IPRO It takes a team INTERPROFESSIONAL PROJECTS PROGRAM

IPRO 342
HYBRID ELECTRIC VEHICLES:
SIMULATION, DESIGN AND IMPLEMENTATION
SPRING 2006

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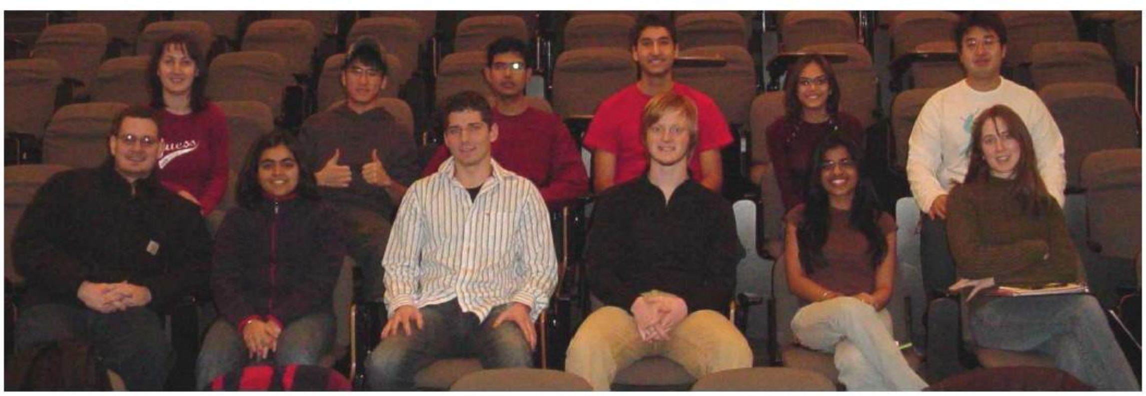

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Introduction

Welcome to IPRO 342 Hybrid Electric Vehicles: Simulation, Design and Implementation. We are a group of students and faculty ready to go hybrid. We are dedicated to the use of electrical power to drive automobile subsystems, which historically have been driven by a combination of mechanical, hydraulic and pneumatic systems. Use of electrical power transfer systems is seen as a dominant trend in advanced automotive power systems. In his project, hybrid heavy-duty vehicles, particularly, a Bluebird Vision school bus and a CTA Nova transit bus, will be simulated and their performance as well as fuel economy will be studied under varying conditions. Three dimensional models of these buses will also be developed to assess the feasibility of an actual hybrid transformation. Also, a preliminary cost analysis will also be performed to analyze the economical benefits of hybridization.

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Objectives

The IPRO 342 team embarked upon several objectives during the semester. The team aimed at successfully modeling the conversion of a CTA bus and a school bus chassis to hybrid electric drive trains. The CTA bus group pursued the design and simulation of a retrofit parallel HEV design, while the school bus group pursued that design along with a new parallel drive train with a downsized engine and a new parallel drive train with an integrated starter/alternator. In addition, both teams aspired the modeling of the conventional drive trains of an average CTA bus and the Bluebird Vision Model school bus. These conventional models will be used to compare the efficiency of the hybrid drive trains. In addition, the teams also aimed to model the final layouts and appearances of the hybrid and conventional drivetrains in three dimensions. Finally, the team has agreed to create and maintain a website regarding the project and to perform an initial cost analysis for the project.

Assignments

ADVISOR Team: Jae Suk, Alex, Priscilla and Taekmin

- Create and simulate the various hybrid models using ADVISOR
- Modify the M-Files to be compatible with ADVISOR
- Optimize the hybridization ratio

Batteries and Motor Team: Deep, Dipti and Ana

- Researching batteries and motors available in the market
- Choosing the optimum battery and motor size

Mechanical Design Team: Kevin, Jose, Dan and Rob

- Use UNIGRAPHICS NX2 to model the conventional and hybrid drivetrains
- Incorporate the hybrid components into the 3-D Models

Cost Analysis: Sapna

- Research and perform a cost analysis on fuel savings and pay back periods for the models

Webmasters: Shameek and Jasmine

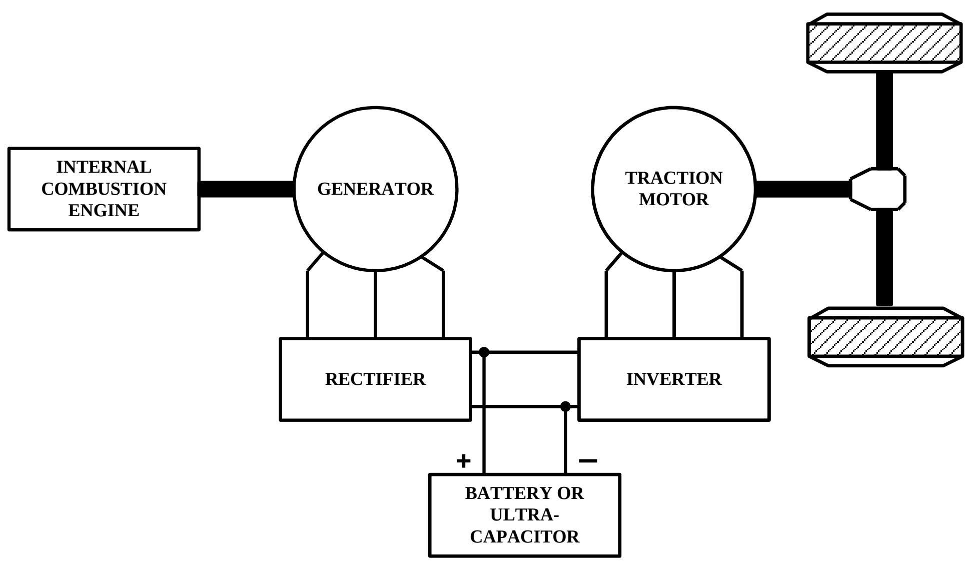
- Create and maintain a website for the project

Research

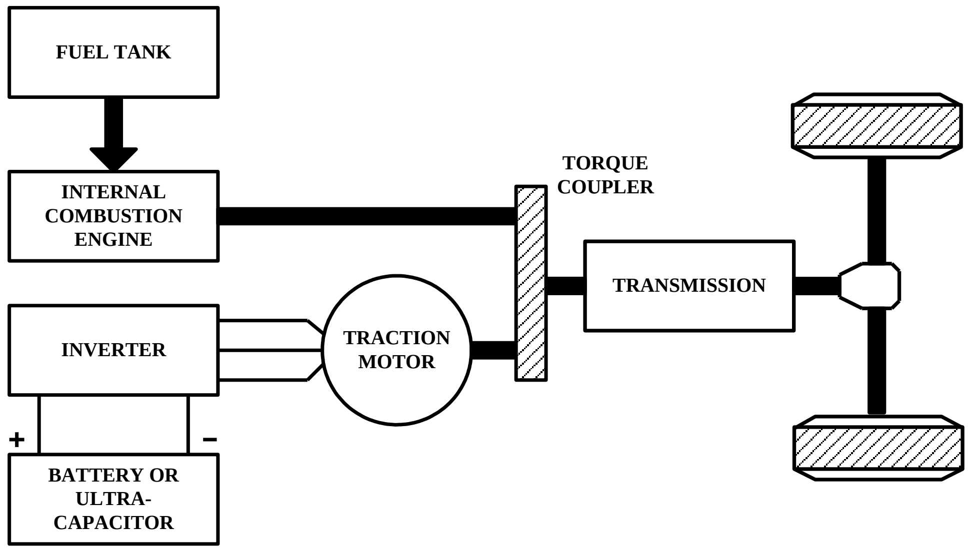
Topology Research

Hybrid Electrical Vehicles use gasoline to power the internal combustion engine (ICE) and use electric batteries to power the electric motor. There are two main types of hybrids, which differ in the connection of the electrical and fuel parts. These two categories are the series and parallel designs.

