A PARALLEL HYBRID-ELECTRIC SPORT UTILITY VEHICLE: FUTURETRUCK 2002

FINAL REPORT

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EXECUTIVE SUMMARY

This final report details the development of the University of Idaho hybrid-electric sport utility vehicle and gives an overview of requirements, summarizes design features and illustrates research results.

The objectives of the University of Idaho FutureTruck project were to:

- Convert a 2002 Ford Explorer Sport Utility Vehicle from the stock condition into a parallel hybrid-electric vehicle for participation in the June 2002 FutureTruck competition.
- Complete the development of software tools that are useful in designing, modeling, and in collecting real-time data from the vehicle. These tools will not only have benefit for the proposed FutureTruck project, but will also be made available on a national level to aid in the development of hybrid-electric vehicles.
- Organize and guide the student FutureTruck team similar to an actual company responsible for rapid development of clean vehicle technologies. The team structure will be multidisciplinary with representation from all aspects of new product development including design, engineering, manufacturing, marketing, economics, and public relations. Leadership techniques, management processes, and design principles will be emphasized.
- Educate industry and the public on the benefits of clean vehicle technologies and the outcomes of the project. The selected audience will include students, consumers, industry leaders, and policy makers.

The University of Idaho Advanced Vehicle Concepts Team (AVCT) successfully completed the development of a parallel, hybrid-electric sport utility vehicle. At the 2002 FutureTruck competition, the vehicle placed 7th overall among 15 teams, was one of only three vehicles to attain ultra-low emissions vehicle (ULEV) standards, placed 2nd in the acceleration event,

and first in the trailer tow event. The team also won an award for the most innovative use of aluminum.

This success was the culmination of a yearlong effort by a multidisciplinary student team that followed business principles to optimize engineering, education, and evaluation outcomes. With a donation of $25,000 from National Instruments, the team developed a single system for hybrid control, diagnostics, data acquisition, telematics and entertainment. Additional donations helped fund telemetry equipment, heat reflective paint, low rolling resistant tires, original equipment manufacturer parts, team travel, and outreach activities.

The team organized 10 public events and demonstrated clean vehicle technologies to students from junior high to college level. The demonstrations, besides creating public interest, also helped validate predictions from computer modeling. An analysis tool called SmartDesigned Vehicles (SDV), developed initially by David Alexander [1], had predicted the vehicle's performance within 8 percent of dynamometer test results. Testing at the California Air Resources Board test facility during the FutureTruck 2002 competition verified the accuracy of SDV in predicting that the modified vehicle could achieve a 25 percent improvement in fuel economy while achieving ULEV standards and maintaining stock performance levels.

DESCRIPTION OF PROBLEM

The Department of Energy FutureTruck competition established the basic requirements for vehicle development. Fifteen universities participated in FutureTruck 2002, with the goal of decreasing the environmental impact and energy-consumption associated with Sport Utility Vehicles (SUV). Teams modified donated 2002 Ford Explorers the following objectives:

- To improve the fuel economy by 25 percent
- To reduce Greenhouse Gas Emissions
- To meet California ULEV limits while maintaining the stock performance and comfort of the Explorer [2].

In addition to the objectives set forth by FutureTruck, AVCT goals required the vehicle make use of current technology, be highly functional in the regional mountainous environment, and be readily adaptable to high volume manufacturing.

Hybrid vehicle design requires accurate analysis tools to determine what is required to meet specified performance criteria. Most vehicle-modeling software programs are restrictive in the way that they solve the vehicle governing equations. They require that a vehicle be fully specified and a drive cycle selected before performance and energy-use predictions can be made. While this model is popular and useful for simulating pre-configured vehicles, it is cumbersome when designing new and alternative vehicles. The algorithms developed in this research enable the user to freely select vehicle performance or component parameters in any permissible combination to perform innovative vehicle design analysis.

Training and education are important for advanced vehicle technologies to be produced by the manufacturers and accepted by the customers. Students, tomorrow’s workforce, will determine how successfully the nation transitions to hybrid-electric vehicles. Working on a multidisciplinary team allowed students to explore theoretical concepts, develop innovative ideas, and conceive new definitions for future vehicles.

APPROACH AND METHODOLOGY

Our approach was to first learn how a business would attack a rapid development project for a new vehicle and then employ those business practices that would are most critical for project success. The principle of using all available resources led to an early decision to build a multidisciplinary team, which enabled simultaneous efforts to occur in the areas of engineering design, software engineering, and education outreach.

Vehicle Development

A myriad of approaches can be taken to make improvements in emissions and fuel economy. The stock power train may be modified or radically changed to incorporate new technologies such as hybrid configurations or all electric vehicles. Each modification has an associated performance and economical cost that must be considered in order to produce a marketable vehicle. The Electric Power Research Institute formed the HEV Working Group (HEVWG) to evaluate HEV configurations. HEVWG has conducted research on the market potential, cost, and environmental performance of several parallel hybrid configurations [3, 4]. Their findings indicate that the market penetration for a parallel hybrid is large despite the increased cost in converting a conventional vehicle to a parallel hybrid system. Considering these findings and the results from modeling conducted by AVCT, a mild parallel hybrid configuration was chosen for the University of Idaho FutureTruck, nicknamed “Summit.”

In order to meet the fuel economy improvement objectives, a hybrid vehicle configuration is necessary [5]. In a series or parallel hybrid configuration, two types of energy converters are used. Through the control of the two converters, optimal fuel usage may be realized. Although there is some debate over which configuration will lead to the best improvement in fuel economy [6, 7, 8].

The development cycle of the Idaho FutureTruck was a three-phase process: configuration modeling, system design, and testing. Modeling and simulation of various power train configurations for an Explorer class vehicle began in the summer of 2001. Configurations were evaluated to identify the best configurations that would meet the FutureTruck and AVCT goals. More simulation and modeling was conducted to determine the best components and control strategy or the system. The design phase relied upon Failure Modes Effects Analysis (FMEA), kinematic design principles, and experimentation to identify reliability and functionality issues. To verify the system, extensive testing was conducted during and after the design phase. Appropriate modifications were made based on test results.

A mild parallel hybrid scheme was determined to best meet the goals of both FutureTruck and AVCT. Summit used a series electric motor as a starter and low RPM torque-booster directly coupled to the IC engine. The engine was a modified Ford 4.0 Liter with increased compression ratio, thermal-coated piston crowns and cylinder heads, extrusion honed exhaust manifolds, blueprinted dimensions and tolerances, and improved flow heads. To capture vehicle deceleration energy, a generator set was coupled to the drive train to convert the mechanical braking energy into electrical energy stored in the lead acid batteries. A solar-electric system was added as an additional energy source. A passive cooling system replaced the conventional water pump and reduced cooling loads associated with the engine and passenger compartment. A unique thermal conditioning system improved comfort and reduced air conditioning compressor loads on the engine.

Modified 4.0 Liter Engine

Significant IC engine modifications were performed in an effort to improve efficiency. The Ford 4.0 Liter piston tops and cylinder heads were coated with SwainTech’s TBC (Thermal Barrier Coating) [9]. This coating worked to thermally insulate the combustion chamber for more complete combustion of the fuel.

