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University of Tennessee 1995 Hybrid Electric Vehicle Design

1995 HEV Design Class

ABSTRACT

Engineering students at the University of Tennessee, Knoxville have converted a 1995 Dodge Neon into a hybrid electric vehicle. The vehicle features a parallel drive system incorporating a one liter displacement engine fueled with compressed natural gas, a brushless permanent magnet DC electric motor, a 200 volt lead-acid battery pack, and special low rolling resistance tires. Vehicle emissions are controlled by the use of an electronic engine control system, multi-point port fuel injection, and three-way catalysts formulated for natural gas. The vehicle also features a heating and air-conditioning system powered from the battery pack using heat pump technology and a "heat battery" for storing waste energy from the engine.

The completed vehicle has a pure electric predicted range of 19.3 km at a steady speed of 56.3 km/hr and, when fueled with natural gas at 25 MPa, has a predicted range of over 400 km at a steady speed of 88.5 km/hr. The vehicle should accelerate to 100 km/hr in 13.5 seconds. Although there is some loss of available trunk space, the passenger space remains unaffected by the conversion.

INTRODUCTION

In the winter of 1994, Engineering students at the University of Tennessee were presented with the opportunity to submit a proposal to receive a Dodge/Plymouth Neon for hybrid electric conversion and competition in the 1995 Hybrid Electric Vehicle Challenge. Over the following weeks, a group of students put together a proposal for the conversion of this vehicle which demonstrated the technical feasibility, innovation, commitment, and capability of the University of Tennessee to design and construct a competitive entry. On March 30, 1994 the final decision of which proposed schools would receive one of the twelve 1995 Dodge Neons was made and the proposal of the University of Tennessee, Knoxville was deemed worthy. With this successful effort began a year long process of

fund raising, conceptual design, implementation, and evaluation of the student designed hybrid electric vehicle conversion.

For summer term 1994, a special topics class devoted solely to the task of assessing the stringent requirements of the Neon class was offered. Students were presented with draft rules for the competition and the process of identifying major obstacles to be overcome began. After careful examination of the draft rules, items of most concern to team members were the implementation of a suitable heating and cooling system for the passenger compartment (a feature never before required of a hybrid electric competition vehicle), configuration for the drivetrain and the selection of an appropriately sized electric motor, heat engine and coupling methods necessary to meet acceleration requirements, subsequent conversion of the heat engine to use compressed natural gas (CNG) as its fuel, and packaging of these and other vehicle systems in a manner that would not be merely acceptable to today's environmentally conscious consumer, but furthermore desirable. The topics of concern mentioned above as well as other important aspects of the University of Tennessee's entry in the 1995 Hybrid Electric Vehicle Challenge are included in this report with detailed descriptions of the steps taken by each design subgroup to ensure that the completed vehicle, more than just the sum of its mechanical and electrical components, is a success.

OVERALL DESIGN CONCEPT

CONFIGURATION DECISION- The first draft of rules required the acceleration for the Neon HEV to be 0 to 100 kph in no more than 15 seconds. During conceptual design, the HEV Design Team deliberated between a series or parallel configuration with this requirement in mind. With the aid of a specialized EV software package, the design team was able to predict the performance characteristics of each configuration.

The series configuration demanded that either one large electric motor or two smaller electric motors be

used in order to adequately accelerate the vehicle. Modeling showed that a single large electric motor would more than adequately accelerate the vehicle, but motor efficiencies severely decrease under cruise conditions. Similarly two smaller electric motors would adequately accelerate the vehicle, but cost effectiveness and packaging presented problems which could easily be avoided by employing a parallel configuration. Also, overall efficiencies could be compromised since fuel energy must be multiplied by several efficiencies before reaching the drive wheels.

With a parallel configuration the software predicted that a medium sized APU and a medium sized electric motor could easily accelerate the vehicle quickly enough to meet the 0 to 100 kph requirement as stated in the first draft of competition rules. To maintain cost effectiveness and packaging simplicity the electric motor was chosen to assist the APU in lieu of being the primary power source. In this manner the electric motor would provide extra power under load conditions or power the vehicle in ZEV mode.

Simulations using both SIMPLEV and student-written software provided information relative to the drivetrain decision. Acceleration predictions in Table 1 provided the final data for the design decision.

Driveline Configuration	0-100km/h times
• Uniq Mobility SR-180	20.0 seconds
• Gasoline-powered Geo	31 seconds
• Uniq Mobility SR-180 and CNG-powered Geo	13.5 seconds

Table 1: Acceleration Design Predictions

COMPONENT SELECTION- Each individual subsystem is addresses in the following sub-headings:

Auxiliary Power Unit- The engine choice to be used as the APU for the Neon was based on size, weight, orientation, and power capabilities. The engine must be light to improve the efficiency of the vehicle and also to keep the weight of the Neon within the limits set by the competition rules. It must be small enough to fit in the allotted space while still allowing room for the electric motor and drive train components and it should be liquid cooled since there won't be adequate room for the ventilation required by an air cooled engine. The engine should also have as few cylinders and as low a displacement as possible in order to reduce friction and pumping losses respectively and to minimize emissions.

For these reasons, a 1.0L Suzuki/Geo engine was selected for our application. The 1.0L Suzuki/Geo engine is one of the smallest and lightest 4-stroke engines available. It is comprised of three cylinders, is liquid cooled and produces about 55 hp stock. Figure 1 shows a cross-sectional view of this engine.

APU Modifications- The APU was modified to run on compressed natural gas (CNG) by first raising the engine's compression ratio. This was accomplished by

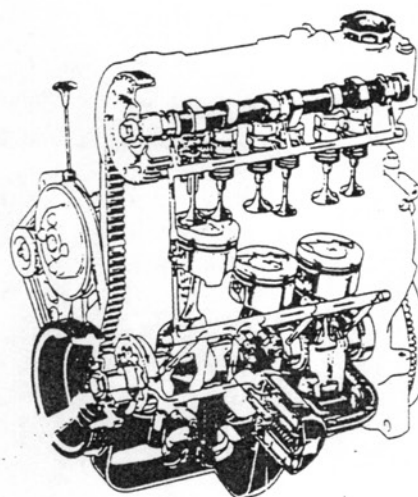


Figure 1: The 1.0L Suzuki/Geo Engine

milling material from the face of the cylinder head in order to reduce clearance volume. The operation is common, fairly quick and economical, and could be performed at a local engine machine shop. The decrease in clearance volume is based on the thickness of material milled from the face and was then approximated assuming that the cross-sectional area of the chamber remains the same. The compression ratio was calculated as follows:

$$\text{Compression Ratio} = \frac{\text{Vol.}_{\text{swept}} + \text{Vol.}_{\text{clearance}}}{\text{Vol.}_{\text{clearance}}} (1)$$

This method is considered acceptable as the actual compression ratio will actually be somewhat greater than that indicated by calculations based on this assumption. The maximum removal thickness was set at 3.048 mm in order to avoid milling through the sides of the threaded bolt holes used for mounting the intake and exhaust manifolds.

The head was milled in two steps so that the valve clearance could be checked intermittently. With 2.032 mm removed from the head, the compression ratio was increased from 9.2:1 to 9.9:1. The valve clearance was found to be adequate for further milling of the head and an additional 1.016 mm was removed from the head to give the maximum (3.048 mm) removal. This finally raised the compression ratio to 11.1:1 and a valve clearance in excess of .6350 mm.

Due to the head milling procedure, timing belt tension and timing adjustments were made. The existing stock tensioner was inadequate to take up the slack resulting from the milling procedure. The problem was resolved by installing a stock tensioner off of a Geo Sprint which has a larger radius of approximately 5 mm.

