Electric Vehicle Conversion Design

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Abstract

The conversion process of an internal combustion engine to an electric vehicle powered by batteries comprises many steps from choosing the vehicle, sizing a motor, and the type of batteries. This project takes a 1980 Datsun 280zx and converts it to an all electric car with a DC motor and lead acid batteries. The power steering and power assist are reused as well as air conditioning components.

Key Words: electric car, Peukert's effect, discharge rate

Introduction

Operating a battery electric vehicle will eliminate emissions inside our cities and reduce our dependence on oil. The energy used for our electric transportation will be as diverse as the electrical grid obtaining energy from coal, natural gas, nuclear, and some renewable forms. The current electric vehicles available have performances similar to high end sports cars and ranges over 100 miles per charge but remain cost prohibitive ($100,000 for the Tesla Roadster, $40,000 for the Chevy Volt) for most of the population. Converting an existing vehicle to operate with an electric motor and battery power can provide the majority of the population an all electric commuter car for under $10,000.

During the infancy of the automobile, electric and gasoline vehicles competed for dominance of the market. The all electric vehicle lost because of the lack of range from current battery technology. Until recently the electric car was dormant. The number of electric vehicles on the roads is increasing every year as people become more environmentally conscious and gasoline prices are volatile.

Discussion & Results

Mechanical Design

Choosing a Vehicle to Convert

An electric conversion will act very similar to the vehicle being converted. A gas guzzling SUV will have more room for batteries but it will be an electricity guzzling vehicle. A small car will be more efficient but can't hold the batteries that a larger vehicle can. The weight of the vehicle will play a pivotal roll in deciding what motor to use and whether or not to use direct drive of a transmission. Rear wheel drive vs. front wheel drive will decide how the motor is mounted and can add complexity. Newer vehicles have computers and modern electronics which may never work properly if the internal combustion engine is removed. Our project timeline consisted of only nine months to design and construct so we chose a vehicle to simplify the conversion.

Figure 1: 1980 Datsun 280zx

We found a 1980 Datusn 280ZX on craigslist that fit our criteria. The engine was not running so the vehicle was cheap but in overall good condition. It is a five-speed manual rear drive which allowed for a smaller motor to be used (larger motor required for direct drive) and inline mounting. The electronics were simple, a 3.7 drag coefficient, curb weight of 2800lbs, and enough room for the batteries.

Electric Motor

Induction and direct current (DC) are the two families of electric motors typically used in electric vehicles each having their pros and cons. The induction motor works on alternating current (AC) power and is controlled using a variable frequency drive (VFD). These motors come in all different sizes and can provide all of the horsepower and torque needed for any conversion. Because of how they function, they naturally lend themselves to regenerative braking using the motor to stop the car (not completely, physical brakes are needed even with regenerative breaking) and recharge the batteries. Drawbacks of induction motors are their cost where some systems can reach upwards of $25,000.

DC motors are more common and the cost of comparable power motors makes them more attractive than induction motors. These motors fall into two categories of permanent magnet (PM) and series DC. PM have the advantage of regenerative breaking much like the induction motor.

Choosing a motor will depend on the weight and aerodynamics of the car. The starting torque required to move our vehicle in first gear with an estimated end weight of 3200lbs is 72 ft-lbs (see calculations in Appendix 2). The torque needed to maintain a speed of 65mph in 5^{th} gear is 52 ft-lbs. Based on these calculations we chose the series DC motor WarP9 from Warfield Electric (see performance curve in Appendix 1). The motor has the toque to move our vehicle, is specifically made for electric vehicles, and has a dual shaft for accessory mounting. Grassroots Electric Vehicles (www.grassrootsev.com) sells this motor for $1670 making it cost competitive with alternative motors in its same class.

Figure 2: WarP 9 Motor

The WarP9 weighs 158 lbs, has a 9" diameter and is 15"long. The length and diameter of the motor made fit well with our 280zx. The drive end shaft is coupled to the flywheel taken off of the original motor. A clutch disc is mounted to the flywheel as it was in the original vehicle and is set inside the bell housing of the transmission. A cover plate was built and the motor is attached to it via a motor cage built from aluminum angle. The commutator end of the motor is mounted to a cross member of the vehicle frame just inside of where the original ICE was mounted.

Rubber pads are placed beneath every mount to isolate some of the vibrations. A brace was added to help support the bell housing of the transmission as well.

