

# Challenge X Vehicle Architecture Design Analysis and Selection

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## ABSTRACT

Development of a hybrid electric vehicle powertrain conversion for an existing vehicle platform involves extensive research, modeling, and simulation to determine optimal configurations and component selections to meet system design requirements. In accordance with the Challenge X Vehicle

## INTRODUCTION

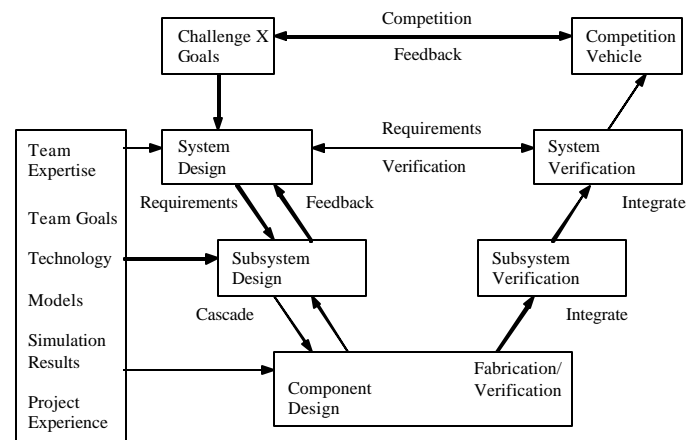
Consistent with our Challenge X proposal, the University of Tennessee team is focusing on a hybrid electric vehicle comprised of a heat engine, electric motor, and conventional energy storage devices.

The Powertrain System Analysis Toolkit (PSAT) simulation tool provided by Argonne National Laboratory has been used as the primary means to evaluate a variety of possible powertrain configurations. The University of Tennessee team has extensive experience with both pre- and post-transmission parallel hybrid electric powertrains, and these were thoroughly investigated through simulation and packaging analysis to arrive at viable subsystem designs and ultimately component selections. Simulation results provide only one means of evaluating a particular design. Cost factors have been developed by the team to more accurately assess the validity of a given candidate powertrain. Such factors as past team experience, financial considerations, packaging, implementation ready (IR) technology, are just a few of items that must be addressed. After careful consideration of all the pertinent factors, a robust and practical design is proposed for the purpose of prototype development.

## CONCEPTUAL DESIGN PROCESS

Team Tennessee maintains that the systems engineering approach is the most efficient path to properly designing a successful Challenge X vehicle. The methodology of the systems engineering "V," shown in Figure 1, is adhered to

and summarized herein for the initial stages of the vehicle design.



**Figure 1 Systems engineering "V" model for UT Challenge X vehicle development**

The left half of the V model is the focus for year one, with emphasis being placed on the first half of the year. The right hand side of the V model will be addressed during years two and three. The team will develop a conceptual design based on the competition requirements and the goals established by the team. The team will then progress down the left hand side of the systems engineering model designing subsystems that meet the system level design, cascading requirements for component features based on subsystem designs, and developing verification requirements for competition intent confirmation testing. This process will be executed in an iterative, as well as parallel, manner that will rely on utilization of a variety of available engineering tools. The UT team will use modeling and simulation to develop its system and subsystem designs, and to provide feedback to preceding levels of the system-engineering model. Feedback to preceding levels is critical to evaluating design trade-offs along the way that must be reconciled and balanced to ensure a successful design that meets the system level targets.

Two fuels were considered for use in Challenge X, E-85 and B-20. We have experience with both fuels in previous Advanced Vehicle Technology Competition (AVTC) projects. Both of these bio-based fuels exhibit a greenhouse gas emissions advantage in the well-to-pump phase, as shown in greater detail in a following section. The use of E-85 suggests the use of a spark-ignition engine, while B-20 dictates a compression-ignition engine. Compression-ignition engines are very efficient and therefore have lower pump-to-wheels energy consumption and lower greenhouse gas emissions. Spark-ignition engines exhibit lower efficiency than compression ignition engines and thus higher pump-to-wheels energy consumption, but there are technologies available, or under development, to improve their efficiency.

Selection between these fuels obviously has impact on the overall vehicle configuration. Different control strategies must be considered for these two different types of engines. Equally as important, the emissions control strategy is impacted by both the fuel choice and the implied engine configuration choice. These trade-offs in efficiency, emissions, energy management, and drivability must be considered in the modeling and simulation work, which will result in the fuel and technology selection. Well-to-wheels energy consumption and emissions analysis have been employed to fully assess the impact of the two fuels considered.

Exhaust aftertreatment is also an important part of the overall vehicle configuration that is strongly affected by the fuel and engine technology choice. The emissions control systems for compression-ignition engine are not mature, and emissions of NO<sub>x</sub> and PM are challenges. However, systems are being developed that efficiently treat the exhaust from compression ignition engines. Exhaust aftertreatment for spark-ignition engines, the three-way catalyst, is mature and well understood technology.

The Powertrain System Analysis Toolkit (PSAT) simulation tool provided by Argonne National Laboratory was used as the primary means to evaluate a variety of possible powertrain configurations. Various energy storage solutions will be simulated to model effects on overall system efficiency. The team will consider fuel economy estimates, overall system efficiencies, environmental impact due to emissions and fuel selection, weight considerations, basic control strategies, and viable technologies as figures of merit for design decisions. With respect to fuel selection, a complete well-to-wheels analysis will be performed using the GREET model.

## LITERATURE REVIEW

Various publications related to the design and development of advanced vehicle technology was reviewed during the development process. Parallel hybrid configurations are considered to be more efficient than comparably sized series drivetrains due to the higher efficiency of the mechanical connection relative to the

series system with a purely electric powerflow [1]. The literature also suggests that the efficiency gains derived from hybridization can be very sensitive to the finite efficiency of the chosen energy storage system and the incremental weight of increased hardware. A low storage requirement powertrain would provide a substantial weight savings in comparison to a comparable traditional hybrid, which would provide an electric only mode of operation [1]. A smaller capacity battery pack provides the low storage requirement while reducing the battery physical size and weight.

Regenerative braking plays an important role in the cycle efficiency of a hybrid powertrain. Medium hybrids have the ability to more aggressively recapture kinetic energy due to the fact that the high voltage system is sized for higher power levels. More kinetic energy that is recaptured leads to increased driving efficiency [2].

The concept vehicles developed by Ford, GM, and Chrysler as part of the Partnership for Next Generation Vehicles (PNGV) all used compression ignition (CIDI) engines. These engines offer inherently higher cycle efficiencies compared to gasoline SI engines [2]. The fuel economy target for the PNGV vehicles was to triple the average fuel economies of typical vehicles (on the order of 80 MPG). The research lead by the PNGV companies concluded that a compression ignition engine was the only means of accomplishing this lofty goal.

A typical operating strategy for hybrid electric vehicle is to employ engine start/stop during vehicle idle conditions. The fuel economy impact of a stop/start algorithm can be enhanced by eliminating the fueling process during the vehicle braking mode (known as Early Fuel Cutoff) as well as vehicle idle conditions [3].

Production level components need to be durable. The literature suggests that from a life-cycle cost point-of-view, a parallel configuration offers the best solution over series configuration [4].

## VEHICLE TECHNICAL SPECIFICATIONS (VTS)

To begin the process of sizing and selecting a proper powertrain, the specifications with which the vehicle must comply must be carefully determined. Team Tennessee has a goal of designing an advanced powertrain vehicle capable of meeting a variety of metrics established by the demanding consumer and the internal objectives of the team. Table 1 below outlines the objectives of the Team Tennessee Challenge X vehicle. Based on these metrics, the team can proceed to size components and decide on appropriate powertrain configurations that best meet these goals.

During the conceptual design process for a powertrain, a trade-off between acceleration performance and fuel economy objectives must be addressed. The VTS displayed in Table 1 represents the final iteration of this

trade-off process. The team decided to relax the IVM to 60 MPH metric in order to attain higher fuel economy benefits.

The VTS shown in Table 1 reflects vehicle level specifications only and does not contain design validation planning and report (DVP&R) documentation or corresponding test specifications. The team will develop an internal DVP&R document and associated test methodologies in order to validate whether the developed powertrain/vehicle meets the VTS. The responsibility of developing the “official” DVP&R for the competition validation of the design belongs to the organizers.