The engine was completely rebuilt, including the replacement of all the gaskets and bearings, the oil pump, and the water pump. The decision was made to use oversize pistons even though no compression gain

would be achieved. Boring the engine to accept oversize pistons would allow proper cross hatch to be established for correct ring seating. The crankshaft/connecting rod/piston assembly was also performance balanced to minimize vibration and the crankshaft was polished for proper bearing contact. A three angle valve job was performed to ensure proper seating between the valves and the cylinder.

The decision was made to use multi-port fuel injection in the three cylinder Suzuki engine. The injectors were placed directly in the head. This decision was made because of the better emissions that can be achieved with multi-port as compared with throttle-body injection. With multi-port fuel injection, each cylinder receives a more equal distribution of fuel. With throttle-body injection, it is nearly impossible to distribute an equal amount of fuel between each of the three cylinders.

Initially, the injectors were to be placed on the runners of the intake manifold. However, after further investigation, it was determined that the injectors could be readily placed in the head. The decision was made to place the fuel injectors directly into the cylinder head rather than in the intake manifold. This was accomplished by drilling and boring a hole directly into each intake port. The engine head was designed by Suzuki so that a fuel-injected model of the engine could be produced with only an additional drilling process. The placement of our injectors utilizes this provision. The three 19.05 mm diameter holes each hold a fuel injector boss which was welded to hold it in place. The fuel injectors were then placed into the bosses and held in place by the fuel rail.

The first step in fuel injector selection was to determine the required fuel flow of natural gas. The following formula is a good guideline:

$$Q = \frac{\text{Max HP} * \text{BSFC}}{\# \text{ cylinders}} \quad (2)$$

Assuming a BSFC of 0.45 for a naturally aspirated engine and maximum horsepower of 37 kW, the flow required per injector reduces to 56.7 g/min of natural gas at 689 kPa. BOSCH has developed an empirical relationship between static flow of N-heptane and Natural Gas in the form of :

$$Q\text{-stat N-heptane} * 0.0842(270 \text{ kPa/P}) = Q\text{-stat CNG} \quad (\text{at } 689 \text{ kPa}) \quad (3)$$

where P is the testing pressure. Based on the conversion the injector should support 673 g/min of N-heptane.

With the flow requirement determined a supplier had to be determined. SIEMENS donated two complete sets and were enthusiastic to help in any way they could. Based on their experience with Natural Gas they have found that 14.9 kW requires 56.7 g/min of CNG at

689 kPa. This correlates exactly with our prediction. They were willing to donate 3 injectors immediately that flow at 642 g/min at 689 kPa. This will support approximately 33.56 kW. However, increasing pressure to around 758.4 kPa will increase the flow to 672.8 g/min. These injectors have a coil resistance of 2.4 Ohms, which makes it favorable since the TEC 2 injector output is designed around this resistance. After testing is complete, they are going to supply an additional complete set of injectors for spares at the competition. These injectors are designed to provide a linear flow rate over a duty cycle range of about 35-85 percent.

An after market engine controller had to be chosen that would operate the Suzuki engine with Natural Gas as the fuel. This engine controller also had to be very flexible and programmable, as to allow optimum power and minimum emissions to be produced.

Many engine controllers were investigated, but the Electromotive TEC 2 seemed to be the best suited for the task. Reasons include the fact that it is engine-mountable (good for operation on the dyno), it has a programmable general purpose output (good for controlling EGR), it has distributorless ignition coils that fire the plugs with 120mJ for duration of 1200 μ sec (thorough burn helps emissions and power drastically), and people in the project were already familiar with the Electromotive system and its calibration tools.

APU Testing- The natural gas GEO engine was operated on an engine dyno to calibrate the fuel delivery and ignition, as well as estimating operating parameters that could be expected when the engine would later be in the vehicle.

The approach to this calibration was simple but time consuming. After the hardware aspect of the fuel and ignition system were in place, it was time to crank and start the engine. After successful starting, the next goal was to rough-out the fuel management curves to provide a running condition at all operating points. Then, the volumetric efficiency table would trim out the injections in order to keep EGO closed loop feedback error to a minimum.

The group and faculty advisor felt the need to verify that the measured A/F ratio was accurate. To do this, % CO was measured on the two different exhaust analyzers as a function of measured A/F ratio. According to both analyzers, the elbow of the %CO curve (the theoretical stoich point) landed around 13.8 A/F ratio. This trend can be seen in Figure 2.

According to theory, the stoich point for Natural Gas should be a gravimetric 17.1. This represents considerable error between the determined stoich point and what the TEC 2 was reporting. The values obtained from the Portable Gas Analyzer (and Sun Analyzer) were considered more accurate and therefore the calibration was adjusted as needed, using the TEC 2 measured value of 13.8 as stoich.

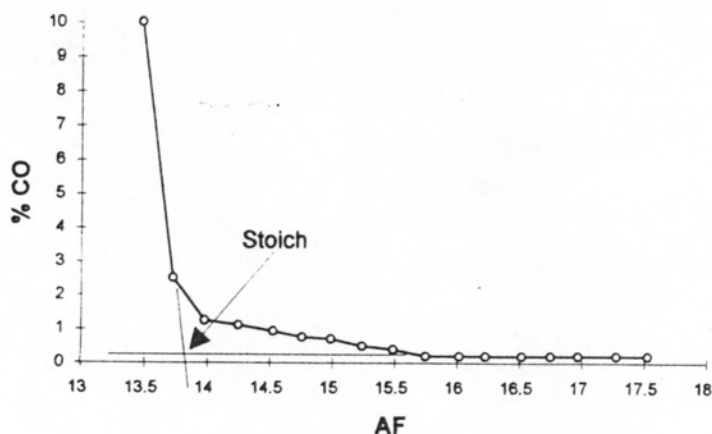


Figure 2: Percent CO Based on Air/Fuel Ratio at 1800 RPM, 55 kPa and 0.9 TPS

The process of selecting a suitable raw fuel curve consisted of manual trial and error runs. As the curve was adjusted, EGO correction was monitored at a range of operation points. As these corrections came closer to zero, the raw curve improved, by nature. Final values were 0.375 for IOT and 6.5 for TOG (see Electromotive TEC 2 manual for a description of these parameters). After the raw fuel values were obtained, it was decided to raise the fuel pressure in order to bring the pulsewidth back down. Based on the injector pulsewidths and the expected operating speed of the engine, it was determined that the current pulsewidths might be exceeding the recommended 85% duty cycle of the injectors. By raising the fuel pressure from 95 to 110 psi, the pulsewidth was decreased two to four tenths of a millisecond. The raw fuel curve was based on the parameters chosen, being that the injectors would all fire simultaneously (every other spark event - 1.5 times per revolution).

The volumetric efficiency table is designed to compensate for the non-linearities in the fuel delivery map of an internal combustion engine. Additionally, since the dyno fuel pressure regulator is not manifold pressure referenced (by design), the Volumetric Efficiency (VE) table must take into account the varying pressure difference across the injector as MAP varies. The VE table was completed by iteratively examining the EGO correction at each operating point in the map.. Then, the VE table was adjusted accordingly such that the EGO would have to correct a minimum amount.

The spark advance table was also done iteratively by measuring the minimum advance for best torque (MBT) at each operating point in the table. The crank angles obtained were treated with some skepticism, however, as the torque output reading on the dyno was very unstable and undependable. The reading would change dramatically from day to day, as well as the inability to keep the torque constant while the engine was held at steady state. The sheared crank index key, later found, was likely the cause of most of this scatter.

Fuel enrichments were then handled. It was found that virtually no startup or temperature enrichments were needed, due to the use of a gaseous fuel. The acceleration and deceleration enrichments were left for in-car tuning.