Passive Cooling

The AVCT developed a passive cooling system, with the radiator mounted on the hood, to reduce under-hood temperature gain from the radiator. The system operated on the thermal siphoning principle, which eliminated the need for a continuously running coolant pump.

(Fig. 1.) By locating the heat-generating engine below the head level of the radiator, the less dense hot coolant flows upward displacing the denser, cooler fluid in the radiator without the need of a pump. Prior to design and installation of the passive cooling system, AVCT members performed tests in a Honda Civic and a Ford Econoline van to determine cooling performance and sizing constraints. Results from this test indicated that thermal siphoning in passive cooling produced adequate coolant flow to maintain the typical heat extraction of a stock vehicle running on conventional fuels. In addition, using the coolant pump, 8 to 10 percent of the available engine power could be saved [10].

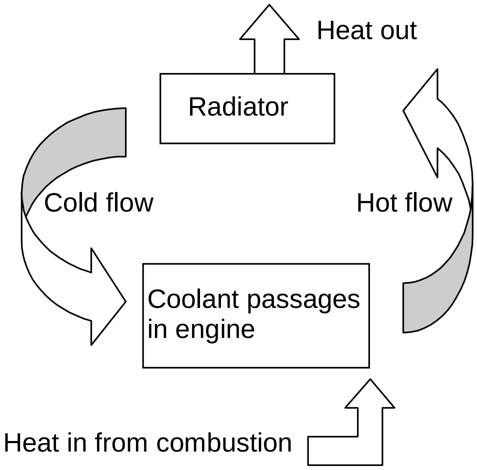


Figure 1 The thermal siphoning process.

In order to meet the stock heat removal capacity for the passive cooling system, a radiator 107 by 18 cm was specified. Mathematical modeling showed that a grid of tubes on the roof would not provide enough cooling capacity without a substantial number of fins. Therefore a radiator was needed. To maximize heat transfer and reduce weight, a custom heat exchanger was constructed of aluminum. The supply and return tubes provided approximately 10 percent of the total cooling capacity. The air conditioning condenser was also mounted on the roof in front of the engine’s heat exchanger.

An auxiliary electric pump initiated flow after engine start and augmented the thermal siphon during heavy engine loads when heat generation is greatest. When the engine was cold, the pump removed air pockets in the system, which would restrict thermal siphoning. A centrifugal pump manufactured by EMP was selected due to its efficiency, weight, and 36 volt operating voltage.

Figure 2 illustrates how moving heat sources to the vehicle's roof affected heat transfer from the engine and passenger compartment. Heat transfer is proportional to the temperature difference across the thermal boundary. In this illustration, assuming nominal temperatures for a typical summer day and a typical automobile, relocating the radiator and condenser would decrease the cooling load on the engine and passenger compartment by 52 percent and 30 percent respectively.

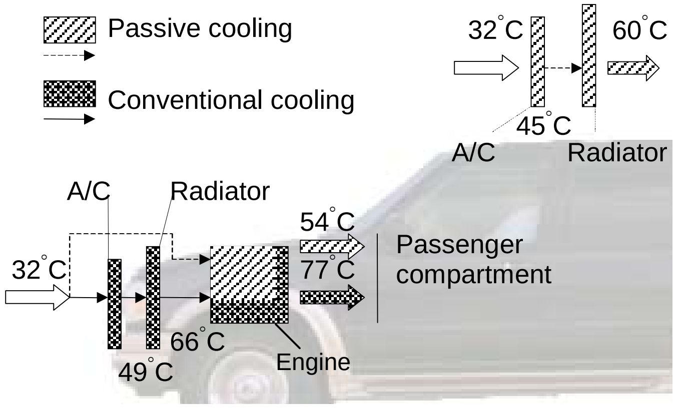


Figure 2 Typical conventional and passive cooling temperatures taken are at idle. Passenger compartment temperatures are pre-firewall.

Fuel System Modifications

To improve engine performance and reduce emissions, the fuel system was converted to E85, which is 85 percent ethanol and 15 percent unleaded gasoline. The Ford Explorer is available as a flexible fuel vehicle that uses a revised power control module (PCM) and a special sensor to measure the ethanol content. This is an electronic approach that allows operation on fuels with varying ethanol content. Lacking availability of FFV parts and PCM reprogramming capabilities, the UI team chose a mechanical approach for the conversion. Theoretical stoichiometric ratio for E85 is about 10:1 while the stock PCM attempts to maintain 14.7:1. By using over-sized fuel injectors, the PCM was fooled and the proper amount of ethanol was injected. The AVCT used an equation provided by Ford to size the injectors based on brake-specific fuel consumption and maximum horsepower. This simple approach optimized the use of standard components. However, it did require changing injectors for different fuel types. To ensure compatibility with ethanol, the AVCT installed ethanol compatible fuel lines, tank, fittings, pump, filter, pressure regulator, and injectors. Compatible materials include polyethylene, nylon, and stainless steel. For cold starts, the Summit's control system would need a resistance heater on the stainless steel fuel line.

Emissions Control

Baseline dynamometer testing showed that the stock Explorer satisfied the California ULEV emissions standards in all categories except oxides of nitrogen (NOx). To reduce NOx, the fuel system was converted to E85 as previously described. To reduce CO and HC emissions, the exhaust manifold passages were extrude honed to reduce the surface area that the exhaust gases contact, which reduced heat loss in the manifolds. This allowed the catalytic converters to heat more quickly and reduce CO and HC emissions during cold start.

Electrical System

A dual-voltage system enhanced manufacturability and powered Summit's electrical demands. Stock vehicle accessories were powered by a traditional 14-volt system; a 42-volt system powered high-amperage HEV loads. The dual-voltage design improved manufacturability by being compatible with present day components while offering enhanced component sizing and safety for high-energy components. Figure 3 illustrates the steady growth in vehicle electrical loads and the limits of higher voltage systems [11].

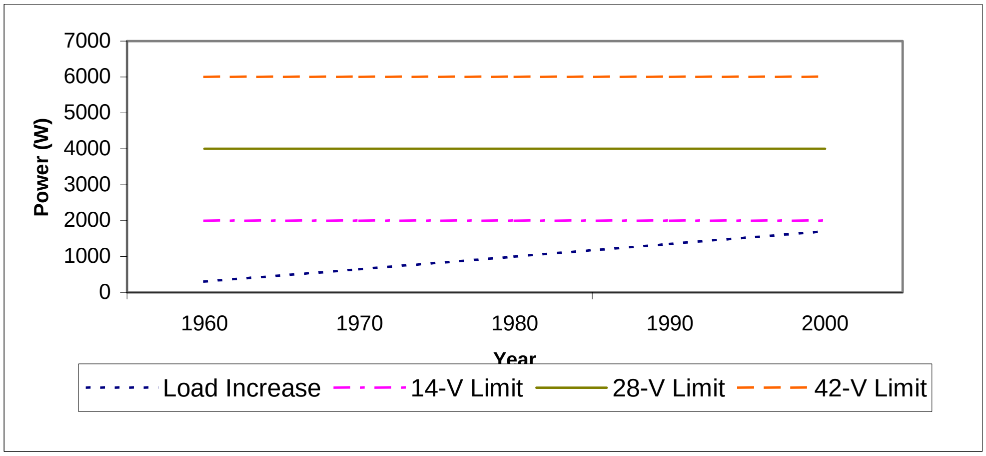


Figure 3 Power generating capabilities of various voltages.