**Table 1 University of Tennessee VTS**

Description	Test Year	Modeling/ Inspection/ Testing	Base Vehicle (V6)	Competition Target	VTS (Team Selected)
IVM -60 MPH	1,2,3	M,T	? 8.9	?9.0 s	?8.9s
50-70	1,2,3	M,T	?6.8	?6.8	?6.8
Vehicle Mass	1,2,3	M,T	?4000 lbs	?4400lbs	?4200lbs
MPG	1,2,3	M,T	?23.3 mpg	?32.0 mpge	?32.0 mpge
Combined EPA					
Highway Range	1,2,3	M,T	?320 mi	?200 mi	?200 mi
Passenger Capacity	1,2,3	M,T	5 Passengers	5 Passengers	5 Passengers
Emissions Cert Level	2,3	T	Tier 2, Bin 5	Tier 2, Bin 5	Tier 2, Bin 5
Trailer Capacity	2,3	M,T	3500 LBS	2500 LBS	2500 LBS
Cargo Capacity	2,3	I	68.6 Cu. Ft. behind front seat		60 Cu. Ft. behind front seat
Starting Time	1,2,3	T	<2.0 s	<5.0 s	<5.0 s
Noise Emission	1,2,3	T			<75 dbA

**INITIAL VEHICLE INTEGRATION ANALYSIS**

Packaging is an important parameter in determining an appropriate powertrain configuration for the target vehicle. The packaging environment for the Chevrolet Equinox is constrained due to the unibody construction of the vehicle. The support structure of the vehicle is integrated into the body structure. Larger vehicles such as full size SUVs use body to frame construction where the support structure and the body are separate. The frame to body construction provides more space under the vehicle to add powertrain components because components can be mounted to the frame side rail. Though the unibody construction reduces the overall weight of the vehicle the side rail mounting areas and underbody space are significantly reduced. Converting a vehicle’s architecture at times requires modification to the body structure to properly mount additional powertrain components. This may include the removal of sheet metal from the body or the addition/removal of crossmembers to/from the frame. These types of modifications can adversely affect the safety, utility, or performance of both body to frame and unibody vehicle designs, but the unibody design is more sensitive to these changes. This is because the body and frame of the unibody is built as one entity meaning altering the body can directly alter the support structure. The body and frame in the body to frame design only contact at certain locations so the body can be modified without affecting the frame. Because the Equinox provides limited packaging space and its structure is more

sensitive to sheet metal modifications, component packaging can determine whether or not a particular vehicle configuration can be implemented. At this stage of the vehicle development process component packaging is considered to be on the macro level. Only major components of a particular configuration are modeled to determine the general location and spacing. Integrating different vehicle architectures into an existing design requires the removal of some stock components because their function is no longer needed and the space can be used for components related to the new architecture. The criteria for determining the removal of stock components from the vehicle is based on competition requirements such as having a removable gas tank, architecture hardware requirements, and stock component to new component interaction. Stock components identified for removal include: spare tire, fuel tank, stock engine, and engine exhaust system. Each vehicle architecture under consideration include the same general components (high voltage battery pack, internal combustion engine, traction motor, motor controller, and competition specified fuel tank). Though it is not required to maintain the stock cargo volume during the year’s one and two of the competition, it is required during year three. Therefore, effort is made to package components to meet the year three specification.

The installation of each powertrain configuration poses different packaging constraints. Placement options of the battery pack are limited because its dimensions will not allow proper ground clearance when mounted underneath the vehicle. The only option is to either mount the pack in the cargo space or the spare tire compartment. With year three in mind, the pack is mounted in the spare tire compartment for each configuration to be considered. Now that the battery is constrained, the only difference in each configuration is the placement of the electric motor and hardware required for integration.

Both the series and the pre-transmission parallel architectures require the electric motor to be integrated into the engine compartment. The engine compartment volume is limited because many of the stock vehicle components such as master cylinder, air condition system, steering components and other stock vehicle components are mounted in this region. These components will remain their stock locations for all considerations. Adding the motor to the engine compartment is considered to be a difficult integration option due to the limited compartment volume. Though having the motor in the front of the vehicle may be a difficult integration option, packaging in the rear of the vehicle is increased. The region where the stock fuel tank is mounted can be used to mount the competition fuel tank, motor controller, and other small components. The new engine’s aftertreatment system packaging is also increased. The increased flexibility of packaging components in the rear and underside of the vehicle is considered advantageous for the integration consideration.

The post transmission configuration is considered to be the most difficult architecture to package. This is because the entire stock vehicle architecture must be changed. The Equinox is a front wheel drive vehicle; therefore, the only way to implement the post transmission design is to convert the vehicle into a rear wheel drive vehicle so the motor can be coupled to the output of the transmission. The volume under the vehicle is significantly reduced due to the addition of the transmission, drive shaft, the need to modify the floor structure to accommodate the transmission housing that is now mounted perpendicular from the stock transmission. The amount of work required is considered better used in developing and refining a more space efficient design.

Implementation of the through the road vehicle configuration, unlike the pre-transmission parallel and the series configurations, does not require the addition of large components to the engine compartment, thus providing flexibility to integrate the required engine hardware. This architecture would require mounting the motor to the rear axle of the vehicle. The motor would be coupled to the rear axle via a gearbox with the motor output shaft orientated perpendicular to the rear axle input shaft. This assembly would be located in the stock fuel tank volume. This space would still allow mounting for the motor, gearbox and space for other smaller vehicle components. The fuel tank would be mounted to the floor of the vehicle along the sub-frame. All vehicle components can be installed in designated location without interference between other components. Stock components can remain in their respective locations. The implementation of the through the road configuration is considered to be mildly difficult.

The integration of each powertrain configuration is ranked using the logic and assumptions described above. The initial vehicle integration analysis is summarized in table 2.

Table 2 – Summary of Integration Analysis

	Packaging	Modification	Cost	Time
Pre-transmission	Red	Yellow	Green	Green
Post-transmission	Red	Red	Red	Red
Series	Red	Yellow	Green	Yellow
THRU the Road	Green	Yellow	Green	Green
Easy	Green			
Neutral	Yellow			
Difficult	Red			

Architecture selection

Selection of the best configuration and subsystem components comes as a result of evaluating all necessary

parameters and analyses against a group of criteria chosen by the team. The selection criteria for determining the best approach in resolving VTS objectives are summarized below.

Architecture selection criteria

The selection criteria chosen by team are as follows:

**VTS Targets:** The competition organizers have set forth targets in the form of a Vehicle Technical Specification. The University of Tennessee has set forth a modified version of this base specification as the objectives that must be met by our design. PSAT simulation of the component matrix for a variety of powertrain configurations gives insight into the validity of a particular design approach. Such items as IVM to 60 MPH, grade ability, UDDS and HWFET fuel economy predictions are used as part of the criteria for validating a particular configuration of components as potential candidates for the conceptual design philosophy.

**Past Team Experience:** The University of Tennessee is a long time participant in alternative fuels competitions, with emphasis on hybrid electric powertrains and controls. The team has developed a significant knowledge base in this area and shall draw upon this pool as a factor in determining the practicality and level of implementation readiness for a candidate technology. The team will utilize a “Lessons Learned” approach from past competitions in order that past mistakes are not repeated.

**Financial:** The team must consider the financial impact that a candidate design may have on the project. Certain technologies or configurations may require significant financial resources to realize. These requirements must be weighed against the other selection criteria in order to propose an acceptable, yet practical, design.

**Packaging Requirements:** The team must not lose sight of the fact that the simulation does not offer any information pertaining to packaging of a particular powertrain. The team must use information that is available and determine if a configuration that meets or exceeds team objectives can be physically packaged in the Equinox environment.

**Component/Subsystem Availability:** The team must be conscious of the fact that a component that has been sized for optimum performance in PSAT may not be physically available. Trade-offs must be considered in this case and simulations performed again in order to create a more complete package for a candidate powertrain that can be built.