The intake runner lengths were then varied, starting from 610 mm and being cut in 50 mm intervals down to 355 mm. The minimum practical length due to the distance from the plenum to the head flange was 355 mm. It was found that runner length did not affect low end (below 2000 RPM) or top end (above 3600 RPM) performance. Mid range performance greatly favored longer runners. It was proven that 510-560 mm runners were optimum.

Problems were encountered while the engine was on the dyno pad. First, due mainly to the rigid mounting of the engine, severe vibrations and noise in the 1800 - 2200 RPM range were encountered. These vibrations had many ill side effects on sensor readings (RPM) and caused bolts to loosen and back out of place. A problematic situation arose when it was discovered that the key which indexed the front crank pulley onto the crank had sheared and deformed. This had created approximately 11 degrees of slop in the spark and 5.5 degrees of play in the cam timing. We were left with few options, and decided to install a straight key and run 6 degrees of cam retard. This was chosen over 3 degrees of advance (the other belt placement option) as to increase the top-end performance, where we seemed to be lacking. A lack of time forced us to accept this cam timing as the best option.

Lastly, as shown in Table 2, we measured EGT with a probe inserted in the center of the exhaust manifold. We tested a typical operating range of 2 engine speeds and a variety of loads. Also, engine friction and accessory losses were measured. Friction was measured in two ways: steady MAP - various RPM, and steady RPM with various MAP. As expected, friction increases nearly linearly with speed. On the MAP test (throttling losses) the torque required to turn the engine at 2300 RPM ranges from 13.6 N*m to 10.8 N*m as the throttle is opened from nothing to WOT.

RPM 2300	
MAP kPa	Temp C
40	549
50	616
60	640
70	649
80	667
90	686

RPM 3200	
MAP kPa	Temp C
40	549
50	616
60	640
70	649
80	667
90	686

Table 2: Exhaust Gas Temperature Study

Electric Motor- The electric motor is a Unique Mobility SR180P, DC permanent magnet, Neodymium Iron Boron, synchronous motor. This motor is rated at

31.3 kW for continuous operation, with a peak intermittent rating of 46.2 kW. The continuous stall torque is 57.6 N*m and the intermittent stall torque is 81.3 N*m (power and torque ratings are for an input voltage of 195 V). This motor offers regeneration to zero speeds, four quadrant operation, high efficiency, and closed loop speed control. Dynamometer test were run on the motor to check the efficiency and power of the motor. Figure 3 shows manufacturer specifications of torque and efficiency for the motor. This motor is air cooled, and utilizes a fan to force air through the windings. The maximum winding temperature is 149 °C.

The motor controller for this motor was a Unique Mobility CR20-300. The controller has a maximum voltage input around 200 volt DC and current rating of 275 Amps. The controller contains all the electronics and software necessary to operate the motor.

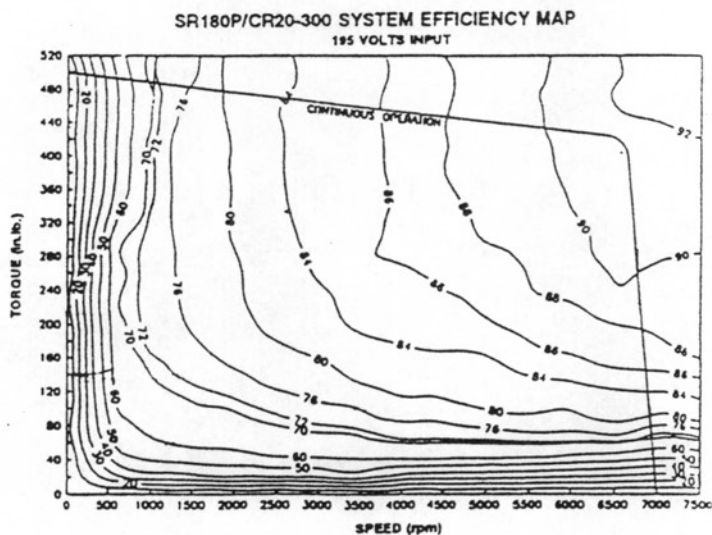


Figure 3: System Efficiency Map of Unique Mobility SR180P Electric Motor

Battery Pack- Lead-Acid U1 DC-9 batteries manufactured by Exide Co are the main electrical energy storage device chosen for the UT HEV. Lead-acid batteries provided several advantages over other types of batteries including commercial availability, recyclability, and cost. The U1 DC-9 was chosen because of its light weight, small size, and required performance. Initial calculations predicted that the pack must deliver 1.49 kWh to meet the ZEV range requirement and 2.49 kWh to meet the HVAC system power requirements during the heating-mode test. In accordance with these requirements, the final battery pack met the specifications in Table 3.

To confirm the capability of the battery pack under competition test conditions, several tests using the main traction motor have been conducted. These dynamometer tests have confirmed that the battery pack does meet the requirements of the competition and also have provided characteristics of the battery pack. For

Exide U1 DC-9

Dimensions:	h: 18.6 cm
	w: 19.7 cm
	d: 13.2 cm
Number of batteries:	16 units
Weight per battery:	9.3 kg
Nominal pack voltage:	192 V
Cell Capacity:	17.3 Ah
Total pack energy:	2.9 kWh

Table 3: Battery Pack Specifications

example, the constant current energy draw characteristics are shown in Figure 4.

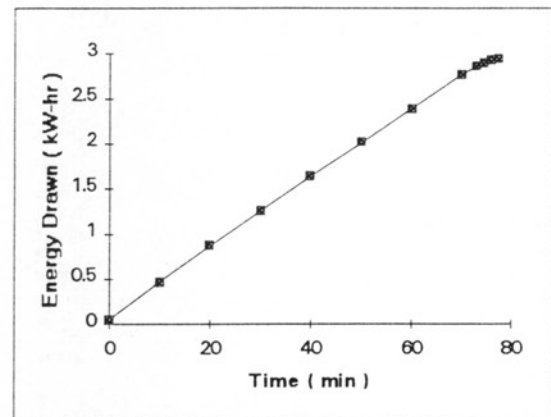


Figure 4: Constant Current Test - 13 A

The chosen charging system is manufactured by Good-All Electric and provides 90+% of full state of charge in only two hours of charging. The system uses a maximum 13A charging current.

Fuel System- Throughout the design of the CNG fuel storage and delivery system, the primary considerations were safety and the steady, efficient delivery of compressed natural gas to the fuel rail of the engine. The schematic design of the system is shown in Figure 5. The fuel system was designed and installed beginning at the CNG storage cylinder and stopping at the inlet to the fuel rail of the APU.

Several factors played a part in the selection of the CNG storage tank location and type. Safety of the vehicle passengers from gas exposure and protection of the storage cylinder from impact damage were large concerns. In addition, it was in the best interests of the team, and sound design practice, to achieve the largest reasonable storage capacity possible. Tank placement was also affected by the size and type of tanks available for application. The choice was made to use one storage cylinder which is 406 mm in diameter and 848.4 mm long. It was placed in the trunk directly behind the rear seat of the vehicle. The tank is an EDO Literider Model 80, which has an internal volume of 75,495 cubic centimeters and weighs only 24.5 kg when empty. It is certified to ANSI AGA NGV2, and its maximum operating pressure is 25 MPa. The EDO was selected over other brands due to its lightweight but durable

