particulates. Some penalty in fuel economy must be tolerated when diesel fuels are substituted by CNG and propane however.

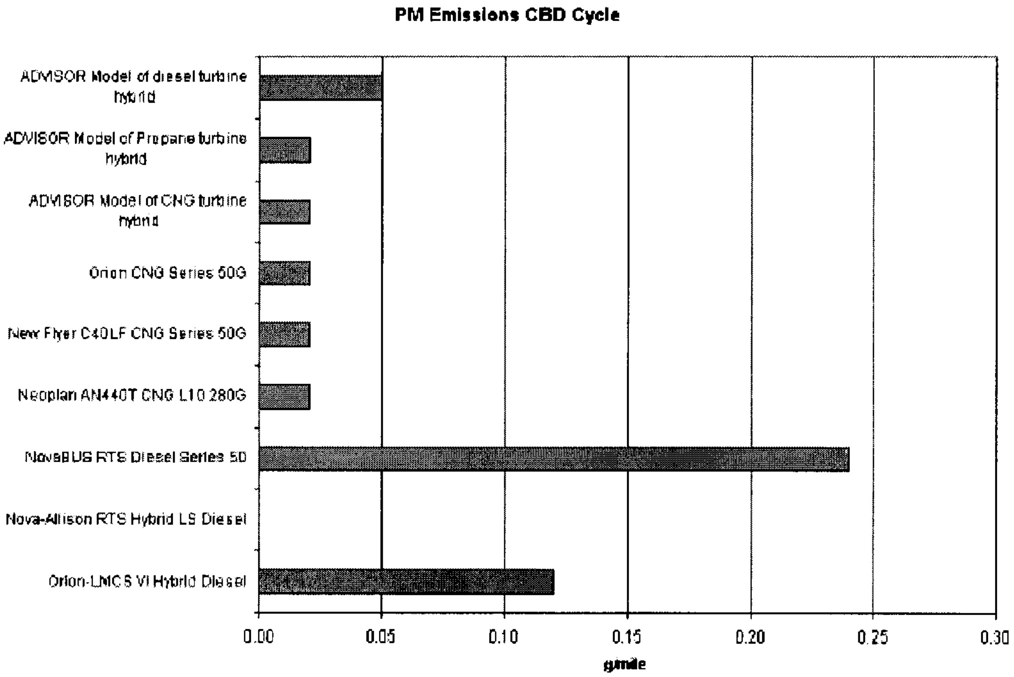


Figure 21. Comparison of particulate emission for various buses (CBD cycle)