Evaluation and Selection

Team Tennessee has elected to pursue a through-the-road parallel hybrid powertrain configuration for its entry in the competition. The most compelling factor influencing

this selection was cost, packaging, and other features such as complete subsystem isolation and redundancy. This concept was important to the team simply due to the fact that the vehicle could operate completely independently from the high voltage system in a limited operating strategy mode should problems arise. In addition, simulation of the system was performed in this limited operating mode and showed that fuel economy would be minimally compromised while the acceleration capability of the vehicle would be moderately affected. Separation of the high voltage system from the heat engine yields a greater degree of flexibility for the design in terms of control strategies, packaging, and overall implementation.

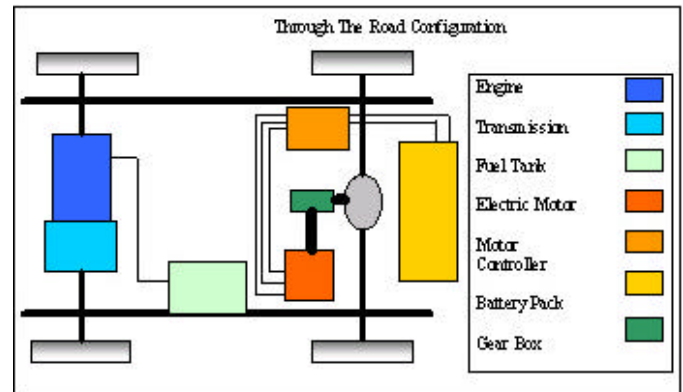
The pre-transmission parallel configuration was removed from contention due to packaging constraints and reduction in cycle efficiency through reduced regenerative braking capabilities. Perhaps the only affordable pre-transmission configuration that could be reasonably packaged in the Equinox is the start/alternator approach. A start/alternator design, which is a special case of a pre-transmission parallel configuration, does provide the required idle start/stop functionality that boosts fuel economy. However, it has been discounted due to the fact that a starter/alternator cannot supply the necessary power boost level required when substantially downsizing the engine. IVM to 60 MPH performance would be compromised when downsizing the engine to achieve fuel economy targets. This approach would not meet team VTS objectives.

The post-transmission parallel configuration can be removed from the list of viable choices due to packaging and practical considerations. Assuming the base vehicle for the competition is a two-wheel drive, which consequently means a front-wheel drive for the Equinox, and then the possibility of creating a post transmission becomes non-existent. One means of actually packaging this drivetrain is to use wheel motors. This approach then falls prey to component availability and financial constraints.

The only configuration that can be realized given the constraints of the team and respectfully meeting the competition objectives is the through-the-road parallel. This configuration still presents a packaging challenge, but one that appears surmountable. The benefits of this type of configuration are increased cycle efficiency due to the ability to implement a series regenerative braking system. This accomplished simply by the fact that the traction motor is directly coupled to the rear wheels. This may present some drivability concerns, but those can be addressed through calibration. The other key feature afforded by this approach is system redundancy. The high voltage system is completely separated from the heat engine drive system. Should one system fail, the other can function in a limited operating mode.

## INITIAL PACKAGING ANALYSIS

The initial integration analysis determined the through the road hybrid configuration would be the easiest to implement. Figure 2 shows a schematic layout of the required hardware.



**Figure 2 Through-the-Road schematic**

Generic CAD models of components were developed and placed into Equinox assembly drawings provided by GM to determine a high-level integration scheme for additional powertrain components. Sub-assemblies representing locations on the vehicle where components will potentially be installed were developed giving component placement relative to stock components. The two main areas of interest to exploit used space are the engine compartment and the rear undercarriage and surrounding structure (shown in Figure 3). The through-the-road vehicle configuration requires the electric motor to be coupled to the rear axle. This is accomplished via a custom gearbox. Figures 4, 5, and 6 illustrate the hardware and packaging concepts for the rear subassembly. The motor is mounted perpendicular to the rear axle output shaft. This is done to keep the motor and gearbox assembly in the space where the stock gas tank is normally mounted. The competition fuel tank is mounted along the side rail of the vehicle's sub-frame. As shown in the figures, the battery pack is located in the spare tire volume. This tire will be removed from the vehicle, and the vehicle will use run flat tire technology thus maintaining the vehicle's utility. Modification to the floor pan in the region where the spare tire is mounted will need to be modified. It is possible that modification to this area can be done without altering the integrity of the support structure by reshaping the surrounding sheet metal. Further analysis of this modification will be done to insure the safety, performance, and durability is maintained. The rear subassembly in figure 4 shows component orientation relative to the existing structure. UT components added to the assembly include: battery pack (orange), electric motor (red), gear box (yellow), fuel tank (blue). Figures 7 and 8 illustrate the engine compartment with general component packaging. The engine compartment will be used to mount the electrically driven component such as

power steering, water pump, and a/c compressor as well as any vehicle controller's. A volume model of the desired engine is used to insure the installation of engine will not interfere with the existing structure.

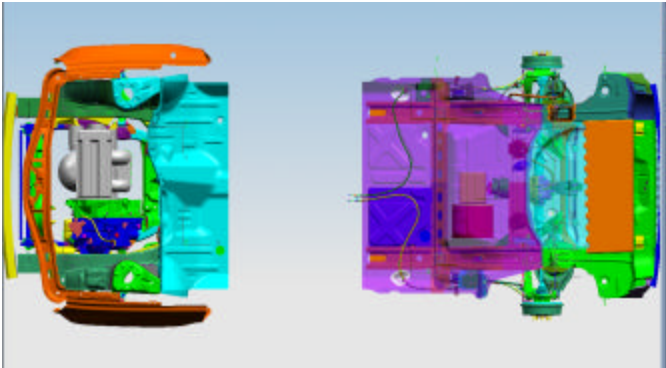


Figure 3 CAD Model of Subassemblies

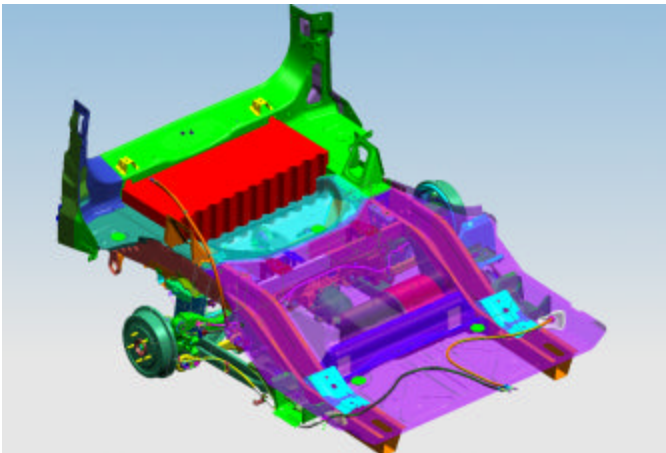


Figure 4 - Rear sub-assembly

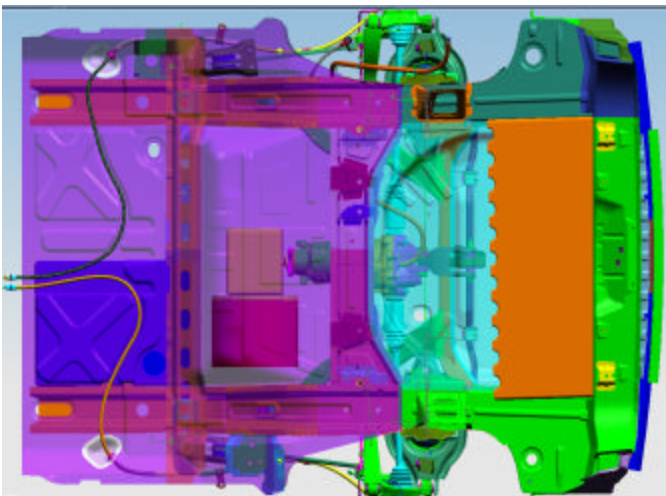


Figure 5 - Rear sub-assembly (top view)