The 42-volt battery pack, mounted beneath the third seat, was composed of 12 Odyssey PC680 sealed lead acid batteries creating 96 total amp-hours. The battery for the 14-volt system was mounted under in the engine compartment. Figure 4 shows the dual-voltage system. The 42-volt battery pack, with batteries arranged in series and parallel, provided the capacity specified by modeling and facilitated charge balancing during regenerative braking.

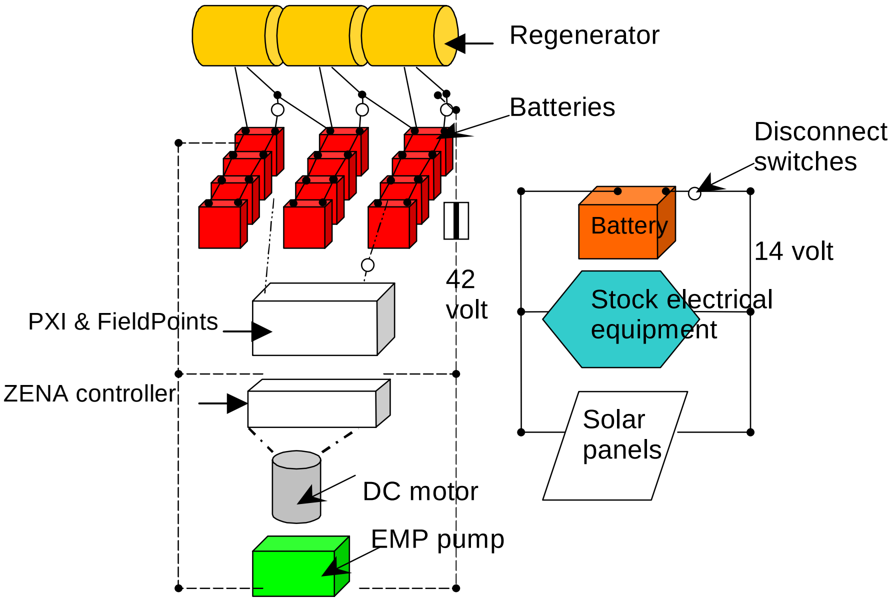


Figure 4 Electrical schematic.

The electrical system, classified as low voltage because it is less than 50 volts, minimized complexity and enhanced safety while still meeting the power demands of our mild HEV design. Maintaining this vehicle or responding to an accident involving this vehicle would not require personnel specially trained in high voltage procedures.

Power Assist

The power assist mode functioned during vehicle acceleration. Modeling showed that, to optimize the torque available from the electric motor, power assist would function best with the transmission in second gear and up to a vehicle speed of 29 kph. Safety checks before starting the motor included temperature of the electric motor and battery state of charge. While accelerating, the A/C compressor and alternator charging was disabled to reduce the applied load to the engine. The voltage applied to the electric motor was a function of throttle position, maximum voltage that could be applied to the motor based on state of charge of the battery pack, and vehicle speed.

The electric motor was coupled to the harmonic balancer of the engine. The aluminum motor mount, bolted to the engine, was designed to buckle in the event of a front-end collision. Figure 5 shows the percent motor output as a function of throttle position and vehicle speed.

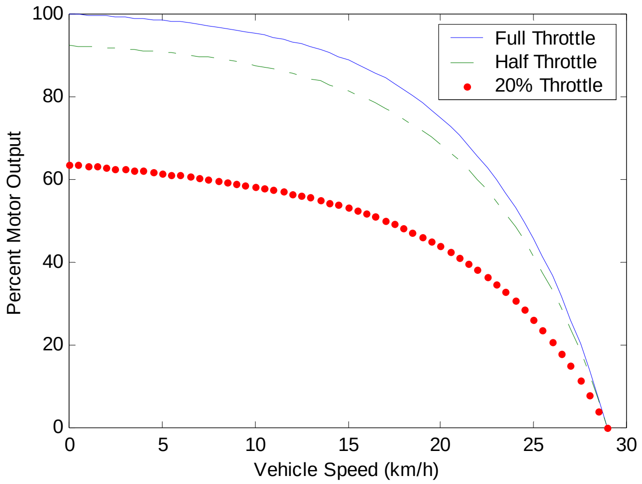


Figure 5 Electric motor output vs. vehicle speed.

Regnerator

The generators used for regenerative braking were connected by a ribbed belt to the pinion of the rear differential. Mounting the regenerator between the frame rails maintained the stock ground clearance and provided protection from road debris.

Regenerative braking (regen) was activated during braking events. A signal from the brake light switch, vehicle speed, and battery pack state of charge was checked before activating the regenerator. The percent regen was a function of brake fluid pressure, vehicle speed and battery state of charge. Regen gradually faded at low speeds to simulate normal braking.

Thermal Conditioning

A major accessory load in the system is air conditioning. A University of Idaho senior design team developed a cooling system that boasted the same cooling capacity as the stock system while using less energy. The thermal conditioning system for the passenger compartment included a downsized air conditioner along with cooled seats, automatic air ventilation, low emissivity/high reflectivity coatings around the passenger compartment, and light-blocking films on the side windows. Compared to the stock vehicle, the cooling load for the modified vehicle’s passenger compartment decreased 40 percent.

Typical vehicle air conditioning systems require 4,000 watts of mechanical power; the human body dissipates only approximately 100 watts. Cooling the seats is an energy-efficient way to keep the passenger comfortable. Conventional air-conditioning systems cool the air around the person by convection, a relatively slow heat transfer process. Chilled seats remove heat by conduction, a faster and more efficient process.

Solar Panels

Two USF-32 flexible solar panels on the roof of the vehicle helped maintain battery state-of-charge. During winter testing in North Idaho, each panel produced 10 watts. Output during summer months in Arizona was expected to reach 64 watts peak. To maximize solar exposure, the panels were mounted on the vehicle’s roof.

System Control

The control system in the vehicle managed data telemetry, electric motor operation, regenerator operation and accessories. National Instruments FieldPoint 2010 modules were used as real-time controllers. These modules were mounted in the engine compartment and in the rear of the vehicle (Fig. 6). The FieldPoint in the engine compartment was used to control the speed of the electric motor while the module in the rear of the vehicle was used as the battery pack monitor. The two FieldPoint modules shared data and responsibility for system control.

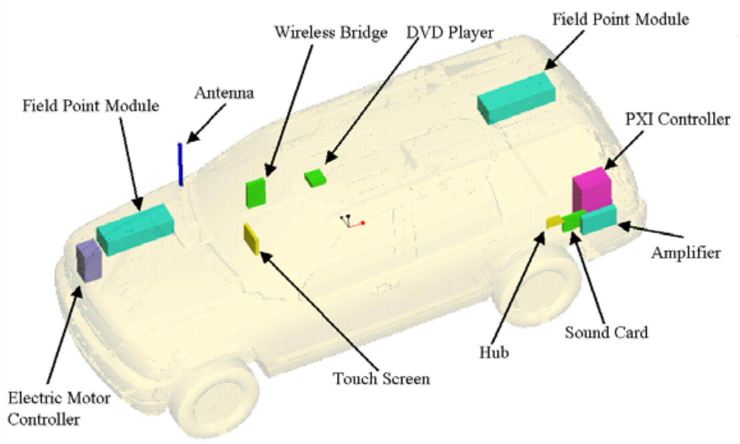


Figure 6 Control system locations.