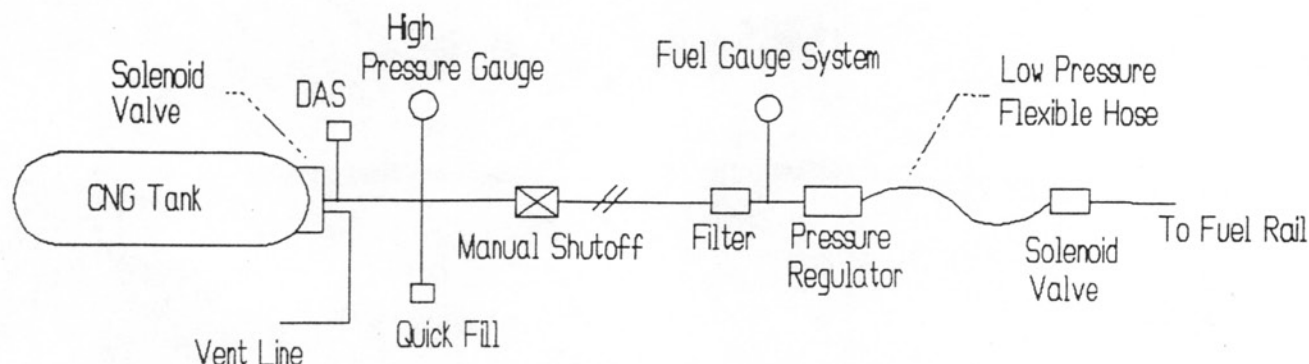


Figure 5: Fuel Supply System Schematic

fabrication. Since it is lined with thermoplastic rather than steel, its empty weight is almost half that of steel-lined cylinders of the same size.

Other options given serious consideration were the use of two smaller cylinders mounted either on the vehicle underbody under the rear seating area or under the rear seat above the floorpan. The choice which was made allows for a larger storage capacity while still weighing less than the other two options. The lone disadvantage seen with this choice was the trunk space which was eliminated by the CNG cylinder. Consumer acceptability is also a consideration of the HEV Challenge, so it was desired to not reduce passenger or cargo space in the vehicle. The cylinder arrived equipped with mounting brackets from EDO. It is of course imperative that the CNG cylinder be secure and protected from a severe impact. The brackets from EDO employ very high factors of safety in assuring that the tank will not be damaged or broken free. The tank solenoid valve located on one end of the cylinder was also obtained from EDO and it serves as an automatic lock-off valve. It extends 50 mm from the end of the cylinder and it houses the natural gas ports.

The next consideration was the design of the fuel fill area located at the stock fuel door of the Dodge Neon. All gas lines run from the tank to the fuel door were 3/8-inch stainless steel tube except for the 1/4-inch stainless steel venting line routed from the tank to the exterior of the vehicle. In order to route lines to the fuel door, a 76.2 mm hole was drilled in the right rear wheel well, and a 101.6 mm long threaded PVC tube was fitted in the opening and sealed with a polyurethane washer. The 3/8-inch gas line delivers compressed natural gas from the tank to a four-way cross connection located on the interior side of the wheel well. From the other three connections, gas flow is delivered to: 1) a Staubli quick-connect fuel fill, 2) a Noshok high pressure gage, and 3) a 1/4-turn manual shut-off valve. All three of these components are securely mounted to a plate of 16-gauge mild steel which is bolted to the fuel door. An earlier design had the manual shut-off valve placed on the body frame under the side of the vehicle. However it was later decided that it was feasible to mount all three components behind the fuel door. It is believed that this

is a far better design than before because the manual shut-off is much more quickly accessible and convenient. The 1/4-turn shut-off is a ball valve that is open while pointing toward the front of the vehicle and closed when pointing away from the car. There was no modification to the exterior of the fuel door, so its appearance and operation were not altered. In addition to the three gas lines exiting the trunk through the wheel well, the 1/4-inch vent line also exits and follows the wheel well to the underbody of the car where it vents under the trunk toward the rear.

Upon exiting the manual shut-off valve at the fuel door, the gas line is stepped down to 1/4-inch. The line follows the wheel well to the underside of the car. It routes along the frame near the side of the vehicle until it is past the battery pack which is mounted under the rear seat. Insulated line hangers were used to support the stainless steel fuel lines every 0.6 m or so. Once clear, the line takes a turn to the center of the car's underside in order to run along the path of the old gas lines of the Neon. This path also leads it straight to the regulator.

The Tescom pressure regulator was chosen mainly due to its reputation as a reliable source of steady gas delivery. It has a unique piston shape design that helps it avoid pressure surges or drops when handled roughly. Its location is directly in the center tunnel formerly occupied by the Neon exhaust. Now it shares the area with the car's exhaust. A 15 micron filter is located in the gas line just before it enters the regulator. The regulator has a filter built-in, but Tescom recommended installing another finer one. The 1/4-inch port on the regulator receives the high pressure CNG and distributes gas at 792 kPa through its 3/8-inch outlet. The end of the piston-shaped regulator contains the water flow inlet and exit.

The low pressure gas travels through flexible hose to a solenoid in the engine compartment. Both this and the tank solenoid wires run separately to the TEC-2 motor controller. The flexible hose carries the 792 kPa compressed natural gas to the fuel rail. A fuel gage kit is installed to read the high pressure side and relay that fuel level to the stock Neon fuel gage.

Power Transmission- To achieve a motor-assist configuration, an overrunning sprag type clutch was

used in conjunction with the stock Neon clutch. This allows the APU to deliver power to the transaxle to drive the vehicle or provide power to the electric motor to charge the batteries during operation. Since the motor doubles as a generator, it can either supply power to or receive it from the APU saving weight on a separate generator system.

To handle the power transfer between the electric motor and the APU, a Warner Electric FSO sprag clutch, model 400, was chosen. In order to maintain optimum operating speeds for both power sources, a motor to APU ratio of 1.3 to 1 was selected using Gates sprockets and a 36 mm wide Polychain (a durable toothed belt recommended by Gates for this particular application). For a parallel configuration a jack shaft had to be designed for the electric motor to be connected to the power transmission system. The design of the jackshaft incorporated the overrunning clutch, sprockets and a support bearing. The bellhousing was then designed with a threefold purpose of aligning and mounting the APU to the transaxle, mounting the electric motor to the APU, and to protect against high speed rotating parts in the event of breakage. Figure 6 shows an assembly drawing of the power transmission components.

Auxiliary Components- A DC-DC converter, built by Mesa Power Systems was chosen to replace the alternator used in the original Neon. This saved space under the hood needed to mount the motor and APU in a parallel configuration. The DC-DC converter was primarily used to charge the Neon's 12 volt battery and to power non stock systems such as the battery pack fans and HVAC controller.

A 250 volt and 300 Amp breaker was chosen as the battery disconnect switch. To comply with the regulations on switch location the breaker was located immediately to the rear of the main battery bank. The switch to trip the breaker was located between the driver seat and door. This location met both of the regulations imposed by the rules, section 16.7, by allowing the driver to easily throw the switch from inside or outside the car.

The original power rack and pinion steering system in the Neon was replaced with a manual steering unit. This opened space under the hood and saved 5.44 kg in weight. The manual rack had a gear ratio that allowed the Neon to U turn within a 12 m circle which was the requirements of the rules in section 16.17.

A vacuum pump was required to operate the brakes and HVAC in ZEV mode. A pump was obtained and connected to a reservoir via a 1/4" vacuum tubing.