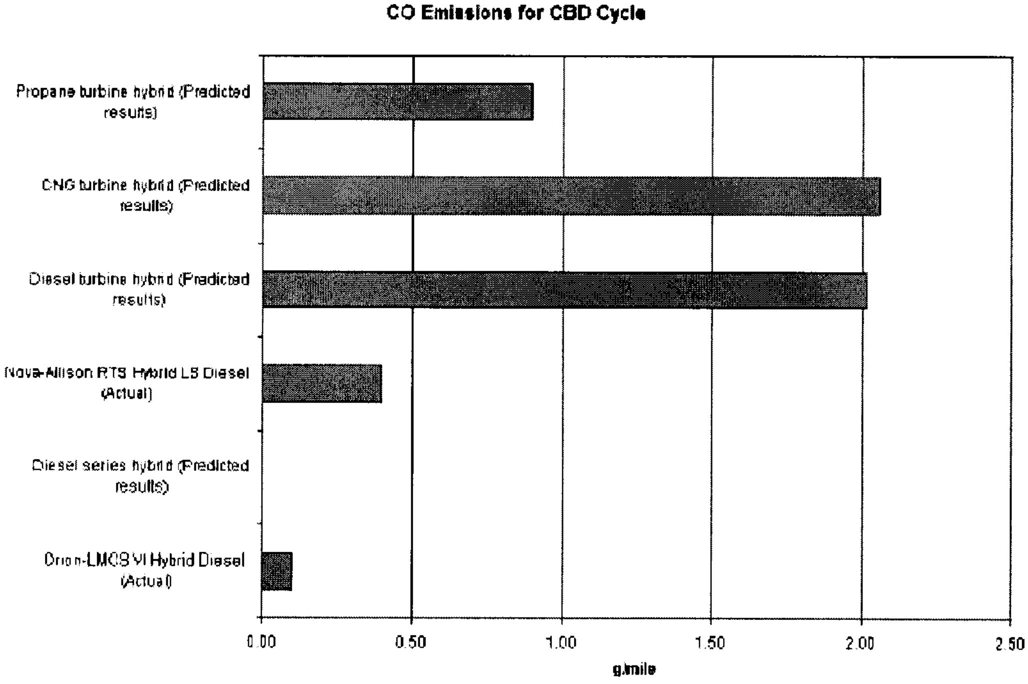


Figure 22. Comparison of carbon monoxides for various buses (CBD cycle)

Table 11. Effect of drive cycle on gas turbine emission and fuel economy

	CBD Drive Cycle			**Colorado Drive Cycle**			**Long Beach Route 192**		
FC ON time	450 Seconds			715 Seconds			1210 Seconds		
Distance	2 Miles			1.6 Miles			5.2 Miles		
Power	60 kW			60 kW			60 kW		
Av. Speed	12.6 MPH			4.5 MPH			14.3 MPH		
	Emissions (g/mile)			Emissions (g/mile)			Emissions (g/mile)		
	CNG	Propane	Diesel	CNG	Propane	Diesel	CNG	Propane	Diesel
NOx	1.31	2.66	3.77	2.59	5.29	7.49	1.35	2.75	3.90
HC	2.11	2.11	1.51	4.19	4.19	2.99	2.18	2.18	1.56
CO	2.06	0.90	2.01	4.09	1.80	3.99	2.13	0.94	2.08
PM	0.02	0.02	0.05	0.04	0.04	0.10	0.02	0.02	0.05
MPG	3.1*	3.1*	3.0	1.6*	1.6*	1.6	3.0*	3.0*	2.9*

Carbon Monoxide

Carbon monoxide emission can be significantly lowered by switching from conventional to hybrid vehicles (Figure 22). Because of the strong correlation of CO emission with cold startups and transient operation, the degree at which hybrids reduce CO emissions depends on the control strategy used, and the effectiveness of this strategy in reducing transient operations. As is seen in Figure 23, the CO concentration drops with increase in the cycle average speed, i.e. cycles with more time spent on cruising and/or has a lower number of braking and accelerations.

CNG buses show elevated levels of CO gases. The is partially due to low temperatures resulting from very lean burn combustion strategies used for minimizing NOx emissions. Propane-operated vehicles also show higher levels of CO emission, although not as much as those fueled by methane.