In a series design, the ICE is not directly connected to the drive train and instead powers the electrical generator. The electricity from the generator is used to move the vehicle, while excess energy is used to charge the batteries and not allowed to fall below a certain predetermined minimum. The battery is usually maintained at about 65%-70% of maximum charge. This is such that when a large amount of power is required, it can be sourced from the battery as well as the engine. The main advantage of this system is that the ICE only works at its ideal combination of speed and torque that enables low fuel consumption and therefore higher efficiency. Series hybrids are useful in drive cycles that include many stops and starts like that of typical city driving. The downside to the series design is that there are two stages of conversion of energy between the ICE and the wheels that leads to some loss of energy. Also, because of separate motor and generation it might lose on some efficiency. A diagram of this drivetrain is shown below.



In a parallel design, the electrical and the ICE systems are connected to the transmission. The vehicle can be powered by the ICE, the electric motor or both together. There are many ways in which the different portions can be balanced to provide motive power. One way that is popularly used is to use the motor alone at low speeds and the ICE alone at high speeds. This is when the motor is used to charge the battery. Accessories such as air conditioning and power steering are usually powered by the electric motor, so that it keeps running irrespective of the state of the ICE. This increases the efficiency by allowing the modulation of the power to these systems. One advantage of the parallel system is the lower number of stages of conservation of energy leading to less energy losses. Regenerative braking also lowers energy losses during braking. The diagram below pictures the parallel hybrid drivetrain.



There also exists the series- parallel combination that seeks to combine the advantages of both series and parallel systems. However, the downside of this model is that its complex design leads to higher costs. This design differs from the series design in that there exists a physical link between the motor and the generator, and differs from the parallel design in that there is an extra generator. This configuration is shown below.

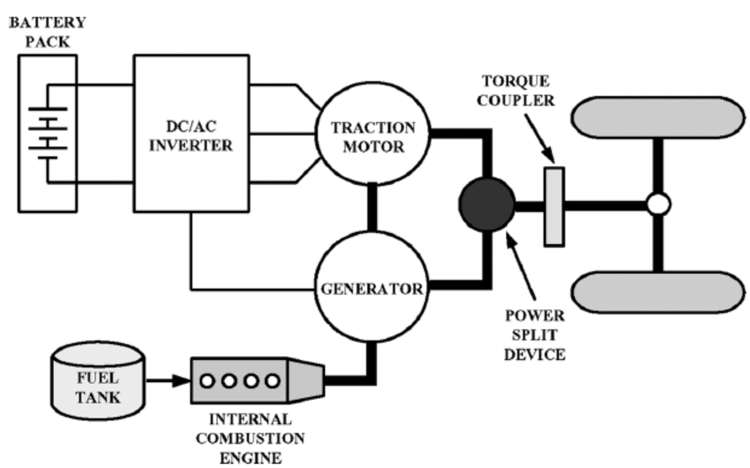


Fig. 7. Typical drive train configuration of a series-parallel combined HEV.

The parallel configuration was chosen by both teams due for the hybrid models to its favorability in a retrofit design.

Bus Research

Much research was done on bus models and types. The bus models chosen were the Nova Bus LFS 6400 for the CTA model and the Bluebird Vision Type C for the school bus models. The Nova Bus was chosen for the CTA models because it was a relatively old bus, which would be good for the retrofit model. Also, it is the most common bus found in the CTA fleet. The Vision model was chosen by the school bus team because it is the most common model of school bus produced by Bluebird.
The specifications for these buses, which are essential to ADVISOR simulations and 3-D modeling were researched and compiled.

<u>Nova Bus LFS 6400</u>

- Length: 488 inches
- Width: 102 inches
- Height: 123 inches
- Wheel Base: 244 inches
- Gross Vehicle Weight Rating: up to 39,000 lbs (17690.3 kg)
- Engine: Cummins ISL 8.3L 280 HP
    - Torque Operation Range: 1200 – 2200 rpm
    - Max. Torque: 1220 N-m at 1200 rpm
    - Max. Power: 215 kW at 2000 rpm
- Transmission: ZF Ecomat Automatic Transmission
    - Max. Permitted input speed: 2800 rpm
    - Series: HP 592C
    - No. of Gears: 5
    - Gear Ratio [3.51 1.90 1.44 1.00 0.74]

<u>Bluebird Vision</u>

- Length: 289 inches
- Width: 96 inches
- Height: 120 inches
- Wheel Base: 152-157 inches
- Engine: CATERPILLAR® C7 190 HP
    - Torque Operation Range: 1440–2500 rpm
    - Max. Torque: 1440 N-m
    - Max. Power: 154 kW
- Transmission: Allison PTS 2500 Automatic Transmission
    - No. of Gears: 5
    - Gear Ratio [3.43 2.01 1.42 1.00 0.83]

Battery Research

Two types of batteries are currently main-stream for hybrid vehicles: Ni-MH (Nickel-Metal Hydride) and Lead Acid. Lead-acid batteries were invented in 1859 by French physicist Gaston Plante. They are a type of galvanic cell and are the most commonly used as rechargeable batteries. They represent the oldest design with one of the lowest energy-to-weight rations, although the power-to-weight ratio can be quite high. They are relatively low cost and can supply high surge currents needed in starting motors. Modern cars use lead acid batteries for this purpose.

Each cell contains (in the charged state) electrodes of lead metal (Pb) and lead (IV) oxide (PbO_2) in an electrolyte of about 37 % w/w sulfuric acid (H_2SO_4). Modern designs have gelified electrolytes. In the discharged state both electrodes turn into lead (II) sulfate and the electrolyte turns into water. This is why discharged lead-acid batteries can freeze. Lead-acid batteries for automotive use are not designed for deep discharge and should always be kept above a certain charge level. Their capacity will severely suffer from deep cycling, due to sulfation, or hardening of the lead sulfate.