Motor Controller

The controller has to meet the capacity of the motor being used. Our motor has a voltage limit of 192V and the OEM recommends nothing over 170V. Voltage on the motor is directly proportional to the RPMs of the motor and amperage has a nonlinear relationship to torque. Several companies manufacture DC motor controllers: Curtis, Alltrax, Kelly Controls, and Café Electric. The Zilla controller made by Café Electric was our first choice because of its price and power capabilities. Because they price the controller to affordable to people doing these conversions, they are highly sought after and there is a waiting list. We chose the Kelly controller KDH14650, which will have a power output capability of 144V and 250 amps continuous for $1,300. The motor controller can limit the performance of the motor and therefore the vehicle if it is sized too small.

The Kelly controller is mounted to an aluminum sheet to aid heat dissipation which is recommended by the OEM. A 500 amp fuse and a main contactor are mounted to the same board. Two LED indicator lights from the controller are mounted in the dash display next to a guide for easier troubleshooting from inside the cabin. An RS232 cable is used to change the settings of the controller such as under or over voltage of the battery pack, throttle type, current limitations which is also mounted on the driver side cabin near the floor for easy reprogramming from inside the cabin.

Power Steering and Brakes

Our original vehicle had power steering and brakes. While removing the ICE we saved the power steering pump and mounted it onto the driver's side motor cage. An accessory pulley and belt provide the power just as it was in the original setup. One drawback is that the car does not have power steering when the motor is not moving unlike an ICE idling at 700 rpm. The vacuum assisted brake is solved using a separate 12V vacuum pump commonly used for high horsepower engines. A PVC tank mounted by the driver side headlight stores vacuum and a switch will turn on and off our pump keeping 14 to 17 inHg vacuums.

HVAC Considerations

Free heat that is a normal by product of a 20-30% efficient gasoline engine cannot be totally replaced. Electric vehicle conversions such as this would not be ideal for colder climates where this heat is essential. Our project uses three 12V 156 watt heaters to provide some heat and a windshield defroster. A heater is mounted under the dash on the driver side and on the passenger side. The third is mounted where the heater core used to be. It is highly recommended that if the heater core is not being used that it be removed because they will smell after some time if left dormant.

This vehicle is going to be a commuter car in the hot climate of the American Southwest where air condition is critical in summer heat. The air compressor, condenser, and air conditioning components were salvaged from the original engine. The compressor is mounted to the passenger side motor cage and is powered by the same accessory pulley as the power steering pump. The whole system was rerouted using soft copper tubing and fittings. One option that was considered was to run a separate smaller motor for the sole purpose of providing power for the air compressor. The drawback to using the pulley is that the air will not be compressed when the car is stopped. We chose to use the pulley for simplification and cost considerations. Our vehicle has a manual transmission and the motor can be kept at idle with the clutch disengaged if it becomes necessary. We will perform tests to see how much the HVAC system will affect our range.

Figure 3: Motor mounted with power steering (right) and air conditioning compressor (left)

Vehicle System Monitoring

Much of the vehicle monitors were for emissions, electronic ignition, and engine monitoring. Removing the engine left a number of the original indicators useless such as oil temperature and pressure, fuel gauge, tachometer, battery voltage, and water temperature. The speedometer of the car operates on a cable coupled directly to the transmission and is able to be reused.

We still need to monitor certain vehicle components such as motor temperature warning, battery life, DC brush indicator, brake vacuum, and tachometer. The only original indicator that can be used besides the speedometer is the tachometer; the others will have warning lights and new gauges added. The tachometer is an important measurement for our motor because it can fly apart if the rpm reaches above 8000. The WarP9 is most efficient between 2500 and 3000 rpm so the operator can shoot for this range. The electronic ignition system provided the input for the original tachometer which could not be replicated. The needle operates on a DC voltage range so we mapped the rpm to the appropriate DC voltage. Using a photo sensor and light reflecting tape on the accessory pulley, we are able to count revolutions and convert the frequency to the corresponding DC voltage.

A generic automotive vacuum gauge works for monitoring the tank vacuum. The Warp9 comes with temperature and brush sensors. The motor has H insulation rated up to 180 °C and the temperature sensor is a normally closed switch that opens at 120 °C triggering a warning light in the cabin. The brush sensor will place the full armature to stator voltage across is switch once the brushes have worn enough to be replaced. A light will come on alerting the operator to change the motor brushes when this occurs.