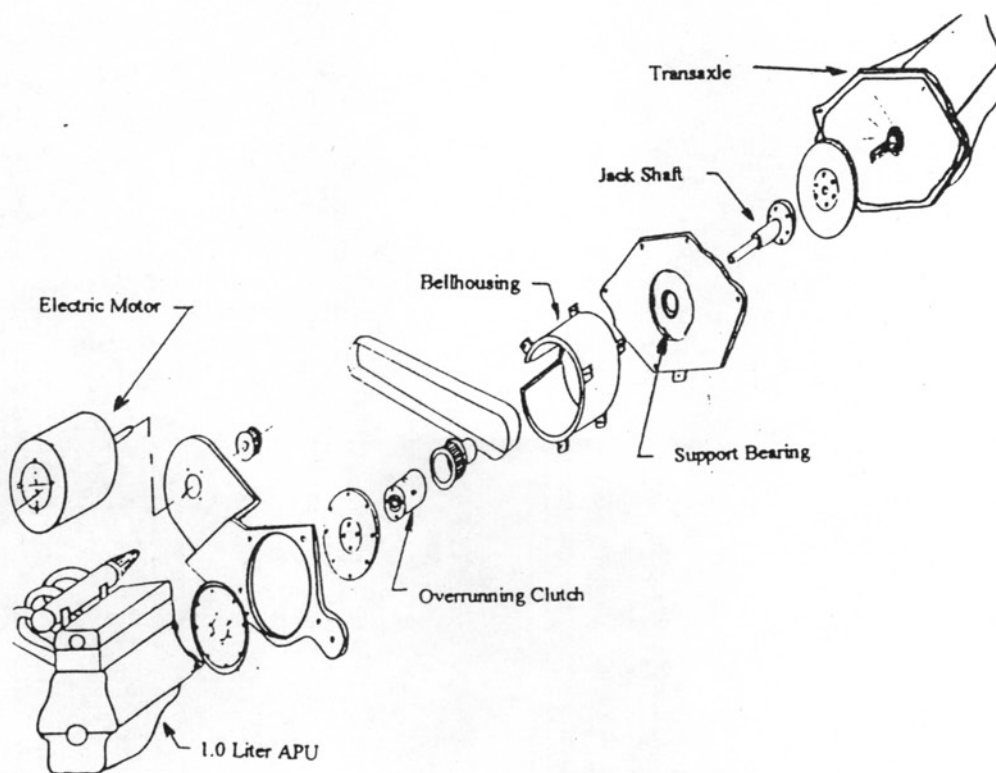


Figure 6: Assembly of Power Transmission Components

The pump was connected to a pump switch which was connected to a relay. When the pump switch loses vacuum the relay sends a signal to the pump to come on. The intake manifold was also connected into the vacuum system with a check valve. By doing this the pump does not have to run in the HEV mode.

HVAC- See HVAC Section.

SYSTEM PACKAGING- In keeping with the KISS principle (Keep It Simple, Student) the design team strived to make the packaging appear simplistic and aesthetically pleasing. Care was taken to maintain the original design considerations as first envisioned by Chrysler engineers. For instance, careful deliberation was taken in choosing the locations of the CNG tank and batteries. The CNG tank was mounted in the trunk between the rear strut towers for three reasons. First, the design team felt that the tank would be better protected in the trunk rather than under the vehicle. Also, capacity to weight ratio for a single large tank is less than two smaller tanks of equivalent capacity that would be required for mounting under the vehicle. Lastly, this mounting location eliminates the need to raise the rear seat pan to heights which may be uncomfortable for taller passengers. Although significant trunk space was lost, the rear fold down seat feature was utilized to service the fire suppression system as well as the HVAC controller.

In conjunction with determining the location of the CNG tank, the location of the batteries was chosen to be under the rear seat. This design consideration provided better weight distribution than locating batteries in the trunk and the CNG tanks under the rear seats. Removal and installation of the battery tray can be easily accomplished from underneath the raised vehicle. The danger of acid spillage and hydrogen gas buildup in the vehicle is virtually eliminated by placement external to the vehicle, under the rear seat pan. A schematic of the design is shown in Figure 7.

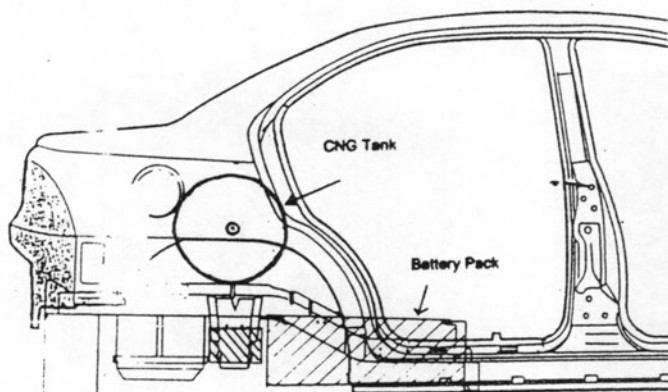


Figure 7: CNG and Battery Pack Location

In order to retain the stock Neon driving feel, the conversion utilizes the factory transaxle, shift linkage, and clutch system. Since an auxiliary electric vacuum pump was added, the power assisted brakes were also maintained. The design goal of the team was not to

change the original intent of the Chrysler engineers, but to replace the Neon engine with a comparable ULEV power source.

Since the U.T. HEV incorporates custom auxiliaries, care was taken in choosing tasteful and tactful locations for each addition. For instance, the HVAC motor/compressor was mounted neatly in front of the transaxle, completely independent of the motor/APU. Likewise, the DC to DC converter was conveniently located near the high voltage power source.

The pack contains 16 batteries arranged in two rows of six and one row of four as shown in Figure 8. The battery pack enclosure has been fabricated from lightweight aluminum and weighs only 18 kg as shown in Figure 9. However, the pack is strong enough to be a part of the chassis. The battery tray has 16 sections to hold batteries, each section is separated by the wall made of aluminum. This structure makes the pack stronger than just holding the 150 kg of batteries. In addition, the cover, also made of aluminum, is tightly secured on the tray and adds more strength to the whole pack.

Two ventilation fans provide 12 CFM of air circulation to ensure battery gases are vented from the pack. The tray has an open bottom structure which allows air to flow into the pack from the bottom. The air carries the explosive gas created by charging and discharging processes of batteries to the out side of the pack through the fans located on the top of the pack.

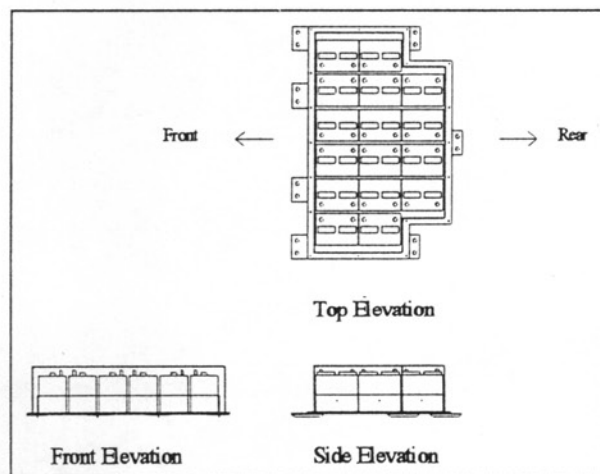


Figure 8: Battery Pack Assembly

Inside the pack, wiring has been optimized between the battery terminals to ensure the shortest total length of wire. This results in lower weight and less energy loss. Battery straps are made from bakelite and securing bolt heads are insulated with a rubber coating. Terminals and cable connections inside the pack are completely covered with thick insulating materials to ensure security. (cf: After a couple of accidents, the wiring is engineered to be the safest in this class.)

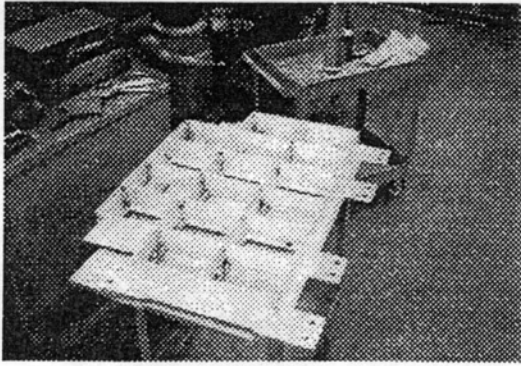


Figure 9: Battery Tray

The pack itself is easy to assemble and disassemble. The battery cover is secured on the battery tray by screws and nuts, and it is easy to mount/dismount. Also, the batteries are secured by the straps which are easily separated/attached by stud bolts (hooks) and nuts. These factors make the batteries inside the enclosure easily accessible as shown in Figure 10. The cover and straps can be made of ABS plastics for mass-production.