LabVIEW, a program developed by National Instruments, provided control of the FieldPoint modules. Once the programs were loaded onto the FieldPoint, vehicle subsystems functioned autonomously thereby assuring that critical controls would not be interrupted. Figure 7 shows the paths of communication in the Summit control system.

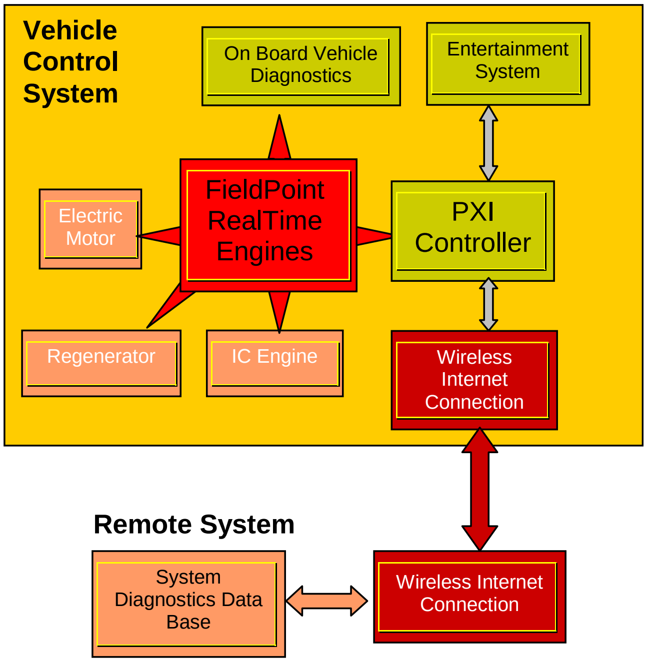


Figure 7 Control system communication paths.

Figure 8 View of the touch screen, which replaced the radio in Summit.

An in-dash flat panel touch screen (Fig. 8) was chosen as the direct user interface to the system. A custom Graphical User Interface (GUI) provided access to the control system. Through this interface, the user can be informed of subsystem status and make adjustments.

The touch screen is a versatile substitute for the many controls that are found on a typical dashboard, such as stereo buttons and climate control.

The data acquisition of Summit was designed to be flexible, expandable, and reprogrammable. The control system monitored battery voltage, throttle position, vehicle speed, and transmission position. The system is also used to perform adjustments as necessary for efficient operation of the hybrid vehicle.

In order to integrate real time control, Internet access, Microsoft Windows and the entertainment system simultaneously, a databus architecture was chosen. This architecture saved weight and the distributed components, such as the FieldPoint modules, reduced packaging. Ethernet and SCSI communication paths allowed compatibility with a variety of inputs, outputs and other processors. The PXI controller provides system programming; the FieldPoint modules provided autonomous control for critical functions. The autonomous control of the FieldPoints maintained hybrid control, even if the PXI controller experienced power interruptions or operating system problems. A wireless keyboard was available for reprogramming.

Entertainment

Driver and passenger features included vehicle diagnostics, Microsoft Windows and Windows supported software, Internet access, RF wireless keyboard, DVD player and XM satellite radio. Sound Blaster's Extigy card, with its onboard Dolby Digital hardware decoder, provided cinema-like surround sound.

DFMEA—Design for Failure Modes Effect

Analysis was performed on all major subsystems in the vehicle. The results of the initial analysis indicated potential failure modes in the passive cooling system were of most concern. In the event of a coolant line rupture, occupants and individuals within reach of the vehicle are at risk of being sprayed with hot coolant. To reduce the severity of this mode, guards were installed over the coolant lines to redirect coolant spray. Also, in the event of a collision or rollover, the coolant pump is be automatically shut down by the inertial sensor.

Weight

With the addition of extra components, the vehicle weight increased by 102 kg as shown in Table 1.

Table 1. Weight Reductions

Gains (kg)		**Reductions/Savings (kg)**	
Motor and mount	27.2	Lexan windows	-11.3
Regenerator	36.3	Rear A/C removal	-9.1
Energy storage	127.0	Aluminum rim	-4.5
Cooled seats	4.5	Running boards removal	-31.8
Control system	2.3	Chassis cross member removal	-4.5
Passive cooling	9.1	Fuel tank	-34.0
		Insulation removal	-9.1
Totals:	206.4		-104.3

Manufacturability

A cost analysis was performed on Summit to assess the

- Life Cycle Costs
- initial costs or savings to the consumer
- change in maintenance costs to the consumer
- savings in fuel costs that the consumer could expect over the useful life of the vehicle

To conduct this assessment, assumptions about vehicle life, total mileage, maintenance costs, and fuel prices (Table 2) were made.

Table 3 lists the change in cost associated with each major modification to the Explorer. The total change in initial cost to the consumer was $4,984, with a total change in maintenance costs over the vehicle life of $440.

Table 2. Assumptions for life cycle cost analysis.

Vehicle life	13 years
Mileage life	233,355 km (145,000 mi)
Mileage, first 9 years	144,841 km
Maintenance, first 4 years	30% of total

Table 3. Costs of Vehicle Modifications

	∆VC **Change in Vehicle Cost**	**∆MC0-4** **Change in Maintenance Cost Years 0-4**	**∆MC5-13** **Change in Maintenance Cost Years 5-13**
E85 Modified V6 Engine	$0	$0	$0
DC Motor & Controller	$1,300	$0	$0
Batteries	$695	($85)	$525
Regenerator	$2,670	$0	$0
Solar Cells	$420	$0	$0
Passive Engine Cooling	$1,650	$0	$0
Lexan Windows	($2,700)	$0	$0
Thermal Conditioning	$1,100	$0	$0
Totals	$4,984	($85)	$525

Using a gasoline price range of $0.26 to $1.06 US dollars per liter ($1-$4/gal), the net present value of the modifications costs were calculated (Table 4). Breakeven would occur when gasoline prices exceed $0.79 per liter ($3/gal).

Table 4 Net Present Value of the Vehicle Modification Costs

	$0.26/L	$0.53/L	$0.79/L	$1.06/L
NPV	$1,181	$2,646	$4,117	$5,588

Software Development

Simulation software is used in the automotive industry and government to evaluate vehicle energy-use, emissions, and performance. *Fundamentals of Vehicle Dynamics* (Gillespie 1992) outlines the standard approach for simulating vehicle performance. This approach models the power requirements to maintain a desired velocity. The power flow through each component is modeled in response to a velocity request at the wheels. Using Newton's second law, $F=m*a$, the force at the wheels to meet the requested velocity is calculated. This force is then transferred through each component up to the engine, taking into account appropriate component inefficiencies and operational constraints. Other researchers take this similar approach [12, 13, 5, 14, 15, 16, 17].

Vehicle simulators that model operational requirements based upon a velocity at the wheels are defined as backward facing models. The term backward facing defines the direction that the power flows through the model in order to meet the performance demand at the wheels. Backward facing models are fast, reliable, and require a straightforward solution strategy.