Electrical Design

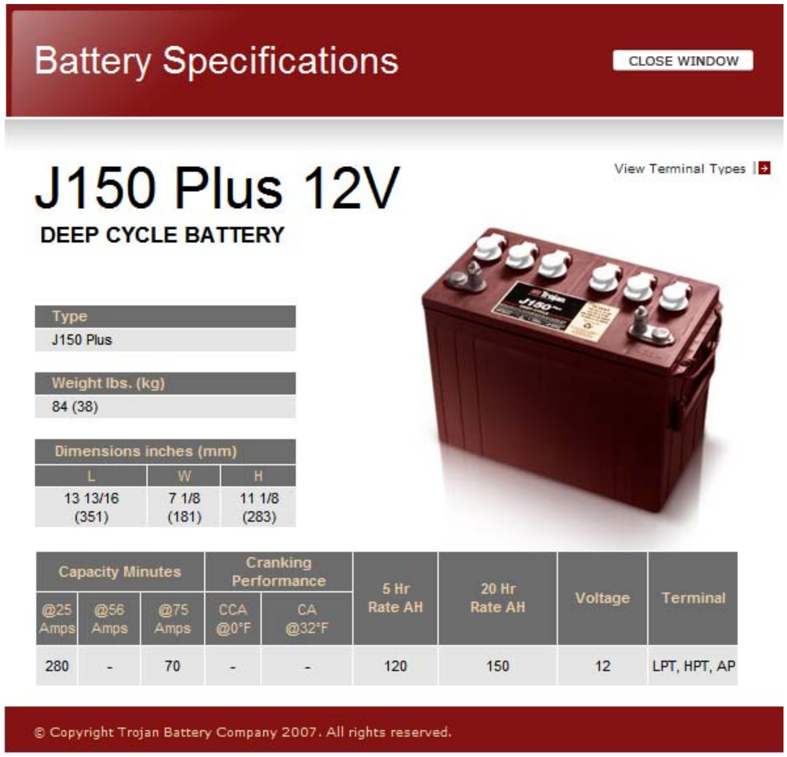
Batteries

There are several options for batteries depending on the conversion budget. Many hybrids use nickel metal hydride to store energy for electric drive. The ideal batteries are the newer $LiFeO_4$ because they are light weight, have a large energy density. The disadvantage currently is they are expensive (about $25-$45k depending on the size of the battery pack). Lithium ion batteries have similar benefits but are still just as expensive. A significant advantage of lithium based batteries apart from their light weight and energy density is their 2000 plus cycle life as compared with 300 to 700 cycles for lead acid. Due to budget constraints keeping the whole conversion under $10,000, we chose the Trojan J-150 deep cycle lead acid batteries for the 12V 150 amp hours (AH) and 700 cycle life.

Figure 4: Batteries and motor controller mounted under the hood.

The energy of the battery pack is found by multiplying the number of batteries by the volts of each battery and by the estimated amp hours.

By physical constraints, we were able to fit sixteen batteries in our 280zx. This would give a battery pack of 28.8 kWhr. We have them configured in two rows of eight series connected batteries connected in parallel creating a battery pack of 96V and 300 AH at a 20 hour discharge rate. At 84lbs per battery, the weight of the total pack is 1344lbs. We expect to replace these batteries after two and a half to three years of use.



Capacity Minutes			Cranking Performance		5 Hr Rate AH	20 Hr Rate AH	Voltage	Terminal
@25 Amps	@56 Amps	@75 Amps	CCA @0°F	CA @32°F				
280	-	70	-	-	120	150	12	LPT, HPT, AP

Figure 5: Battery specifications from Trojan Battery Company

If a conversion does decide to use lead acid batteries, they should be designed for deep cycle. Although cheaper, regular off the shelf automotive batteries are designed to provide high amperage for the starter motor over a short time and then be recharged by the alternator. Automotive batteries will not last in electric vehicle applications. Batteries should be marked deep cycle and rated in amp hours instead of only cranking amps.

Charging

The battery charging depends mainly on where the vehicle is being charged and how fast the batteries can be charged. Lead acid batteries are most efficient with slow charge and discharge. Charging the batteries too quickly can cause a false full as charges build up on the lead plates. The outlet will be a limiting factor as well where most garage outlets have a 15 or 20 amp fuse.