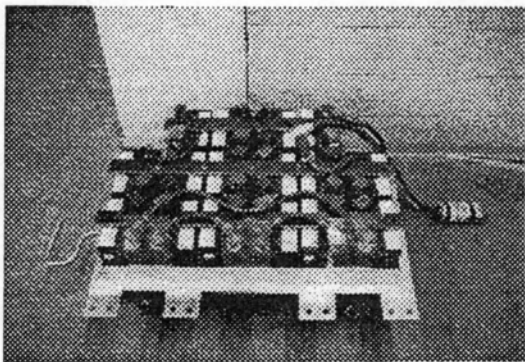


Figure 10: Battery Pack Assembly

CONTROL STRATEGY

A vehicle controller was designed, tested and built to meet the requirements of the 1995 Dodge Neon Hybrid Electric Vehicle Challenge. The main component of the controller revolves around the Motorola 68HC11EVB microcontroller. An algorithm was developed to allow the vehicle to operate as a Hybrid Electric Vehicle (HEV) or as a Zero Emission Vehicle (ZEV), a pure electric car. In HEV mode the primary power source for vehicle motion is the internal combustion engine (APU), and the controller regulates power assistance to the APU via the Uniq Mobility Electric Motor (EM) under heavy or severe loads. In ZEV mode the controller provides an interface between the driver's throttle pedal and the EM. While in either mode, the control algorithm provides means for regeneration of the battery pack based on state of charge (SOC) of the battery and vehicle loading. With the exception of the manual regenerative braking, the operation of the vehicle controller is purely passive, having no external adjustments to alter the control algorithm.

MODES DESCRIPTION- The University of Tennessee's Dodge Neon was converted to a hybrid electric vehicle utilizing the parallel configuration, where, in HEV mode, the APU provides the primary power for locomotion, with the EM providing assistance under heavy loads. It is the sole responsibility of the vehicle controller to monitor the loading on the vehicle and determine when to activate the EM to provide power assistance. Moreover, the controller must be able to determine the magnitude of the loading the APU is under, in order for the EM to provide ample assistance and maintain driveability. By competition rules the controller must operate with a single control algorithm for all events of the competition.

In ZEV mode, the controller needs to monitor a driver input to determine the required power/speed output of the EM. Since by competition rules all conventional driver controls (steering, braking, etc.) must be maintained, an existing driver control mechanism will be used as input to the controller.

HEV ELECTRICAL ASSIST- Because of the nature of coupling two motors together, much less an electric and natural gas one, a great deal of thought went into the design of the HEV control mode. It was first determined that the vehicle would be principally a natural gas vehicle, and the electric motor would be utilized to assist the natural gas engine. The goal of this assistance was to improve both emissions and fuel economy by allowing the natural gas engine to run within a certain loading window of maximum efficiency. The problem faced was determining what source could be monitored to indicate a need for assist of the APU.

It was determined that the loading on the APU, and therefore need for assist, could be determined and easily monitored by the manifold absolute pressure (MAP). With a way to monitor the need for assist, the controls group faced the problem of determining how to command the electric motor controller to provide that assist. To 'assist' the APU, a method was needed to command additional torque to the transaxle at a given speed. The main problem encountered was that a means of directly controlling the amount of torque that the electric motor provided was not available. The Uniq Mobility motor utilized in the Neon only possesses the means of being commanded a desired speed.

To overcome this problem, it was decided that the need to directly control the amount of torque was unnecessary. Instead, the desired speed would be calculated, and the motor controller would provide the necessary torque, within reason, to reach that speed. So, how can that be done? In other words, how can one calculate the desired speed to raise the torque a certain amount? Our design for assisting the APU simply works to increase the speed based upon how far the MAP signal is out of an operating window of maximum efficiency. This speed assist profile runs from a commanded speed of zero for MAP readings below a predetermined threshold and increases linearly to full scale for maximum MAP.

The 68HC11 was programmed using the C computer language. In C, the commanded speed, based on MAP is found by a mathematical equation. In order to make the commanded speed profile linear, the following equation was developed. In this equation MAP_{th} is the threshold for assist and N_{act} is the actual speed of the motor. The 10 refers to full scale commanded speed. The 5 refers to a full scale MAP reading.

$$N_{com} = \left(\frac{10 - N_{act}}{5 - MAP_{th}} \right) MAP + N_{act} - \left[MAP_{th} \left(\frac{10 - N_{act}}{5 - MAP_{th}} \right) \right] \quad (3)$$

The result is an output for commanded speed that is greater than the present speed of the electric motor when then MAP signal reads higher than the MAP threshold. The following figure provides a demonstration of Equation 1 for different scenarios of the EM's actual speed. Actual speeds (represented by voltage magnitude) of 0, 3, & 9 volts are shown in Figure 11.

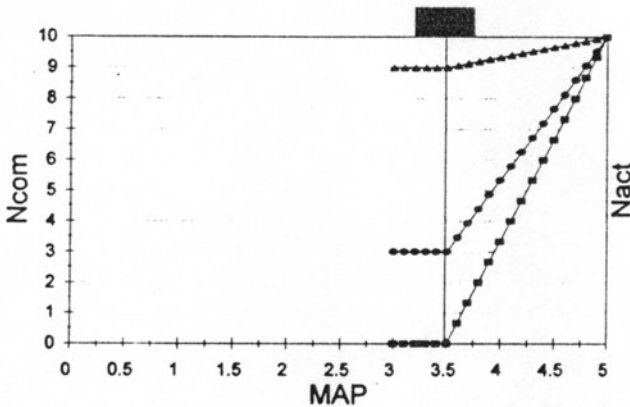


Figure 11: Map Threshold versus Speed

IMPLEMENTATION- In both ZEV and HEV modes the controller monitors, via RS-232 communication, the state of charge (SOC) of the batteries to determine both the need for regeneration and the ability to assist in HEV mode, or drive in ZEV mode. In order to monitor the state of charge of the batteries, the Controls Group had to develop a scheme for monitoring. We decided to employ the use of a kilowatt-hour meter used in a previous HEV to determine voltage and current.

An algorithm was developed for the 68HC11 that would estimate the SOC of the battery pack at any time during operation. The SOC can only be estimated since the coefficients of efficiency when charging or discharging are dynamic and cannot be predicted (coefficients partially based on losses in the system). Therefore, an average efficiency coefficient is used in the algorithm for discharge (1.1) and recharge (0.9) of the battery pack. In order to determine the SOC, an educated guess has to be made of the amount of maximum kilowatt-hours available from the battery pack

when fully charged. This value is programmed into the 68HC11 and used as the set point to indicate full SOC. Since the kW*hr meter measures kW*hr used in an accumulative manner, the current level of SOC is to be based on a previous kW*hr reading and a present kW*hr reading. A difference is taken between the present and previous reading. If the result is positive, then this is an indication that the batteries have been recharged. (The kW*hr meter accumulates kW*hr used from zero; therefore, the reading would be negative if charge is being used.) This result would be multiplied by the charging efficiency coefficient and added to the current available kW*hr, and then divided by the theoretically maximum value to calculate a percentage, which is used as an indication of percentage of SOC available. If the difference results in a negative value, then it is an indication that charge is being used from the battery pack. The result would be multiplied by the discharging efficiency coefficient and subtracted from the current level of SOC. The percent SOC is calculated in the same manner as previously described.