Forward facing vehicle simulators take a requested speed and control the throttle to regulate the power to the wheels. Forward facing models require smaller time steps, more component feedback, and advanced simulation control for accurate vehicle modeling. Figure 9 illustrates the difference between backward and forward facing simulations.

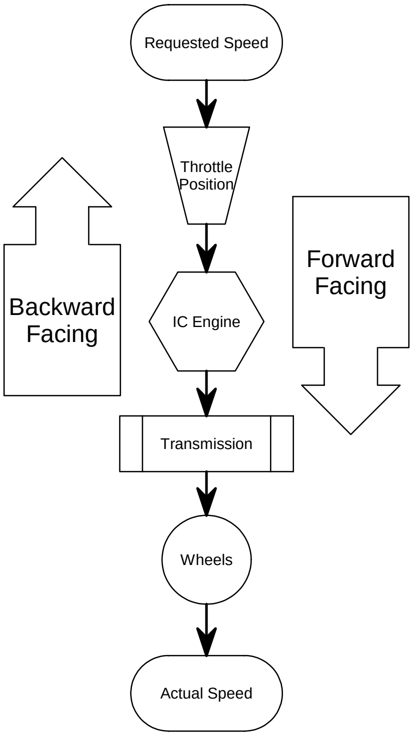


Figure 9. Graphical depiction of forward and backward facing vehicle simulation strategies.

SDV was validated with vehicle test data collected from a 2002 Ford Explorer. The Explorer was mounted on a SuperFlow SF-602 water-brake chassis dynamometer. The front drive shaft was removed from the Explorer and the transfer case was locked in high, all-time, four-wheel drive. An engine speed sensor was mounted to the transmission bell housing to monitor engine speed. On-board diagnostics were monitored using an EASE diagnostics OBDII scan tool. OBDII data were downloaded to a PC.

Two test procedures were performed on the dynamometer. The first test was a modified step test. It consisted of applying constant pressure to the throttle pedal and incrementally increasing the load on the vehicle through the drum on the dynamometer. The load was changed by 3.7 kW (5 hp) increments. The dynamometer load was held constant for approximately 10 seconds for data acquisition.

Since the dynamometer is designed for heavy-duty vehicles, it is not the ideal equipment for testing a light-duty, spark ignition engine. Therefore, it was not automatically controlled with the built-in PID controller. The only way the dynamometer would stabilize when under load conditions was by conducting each test manually. Additionally, the engine was tested at relatively high speeds because at low speed and low load, the dynamometer would not stabilize.

Using the Explorer input parameters, SDV predicted vehicle speed and torque at the wheels. Engine speed and power from the dynamometer were used as input to SDV. The coefficient of aerodynamic drag was set to zero because there were no wind loads on the vehicle while operating on the dynamometer.

Figures 10, 11, and 12 show close correlation of SDV with test data for three different throttle positions. The throttle positions for tests 1, 2, and 3 were 35 percent, 38 percent, and 28 percent. The difference in vehicle speed and wheel torque between SDV and the test data were at most 8 percent. Most of the deviation occurred at the higher power loads with SDV over predicting vehicle speed and under predicting wheel torque.

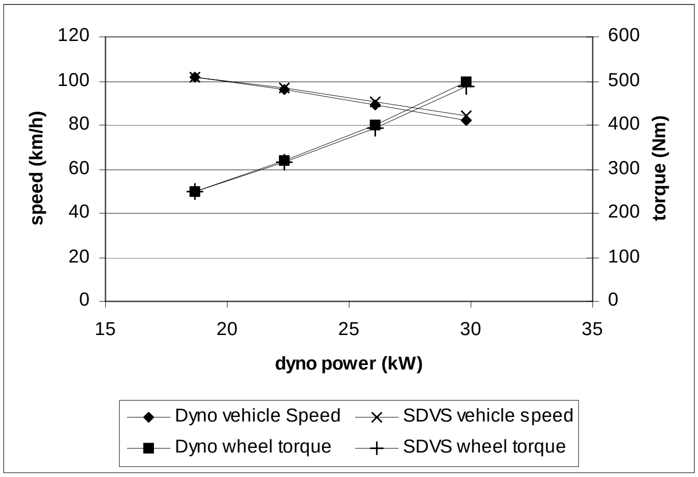


Figure 10 Test 1: Comparison of SDV with vehicle data collected on a dynamometer.

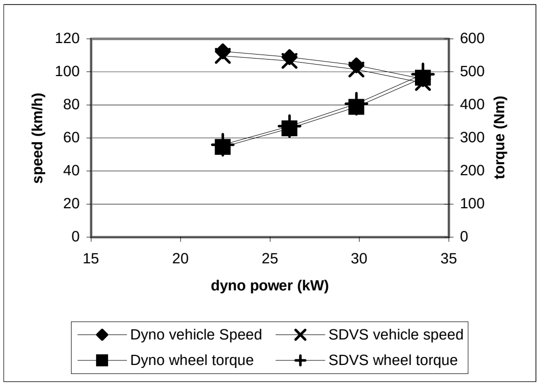


Figure 11 Test 2: Comparison of SDV with vehicle data collected on a dynamometer.

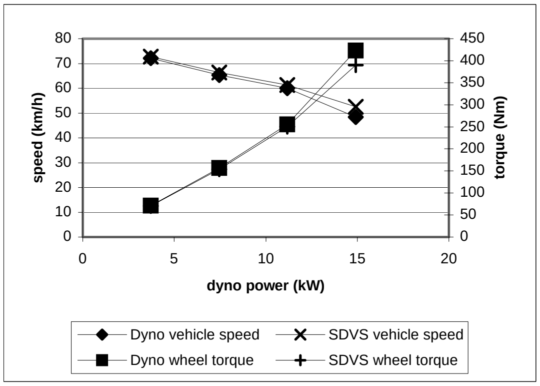


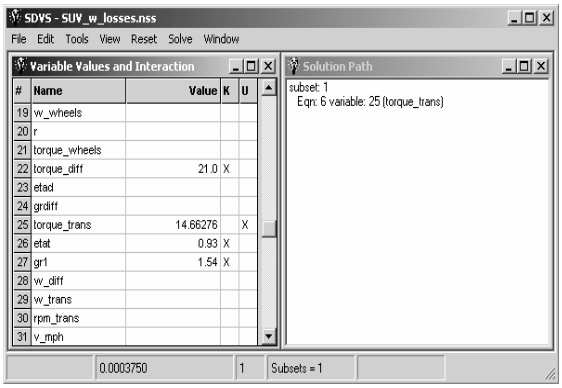
Figure 12 Test 3: Comparison of SDV with vehicle data collected on a dynamometer.

Case Studies

The following case studies illustrate the unique features of SDV. With figures showing the SDV user interface, the cases will step through how SDV can be used for variable selection, highlighting variable interactions, and component sizing based on performance criteria [1].

Case Study #1: Selecting Variables for Solution

The following examples demonstrate the advantages of using SDV during variable selection. In the first example (Fig. 13), a target variable is selected. All other variables are originally unspecified. Once three other variables are specified as known, an equation is placed in the solution path. Equation 6 is identified in the solution path and is used to solve for the target variable. Known variables are identified with an X in the K column. Similarly, unknown variables are identified with an X in the U column.