The end user of the car has a garage electrical outlet with a 20 A fuse. We selected the PFC1500 made by Zivan because it can charge at voltages up to 144V and pulls 12A from the wall outlet. Instead of pulling an electrical chord up to the vehicle, we incorporated a retractable chord reel to be pulled from the original gas cap.

12V Power Supply

The original car electronics such as lights, horn, and stereo still operate on 12V DC and a separate power supply is needed. Currently there are three options to provide this power.

First is to have a separate battery. A deep cycle battery will provide enough energy for a daily use as long as it is recharged with the rest of the battery pack daily. Some drawbacks to this are the requirement of an additional battery charger for 12V and a variable voltage as the battery discharges.

A second option is to attach an alternator to the motor and use a regular car battery. This will indirectly take power from the larger battery pack by adding a load on the motor. The energy has to undergo conversions from electrical to mechanical to electrical which have losses associated with each transformation. This is a more convenient solution is that the battery does not need a separate charger but it is not ideal.

A third option is to have a DC to DC converter. These devices step down the voltage from the battery pack to 12V. A bonus for this option is that the 12V is constant even when the battery pack voltage decreases or increases. A drawback is that they can be expensive and need to be sized to be able to provide enough power to run all of the car electronics. For our project we chose this option because it provides a constant voltage supply for our battery monitoring system and will not require any additional charging equipment.

Battery Monitoring System (BMS)

On the original vehicle knowing how much gas was left in the tank was easily measured and displayed. This is much more complicated and involved with an electric vehicle. The BMS (also known as Battery Management System) is needed to display how much battery energy is left in the battery pack and to prevent from over discharge of the batteries.

Lead acid batteries have a number of issues that will be discussed in this section. The first is the state of charge (SOC) and depth of charge (DOC). SOC is how full the battery is measured in percentage. DOC is how discharged the battery is in percentage. Lead acid batteries should rarely if ever have a SOC below 20% or DOC above 80%. In some cases if a battery is discharges below this it might have permanent damage and not be rechargeable. The batteries in most conversions are the largest expense and need to be protected and there are different ways of measuring SOC.

The battery manufacturer measures SOC in two ways as seen in Appendix 3. The specific gravity of a battery is measured by opening the caps and placing a hydrometer inside. How far the hydrometer sinks in the acid will indicate a state of charge. This is very impractical to be implemented on a moving automobile. Voltage reading is the second option used by the OEM and is the route we took. Measuring the voltage of each battery when they are wired in series up to 96V presents its challenges. With the use of differential amplifiers and microcontrollers, our BMS will read the voltages of each battery within 0.05V and display them for each battery on two LCD screens mounted on the dashboard. An advantage in monitoring each battery instead of the entire battery pack has the advantage of identifying problem batteries that need replacement and how unbalanced the batteries become. When wired in series, the batteries nearest the cathode will drain more quickly than those nearest the anode. This phenomenon can be demonstrated and monitored by measuring individual batteries.

Another method for indicating battery pack status is by measuring the current drawn out of them. The fundamental obstacle to this technique is Peukert's Effect. The capacity of a battery decreases as the rate of discharges increases. A deep cycle lead acid battery is rated in amp hours but the discharge rate should also be displayed. The Trojan J-150 batteries have a 150 A-hr at a 20 hour discharge rate. This means that the battery can provide 7.5 amps for 20 hours. If the battery is discharged with a constant 15 amp draw, it would not last 10 hours. Our batteries discharged at 75 amps will last 70 minutes giving an amp hour rating of 87.5 A-Hr. The capacity decreases at an exponential rate by the equation:

$$T(I) := \frac{R}{\left(\frac{I \cdot R}{C}\right)^n}$$

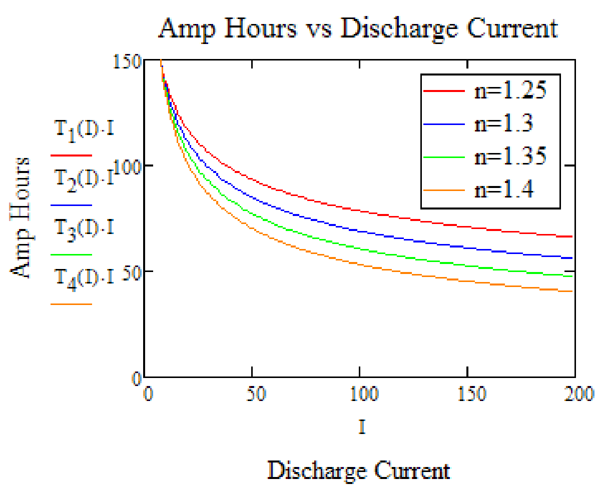


Figure 6: Amp hours affected by Peukert's Effect

Where T is the time the battery will last at the discharge rate I. C is the amp hour capacity given by the OEM, 150AHr in our case and R is the hours of discharge at the amp hour rate which is 20 hours in our case. R will have a normal value of 20 or 100 hours. N is the Peukert's coefficient that ranges from 1.2 to 1.4 in flooded lead acid batteries.[1]

To measure capacity by discharge current is quite involved because the amp hour rating is not constant. The system would have to measure current for a period of time and integrate the current of the time period giving the amp hours used. The integrated amp hours would have to be divided by the corresponding amp hour rate at the average discharge current for that period.

This would give a percentage of the total energy used for that period. The same would have to be done while charging the batteries. This is possible to accomplish and can be very accurate if the Peukert's coefficient it known. The drawback is that as the batteries age, the efficiency decreases increasing Peukert's coefficient. After heavy usage of daily driving over 6 months or a year the above calculation would be inaccurate displaying more capacity than what is available. The voltage will on the other hand will decrease faster as the batteries age and will still be accurate. For this reason we chose to measure capacity by voltage.

To selectively measure each battery when they are in series up to 96V, we used an essential differential op amp made by Linear Technologies LT1990CS8 which can have up to 200V input. We used an Atmega 16 microcontroller and digital multiplexer to obtain and display the voltages on a graphical LCD screen.

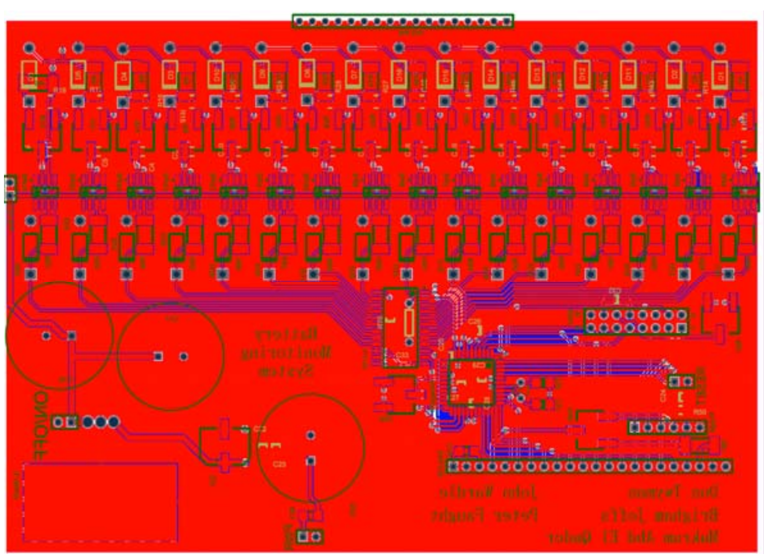


Figure 7: Four layer PCB layout of BMS

Social impact

The project will have a good impact on the social life of the users. First Substitution of gas-powered cars with electric vehicles is quite beneficial to your health since the exhaust of gasoline-fueled vehicles contains a variety of harmful chemicals that can seriously affect your health. These substances enter our bodies as we breathe and are then transported to all major organs. The respiratory system suffers the most obvious negative effects, but there are also impacts to blood and coronary systems, and the central nervous system. Last but not least, car exhaust includes carcinogenic chemicals. Second Driving an electric car costs about $0.03 per mile, which is about 2 times cheaper than a gasoline-powered car. In certain cities and prefectures, electric cars have discounted or free parking and highway fees, as well as tax breaks on the purchase price. The main downside is the initial high cost, but national, prefecture and city subsidies may get you a discount of up to 50%. Third, Using electric cars can definitely influence your lifestyle. To start with, you'll make no more trips to the gas station. Instead, you'll get into the habit of plugging your car in every night at home. With a charging time of 4 – 8 hours, and its limited range of 120 km, an electric car can satisfy most of the needs of the average urban commuter. But for the occasional trips of more than 100 kilometers, you would need to use public transport or rent a car.