The controller will continually monitor the SOC of the battery pack, even while not in operation. This allows the value of percent SOC used by the HEV and ZEV algorithm to be more accurate while in operation. The power drawn by the controller is insignificant. The Uniq Mobility controller has circuitry which automatically protects the battery pack from overcharging by monitoring the voltage level.

In addition to determining the ability to regenerate by monitoring the state of charge of the batteries, the controller also determines the amount of regeneration, or loading of the car to charge the batteries, by monitoring the 'excess power' of the APU

DRIVER AIDS- A kilowatt-hour meter will be used to monitor the kilowatt-hours provided by the battery pack. The meter also measures the current and voltage of the battery pack. This data is provided by the meter via a 9 pin RS-232 interface. Also, a tachometer supplies the driver information on APU speed.

HVAC

Unique problems are encountered in the heating, ventilating, and air-conditioning systems of hybrid electric vehicles. One goal of the HEV Challenge is to create a heating and air-conditioning system that is effective and energy efficient over a commonly encountered temperature range. A vapor compression heat pump utilizing refrigerant 134a is used in The University of Tennessee's entry to provide both heating and air-conditioning. The system is powered by a variable speed permanent magnet DC electric motor which is independent of the vehicle's main drive train. Waste heat from the internal combustion engine is stored in a Schatz Heat Battery to provide nearly free auxiliary heating of the vehicle interior during extremely low ambient operating temperatures. Additionally, the

system is designed to operate in a manner similar to the original equipment heating and cooling system.

The majority of the design decisions were made from an evaluation of the stock Neon system air-conditioning system. Performance characteristics of the existing system components were determined by several tests. Areas of interest included the system's power requirement, cooling capability, and reversed cycle characteristics.

A chassis dynamometer test was performed in the university's lab to measure the overall power requirement of the stock air conditioning system. According to the results of the test, a significant amount of power (4.5-7.5 kW) would be taken away from the main drive motor or the 3-cylinder Geo engine if the compressor was driven by either of them. Another major disadvantage of using the main drive system to power the compressor is poor energy efficiency of the engine (<35%) and relatively low electric motor efficiency (<75%) at low motor speeds. One objective of the test was to determine the power requirement of the system so that the team's battery group could develop a battery pack with enough capacity to handle a forty minute test in competition without charging.

The otherwise stock air-conditioning system was tested with a 1.5 kW AC electric motor driving the compressor. The total electrical power draw for a 40 minute test consisting of dropping the cabin temperature -9.4 °C from 22.8 °C and maintaining the 14.4 °C temperature was 1.3 kW×hr.

Results of an experimental study done by V.C. Mei and F.C. Chen of Oak Ridge National Laboratory prompted the team to use a heat exchanger/accumulator instead of a standard automotive accumulator. Their results showed an increase in compressor volumetric efficiency, resulting in an increase in refrigerant mass flow rate, and a reduction in compressor power consumption. The claim is that a system using the heat exchanger/accumulator can use the entire evaporator capacity, rather than waste 15% of its capacity for the sake of protecting the compressor from liquid slugging. The team felt that this device could improve the system's performance at low cost.

Two orifices that meter the refrigerant flow one direction and check the other were used in the heat pump system. Several tests were performed to determine the optimum orifice size for heating and for air-conditioning as two different sizes are required. The goal was to find an orifice which would give a quick and efficient rise time to a desired compressor discharge pressure. An orifice size of 1.24 mm was selected for further testing in heating, and a preliminary orifice size of 0.81 mm was selected for air-conditioning.

A heat pump test was performed at an ambient temperature of 3.9 °C, with a 1.5 kW electric motor powering the compressor. It took approximately 20 minutes to reach 10 °C in the cabin. The detrimental effect of increasing blower speed on the air temperature too high too

fast was obvious from the duct temperature change. It was observed that the discharge pressure was strongly dependent on blower speed, which controlled the amount of energy removed from the indoor coil. The compressor power requirement was approximately the same as for the air conditioning test. Two other heat pump tests were performed at 13.6 °C and -4.1 °C ambient with similar results. It was obvious that the 1.5 kW electric motor was not enough to achieve a head pressure so that higher temperatures consistent with the desired performance could be obtained.

One of the largest problems that faced the HVAC group in its pursuit to fabricate a heat pump for the Neon competition was the acquisition of a small yet powerful (2.2-3.7 kW) motor to drive the compressor. Both DC and AC motors were considered. While AC motors are much smaller than conventional DC motors of the same output, the conversion of DC power to AC power was found to be expensive and bulky. The power conversion would also cause a reduction in the HVAC system efficiency (most converters found were about 90% efficient). Conventional DC motors, too, were found to be expensive and large. After the group spent much time searching for a motor, one was located. General Electric donated a prototype DC-brushless motor similar to one used in the 1990 solar powered car, "Sunrayce". The motor is rated at just over 2.2 kW continuous with a peak output of about 3.7 kW for a limited period of time. The motor operates off of the main battery pack voltage (208V), with its controller requiring 24 volts. The donation included the controller and most of the hardware necessary to install it. It did not, however, include the actual motor housing. General Electric sent detailed drawings of the motor housing. It was up to the HVAC group to construct it and assemble the motor, while making any necessary modifications for mounting. The original drawings called for the use of steel and aluminum. However, an all aluminum construction for weight reduction was implemented, and cooling fins were added for better heat dissipation.

A reduction was necessary between the motor and the compressor since the motor operates most efficiently at higher speeds (the motor can operate at 8000 rpm). A 3:1 reduction was chosen as this should give sufficient torque at startup, while still giving very good efficiency in the upper 80% to low 90% range at steady-state. The coupling of the motor and compressor is achieved via a timing belt as this gives a more efficient power transfer than a conventional V-belt. This belt does not produce the noise and have the lubrication problems of a standard gear-drive.

An electrolytic capacitor used to absorb transient peak voltages that can damage the controller between the battery pack and the motor controller. A 12 volt to 24 volt DC-DC converter is placed in-between the vehicle's low voltage system and the controller. In addition, for testing purposes a duty box provided by GE

was connected to the controller to gain manual control of the motor's speed and torque.

The motor/compressor unit is mounted in the front driver's side of the engine compartment. Due to space constraints in the vehicle, the motor controller, 12-24 volt DC converter, capacitor, HVAC controller, and the manual control for the motor are mounted behind the rear fold down seats, in front of the CNG tank.

Using the compressor/motor combination previously described, the mechanical design of the R-134a reversible vapor compression heat pump cycle was accomplished. The main components of this system are a 12V solenoid operated reversing valve to direct the flow of refrigerant, aluminum and copper piping to transport the working refrigerant, the heat exchanger/accumulator, two combination orifice/check valves to throttle and limit the flow of refrigerant, and the stock indoor and outdoor coils provided with the Neon refrigeration system.

A limited amount of space was available under the Neon's hood to install the HVAC system components. The locations of the indoor coil and the outdoor coil were considered to be optimum in their original locations since they did not conflict with the team's plans for any of the other components placement. Several tubing materials were considered for the system. However, constraints with the reversing valve and the heat exchanger/accumulator limited the choice of tubing material. Both components were manufactured with all copper fittings. Much of the tubing in the final system is a combination of flexible rubber hose, copper tubing, flare fittings, and soldered connections as appropriate for each component connection. Insulated 3/8" copper tubing was routed in front of the outdoor coil from the reversing valve to the indoor coil and to the outdoor coil.

With the donation of a heat storage device from Schatz Thermo Engineering, the storage of waste heat from the heat engine was possible and auxiliary heating is provided. Using a vacuum sealed heat exchanger. Schatz claims the battery can retain coolant temperatures above 37.8 °C for 10 days at -6.7 °C ambient. To release the stored energy in the heat exchanger the coolant is once again flowed through the device. The heat battery is capable of delivering 600 watt-hours of heat to the passenger cabin or engine block. Preliminary tests showed that the heat battery supplied equivalent to heat pump air temperature for 5 minutes.