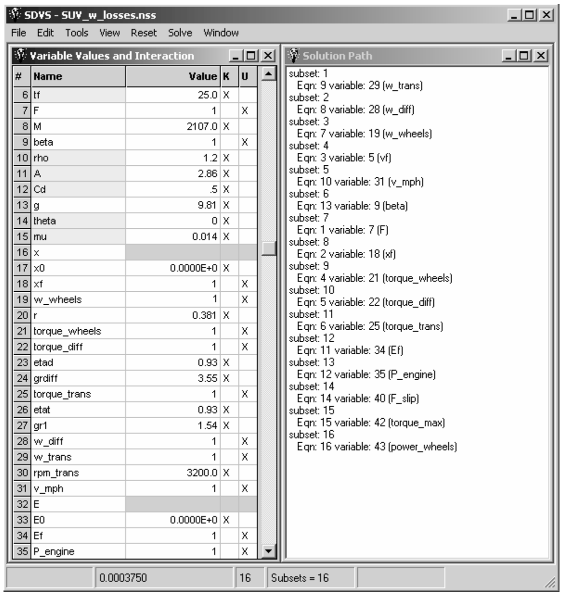


#	Name	Value	K	U
19	w_wheels			
20	r			
21	torque_wheels			
22	torque_diff	21.0	X	
23	etad			
24	grdiff			
25	torque_trans	14.66276		X
26	etat	0.93	X	
27	gr1	1.54	X	
28	w_diff			
29	w_trans			
30	rpm_trans			
31	v_mph			

```
subset: 1
  Eqn: 6 variable: 25 (torque_trans)
```

Figure 13. Variable selection showing an unknown variable and known variables that make a determinant set.

Figure 14 shows the results of the interactions between the variable *P_engine* and the other variables. When variables are specified as either known or unknown, interactions are invoked by clicking in the U or K column opposite the X of the target variable. This highlights all variables that interact with the target variable. In this case, *P_engine* is the target variable and all highlighted variables are those that interact. Variables that were not highlighted do not interact with the target variable. If the goal were to adjust the value of *P_engine*, then changing one of the highlighted variables would cause this to happen. Or, *P_engine* could be changed to a known value and one of the highlighted variables would then have to unknown. This would allow the value of *P_engine* to be set and another variable would be solved instead. We call this variable swapping. This is the type of generalized flexibility that gives the engineer freedom to explore design configurations while always maintaining a well-specified system.



#	Name	Value	K	U
6	tf	25.0	X	
7	F	1		X
8	M	2107.0	X	
9	beta	1		X
10	rho	1.2	X	
11	A	2.86	X	
12	Cd	.5	X	
13	g	9.81	X	
14	theta	0	X	
15	mu	0.014	X	
16	x			
17	x0	0.0000E+0	X	
18	xf	1		X
19	w_wheels	1		X
20	r	0.381	X	
21	torque_wheels	1		X
22	torque_diff	1		X
23	etad	0.93	X	
24	grdiff	3.55	X	
25	torque_trans	1		X
26	etat	0.93	X	
27	gr1	1.54	X	
28	w_diff	1		X
29	w_trans	1		X
30	rpm_trans	3200.0	X	
31	v_mph	1		X
32	E			
33	E0	0.0000E+0	X	
34	Ef	1		X
35	P_engine	1		X

```
subset: 1
  Eqn: 9 variable: 29 (w_trans)
subset: 2
  Eqn: 8 variable: 28 (w_diff)
subset: 3
  Eqn: 7 variable: 19 (w_wheels)
subset: 4
  Eqn: 3 variable: 5 (vf)
subset: 5
  Eqn: 10 variable: 31 (v_mph)
subset: 6
  Eqn: 13 variable: 9 (beta)
subset: 7
  Eqn: 1 variable: 7 (F)
subset: 8
  Eqn: 2 variable: 18 (xf)
subset: 9
  Eqn: 4 variable: 21 (torque_wheels)
subset: 10
  Eqn: 5 variable: 22 (torque_diff)
subset: 11
  Eqn: 6 variable: 25 (torque_trans)
subset: 12
  Eqn: 11 variable: 34 (Ef)
subset: 13
  Eqn: 12 variable: 35 (P_engine)
subset: 14
  Eqn: 14 variable: 40 (F_slip)
subset: 15
  Eqn: 15 variable: 42 (torque_max)
subset: 16
  Eqn: 16 variable: 43 (power_wheels)
```

0.0003750 | 16 | Subsets = 16

Figure 14 Example of variable interactions.
Highlighted variables interact with target variable *P_engine*

Case Study #2: Relevant Parametric Studies

This case study demonstrates the benefits of SDV when selecting variables for parametric analysis. One difficulty in designing parametric studies is deciding which variable, when incrementally changed, will effect change in another variable. Algorithms in SDV highlight variable interactions for easy identification and selection and prevent the user from selecting a singular set of unknown variables. The following examples were developed to illustrate this functionality.

Example #1: Acceleration Performance vs. Vehicle Frontal Area

In the following example, vehicle frontal area A is the parametric variable and a velocity profile is calculated. *A* interacts with *vf*, therefore it is a relevant choice for the parametric variable. The effect frontal area has on top end speed is clearly demonstrated in Fig. 15.

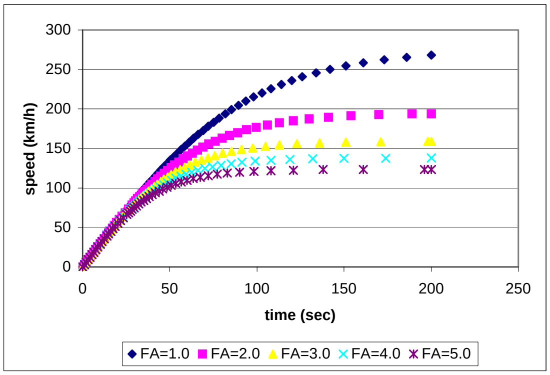


Figure 15 Relevant parametric analysis of vehicle maximum acceleration effort as a function of frontal area.

Example #2: Acceleration Performance vs. Total Energy and Engine Power

In example #2, the energy requirements and engine power are calculated as functions of time. It was determined through variable interactions that both energy use and engine power interacts with the target variable final time *tf*. As the time required for acceleration increases, the power requirement decreases and total energy use increases as is seen in Fig. 16. Knowing the variable interaction before conducting the parametric analysis prevents the user from selecting a variable that will not affect the solution of the target variable.

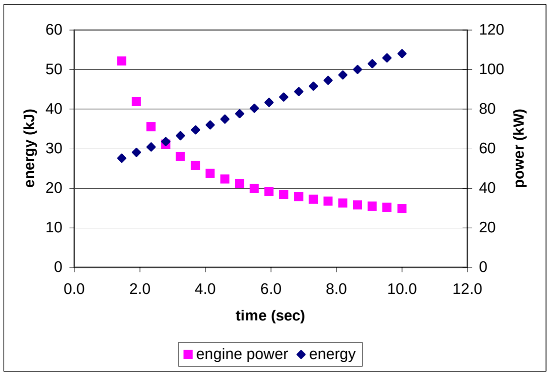


Figure 16. Parametric analysis of engine power and total energy as a function of the time it takes to accelerate from 64 to 97 kph (40 to 60 mph).