Safety

Safety was the first concern after obtaining the car. New brake pads and calipers were added and the rotors were turned. New tires were put on as well. An failure mode and effects analysis (FMEA) was created before any testing to prevent injury and damage,

Conclusion

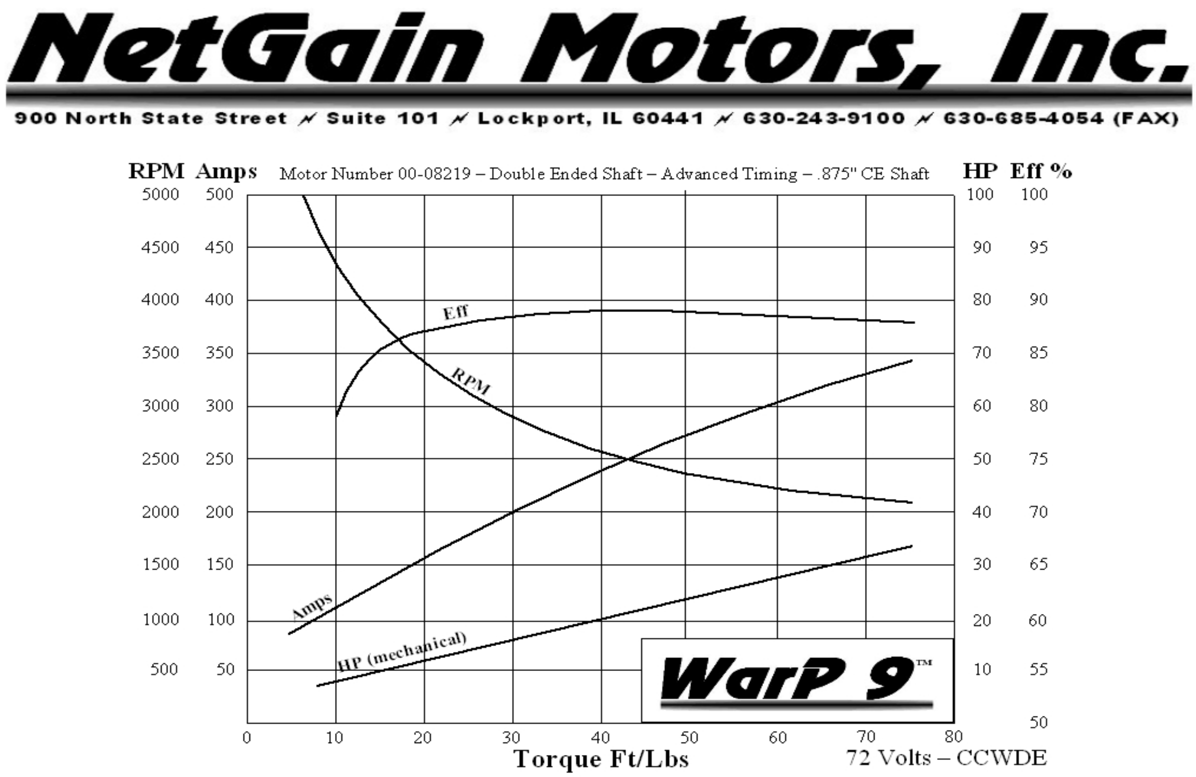
The converted vehicle is in its optimization stages. Our design of experiment consists of acceleration and top speed tests with varying number of batteries. The range test will also be conducted varying the number of batteries and different noises such as air conditioning and lights. On our initial tests we have observed the phenomenon that the battery closest to the cathode side will drain faster than the rest of the batteries placed in series. This will be an additional benefit to monitoring each battery as not all of them will read the same voltages. Because of this we recommend rotating the batteries every couple of months.

References

1) Gibson, Chris. “Peukert’s Equation.” 04 February 2008. SmartGuage Electronics. <http://www.smartgauge.co.uk/peukert2.html> Oct 2008.

2) Leitman, Seth, Brant Bob. Build Your Own Electric Vehicle. New York Mcgraw Hill. 2nd Ed. 2009.