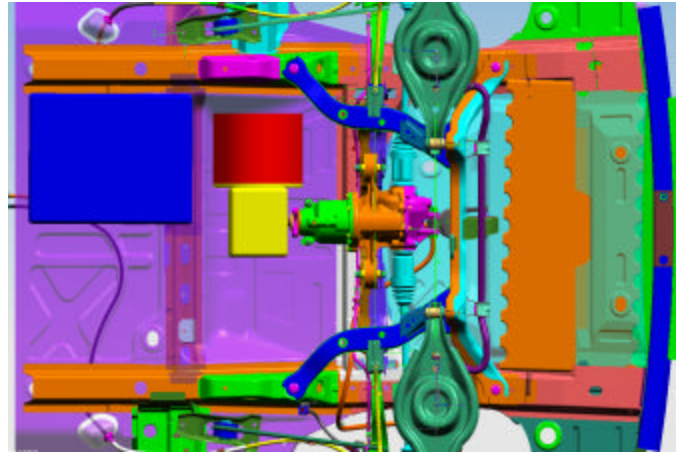


Figure 6 - Rear sub-assembly (bottom-view)

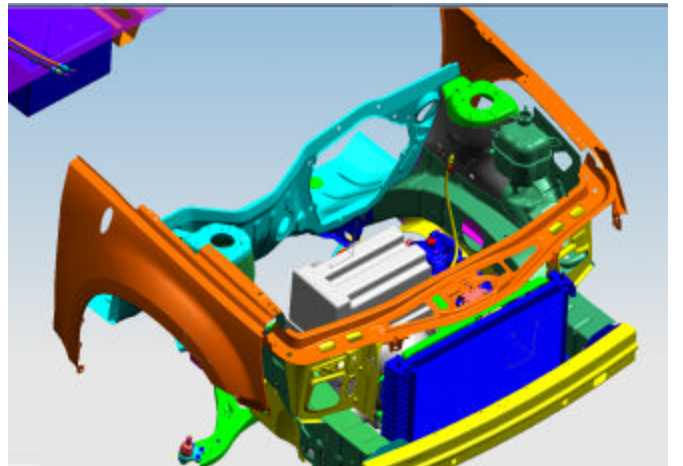


Figure 7 - Engine compartment sub-assembly

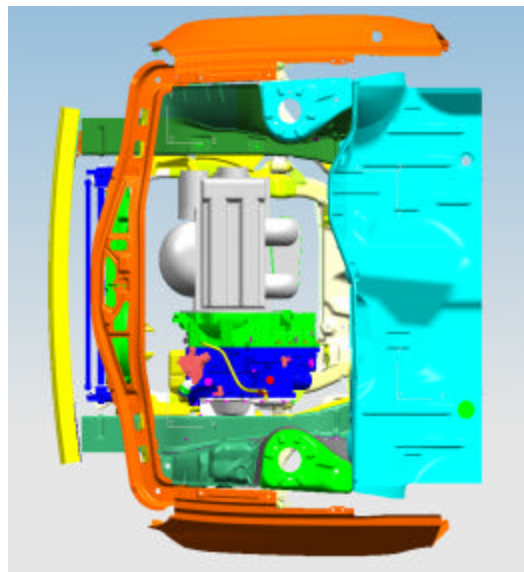


Figure 8 - Engine packaging

## FUEL SYSTEM ANALYSIS

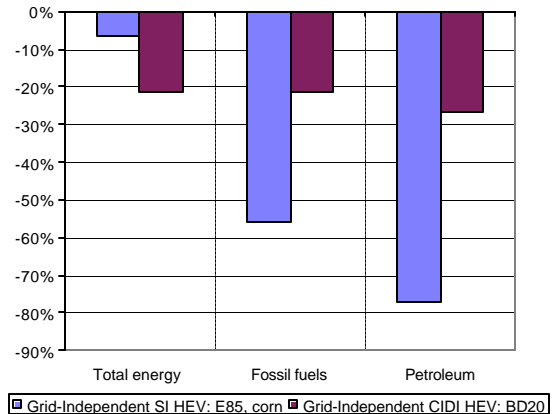
The energy use and environmental impact of a vehicle in operation extend beyond merely the on-road fuel consumption and emissions. The total life cycle energy use and emissions include:

- Production, processing and transportation of raw materials into manufacturing materials
- Manufacturing of the vehicle components
- Assembly of the vehicle
- Production, processing and transportation of the fuel
- On-road operation of the vehicle
- Maintenance of the vehicle
- Disposal of the vehicle

Analysis of the total life cycle energy consumption and emissions associated with vehicle operation is beyond the scope of this project. To a great extent, the vehicle technology does not affect the energy consumption and emissions for production and disposal of the vehicle. Advanced vehicle technologies certainly differ from conventional vehicles in these areas. For example, the energy storage system for hybrid electric vehicles requires more energy and generates greater emissions for production and disposal compared to a conventional vehicle. However the major content of the vehicle is common to both conventional and advanced vehicles, and therefore, the vehicle technology most affects the in-use energy consumption and emissions. To compare the total energy use and emissions for different vehicle technologies, the analysis must include the production, processing and transportation of the fuel and the on-road operation of the vehicle. This methodology has been termed a Well-to-Wheels (WTW) analysis.

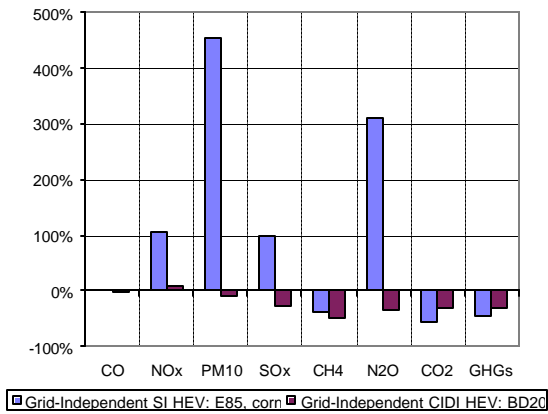
The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was developed at Argonne National Laboratory for the purpose of analyzing the WTW energy use and emissions associated with production, processing, transportation and use of a fuel in a vehicle. The model is capable of analysis using near-term and long-term assumptions regarding the total fuel cycle, and several vehicle technologies may be considered in the analysis. For the two fuels under consideration, E85 and B20, a WTW analysis was performed using the GREET model. The long-term vehicle/fuel systems option was employed in order to model the advanced hybrid vehicles. The two vehicle configurations evaluated were grid-independent hybrids for the two fuels considered. The GREET model uses pump-to-wheels fuel economy improvement predictions for the long-term option that are not reasonable for this analysis. The competition target fuel economy, 32 mpg gasoline equivalent, was substituted for the default values in the spreadsheet. The stock Equinox

fuel economy was used for the baseline conventional gasoline vehicle. In this manner, the advanced hybrid models and the Well-to-Pump (WTP) analysis for the fuels could be used, and the Pump-to-Wheels (PTW) analysis would reflect the vehicle under consideration.



**Figure 9 WTW energy consumption compared to stock vehicle**

Figure 9 shows the WTW energy consumption for the two fuels compared to the stock vehicle per the analysis described above. Figures 11 and 12 show that for both fuel technologies the overwhelming portion of the total energy consumption is attributed to vehicle operation. The reduction in total energy consumption is greater for the B20 fuel; this is primarily due to the more efficient operation of the CIDI engine for the B20 fuel compared to the SI engine for E85 fuel. However, the decrease in fossil fuel and petroleum energy consumption is greater for the E85 fuel. This is due to the composition of E85- it is 85% non-petroleum fuel compared to only 20% non-petroleum fuel for B20. Figure 12 shows that for E85 the greatest portion of the fossil and petroleum fuel energy consumed is during the production of the fuel. Whereas, the greatest fossil and petroleum fuel energy consumption is due to vehicle operation for B20 fuel.