There are however, certain disadvantages for using the lead acid battery. Right now, the weak link in any electric car is the batteries. There are at least six significant problems with current lead-acid battery technology:

- They are heavy (a typical lead-acid battery pack weighs 1,000 pounds or more).
- They are bulky.
- They have a limited capacity (a typical lead-acid battery pack might hold 12 to 15 kilowatt-hours of electricity, giving a car a range of only 50 miles or so).
- They are slow to charge (typical recharge times for a lead-acid pack range between four to 10 hours for full charge, depending on the battery technology and the charger).
- They have a short life (three to four years, perhaps 200 full charge/discharge cycles).
- Even though they are cheaper than Ni-MH, they are still expensive.

You can replace lead-acid batteries with NiMH batteries. The range of the car will double and the batteries will last 10 years (thousands of charge/discharge cycles), but the cost of the batteries today is 10 to 15 times greater than lead-acid. In other words, a NiMH battery pack will cost $20,000 to $30,000 (today) instead of $2,000. Prices for advanced batteries fall as they become more popular, so over the next several years it is likely that NiMH and lithium-ion battery packs will become competitive with lead-acid battery prices. Electric cars will have significantly better range at that point.

For now, both groups have chosen to use the lead acid batteries on their hybrid models. The CTA bus required a deep cycle battery whose specifications were decided by the ADVISOR simulations. The parallel design of the CTA bus requires 46 modules of a 12V /85Ah lead- acid battery. The team considered automotive batteries by several manufacturers including SBS, Horizon, Genesis and Power Sonic. In the end we had to decide on a battery that was the closest match in terms of specifications as well one that was economically viable. With some research, the team decided on 42 modules of a 12V/95Ah battery manufactured by Odyssey. This was priced at $259.95 per module. This battery is considered a deep cycle batter and comes with a 2 year warranty. A picture of the battery is shown below.

- **Model** Odyssey PC 2150
- **Type** Lead-Acid
- **Voltage** 12V module
- **Rating** 100 Amp Hours
- **Length** 13.0"
- **Width** 6.80"
- **Height** 9.40"
- **Weight** 75 lbs

Motor Research

The two types of motors that were considered were the AC Induction Motor and the Permanent Magnet Brushless DC Motor. The AC Induction Motor was chosen because AC induction motors are popular choices for heavy-duty diesel hybrid electric transit buses. They are inherently rugged, cost-effective, and efficient. Induction motors are viable for hybrid electric buses, since they can run at higher speeds and have internal liquid cooling capabilities. Due to this, a higher power to weight ratio can be achieved. In addition, induction motors offer high reliability and suitable vector control allows for independent and efficient torque control over a wide speed range. A picture of the motor chosen for the models is shown below with its specifications.

- **Model** General Electric AP 902
- **Application** Automotive Duty
- **Phase** Three Phase
- **Motor Type** Severe Duty
- **Horsepower** 100
- **RPM** 3600
- **Volts** 460
- **Hertz** 60
- **Enclosure** TEFC
- **Rotation** CCW/CW
- **A_dim** 20.8'' (height)
- **C_dim** 36.4" (depth)
- **Weight** 1480 lb

Inverter Research

A picture and the specifications of the inverter chosen are shown below:

- **Model** Saminco M1-250
- **Voltage Range** 450V (min); 900V (max).
- **Power Rating** 250kW @ 460V.
- **S/W Frequency** Up to 10 kHz;
- **Temp** -40 to 105 ºC.

Results

ADVISOR

At the core of IPRO 342 is ADVISOR, an acronym for **Ad**vanced **V**eh**i**cle **S**imulat**or** for systems analysis. ADVISOR is complete with files containing tons of information about different vehicles, their layouts, their components, weight, etc. This software allows us to try out our different designs for the buses and then optimize the results they produce by tweaking the components of the vehicle and simulating them again. Thus our main goals are to complete our simulations accurately based on our ideas of what will work best for each design.

M-File Customization

ADVISOR is an extremely comprehensize software package, however there is something missing: files that contain the specifics on the buses that we want to hybridize. For the school bus, we have focused our energies on the Blue Bird Vision, but ADVISOR only contains data on the Orion VI urban transit bus. So, the process of examining and editing the M-files (ADVISOR runs on Matlab) is crucial to determining what specifics are needed to run the simulations. The following is an example of the type of M-file contents that the school bus group's ADVISOR experts rehashed.

```
veh_cg_height=0.25*122/39.37;
veh_front_wt_frac=0.3636;%Front_Axle*(Front_Axle+Rear_Axle)=12000/(
12000+21000)
veh_wheelbase=217/39.37; % (m)
veh_glider_mass=(31000-(150*54))*0.453592;%(kg)=GVWR-
max_cargo_mass=(31000- (150*54))*0.453592
veh_cargo_mass= 150*27*0.453592;% (kg) 27 people at 150 lbs/person
(1/2 passenger load) = 150*27*0.453592
```

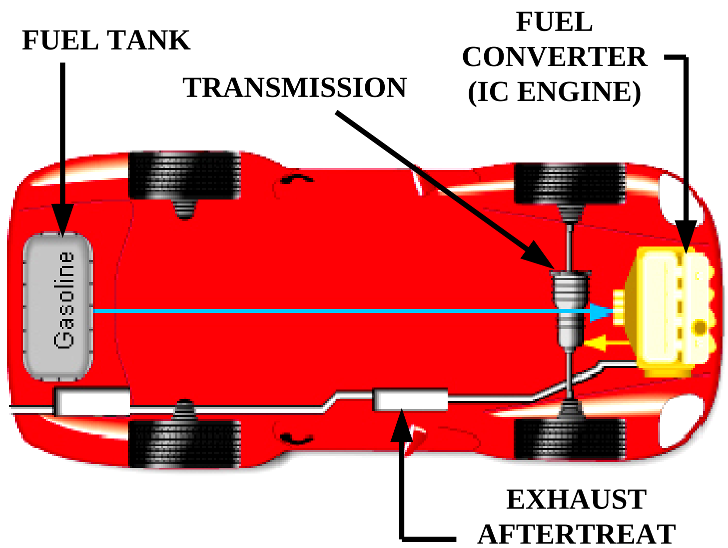
Also, the Orion VI bus was inadequate for the CTA Nova model and the following shows the modifications done to compensate for this..