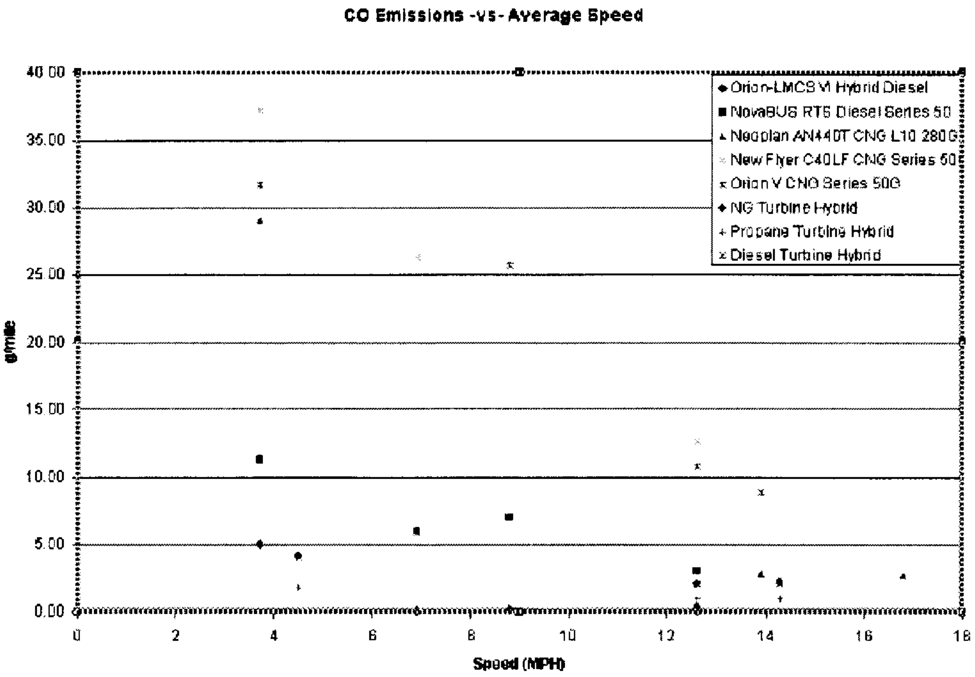


Figure 23. Effect of drive cycle on carbon monoxide emission

Hydrocarbon

In general, vehicles produce higher emissions at lower average cycle speed. This is due to the large number of stop-and-go and steep transients that associates with rich fuel/air mixtures (acceleration), and sudden quenching (deceleration). Hybrid buses (Orion and Nova-Allison) have generally lower total HC emissions by more than 50% than conventional buses (Nova RTS Series 50). As is the case with CO, buses fueled by natural gas produce considerably higher THC emissions. Similar results are seen for gas turbines (Figure 24).

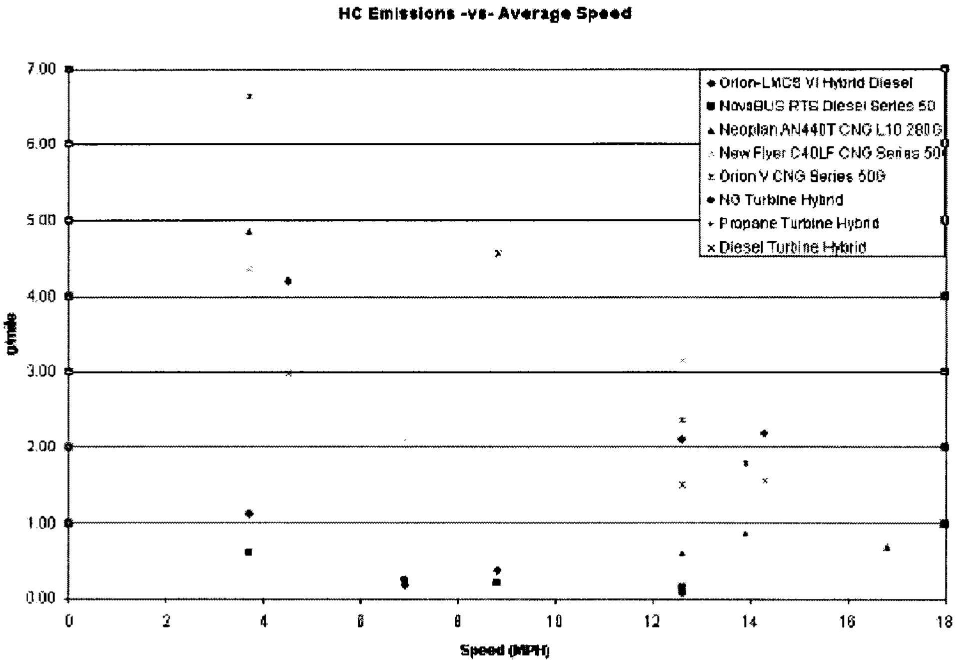


Figure 24. Effect of drive cycle on hydrocarbon emission

NOx

Nitric oxides emissions from hybrid vehicles are shown to be about 30-40% lower than conventional diesels. This can be attributed to the lean burn engines of hybrid buses. As with CNG, no clear conclusions can be drawn, as the level of NOx emissions depended strongly on the drive cycles. Gas turbines run at even leaner mixtures, so nitric oxides and particulate emissions are substantially lower.