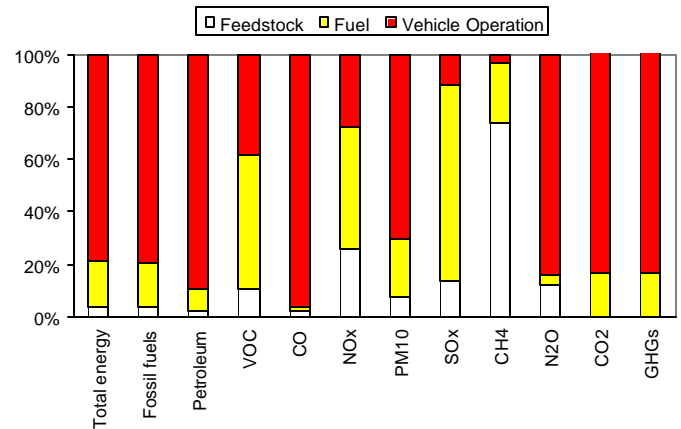


**Figure 10 WTW emissions compared to stock vehicle**

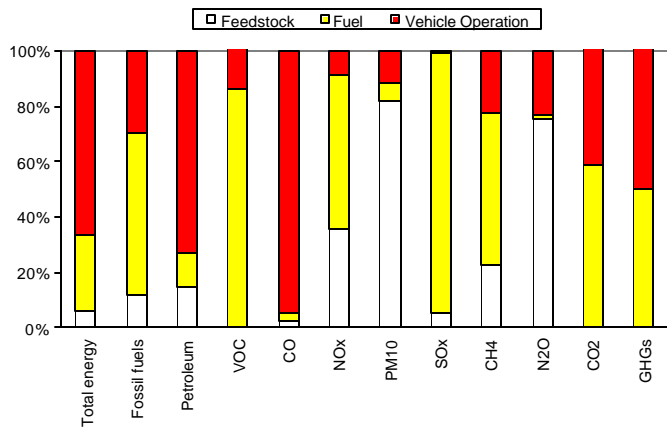
Figure 10 shows the WTW emissions for the two fuels compared to the stock vehicle per the analysis described above. The various individual emissions are addressed:

- **CO-** The CO emissions are not significantly different for either fuel compared to the stock vehicle. For both fuels, Figures 11 and 12 show that the CO emissions are nearly entirely from the vehicle operation. CIDI engines typically produce very little CO, and what is produced is easily eliminated in an oxidation catalyst. Modern three-way catalysts for SI engines are very effective at removing CO from the exhaust. Both ethanol and biodiesel are oxygenated fuels, and would therefore tend to reduce CO emissions.
- **NO<sub>x</sub>-** The slight increase in NO<sub>x</sub> emission for B20 is due to CIDI engine characteristically high NO<sub>x</sub> emissions, although GREET assumes an order of magnitude decrease in NO<sub>x</sub> emissions from CIDI engines, indicating an assumption that aftertreatment systems will become mature for NO<sub>x</sub> reduction in lean-burn engines. The higher emissions for E85 are due primarily to upstream emissions. Data from GREET show that the upstream emissions for E85 are approximately triple the upstream emissions for gasoline, while the upstream emissions for B20 are of the same order as gasoline.
- **PM10-** The particulate matter emissions for B20 are primarily from the characteristically high PM emissions from CIDI engines; Figure 11 shows that the PM10 emissions are primarily from vehicle operation. GREET assumes an order of magnitude decrease in PM10 emissions from CIDI engines, indicating an assumption that aftertreatment systems will become available for removing PM from exhaust. The PM10 emissions for E85 are almost entirely due to production of the corn, particularly from the tillage of the soil.

- **SO<sub>x</sub>-** The SO<sub>x</sub> emissions are primarily due to fuel production for both fuels. The increase in SO<sub>x</sub> emissions for E85 is primarily due to the use of coal in the ethanol production process. The upstream emissions for B20 are on the same order of the upstream emissions for gasoline; therefore, the decrease in SO<sub>x</sub> emissions is due to the fact that biodiesel is sulfur-free.
- **CH<sub>4</sub>-** The reduction in emissions is primarily due to the lower upstream emissions for both fuels.
- **N<sub>2</sub>O-** The increase in N<sub>2</sub>O emissions for E-85 is due primarily to the feedstock as shown in Figure 12. The decrease in N<sub>2</sub>O emissions for B20 fuel is attributable to the vehicle operation since the upstream emissions are slightly higher than for gasoline.
- **CO<sub>2</sub>-** The decrease in CO<sub>2</sub> emissions is due partly to the increase in fuel economy for the hybrid vehicles. Also since this is a WTW analysis, the CO<sub>2</sub> credit for bio-fuels contributes to the decrease.
- **GHGs-** Since CO<sub>2</sub> is the major component in the GHG calculation, a reduction in CO<sub>2</sub> emissions would be reflected in a decrease in CHG emissions.



**Figure 11 Energy and emissions analysis for B20**



**Figure 12 Energy and emissions analysis for E85**

### POWERTRAIN COMPONENT SIZING AND SELECTION

The University of Tennessee has developed a comprehensive list of candidate system components for consideration in the UTK Challenge X hybrid powertrain, and this is shown in the Appendix. The stock automatic transmission will be used as the basis for powertrain modeling and for screening of various drivetrain subcomponents. The team realizes that given a particular engine technology a more suitable transmission with different ratios would likely provide better results. Both compression ignition and spark ignition engines were considered in the component sizing process. The team also investigated nickel metal hydride and lead acid battery technologies as part of its selection process. Permanent magnet synchronous motors were chosen as the sole traction motor technology due to availability, past experience, and high efficiencies. Fuel cells were not considered in our screening process due to the fact that the UT team has no prior experience with fuel cells.

To reduce the size of the matrix to a manageable level and to identify the best candidates for further analysis and simulation, a power density metric was used for rapid screening. The power density for the stock vehicle was found to be 0.076 kW/kg. This value was used to determine sets of prospective engine and motor combinations to be used during the modeling and simulation phase of the design process. Combinations of engines and motors were grouped together that reasonably met this metric. Engine power output ranged from 50 kW to 100 kW, while motor power outputs ranged from 30 kW to 55 kW (battery limited). Estimated overall vehicle mass values were taken from the PSAT model for a given powertrain and component combination. Table 2 lists the power densities for the component combinations chosen for further simulation and analysis.

The engine displacement sizes examined during this analysis revolved around the fact that engine downsizing reduces fuel consumption. A parametric study of the

effects of engine downsizing, and consequently power downsizing, was blended into the study. The team desired to gain an understanding of the effects hybridization play on engine downsizing, and the trade-offs that might have to be considered when doing so. Compression ignition engines became the focus of the team when choosing engine components due to literature reviews and low speed torque characteristics of diesel engines.

Battery sizing is another critical area for the overall design. The nominal voltage, current sourcing and sinking limitations and capacity are all parameters that need to be determined. A low storage requirement (LSR) type of high voltage system has been proposed in the literature. The basic impetus for this approach is the overall reduction in weight of the high voltage battery pack that can be achieved by using a smaller capacity. The downside to this approach is the limited or near zero pure electric capability of the vehicle. Ni-MH technology quickly became the focus of the team due to higher efficiencies and potential availability. The team also investigated lead acid battery technologies due primarily to low cost and past team experience.

**Table 2 Power density matrix**

Powertrain Component Combination	Size	Mass (kg)	Battery Peak Power (kW)	Engine Peak Power (kW)	Power Density (kg/kW)
Stock		1814	N/A	138	0.076
Small engine (CIDI) / large battery		1904	60	51	0.058
Medium engine (CIDI) / large battery		1966	60	75	0.067
Large engine (CIDI) / small battery		1976	30	103	0.067
Large engine (SI) / small battery			30	100	

### WEIGHT ANALYSIS

A detailed base Chevrolet Equinox AWD weight analysis/breakdown has been received from General Motors and was used as the basis for the conceptual weight analysis of the conceptual hybrid design. The VTS requirement for the vehicle weight of the Team Tennessee vehicle is not to exceed 2000 kg. This is slightly lower than the original competition target due to the fact that the team recognizes vehicle weight is a critical factor when considering performance and fuel economy. Preliminary analysis of the base Equinox weight shows that the

expected weight reduction for stock items removed is approximately 320 kg. The items removed are summarized in Table 3. It should be noted that the majority of the items removed must be replaced in some form (for example, the engine). Additional components that are not part of the stock vehicle, such as the high voltage system, must be addressed. Since the team has adopted an LSR approach to the high voltage system, the mass of the high voltage battery pack is significantly reduced compared to previous team endeavors and high capacity battery packs. The high voltage battery and traction motor/inverter represent the most substantial weight increase for the vehicle. Preliminary estimates for these components are 86 kg for the Cobasys Ni-MH battery and 43 kg for the UQM SR218 traction motor and inverter assembly. This yields a hybridization weight premium of approximately 160 kg (including a 25% contingency for additional supporting equipment).