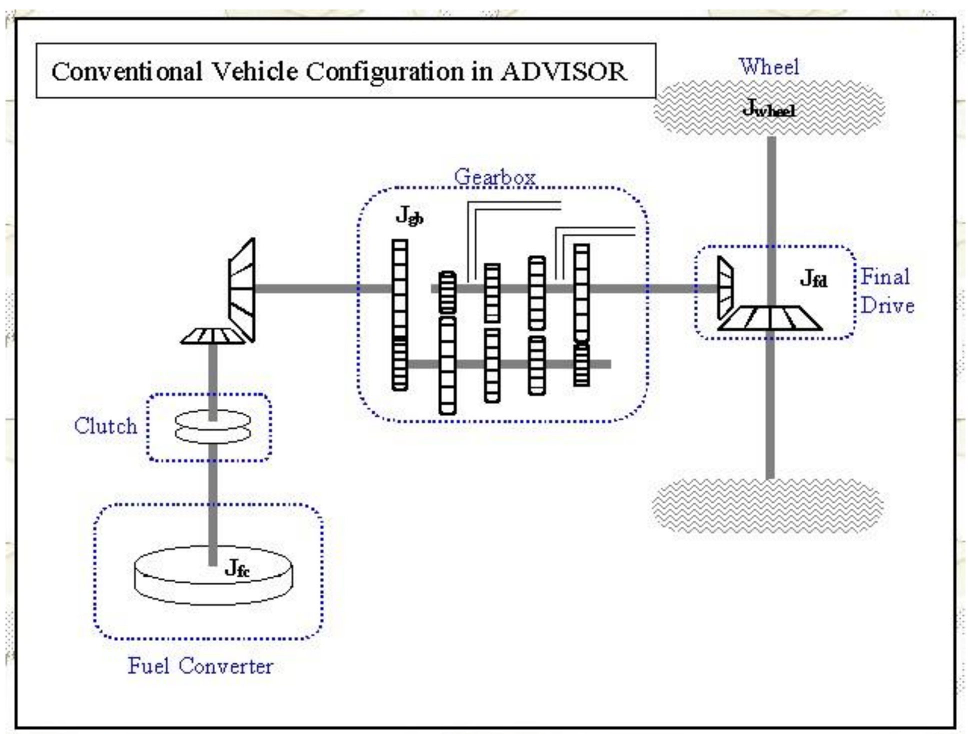
```
veh_FA=8.0942 (m²);
veh_cg_height=0.25*122/39.37 (m);
veh_front_wt_frac=0.35;
veh_wheelbase=6.1976 (m)
veh_glider_mass = 14633 (kg)
veh_cargo_mass=180/2.2046*30 (kg);
```

The modification of these parameters was done through information obtained concerning the specifications of each bus. Other files that had to be modified included the fuel converter file and the transmission file.

Models Developed

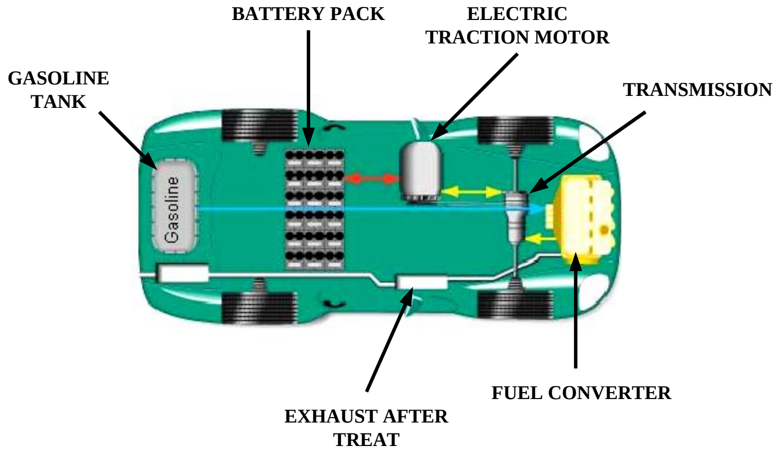
Conventional Bus:
The conventional bus is driven by internal combustion engine which is typical passenger car. It has no additional propelling source but, diesel engine (fuel converter) only. Following figures show overall vehicle configuration.

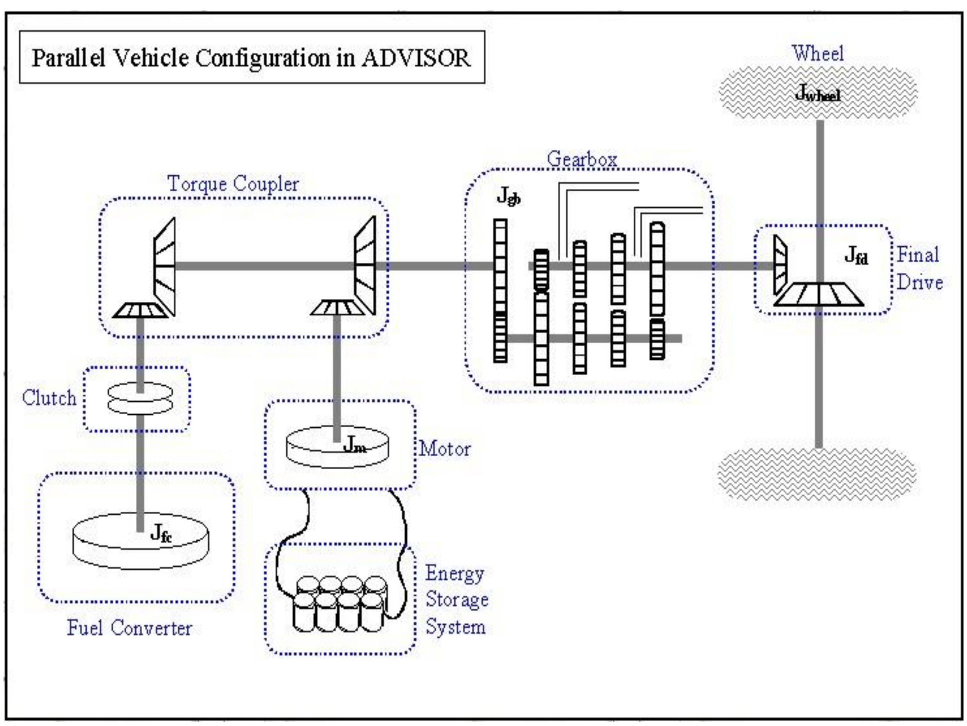




A bus is a heavy duty vehicle so a diesel engine is employed instead of a gasoline engine for more powerful performance.
Hybrid Electric Bus:

For hybrid electric school bus, three design configurations are simulated which are retrofit, parallel new design and ISA. All of them are parallel which are most common at present, connect both the electrical and internal combustion systems to the mechanical transmission. They can be subcategorized depending upon how balanced the different portions are at providing motive power. The different parts between parallel HEV and conventional vehicle are energy storage (battery), motor, torque coupling and powertrain control. The following figures show graphically for better understanding..





For retrofit HEV, which was modeled on both buses, small electrical motor/generator and enough capacity of battery are added on the conventional vehicle. Now, alternator and 12V battery pack do not need more, but they are neglected in the simulation. On fuel converter component max power is set same as conventional. 36 modules of Lead acid battery (ESS_PB_85) which produce 430V, are used. 75kW AC motor with 0.9 peak efficiency is applied. Total output max power is 228kW. TC_DUMMY is used for toque coupling. WH_HEAVY, ACC_HYBRID are used for Wheel/Axle and Accessory components, repectively. Powertrain control component is modified for best performance of fuel converter and electrical motor.