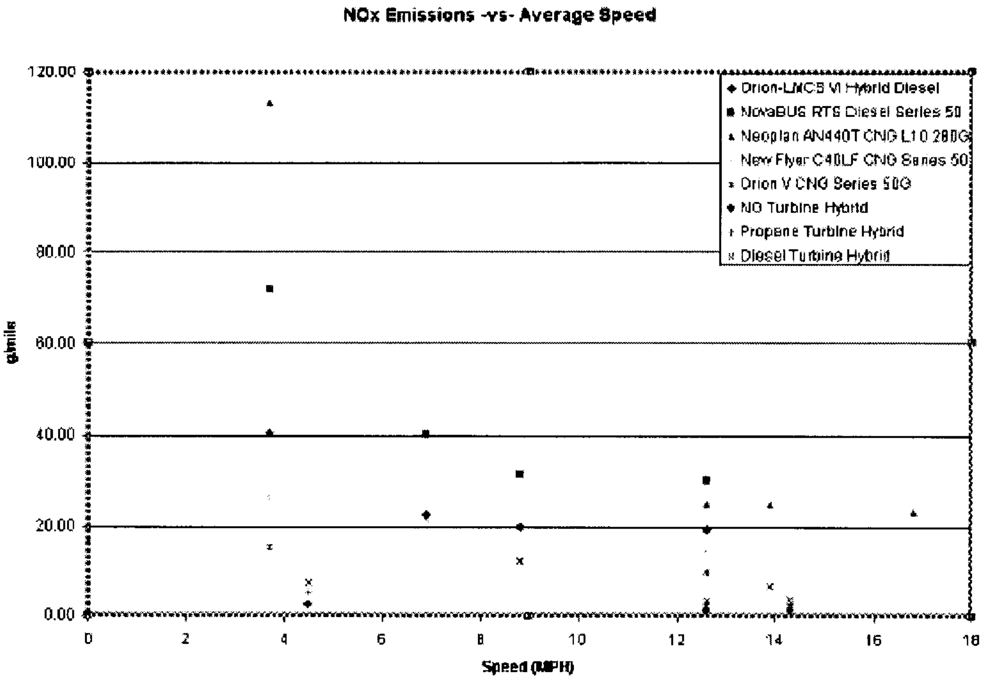


Figure 25. Effect of drive cycle on nitric oxides emission

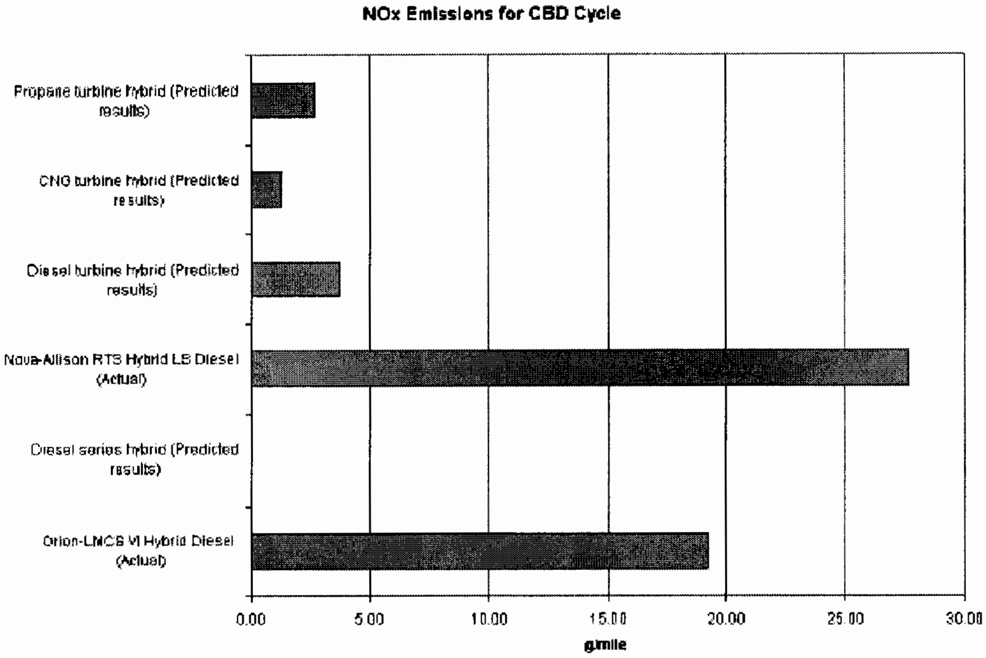


Figure 26. Comparison of nitric oxides for various buses (CBD cycle)

CHAPTER 4 – CONCLUSIONS

The simulation studies were conducted to investigate the operation of hybrid vehicle systems in improving the fuel economy and emissions for operation of metropolitan transportation systems. Long Beach City Transit was used as an example. Based on the result of this study the following conclusions can be drawn:

1. Generally, good correlation exists between measured gas economy data and the predicted simulation results.
2. No emission data were available for the New Flyer buses operating in Long Beach transit fleet, so direct comparison between the actual and predicted data were not possible.
3. Hybrid buses showed significant reduction in the level of emissions. The degree to which depended strongly on the drive cycle and the type of fuels that were

used.