**Table 3 Base Equinox items to be removed**

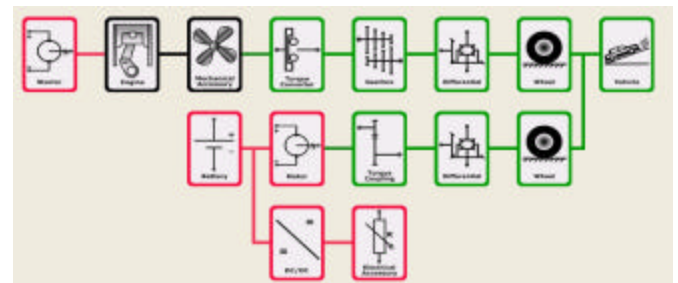
Description	Unit Mass (kg)	Qty	Total Weight (kg)
ENGINE ASM-3.4 L (207 CID)	164.40	1	164.40
TIRE-P235/65R16 N AL2 TL BW	13.06	4	52.26
EXHAUST SYSTEM	19.92	1	19.92
BATTERY ASM	15.02	1	15.02
DEADENER-FLR PNL	5.90	1	14.16
RADIATOR ASM-W/ A/C CNDSR & ENG	13.44	1	13.44
TANK ASM-FUEL	12.11	1	12.11
HOOD	8.45	1	8.45
CONVERTER ASM-3WAY CTLTC	6.94	1	6.94
GENERATOR ASM	6.53	1	6.53
STARTER ASM	2.95	1	2.95
HARNESS ASM-ENG WRG	2.42	1	2.42
MOUNT ASM-ENG	1.80	1	1.80
SHAFT-OUTPUTAWD	1.27	1	1.27
TOTAL			321.68

PSAT simulations have been ran which give limited insight to the mass differences for converting a vehicle from a conventional drivetrain to a hybrid configuration. Stock vehicle modeling estimated the vehicle mass to be 1816 kg (including cargo mass, fuel, and driver). This mass value is used as the basis for comparison during all modeling configurations. Table 2 contains the predicted vehicle masses for the simulated hybrid powertrains. The greatest mass was to be 2000 kg (4200 lbs), which falls in line with the team VTS mass requirements. Further weight reduction action items can be identified once a more formal packaging study and actual component selection and receipt has been completed.

**POWERTRAIN MODELING, SIMULATION, AND ANALYSIS**

Models were developed in PSAT that coincide with the subcomponent combinations and architecture prescribed by the team. A PSAT representation of this configuration is shown in Figure 6. A torque coupling was also introduced to provide flexibility in the gearing of the traction motor to the rear differential. Simulations were performed for the UDDS and HWFET cycles in order to determine a combined unadjusted fuel economy estimate

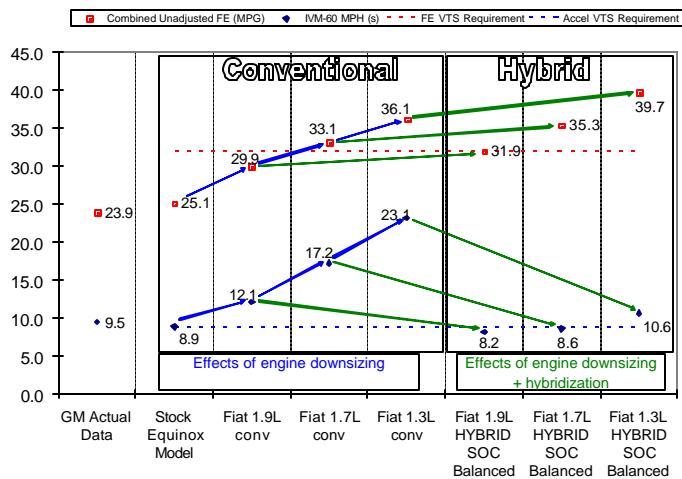
to use a basis of comparison to each other and to the VTS objectives.



**Figure 13 PSAT representation of a through-the-road parallel configuration**

The approach taken by the team was to first understand the benefits of engine downsizing on fuel economy. The purpose of this exercise was to determine if the VTS objective of 32 MPGe was obtainable. The compression ignition engines chosen as part of the powertrain sizing matrix shown in Table 2 were used to perform these simulations. The left half of Figure 7 illustrates the progression of engine size reduction on combined, unadjusted fuel economy. As shown here, the fuel economy targets can be achieved with the 1.7L and smaller Fiat CIDI engines. Consequently, the performance of each succeeding reduction yielded poorer performance. In order to capitalize on the fuel economy benefits while maintaining satisfactory performance, hybridization of these same powertrains were modeled and simulated to determine if the both the fuel economy and performance VTS targets could be satisfied.

The right half of Figure 7 represents a hybridized version of the same three (3) engines modeled as part of the engine downsizing exercise. The through-the-road model from Figure 6 was simulated in PSAT with the powertrain size combinations established earlier in this document. The results show that the combined fuel economy increases slightly while the IVM to 60 MPH times are significantly reduced. The increase in vehicle mass due to hybridization was accounted for in these simulations. The slight improvement in fuel economy, even with a heavier vehicle, can be accounted by engine start/stop operation during idle periods of the UDDS cycle and increased vehicle efficiency due to regenerative braking.



**Table 4 Simulation results for selected VTS targets**

Powertrain Component Size Combination	UDDS FE (MPGe)	HWFET FE (MPGe)	Combined FE (MPGe)	IVM to 60 MPH (s)
Stock (simulated)	21.4	31.8	25.1	8.9
Small engine (CIDI) / large battery	37.5	42.7	39.7	10.6
Medium engine (CIDI) / large battery	32.4	39.6	35.3	8.6
Large engine (CIDI) / small battery	28.9	36.6	31.9	8.2
Large engine (SI) / small battery				

**Figure 14 Comparison of engine downsizing and hybridization effects for core metrics for a through the road configuration**

Figure 7 implies that the medium engine (1.7L Fiat CIDI) / large battery and large engine (1.9L Fiat CIDI) / small battery combinations provide solution that are capable of meeting VTS requirements. However, when comparing the stock simulated Equinox to the actual data provided by GM, a discrepancy is noted of about 1.2 MPGe. Understanding this variation from actual data to simulated data, the team feels that the medium combination provides the best solution since the simulated fuel economy is slightly above the VTS target of 32 MPGe.

The team focused on three (3) core metrics for powertrain modeling that are taken directly from the team VTS. The results are summarized in Table 4. As noted previously, the medium engine/large battery combination provides the best combination for the powertrain to meet the VTS targets.

The top three (3) powertrain configurations based on the core metrics described previously were further evaluated to see if improvements could be made to increase parameters that were marginal.

## CONCLUSION

Team Tennessee has selected a thru-the-road parallel hybrid electric vehicle for Challenge X. The engine will be an approximately 75 kW CIDI engine; the motor will be approximately 75 kW peak permanent magnet, and the energy storage system will be approximately 60 kW peak power.

## REFERENCES

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2. Walters, Jim, Husted, Harry, and Rajashekara, Kaushik, "Comparative Study of Hybrid Powertrain Strategies," SAE 2001-01-2501, August 2001.
3. MacBain, John A., "Simulation Influence in the Design Process of Mild Hybrid Vehicles," SAE 2002-01-1196, March 2002.
4. McKeever, John W., Das, Sujit, Tolbert, Leon M., Marlino, Laura D., and Nedungadi, Ashok, "Life-Cycle Cost Sensitivity to Battery-Pack Voltage of an HEV," SAE 2000-01-1556, 2000.