For simplicity and ease of implementation, a decentralized, mostly manual controls system was developed for the HVAC system. This type of system is similar to the stock HVAC system on the Neon.

A three-way vacuum-actuated valve controls whether or not the cooling water flows through the engine block. This valve is controlled by the HEV/ZEV mode selector on the dashboard. With HEV mode selected the valve allows flow through the entire cooling system including the engine, and in ZEV mode water only flows through the heat battery and

heater core. The mode selection must be made before the vehicle is started.

The water flow through the heater core is controlled by water pumps. A lighted push-button is located on the dashboard which, when depressed, allows current to flow to the electrical water pump, extracting energy from the heat battery. This pump operates at a single speed in both HEV and ZEV modes to preheat the cabin and engine block. When the combustion engine is running, the driver may turn off the electrical water pump to conserve energy.

The HP/AC system operation is controlled by a microprocessor, which varies the compressor motor speed to maintain a desired discharge pressure. The programming logic is as follows:

- Start program when compressor operation is desired by the driver.
- Use HVAC mode selector output to determine desired discharge pressure.
- Run motor at maximum speed until desired discharge pressure is reached.
- Control motor speed to maintain desired pressure by commanding a change in motor speed based on the relative values of desired and actual discharge pressures.
- The mode selection inputs are rechecked frequently to respond to driver command changes.

The final system was tested in a climate control chamber at Oak Ridge National Laboratory. The Neon was cold soaked at -6.7 °C for 12 hours. Temperatures in the cabin were measured by 16 thermocouples during the test. Figure 12 shows the results of the heat pump test. The indoor blower speed was set to speed 1 for 2 minutes, speed 2 for 6 minutes, speed 3 for 10 minutes, and back to speed 2 for the remainder. The target cabin temperature of 70 °F for the competition was reached in 23 minutes with the electric motor running at full speed. The battery pack voltage dropped from 193V to 148.5V at the conclusion of the test. The average system current draw was 13.0 amps. The estimated power draw for a 40 minute test at 20 °F is 1.6 kWxHr.

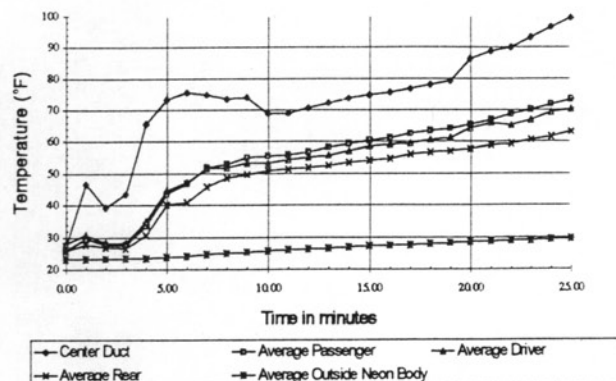


Figure 12: Heat Pump Performance After Cold Soak at 20°F for 12 Hours

EMISSIONS CONTROLS

In choosing a catalyst system several design options were considered. One of the major decisions the group faced was whether or not to use a preheated catalyst. The preheated catalyst considered included electric and flame heated. Both of these systems offer significantly decreased light off times (1). In exchange for the decreased light off times additional energy must be supplied by the vehicle.

An alternative to preheating the catalyst for reducing light off times is locate the catalyst as close as possible to the exhaust manifold. This simple procedure can be effective and is gaining acceptance in the automotive industry. (3) A donation of a small 3-way catalyst from United Emission Catalyst made it possible for us to locate a catalyst within 1 ft of the exhaust manifold. By insulating the exhaust pipe upstream of the catalyst, the light off time can be even further reduced. (4) The UEC Catalyst is composed of a cordierite ceramic substrate that has been loaded with Platinum and Rhodium at a rate of 50 grams/ft³ in a ratio of 5:1. Platinum is effective for lowering HC emissions while Rhodium is used to reduce NO_x emissions. (5) The UEC catalyst is only 400 cm³ in volume.

It has been found that a catalyst consisting of a Palladium and Rhodium composition is more effective for lowering total HC emissions than a composition of Platinum and Rhodium. However, for non-methane hydrocarbons, Platinum and Rhodium has slightly better efficiency. (6) Kim, Park, Jeong, Yoo, and Park found that the most efficient catalyst system for CNG consisted of 2 bricks in series. The first consisting of a Platinum and Rhodium composition and the rear brick being heavily loaded with Palladium. (6) The donation of a large Palladium and Rhodium catalyst from Allied Signal made it possible for us to utilize this configuration. At 1700 cm³, the volume of the second brick makes up for the small volume of the first brick. The exhaust pipe between the two catalysts will also be insulated to aid the rear brick in light off. An advantage of locating the Palladium and Rhodium brick in the rear is that Palladium lights off at a lower temperature and it creates chemical reactive heat. (6) To date, no emission results are available.

SUSPENSION MODIFICATIONS

Initially the curb weight of the Neon was 1088 kg with an approximate weight distribution of 70 to 30 front to rear. The HEV conversion increased the curb weight to 1360 kg with an approximate weight distribution of 55 to 45 front to rear. Side to side weight distribution was 51 to 49 left side to right side which was well within the 5% side to side deviation as allowed by regulations.

In order to compensate for the additional weight on the rear axle, stiffer springs were used to maintain the original natural frequency of the suspension. Spacers were employed with the stiffer springs to

maintain the original ride height of the Neon. Also, to compensate for the additional weight on the rear axle, an oversized sway bar was utilized to increase the roll stiffness of the vehicle. These steps were taken in order to maintain the original driving characteristics, as well as the external appearance of the vehicle.

For aesthetics as well as weight savings, a set of aftermarket alloy wheels were used. This provided a weight savings of 3 kg for each tire and wheel assembly leading to total weight savings of 12 kg. Michelin Coefficient X low rolling resistance ($f_{roll}=0.007$) were used in order to provide a much better coefficient of friction for the vehicle.

MATERIALS AND MANUFACTURABILITY

The Neon conversion was accomplished in such a manner that ease of manufacture was of utmost importance. Aluminum alloys were used extensively in order to save weight, but the ease of machining the alloys provides an extra addition to the manufacturability of the entire vehicle. For high stress areas (e.g. jack shaft) mild steel was used. Components made of mild steel are also easily machined using standard processes. The only component requiring intensive labor to be manufactured is the battery tray. However, This tray can easily be injection molded or cast to save in time and labor expenses. The modification of the rear floor pans can easily be compensated for by the manufacturer simply installing the required flat pans in lieu of the standard Neon pans. The rear crossmembers can likewise be added along an assembly line as the vehicle is initially assembled.

CONCLUSIONS

The University of Tennessee's 1995 HEV is a viable alternative to today's gasoline powered automobiles. The 1.0 L Suzuki engine and the Uniq Mobility electric motor combine to give satisfactory performance compared to that of the stock Neon. The conversion did not incorporate the use of any exotic materials and could be produced on any of today's automotive assembly lines.

For passenger comfort a highly efficient heating and cooling system has been added that is functional in both HEV and ZEV modes. Changing between driving modes is accomplished by simply flipping a switch. Also a high level of safety has been built into the passive controls of the powertrain.

The original design envisioned by Chrysler engineers has been maintained by a minimal loss in consumer acceptability. The cabin compartment has remained unchanged with the exception of the addition of mode switches on the dash. Some trunk cargo space was lost due to the addition of the CNG tank in the trunk. The battery location helps in maintaining the specified weight distribution while isolating the batteries from the passenger compartment for added safety.