4. Fuel economy of as much as 80% could be achieved with proper use of hybrid vehicles for the assigned drive route. Fuel economy improvements were the highest in areas with heavily congested traffics, and where the large number of traffic lights demanded significant number of stops.
5. Turbines could substantially reduce the emission with comparable fuel economy.

In addition, the effort carried out in this study detailed the effect of various control strategies on design of future metropolitan transit systems aimed to increase throughput and at the same time decrease the fuel usage and emission. This can be done by selecting proper mixes of fleets of hybrid and conventional vehicles (buses and vans), by rerouting, and by implementing specific control strategies custom-designed to meet the specific needs. In general, performances of hybrid systems depend strongly on the route (drive cycle) they operate. The greatest advantages over conventional systems are realized in business districts and heavy-traffic city driving with a large proportion of stop-and-go traffic.

Control strategies could fall into one of the following categories:

1. Increase throughput without increasing the total fuel use. This is possible by replacing a number of existing vehicles with hybrids and rerouting them to highly congested areas and to poorer communities where public transportation is most needed.
2. When applying a particular control strategy, there is always some tradeoff between vehicle fuel economy and emissions. Most hybrid vehicles are designed to operate in an optimum operation band. This band can be considerably different if a given situation requires minimizing the emission, or fuel consumption.
    a. Reducing the emissions by assuring that vehicles are operated under optimum conditions which warrants minimum overall emission. This is particularly important in cities where poor air quality (and not necessarily

fuel economy) is of primary importance. Furthermore, using different fuels can prove beneficial if a particular type of emission is of concern.

   b. Similarly, it is possible to change the operating conditions such that overall fuel economy is minimized. Obviously lower fuel consumption is directly associated to reduced emission.

3. Fleets consisting of 100% ZEV can be used if the vehicles operating in short routes and where daily travel demand is sufficiently low that infrequent operation allows adequate recharging between different runs.

Component sizing is also shown to be critical for maintain optimum operation. Hybrid system must be designed to meet the required load with smallest size components. This can be achieved by selecting not only the proper mix of small and large vehicles (buses and minibuses), but also the proper mix of series and parallel configuration. Unfortunately, lack of sufficient number of various size components (mainly motors, controllers, and generators) will limit the choices for optimized operation. As it was shown in this study, both component sizing and control strategy are mission dependent. Simply put--one kind of control strategy and one vehicle configuration cannot adequately meet the needs under different drive cycles and different environmental and economical situations. It should be noted here that this simulation results is based on the existing commercial components, therefore if dedicated optimum component designs are made available, the hybrid system can offer further fuel economy and emission reduction.

Further works are needed to define common scenarios of operation and to design optimum operating conditions for the specific scenario and optimization criteria.

REFERENCES

1. C. G. Hochgra, M. J. Ryan, and H. L. Wiegman, "Engine Control Strategy for a Series Hybrid Electric Vehicle Incorporating Load-Leveling and Computer Controlled Energy Management", SAE International Congress & Exposition, Detroit, Michigan, February 26-29, 1996, Paper No. 960230.
2. "Hybrid-electric Drive Heavy-Duty Vehicle Testing Project", Final Emissions Report, by Northeast Advance Vehicle Consortium (NAVC), M. J. Bradley & Associates, Inc., and The West Virginia University, February, 2000.
3. http://www.cts.nrel.gov/analysis
4. Wipke, K. (1998), Advisor 2.0 -- A Second Generation Advanced Vehicle Simulator For System Analysis, NREL NAEVI '98 paper presented in Phoenix, AZ.
5. Wipke, K.B., Cuddy, M.R., and Burch, S.,D., 1999, "ADVISOR 2.1: A user-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach, " NREL Technical report.
6. Capstone Low Emission Micro Turbine Technology, White paper, July 2000.
7. T.D., Gillespie, 1992, "Fundamentals of Vehicle Dynamics," Society of Automotive Engineers, Warrendale, PA.

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