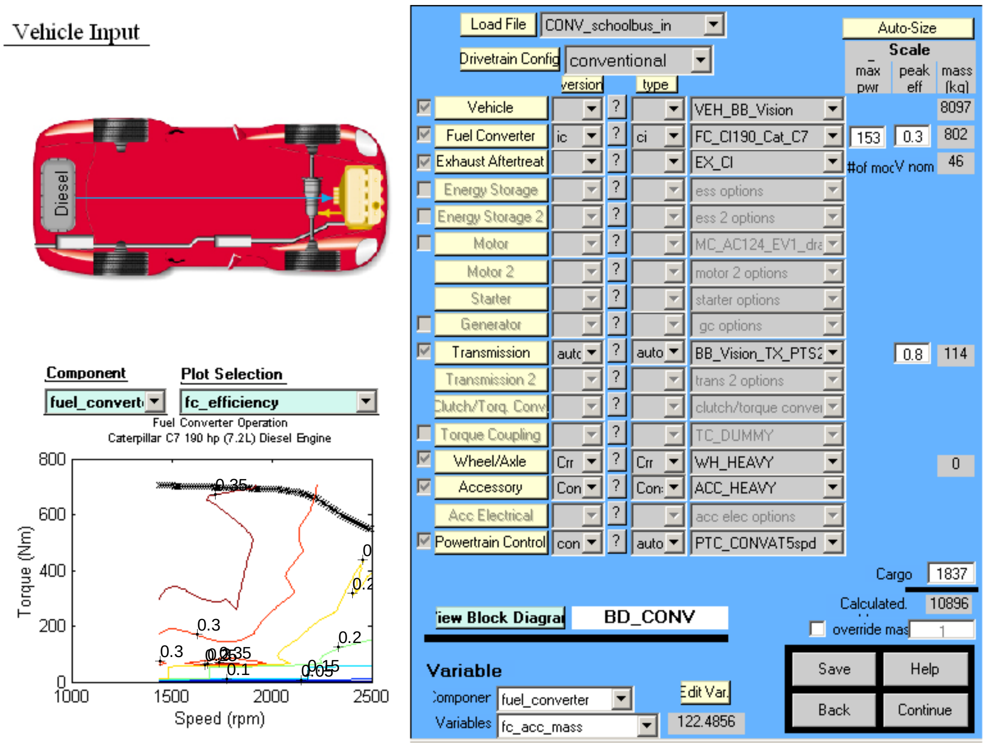
For new design, which was modeled only on the school bus, high output power is not needed. The conventional school bus's engine produces 153kW max power so that given engine size needs to be reduced. By reducing fuel converter's number, 153kW to 90kW, torque versus speed graph is automatically downsized. Motor is also downsized 75kW to 70kW. 160kW of max power propels new design parallel school bus. 42 modules of PB85 model battery (501V) are used for better performance as HEV. The other components, Torque Coupling, Wheel/Axle, Accessory, and Powertrain Control, are same as retrofit HEV. This configuration is expected better fuel economy than retrofit.

The ISA design is based on Honda Insight HEV configuration, so that some components use given Insight's components. This was modeled only on the school bus as well. A 100kW max downsized conventional engine is used. 35 modules of PB91_ucd lead acid battery (425V) are used. 83kW electric motor is applied for the ISA configuration. Torque Coupling and Powertrain Control use given Insight components. The other components are same as other configuration.

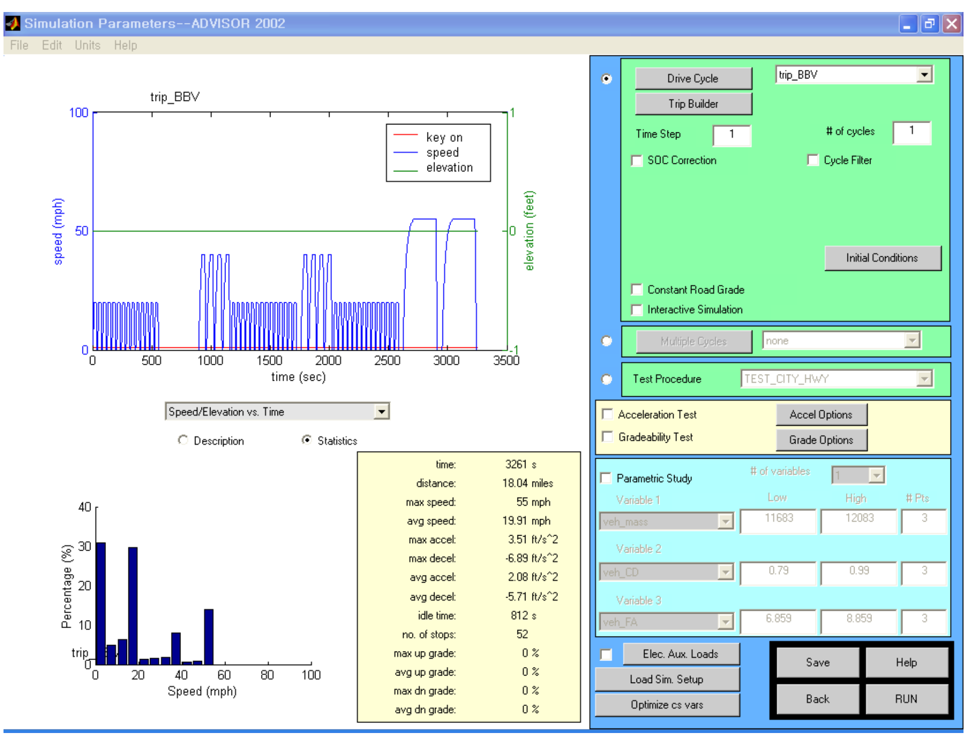
	Conventional	Retrofit	New Design	ISA
Max Fuel Converter pwr	153kW	153kW	90kW	100kW
Feul Conveter	Cat. C7 190hp	Cat. C7 190hp	Cat. C7	Cat. C7
Feul Conveter Efficiency	0.39	0.39	0.39	0.39
Exhaust Aftertreat	EX_CI	EX_CI	EX_CI	EX_CI
Energy Strorage Model	-	PB85	PB85	PB91_ucd
Number of Modules(PB)	-	36	42	35
Output Voltage	-	430V	501V	425V
Energy Strorage Mass	-	896kg	1046kg	931kg
Motor Model	-	AC75	AC75	AC83
Motor max pwr	-	75kW	70kW	83kW
Motor Efficiency	-	0.9	0.9	0.9
Transmission	PTS 2500	PTS 2500	PTS 2500	PTS 2500
Transmission Efficiency	0.85	0.85	0.85	0.85
Torque Coupling	-	TC_DUMMY	TC_DUMMY	TC_INSIGHT
Cargo Mass	1837kg	1837kg	1837kg	1837kg
Overall Mass	10896kg	11883kg	11716kg	11675kg

ADVISOR Simulations

The first screen that appears on ADVISOR is the vehicle input screen. Here is where all the specifications can be modified to cater to the bus of interest.