## APPENDIX

### Candidate Electric Motor List

Company	Power (kW)	Torque (N*m)	Speed (rpm)	Voltage (min)	Voltage (max)	Weight	Type
UQM	35	380	4500	250	400		B, PM, DC
UQM	75	1700	1400	250	400		B, PM, DC
UQM	75	240	8000	250	400		B, PM, DC
UQM	100	550	5000	250	400		B, PM, DC
UQM	30	140	8000	250	400		B, PM, DC
UQM	50	240	8000	250	400		B, PM, DC
UQM	80	380	8000	250	400		B, PM, DC
	10		3000				PM, DC
	50	400	1540		500		
Audi	38	60	12500	200	380	48 lb	S, AC
Siemens	78.4	69	10000	160	380	108 lb	I, AC
Siemens	78.4	175	9700	215	380	150 lb	I, AC
Siemens	78.4	190	9700	215	380	200 lb	I, AC
Siemens	125	360	9700	500	650	264 lb	I, AC
Siemens	150	450	9700	650	650	264 lb	I, AC
MES	38	40	9000	185	400	83.6 lb	I, AC
MES	47.4	50	9000	185	400	91.3 lb	I, AC
MES	56.9	60	9000	185	400	100 lb	I, AC
MES	66.4	70	9000	185	400	109 lb	I, AC
MES	75.8	80	9000	185	400	117 lb	I, AC
MES	85.3	90	9000	185	400	125 lb	I, AC
MES	94.8	100	9000	180	400	134 lb	I, AC
AC Propulsion	150	225	12000	240	450	50 kg	
AC Propulsion	cost	column				30 kg	
Solectria	14	90	12000	288	336	43 kg	I, AC
Solectria	38			120	336	14.45 kg	I, AC
Solectria	14	900	1200	288	336	76 kg	I, AC
Solectria	34	369	8000	240	336	106 kg	I, AC
Solectria	34	369	8000	240	336	161 kg	I, AC
Solectria	34	250	8000	240	336	121 kg	I, AC
Solectria	45	875	4500	240	336	189 kg	I, AC
Solectria	53			120	336	27.5 kg	I, AC
Solectria	45	875	4500	240	336	257 kg	I, AC
Solectria	45	630	4500	240	336	217 kg	I, AC
Enova Systems	50	151					
Enova Systems	60	159	10000				
Enova Systems	90	239	10000				
Enova Systems	120	650	10000			56 kg	
Enova Systems	120	650	10000			65 kg	
Enova Systems	240	1300					

### Candidate Engine List

Engine NO.	Engine			Performance	
	Name	# cylinders / configuration	Displacement (liters)	Max. Power (hp)	Max. Torque (ft-lb)
1	Renault 2.2 dCI	I4	2.2	82	300
2	Renault 1.9 dCI	I4	1.9	66	320
3	Opel 1.7 CDTi	I4	1.7	75	240
4	Opel 1.9 CDTi	I4	1.9	112	315
5	Opel 2.0 Dti	I4	2.0	147	230
6	Alfa Romeo 2.0 JTS	I4	2.0	123	206
7	Alfa Romeo 2.4 JTD	I5	2.4	112	305
8	Alfa Romeo 2.4 JTD M-Jet	I5	2.4	131	385
9	Mercedes Benz E320 Cdi	I6	3.2	152	500
10	Mercedes Benz E220 Cdi	I4	2.2	110	339
11	Mercedes Benz E270 Cdi	I5	2.7	130	400
12	Mercedes Benz E400 Cdi	V8	4.0	194	560
13	Peugeot (DW10BTED4)	I4	2.0	101	339
14	Peugeot (DT17)	V6	2.7	154	597
15	Ecotec	I-4	2.2	104	206
16	Ford DOHC	I-4	2.3	107	202
17	Ford DOHC	I-4	2.0	97	183
18	Ford EEC-V	I-4	2.3	107	209
19	Ford EEC-V	V-6	3.0	110	251
20	Ford EEC-V	V-6	4.0	154	323
21	Duratec 23	I-4	2.3	114	206
22	Duratec 30	V-6	3.0	149	262
23	Detroit Diesel 425OHV	I-4	2.4	85	300
24	Detroit Diesel R425OHV	I-4	2.5	87	300
25	Detroit Diesel R315SOHC	I-3	1.5	66	180
26	Detroit Diesel R420SOHC	I-4	2	88	260
27	Caterpillar3044CT	I-4	3.03	60	258
28	Caterpillar 3054C	I-4	4.41	64	305
29	Caterpillar 3054E	I-4	4.41	64	305
30	John Deere 4024T	I-4	2.44	37	172
31	John Deere5030H	I-5	3.05	74	328
32	John Deere 3029T	I-3	2.9	48	245
33	Volkswagen 1.9 TDI	I-4	1.9	67	210
34	Acura	4 IL	2.4	149	225
35	Saab	4 IL-HO	2	169	294
36	Subaru	4 IL-HO	2.5	157	319
37	Mazda	4 IL	2.3	119	203
38	Mitsubishi	4 IL	2	202	370
39	Mitsubishi	4 IL	2.4	121	220
40	Nissan	4 IL	2.5	131	244
41	Volvo	4 IL	1.9	127	240
42	Volvo	5 IL	2.5	163	320
43	Volkswagen	4 IL	1.8	134	235
44	BMW	4 IL	2	112	199
45	Dodge	I-4 HO	2.4	172	339
46	Dodge	I-4	2.0	112	183
47	Chrysler	I-4	2.4	112	224
48	Chrysler	I-4 HO	2.4	164	332
49	Chrysler	I-4	2.4	134	285
50	Chrysler	V6	2.7	149	258
51	Jeep	I-4	2.4	110	224
52	Kia J3-Tdi	?	2.9	74	309
53	BMW 320d	?	2.0	82	447

Candidate Battery List

Lead Acid		Dimensions(mm):					
Company	Voltage	Capacity (Ah)	L	W	H	D	Mass (kg)
Haze - (China)	12	13	150	97	99	NA	4
Haze - (China)	12	13	150	97	99	NA	4
Haze - (China)	12	14	150	97	99	NA	4.75
Haze - (China)	12	26	165	174.5	125	NA	9.2
Haze - (China)	12	33	193.5	130	166.5	NA	10.4
Haze - (China)	12	44	196	164	170.5	NA	13.5
Haze - (China)	12	65	263	165	190	NA	21.5
Hawker Genesis	12	18	181.61	76.33	167.77	NA	6.4
Hawker Genesis	12	13	175.5	83.4	130	NA	4.9
Hawker Genesis	12	16	175.51	83.36	129.87	NA	6.1
Hawker Genesis	12	26	166.75	175.77	125.91	NA	10.1
Hawker Genesis	12	42	197.5	165.7	170.6	NA	14.9
Hawker Genesis	12	70	330.7	168.2	176	NA	24.3
PowerSonic	4	10	101.6	50.8	93.98		1.4074
PowerSonic	6	12	152.4	50.8	93.98		2.0884
PowerSonic	6	12	109.22	71.12	139.7		2.3608
PowerSonic	6	20	157.48	83.82	124.46		3.7228
PowerSonic	6	36	160.02	86.36	165.1		6.4014
PowerSonic	12	12	153.4	101.6	94	NA	4.17
PowerSonic	12	18	180.3	76.2	167.6	NA	5.94
PowerSonic	12	26	175.3	165.1	124.5	NA	8.48
PowerSonic	12	33	195.58	132.08	154.94	NA	12.031
PowerSonic	12	40	198.12	165.1	170.18	NA	14.0286
PowerSonic	12	55	241.3	139.7	205.74	NA	18.6594
PowerSonic	12	60	261.62	167.64	208.28	NA	23.7442
PowerSonic	12	75	261.62	167.64	208.28	NA	25.0154
PowerSonic	12	100	304.8	167.64	228.6	NA	30.872
PowerSonic	12	110	332.74	175.26	220.98	NA	35.412
PowerSonic	12	140	345.44	172.72	287.02	NA	47.67
Panasonic	6	12	151.13	50	94	NA	2
Panasonic	12	12	151.13	98	94	NA	3.79
Panasonic	12	17	181.1	75.9	166.9	NA	6.5
Panasonic	12	20	181.1	75.9	166.9	NA	6.6
Panasonic	12	28	165.1	125	175.3	NA	11
Panasonic	12	33	195.58	130	155	NA	12
EnerSys - Cyclon	2	12	NA	NA	123.2	51.8	0.84
EnerSys - Cyclon	2	25	NA	NA	158.8	65.3	1.67
EnerSys - Genesis	12	26	195.3	132.6	155.2	NA	10.6
EnerSys - Genesis	12	50	250.4	139.1	207	NA	17.7
EnerSys - Genesis	12	71	281.6	169.2	207	NA	23.5
EnerSys - Genesis	12	87	330.9	169.2	207	NA	27.7
EnerSys - Genesis	12	12	151	98	97.5	NA	4
EnerSys - Genesis	12	17.2	181	76.2	167	NA	6.2
EnerSys - Genesis	12	24	166	175	125	NA	8.65
EnerSys - Genesis	12	32.9	195.3	132.6	155.2	NA	10.9
EnerSys - Genesis	12	38	197	165	175	NA	13.8
EnerSys - Genesis	12	38	197	165	175	NA	13.8
EnerSys - Genesis	12	56.3	250.4	139.1	207	NA	18.7
EnerSys - Genesis	12	65	350	166	174	NA	22.8
EnerSys - Genesis	12	77.5	281.6	169.2	207	NA	24.9
EnerSys - Genesis	12	91.6	330.9	169.2	207	NA	29.8