While some of these analyses are possible in other vehicle simulation programs, the advantage of SDV is being able to quickly select the variables that interact with the target variable. SDV makes it clear which variables to select. Other vehicle simulation programs do not provide this type information. Variables have to be selected based on best judgment or trial and error. This is time consuming especially when conducting computationally expensive parametric analyses.

Case Study #3: Component Sizing

With SDV, vehicle performance parameters can be specified and component-based solutions obtained with the assurance of maintaining a valid system of unknown variables. This type of design analysis is not possible in other vehicle simulation programs. This example determines engine size based on the performance criteria of accelerating from 0 to 137 kph in 20 seconds

The component-sizing variable that was used as the unknown variable was engine output torque. The performance parameter was to require the vehicle to accelerate from 0 to 97 kph (0 to 60 mphs). The parametric variable was the elapsed time for the acceleration and it ranged from 4 to 20 seconds. Configuring SDV in this way gives required output torque, which is related to engine size, as a function of the elapsed time to accelerate which is a performance goal. Figure 17 shows the result of this parametric analysis. This presents a unique design alternative in vehicle simulation software.

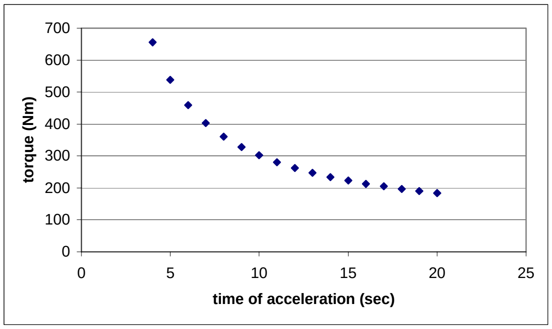


Figure 17. Engine output torque as a function of the time it takes to accelerate from 0 to 97 kph (0 to 60 mph).

Student Team

To accomplish the large task of modifying a Ford Explorer, AVCT used a heavyweight team structure [18]. In the heavyweight team, a designated project manager has firm control over all functional areas. In the FutureTruck project, the functional areas were: Power Train, Operations, Public Relations, Ener-Vations, Controls and Telemetrics, Fuel Systems and Emissions, Testing and Experimentation, and Modeling and Simulation. The team structure is shown in Fig. 18. Each functional area had a team leader, which was the point through which all information for the area passed. This reduced communication gaps and ensured that one person in each area would know what needed to be done. The heavyweight team structure puts the responsibility for the work in the hands of the project manager.

Personnel from functional areas are placed on the team under the guidance of the project manager and team leader. This environment gives the team member a great deal of ownership in the team and the project since little bureaucracy occurs between any member and the project manager. Through this feeling of ownership, the team members are well motivated [19].

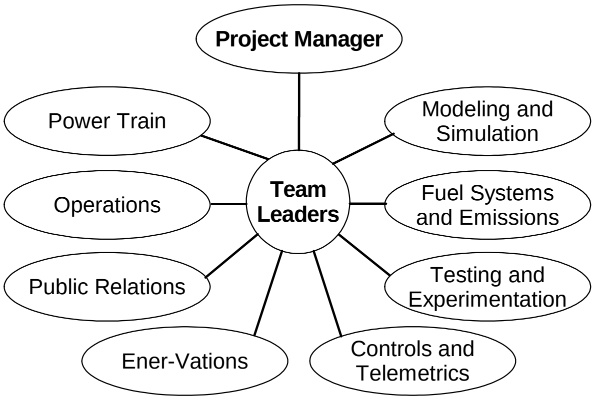


Figure 18 AVCT team structure.

The AVCT team incorporates participants from numerous University departments. Members represent from nearly all UI engineering departments as well as the departments of business, communications, marketing, computer science, and industrial technology. This diversity in the team population provides a general knowledge base from which truly innovative ideas develop. Cross-functional work of this caliber is paramount in order to accomplish such a large-scale project.

Outreach

Education about clean vehicle technologies was as important part to this project as the engineering and evaluation already discussed. Besides educating themselves during the design and development process, the student team also spent time in transferring the lessons learned to outside persons and groups. As a partnership between industry, government, and academia, the FutureTruck competition is structured to encourage the sharing of ideas and information.

Industry was a key player during this project. The primary industrial contact for the student team was the Ford Motor Company mentor. The mentor answered the team’s technical questions, obtained proprietary resources, monitored student progress, conducted safety inspections, periodically visited the university campus, and reviewed reports.

In addition to Ford, other sponsors such as National Instruments, Cisco Systems, Delphi, The MathWorks, PPG, the Aluminum Association, and Parker Ford of Moscow, Idaho, provided equipment, supplies, software, and technical data.

The Department of Energy, the government sponsor, teamed up with Argonne National Laboratory as the organizer. Both of these agencies sought to use FutureTruck as a means to facilitate the nation’s transition to cleaner and more efficient vehicles. They organized workshops, disseminated information from complementary projects, developed rules, provided test facilities, arranged public relations events, established avenues for oral presentations and written technical reports, organized the competition, and published results.

The University of Idaho was one of 15 participating universities from across the U.S. and Canada. Each university contributed a unique design approach, different research, and varied student groups. This diversity broadened the experience beyond what any one team could experience at their home campus. One of the many topics shared among the teams was how they performed outreach. While some teams were close to metropolitan areas where they could take advantage of a wide media selection, our team concentrated on small community events such as Vandal Friday, Basketball games, Engineering Expo, tours in conjunction with Parents' Weekend, the Tour of Solar Homes, and Women in Engineering day The team displayed the vehicle to an eighth grade class and two high school classes, at four university events, an Earth Day show and the workplace of two of our local sponsors.

Figure 19 AVCT members, in yellow and black shirts, describe and demonstrate the clean vehicle technologies to Troy High School students.

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

This section summarizes the results from testing and competition. Testing, which was performed before and after modifications, included over 2000 miles of city and highway driving and three test sessions on a chassis dynamometer.

Test Results

Performance testing was conducted throughout the development of the Idaho FutureTruck. This testing included coastdown measurements for road load coefficients, dynamometer testing for steady state fuel consumption and emissions, and local city and highway driving cycles for fuel economy. Baseline testing was performed on the vehicle in its stock configuration. The same testing procedure was used to evaluate the vehicle after major modifications. This provided the team with significant insight and results of the major design modifications.

Coastdown testing was performed according to SAE standards [20]. A mathematical model was developed according to White and Korst [21] that used velocity vs time data to least squares fit the aerodynamic drag coefficient and rolling resistance force. Twelve test runs were conducted and coastdown time and velocity were measured between 80 and 32 kph (50 and 20 mph). The average aerodynamic drag coefficient and rolling resistance coefficient were determined to be 0.50 and 0.014 for the stock Explorer.

Baseline steady state data were collected on a two-wheel drive chassis water brake dynamometer shown in Fig. 20. Both fuel economy and emissions data were collected during steady state operation that simulated highway conditions. The vehicle was driven in third gear at 4000 rpm with an 11.2 kW (15 hp) load applied to the wheels. This relatively high speed was necessary in order to adequately control the dynamometer. Unfortunately, the dynamometer used was suited for high toque diesel powered vehicles and not vehicles with spark ignition engines. However, it was valuable to test the vehicle on the dynamometer because it provided comparative data between the stock and modified vehicle configurations in a controlled environment.