After setting all components for simulation on the Vehicle Input window, “Continue” button allow to go next step for ADVISOR simulation. In the next step, various parameters can be chosen to get results.



This simulation parameter window shows speed versus time graph to easily understand the drive cycle. On the bottom left, it shows much information about drive cycle graphically and numerically. On the right, any proper drive cycle is chosen at drop option block. As clicking “Initial Condition” button, various initial parameters are changeable such as initial SOC. Finally, “RUN” button makes to see results.

The drive cycles used for the CTA bus and the school bus are shown below.

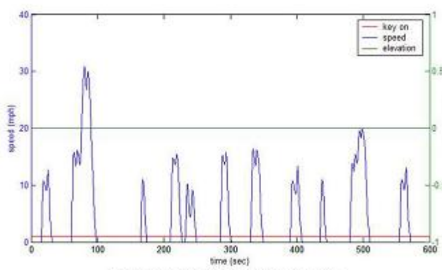


Fig.3 New York Bus Drive Cycle

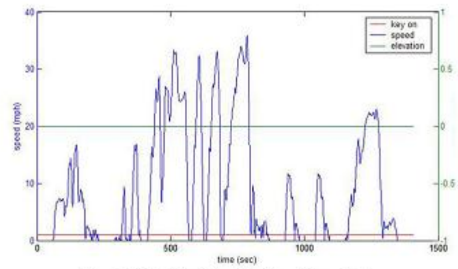
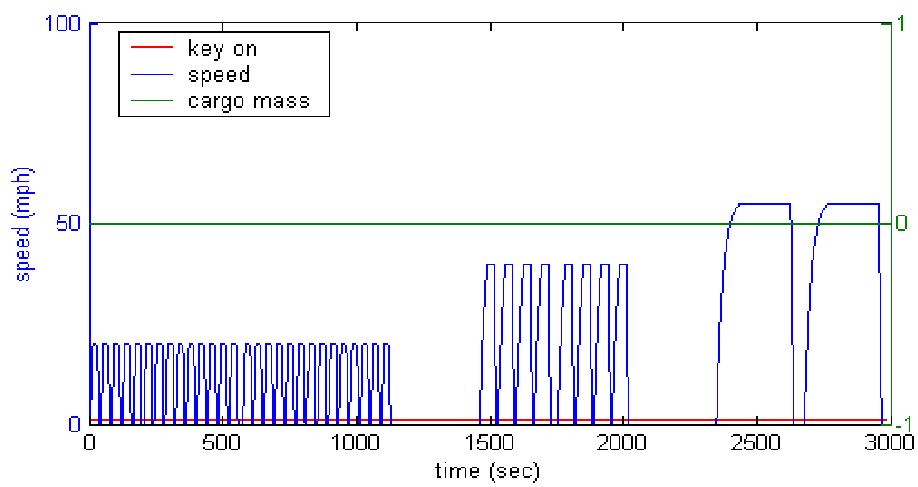
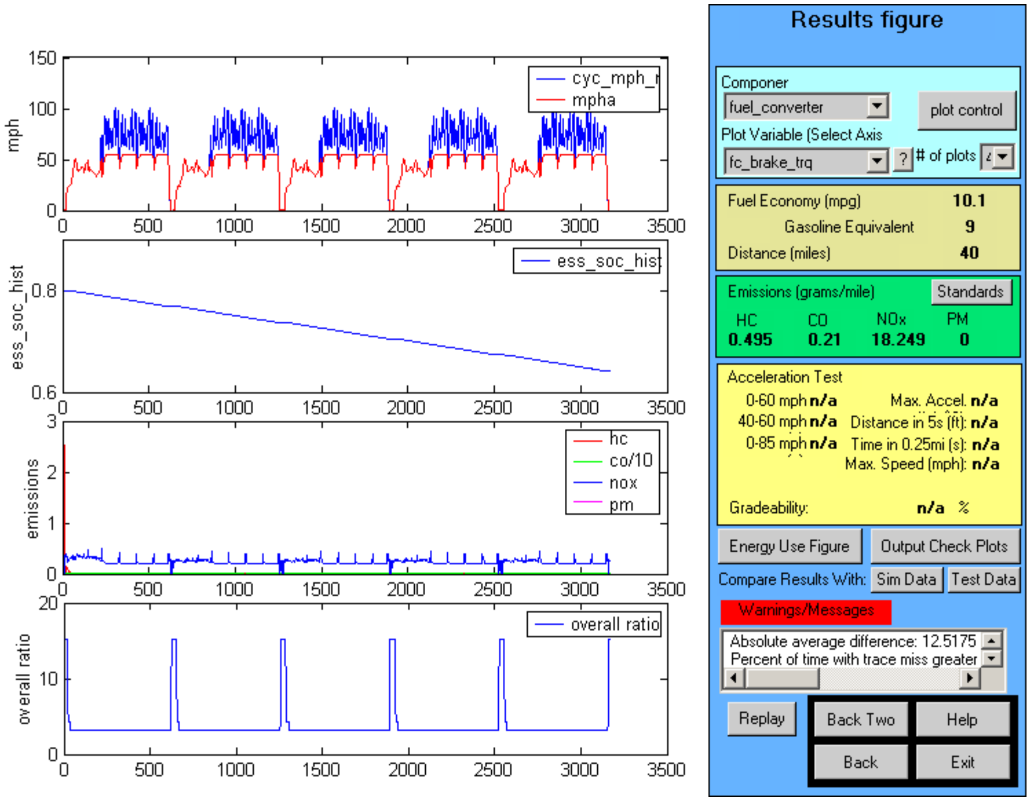


Fig. 4 West Virginia City Bus Drive Cycle



The next image is an example of the simulation result. The very first graph shows how the vehicle travels. The blue line means that the vehicle is supposed to travel, and the red line means that the vehicle actually travels. Second graph shows the state of battery charge, and third and fourth show emission and overall ratio, respectively. On the right, the result figure shows every detail result such as fuel economy that we pursue and others. Emission result is not reliable, because the emission map is not accurate.



From these simulations the following results were tabulated, concerning fuel economies.