Appendix



Appendix 1: Performance curve of Warp 9 motor

<http://www.go-ev.com/images/003_15_WarP_9_Graph.jpg>

Vehicle specifications

Overall Length	$length_{car} := 4340mm$
Overall width	$width_{car} := 1690mm$
Overall height	$height_{car} := 1290mm$
Length X width	$length_{car} \cdot width_{car} = 7.335\,m^2$
Wheelbase	$wheelbase := 2320mm$
Curb weight	$curbweight_{car} := 1260kg$
Gross Car weight	$grossweight_{car} := curbweight_{car} + 300lb$
Weight of Battery pack (16 Lead Acid Trojan J150)	$weight_{battery} := 16 \cdot 84lb$
Weight of Motor (Advanced DC 144 V)	$weight_{motor} := 151lb$
Weight of ICE Motor (includes exhause etc)	$weight_{icemotor} := 800lb$
New Weight of car	$weight_{car} := curbweight_{car} - weight_{icemotor} + weight_{battery} \cdots + weight_{motor}$
	$weight_{car} = 1.575 \times 10^3\,kg$ $weight_{car} = 3.473 \times 10^3\,lb$
Differential Gear Ratio	$AR := 3.7$
Wheel radius	$wheel_{rad} := 14in$

Drag forces

Coefficient of drag $Cd := 0.385$

Density of air $\rho_{air} := 1.2 \frac{kg}{m^3}$

Cross sectional area $A_c := height_{car} \cdot width_{car}$

Drag Force $F_d(v_{car}) := \frac{1}{2} \cdot \rho_{air} \cdot A_c \cdot Cd \cdot v_{car}^2$

$F_d(65mph) = 425.214\,N$ $\quad$ $F_d(65mph) = 95.592\,lbf$

Rolling Resistance

Coefficient of rolling resistance $\mu_{rr} := 0.015$

Rolling Resistance Force $F_{rr} := \mu_{rr} \cdot weight_{car} \cdot 9.81 \frac{m}{s^2}$

$F_{rr} = 231.798\,N$ $\quad$ $F_{rr} = 52.11\,lbf$

Inertial Resistance

0-60 mph time $t_{60} := 12s$

Acceleration $acc := \frac{60mph}{t_{60}}$ $\quad$ $acc = 2.235 \frac{m}{s^2}$

Sum of inertial forces $J_{car} := 0.1lbf \cdot ft^2$

Inertial resistance Force $F_I := acc \cdot weight_{car}$

$F_I = 3.521 \times 10^3\,N$ $\quad$ $F_I = 791.55\,lbf$

Forces & Torque

Total Force at Starting

$$F_{start} := F_I + F_{rr}$$

$$F_{start} = 3.753 \times 10^3 \, N \qquad F_{start} = 843.661 \, lbf$$

Total Force at Top Speed

$$F_{top} := F_{rr} + F_d(65mph)$$

$$F_{top} = 657.012 \, N \qquad F_{top} = 147.702 \, lbf$$

Speed at Wheel to Speed at Shaft

$$Motor_{speed}(v_{car}) := \frac{v_{car}}{wheel_{rad}} \cdot AR \cdot .864$$

$$Motor_{speed}(65mph) = 2.495 \times 10^3 \, rpm$$

Torque needed to maintain top speed

$$T_{top} := \frac{F_{top} \cdot wheel_{rad}}{AR \cdot .864}$$

$$T_{top} = 53.904 \, ft \cdot lbf$$

Battery Range and Capacity

Battery pack capacity
(16 J-150 @ 75AH)

$$Cap := 16 \cdot 12V \cdot 75A \cdot hr \qquad Cap = 14.4 \, kW \cdot hr$$

At top speed 65 mph continuous

$$Dist := \frac{Cap \cdot .8}{F_{top}} \qquad Dist = 39.222 \, mile$$

$$Time := \frac{Dist}{65mph} \qquad Time = 36.205 \, min$$

Appendix 2: Design Calculations[2]

State of Charge as a measure of Specific Gravity and Open-Circuit Voltage				
Percentage Charge	Specific Gravity	Open Circuit Voltage		
		Cell	6 Volt	12 Volt
100	1.277	2.122	6.37	12.73
90	1.258	2.103	6.31	12.62
80	1.238	2.083	6.25	12.50
70	1.217	2.062	6.19	12.37
60	1.195	2.04	6.12	12.24
50	1.172	2.017	6.05	12.10
40	1.148	1.993	5.98	11.96
30	1.124	1.969	5.91	11.81
20	1.098	1.943	5.83	11.66
10	1.073	1.918	5.75	11.51

Appendix 3: State of Charge by voltage of battery

<http://www.trojanbattery.com/Products/J150Plus12V.aspx>