Lithium Ion		Dimensions(mm):					
Company	Voltage	Capacity (Ah)	L	W	H	D	Mass (kg)
Saft - (France)	3.55	45	NA	NA	222	54	1.07
Saft - (France)	3.6	16	NA	NA	178	47	0.68
Saft - (France)	3.55	27	NA	NA	163	54	0.77
Saft - (France)	3.55	41	NA	NA	222	54	1.07
Saft - (France)	21.3/10.65	39/78	190	123	242	NA	8
Saft - (France)	21.3/10.65	43/86	190	123	242	NA	8
Metric Mind	3.6	40	195	115	46	NA	1.4
Metric Mind	3.6	80	230	145	63	NA	3
Metric Mind	3.6	160	295	182	71	NA	5.5

NiCd		Dimensions(mm):					
Company	Voltage	Capacity (Ah)	L	W	H	D	Mass (kg)
PowerSonic	1.2	7	NA	NA	33	91.4	3.72
PowerSonic	1.2	8	NA	NA	33	88.9	3.86
PowerSonic	1.2	8	NA	NA	33	88.9	3.86
Saft - (France)	1.2	7.7	NA	NA	89.1	32.4	0.228
Saft - (France)	1.2	11.6	NA	NA	89	41.2	0.39
Saft - (France)	1.2	8.8	NA	NA	88.8	32.2	0.208
Saft - (France)	1.2	7.7	NA	NA	89.5	32.4	0.21
Saft - (France)	1.2	12	64	123	264	NA	1.5
Saft - (France)	1.2	16	74	123	264	NA	1.8
Saft - (France)	1.2	19	57	195	349	NA	2.6
Saft - (France)	1.2	29	69	195	349	NA	3.4
Saft - (France)	1.2	39	79	195	349	NA	4.1
Saft - (France)	1.2	11	64	123	194	NA	0.9
Saft - (France)	1.2	15	74	123	194	NA	1.2
Saft - (France)	1.2	22	64	123	264	NA	1.5
Saft - (France)	1.2	30	74	123	264	NA	1.8
Saft - (France)	1.2	43	69	195	349	NA	3.4
Saft - (France)	1.2	16	53	123	194	NA	1.1
Saft - (France)	1.2	30	74	123	264	NA	1.8
Saft - (France)	1.2	37	57	123	264	NA	2.6
Saft - (France)	1.2	45	98	195	349	NA	2.5
Saft - (France)	1.2	48	57	123	264	NA	3.2
Saft - (France)	4.8	16	133	123	270	NA	6.1
Saft - (France)	6	16	162	123	270	NA	7.6
Saft - (France)	7.2	16	191	123	270	NA	9.1
Saft - (France)	4.8	24	153	123	270	NA	7.3
Saft - (France)	6	24	187	123	270	NA	9
Saft - (France)	7.2	24	221	123	270	NA	10.7
Saft - (France)	4.8	32	201	123	270	NA	10
Saft - (France)	6	32	247	123	270	NA	12.4
Saft - (France)	7.2	32	293	123	270	NA	14.8
Saft - (France)	1.2	11	46.5	86	196	NA	1
Saft - (France)	1.2	16	46.5	86	276	NA	1.5
Saft - (France)	1.2	21	46.5	86	276	NA	1.6
Saft - (France)	1.2	24	46.5	86	276	NA	1.7
Saft - (France)	1.2	28	61	86	276	NA	2
Saft - (France)	1.2	80	68	192	352	NA	6.9
Saft - (France)	1.2	130	68	192	352	NA	7.5
Saft - (France)	1.2	165	93	192	352	NA	9.9
Saft - (France)	1.2	200	93	192	352	NA	10.6
Saft - (France)	2.4	35	68	195	349	NA	5
Saft - (France)	3.6	35	88	195	349	NA	8
Saft - (France)	6	35	137	195	349	NA	13
Saft - (France)	2.4	70	85	195	349	NA	8
Saft - (France)	3.6	70	121	195	349	NA	12
Saft - (France)	6	70	192	195	349	NA	21
Saft - (France)	1.2	70	158	169	305	NA	13
Saft - (France)	1.2	80	158	169	305	NA	13
Saft - (France)	1.2	90	158	169	305	NA	14
Saft - (France)	1.2	100	188	169	305	NA	16
Saft - (France)	8.4	93	266	171	259	NA	18.9
Saft - (France)	9.6	93	303	171	259	NA	21.5
Saft - (France)	12	93	375	171	259	NA	26.8
Saft - (France)	13.2	93	412	171	259	NA	29.4
Saft - (France)	6	100	248	120	260	NA	12.9
Saft - (France)	6	100	246	123	260	NA	13.2
Saft - (France)	6	136	244	153	260	NA	17
Saft - (France)	1.2	16	46.5	86	196	NA	1.1
Saft - (France)	1.2	21	46.5	86	196	NA	1.1
Saft - (France)	1.2	29	61	86	196	NA	1.5
Saft - (France)	1.2	36	86	86	196	NA	1.9

Silver-Zinc		Dimensions(mm):					
Company	Voltage	Capacity (Ah)	L	W	H	D	Mass (kg)
Saft - (France)	1.45	120	80	68	184	NA	1.4
Saft - (France)	1.45	40	80	35	178	NA	0.625

	NiMH		Dimensions(mm):				
Company	Voltage	Capacity (Ah)	L	W	H	D	Mass (kg)
Cobasys	12	8.8	323	45	86	NA	2.4
Cobasys	12	43	303	130	151	NA	11.7
Cobasys	12	54	303	130	151	NA	11.8
Cobasys	12	85	375	102	176	NA	17.4
Cobasys	144	17	860	850	210	NA	90
Cobasys	288	17	860	850	210	NA	150
Cobasys	336	17	860	950	210	NA	170
Cobasys	576	17	860	850	420	NA	300
Cobasys	672	17	860	950	420	NA	340
Saft - (France)	12	100	390	120	195	NA	18.6
Saft - (France)	24	100	760	120	195	NA	37
Saft - (France)	1.2	15	NA	NA	89.1	32.3	0.25
Saft - (France)	1.2	16	NA	NA	89.1	32.3	0.25
Saft - (France)	1.2	11	NA	NA	89.1	32.3	0.25
Saft - (France)	1.2	14	NA	NA	93	41	0.37
Rabbit Tool	12	15.2	NA	NA	432.3	57.15	1.47
Rabbit Tool	12	16.8	NA	NA	421.6	57.15	2.88
Rabbit Tool	12	18	NA	NA	215.9	101.6	3.9
Rabbit Tool	12	26	NA	NA	303.3	101.6	5.81
Rabbit Tool	12	36	NA	NA	398.526	101.6	7.6726
Rabbit Tool	12	52	NA	NA	573.024	101.6	11.4862
Rabbit Tool	18	18	NA	NA	336.55	101.6	5.8566
Rabbit Tool	18	36	NA	NA	482.6	101.6	8.7168
Rabbit Tool	24	13	NA	NA	303.276	101.6	5.8112
Rabbit Tool	24	18	NA	NA	398.526	101.6	7.6726
Rabbit Tool	24	26	NA	NA	573.024	101.6	11.4862
Rabbit Tool	36	13	NA	NA	482.6	101.6	8.7168
Rabbit Tool	42	13	NA	NA	482.6	101.6	10.0334
Rabbit Tool	48	13	NA	NA	573.024	101.6	11.4862
Rabbit Tool	1.2	8.5	NA	NA	61.6	32.2	0.173
Rabbit Tool	1.2	12	NA	NA	90.5	32.2	0.258
Rabbit Tool	1.2	20	NA	NA	91.2	41.5	0.411