CTA Bus

	Drive Cycle	Fuel Efficiency	Improvement
Conventional	New York Bus	2.2 mpg	
Hybrid Bus	New York Bus	3.2 mpg	33%
Conventional	W. Virginia	3.6 mpg	
Hybrid Bus	W. Virginia	4.8 mpg	45%

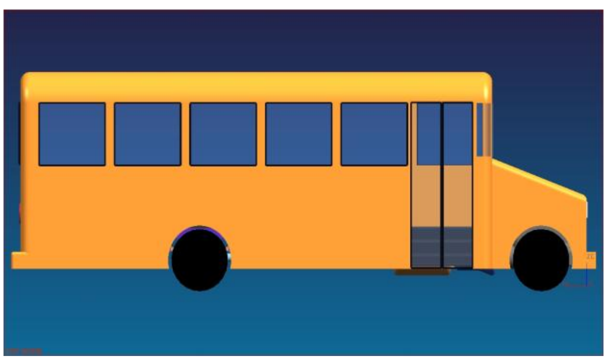
School Bus

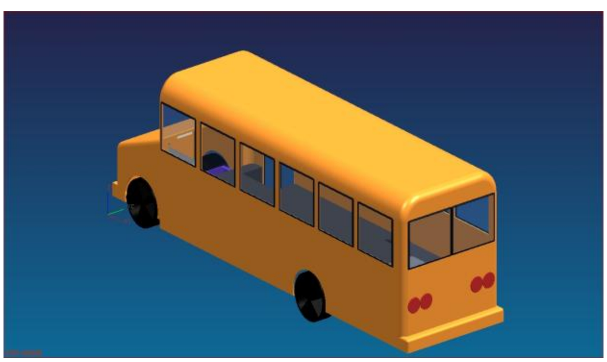
ARTERIAL Drive Cycle	Conv.	Retro.	Nu_dsn	ISA
Fuel Economy (mpg)	5	6.5	8	8.9
Fuel Efficiency Increase	0	30%	60%	78%
CBD14 Drive Cycle	Conv.	Retro.	Nu_dsn	ISA
Fuel Economy (mpg)	4.5	6.4	7.6	5.2
Fuel Efficiency Increase	0	42%	69%	16%
COMMUTER drive cycle	Conv.	Retro.	Nu_dsn	ISA
Fuel Economy (mpg)	6	7.4	8.1	10.1
Fuel Efficiency Increase	0	23%	35%	68%
Averaged Results	Conv.	Retro.	Nu_dsn	ISA
Fuel Economy (mpg)	5.2	6.8	7.9	8.1
Fuel Efficiency Increase	0	30%	52%	56%

3D Modeling:

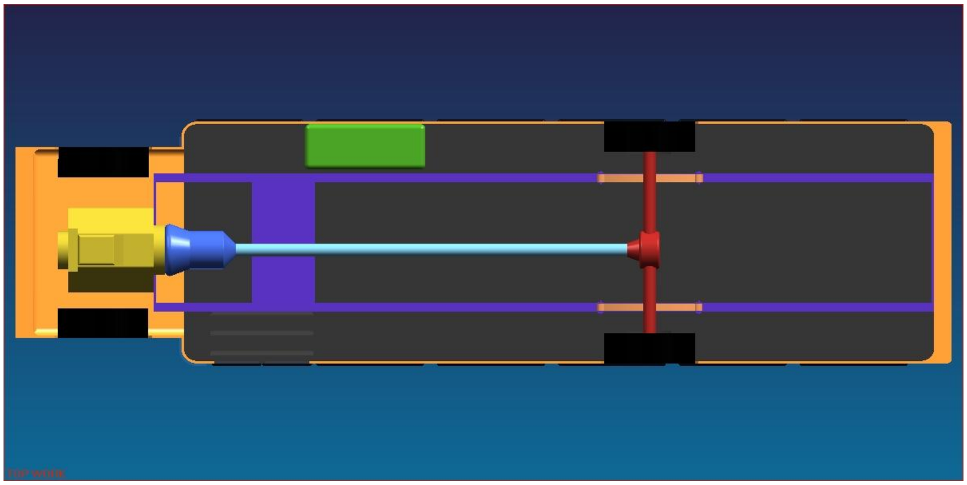
The goal of the 3-D model portion of the project was to provide viewers with a physical sense of the multiple components of the hybrid system. The 3-D model shows where parts of the system, such as the batteries, the torque coupler, the transmission and the engine will be placed in an actual bus. Several specifications were needed for this part of the project. The 3-D modeling was done with Unigraphics NX2. Results of the modeling team are shown below.

External Views

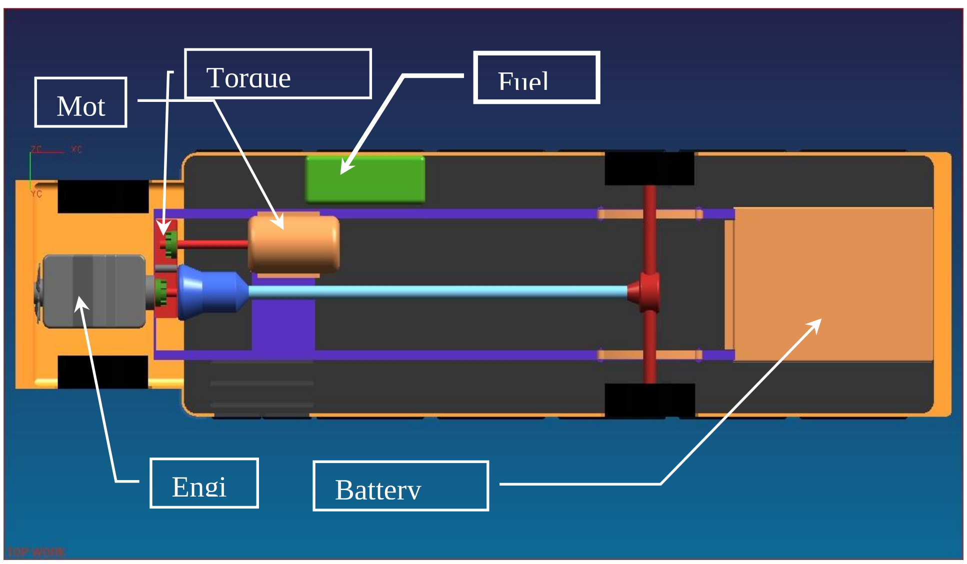




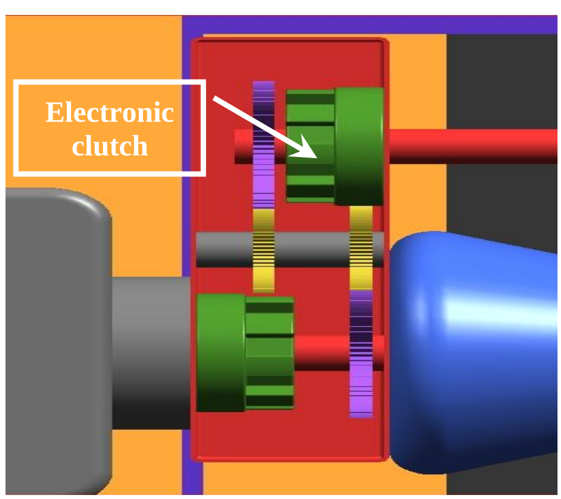
Conventional Configuration



Hybrid Configuration



Torque Coupler



Fuel Cost Analysis:

The average fuel price in the United States as of April 3, 2006 is $2.62 per gallon. This is an increase of about five cents from just the week before. In the Midwest, as of April 3, 2006, the price for diesel fuel is slightly lower, at approximately $2.58 per gallon.