Figure 20 Dynamometer testing on the SuperFlow SF-601 chassis dynamometer.

Emissions and rate of fuel consumption were measured on the dynamometer. The team used a five-gas analyzer to measure CO_2, CO, hydrocarbons, O_2, and NOx. In addition, exhaust temperature was measured with a thermocouple in the tailpipe. Fuel flow rate was measured with a fuel meter connected in line with the vehicle's fuel lines. Mass air flow rate into the engine was measured along with several other stock parameters using the Explorer's On Board Diagnostics (OBD-II) system connected to an EASE Diagnostics Enhanced Ford OBD-II signal converter. Output was recorded on a PC.

Local city and highway driving routes were established to evaluate on-road fuel economy. The city cycle was a 2.9-mile loop around the city of Moscow, Idaho. The highway cycle consisted of a 26-mile one-way trip from Moscow to Lewiston, Idaho. An effort was made to drive each test cycle at the same acceleration rate. City fuel economy results were averaged over ten test runs. The highway cycle was run twice for each vehicle configuration. The changes to the modified vehicle consisted of engine modifications only. At the time of testing, the vehicle was not converted to E85 in order to evaluate the engine modifications.

The stock Explorer and the modified Explorer were tested on the dynamometer. The modified vehicle included changes discussed above under Vehicle Development section. Stock and modified Explorer fuel economy were 7.97 kpl and 9.72 kpl respectively. Emissions results are given in Table 5. Three of the four gases were significantly reduced due to the conversion to E85 fuel and the modifications to the engine. The CO_2 emission was near that of the stock Explorer, having been reduced by 6.6 percent. This reduction may seem small, but over the life of the vehicle, the total reduction in CO2 emissions would be quite substantial.

Table 5. Test results

Performance Parameter	**Summit Modeling**	**Summit Testing**	**Stock**
km/L (composite)	10.12	9.72	7.97^0
Emissions			
CO2 (g/km)	NA	387.6	414.5⊕
HC (g/km)	1.68	.134	.001⊕
CO (g/km)	4.57	.002	.193⊕
NOx (g/km)	1.68	.729	4.498⊕
Acceleration time 0 to 96 kph	9.5	NA	10.7^0
0.40 km time	17.6	NA	17.9^0

HC emissions did not decrease as much as was expected. This was primarily due to the several factors involved in the gasoline to E85 conversion. After the testing was complete, the mass airflow sensor was found to be giving incorrect readings and the fuel pressure was too high. These factors led to a slight richening of the air/fuel mixture, causing the higher than anticipated HC content.

NOx emissions were reduced by 84 percent. That reduction was not enough to meet California ULEV standards, but the test was performed at high speed and high load, conditions where NOx emissions are generally higher than normal. This means that over a standard driving cycle, NOx emissions could be below ULEV standards. The cause for this reduction is most likely due to the lower combustion temperature and exhaust temperature achieved by using E85 fuel.

One surprise reduction was in the CO emissions. This is especially surprising due to the fact that the fuel itself, ethanol, contains a carbon-oxygen bond, so CO could have been provided by non-oxidized portions of the molecules, or by the incomplete combustion reaction. If either of these occurred, the catalytic converter was hot enough to efficiently oxidize any CO that passed through it. It should be noted that during cold-start, the CO emissions were very high. The CO levels subsided to near zero after ten minutes of idling, showing that the catalytic converters must be hot in order to oxidize CO to CO2. Figure 21 shows emissions of the vehicle before and after conversion as well as the ULEV requirements.

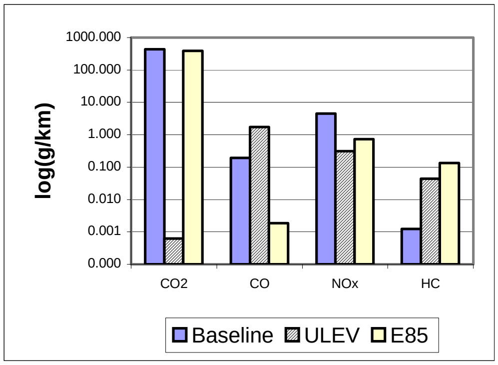


Figure 21 Emission of various greenhouse gases from baseline and post E85 conversion tests and ULEV Regulations.

Competition Results

The Summit vehicle placed seventh overall among the 15 universities competing at Ford’s Arizona Proving Ground in June 2002. It was one of only three vehicles to attain ultra-low emissions vehicle (ULEV) standards, placed second in the acceleration event, and first in the trailer tow event. The team also won an award for the most innovative use of aluminum.

Summit achieved lower greenhouse gas emissions compared to the stock vehicle and the greatest reduction in tailpipe emissions. Calculations for greenhouse gas emissions account for emission produced during the production and distribution of the fuel. Qualifying as an ultra-low emissions vehicle (ULEV) required successful simultaneous control of non-methane organic gasses (NMOG), carbon monoxide (CO), and oxides of nitrogen (NOx). The numbers for Summit from the FTP driving cycle were 0.067 grams/mile of NMOG, 0.8810 grams/mile of CO, and 0.0880 grams/mile of NOx.

The UI vehicle was very reliable and the team was able to complete all test events. One of the few vehicle malfunctions occurred during the on-road fuel economy event when an electronic component prevented the transmission from shifting into overdrive. Running the high speed circuit in a lower gear resulted in worse fuel economy than the stock vehicle. However, the malfunction was quickly fixed and, on the dynamometer test, Summit achieved a 25 percent fuel economy improvement compared to the stock vehicle.

Although increasing fuel economy and lowering emissions were primary competition objectives, teams were not permitted to do this at the expense of vehicle performance. Summit beat the stock vehicle in acceleration (11.757 seconds in the 1/8 mile compared to the stock vehicle's 12.037 seconds) and beat all vehicles in maximum towing capacity. Vehicle design and consumer acceptability were also rated. After fabricating special panels for the passive cooling and mounts for the hybrid components, the UI team received an award for the most innovative use of aluminum.

Conclusion

This paper described how the University of Idaho AVCT approached the first phase of designing and developing an improved version of the 2002 Ford Explorer SUV. The backbone of this project was the multi-disciplinary team, which represented a large cross-section of the UI student population. By implementing a professional, business approach for this project, the team safely modified and tested a modern SUV, gained valuable knowledge and experience, and transferred their enthusiasm to the public. Using a design-build-test methodology and all available resources, the team developed a feasible, mild-hybrid electric configuration that would meet performance objectives. Through a combination of modeling, test-driving, and dynamometer testing, the modified vehicle showed a 22 percent improvement in composite fuel economy, 6 percent reduction of $C0_2$ greenhouse gas, 84 percent reduction in NOx, and 99 percent reduction in the already low CO production. In addition to reducing emissions, the modifications improved vehicle acceleration and passenger comfort.

The FutureTruck project has been a great experience and opportunity for UI students and the surrounding populace. The team is looking forward to implementing their second phase of improvements for an even better example of a future SUV.

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