According to a study done in 2002, there are approximately 450,000 school buses in the United States. A type C conventional bus lasts approximately 12-15 years. According to the Federal Highway Administration, an average school bus drives approximately 8,000 miles every year. Using the national price for April 3, 2006, the average fuel cost for a conventional bus in the year 2006 is shown in the table below.

Drive Cycle	Fuel Economy (mi/gal)	Fuel Cost
ARTRL	5.0	$4,192.00
CBD	4.5	$4,657.78
COMMUTER	6.0	$3,493.33

The next table shows the annual fuel cost for a conventional school bus in the Midwest in the year 2006, using the regional diesel price for April 3, 2006.

Drive Cycle	Fuel Economy (mi/gal)	Fuel Cost
ARTRL	5.0	$4,128.00
CBD	4.5	$4,586.67
COMMUTER	6.0	$3,440.00

For the different school bus hybrid models, and the different drive cycles used, different fuel economies were determined. First, consider the parallel hybrid electric vehicle (PHEV) retrofit model. The table below shows the annual fuel cost for a single bus in the year 2006 (using the April 3, 2006 regional price) in the Midwest.

Drive Cycle	Fuel Economy (mi/gal)	Fuel Cost	Savings
ARTRL	6.5	$3,175.38	$952.62
CBD	6.4	$3,225.00	$1,371.67
COMMUTER	7.4	$2,789.19	$650.81

Now consider the PHEV new design model, under the same parameters.

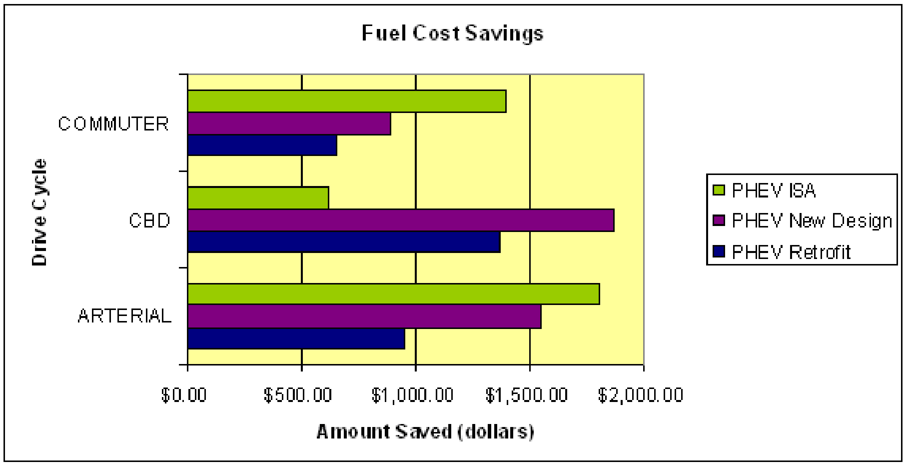
Drive Cycle	Fuel Economy (mi/gal)	Fuel Cost	Savings
ARTRL	8.0	$2,580.00	$1,548.00
CBD	7.6	$2,715.79	$1,870.88
COMMUTER	8.1	$2,548.15	$891.85

Finally consider the PHEV integrated starter alternator design (ISA), under identical parameters.

Drive Cycle	Fuel Economy (mi/gal)	Fuel Cost	Savings
ARTRL	8.9	$2,319.10	$1,808.90

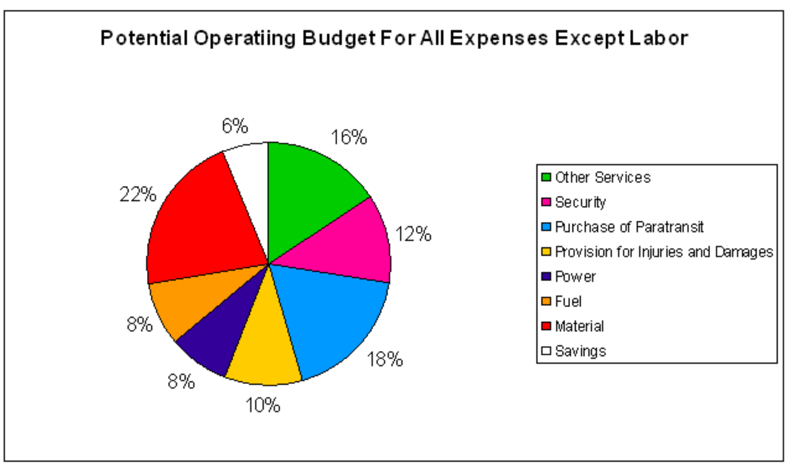
CBD	5.2	$3,969.23	$617.44
COMMUTER	10.1	$2,043.56	$1,396.44

The following chart shows the savings for one bus of each model in a graphical form (in comparison to the conventional model).



The operating budget of the Chicago Transit Authority states that the annual fuel cost for the year of 2005 was approximately $43,258,000.00. Since fuel prices have increased 12.4% since last year. According to this, the projected CTA budget for 2006 is approximately $48,621,992.00. The entire CTA bus fleet includes approximately 2,000 buses. Therefore, each bus consumes about $24,311.00 in fuel.

The average mileage for the conventional CTA bus was 3.1 miles per gallon. The retrofit model reached a fuel economy of 4.4 miles per gallon. This is a 41.94% increase in fuel economy and therefore a savings of 41.94% in the fuel budget. This saves the city $10,196.03 per bus per year. If the entire fleet is converted, this saves the city of Chicago $20,392,063.44. This amount is approximately 2.03% of the entire operating budget. Since approximately 70% of the operating budget of the CTA is invested in labor costs, this leaves only 30% for all the other operating costs of the system. These costs include materials, power, fuel, compensation for injuries, purchases, security, and other costs. Reducing the fuel costs potentially raises the budget for expenses other than labor by approximately 6.8%.



Obstacles

Several problems presented themselves throughout the duration of the semester. The main obstacles were encountered by the ADVISOR and the modeling teams. The ADVISOR teams were responsible for finding all the specifications needed for the conventional modeling of the CTA bus and the school bus. After all these information was compiled they found out that some of the M-files of ADVISOR needed to be modified in order to get accurate results and for the models to be as close to the actual buses as possible. These required a lot of work. The modeling teams in the beginning were trying to find 3-D models of the buses from the buses manufacturers. But since this was not possible, they decided to draw their own models based on the specifications of the buses. For this some of the team members learned how to use Unigraphics NX2.

Conclusions

Several important conclusions were reached in the completion of this IPRO. It was foud that the retrofit approach enables conversion of existing conventional buses to more efficient hybrid vehicles. Also, a new design allows us to downsize the engine making the overall system more efficient. Through ADVISOR simulations, there was significant improvement in fuel economy for the CTA bus and school bus. The 3D modeling helped in visualizing the mechanical system but was not precise enough to use for design. The significance of this project was also reaffirmed because as fuel rates continue to increase, the financial effectiveness of hybrids to grow.

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Acknowledgements

The IPRO 342 team would like to give a special thank you to the following:

Sheldon Williamson
Dr. Ali Emadi
Robert Anderson