Requirement Development for Electrical Vehicles Using Simulation Tools

Wei Zhan, *Member, IAENG,* Make McDermott, Behbood Zoghi, and Muhammad Hasan

***Abstract*— Steady state and dynamic vehicle models are derived for development of requirements on motors and batteries for the conversion of internal combustion engine powered vehicles to electric vehicles. MATLAB simulation tools are developed to establish relationships among motor power and torque, battery weight and specific energy, vehicle weight, speed, driving range, maximum cruise speed, and maximum acceleration. Vehicle level performance requirements such as driving range, maximum cruise speed, and maximum acceleration are established. The simulation tools allow one to translate these vehicle level performance requirements to lower level performance requirements on motor power and torque, battery power and energy, and gear reduction. The simulation tools can also be used to study the trade-offs among the design parameters.**

***Index Terms*— Battery electric vehicle, motor, simulation, vehicle dynamics.**

I. Introduction

Even though the internal combustion engine (ICE) is currently still the dominating power source for automobiles, the cost of fuel and more stringent government regulations on greenhouse gas emissions have led to more active interest in hybrid and electric vehicles. Hybrid vehicles have better gas mileage than ICE-powered vehicles. But they still have the emission problem and the dual power sources make them more complex and expensive. Battery electric vehicles (BEV) have zero emission with a single power source that makes their design, control, and maintenance relatively simple compared to hybrid vehicles. In addition, the wide use of BEVs will reduce dependence on foreign oil, lower the energy cost per mile of driving, and can potentially reduce the cost of electricity by using the vehicle to grid power capability.

The main drawback for BEVs lies in the battery technology. The low energy and power densities cause the weight to be too high or significantly reduce the driving range and other vehicle level performances. Initial cost is another factor that slows the commercialization of electric vehicles. However, the latest developments in battery technologies are making electric vehicles more and more attractive. From lead-acid batteries to nickel metal-hydride (NiMH) batteries, lithium-ion cell technology [9], and the latest nano-technology based batteries [1], the energy and power densities have improved drastically.

Another problem related to BEV is the lack of infrastructure for charging the batteries. The U.S. government is investing heavily on battery technologies and infrastructure for electric vehicles. It has set a target of one million electric vehicles on U.S. road by 2012. Tax credits up to $7,500 for buyers of plug-in electrical vehicles are offered by the U.S. government. The private sector is also investing billions of dollars in electric vehicles. GM and FORD are both planning to roll out plug-in electric vehicles by 2010. All these developments point to a trend toward electric vehicles in the auto industry.

Not only are an increasing number of new BEVs being manufactured, there is also significant interest in converting existing ICE-powered vehicles to electric power. A Google search for “conversion to EV” results in millions of websites and books, many of them providing Do it Yourself kits with focus on removal and addition of components [8]. There is increasing interest in academia in the development of BEVs; for example, an undergraduate senior design project developed an electric vehicle conversion [2]. However, many of these efforts lack consideration of detailed system design requirements. Most of the components for conversions are selected to provide similar output to that of the IEC or by using the vehicle weight to determine the energy and power requirements. The conversion to electric propulsion is a complex process and requires analysis that can be very different from that of an ICE-powered vehicle [7]. Many performance objectives impose conflicting demands. If not designed carefully, the resulting electric vehicle can have many problems such as driving range shorter than expected, battery and motor lacking enough power for desired acceleration, and safety-related design problems. In this paper, first principle models are derived for electric vehicles and used to establish quantitative design requirements. Software tools are developed in MATLAB [10] to allow users to quickly determine expected vehicle level performances for a given motor and batteries. They can also be used to conduct trade-off studies for many design parameters. These simulation tools are more accessible to the users than the more expensive ones such as CarSim and PSAT.

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Throughout the paper, parameters for a Ford F-150 pickup truck are used. The analysis can be applied to other vehicles by changing the vehicle parameters.

The remainder of the paper is organized as follows: steady state analysis is carried out in section II followed by dynamic analysis in section III; section IV contains the conclusions.

II. Steady state analysis

One of the system level requirements for a BEV conversion is the driving range at constant speed. This requirement can be used to derive motor power and battery power and energy requirements. Since the vehicle is assumed to be moving at a constant speed, steady state analysis can be use to study this problem.

The energy required to move a vehicle is determined by the distance it travels and the force it has to overcome. The road load force the vehicle must overcome to move the given distance has three components [3, 6], as illustrated in Figure 1:

1. the component of the gravity force in the direction of travel, if it is an inclined path;
2. the aerodynamic drag;
3. the rolling resistance.

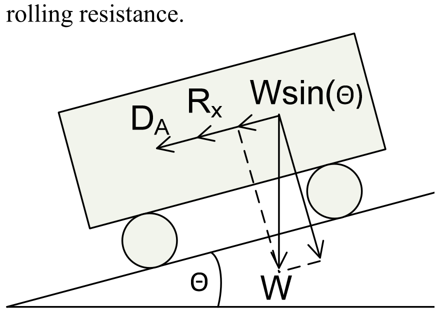

Figure 1. Road load force components

Projected gravity force

The gravity force is decomposed into two components, one in the direction of travel and the other in the direction perpendicular to the surface. In order to move the vehicle up the inclined surface, the vehicle must overcome the gravity force component in the direction of travel. This is given by

$$W_x = Wsin(\theta) \quad (1)$$

where W is the gravity force, θ is the angle of the inclined surface, and W_x is the component of the gravity force in the direction of travel.

On a flat surface, the gravity force is perpendicular to the direction of travel and will not directly contribute to the energy required to move the vehicle.

The gravity force also has an indirect impact on the amount of energy required to move a vehicle since the weight has an influence on the rolling resistance, which will be discussed below.

Aerodynamic drag

The drag is a function of speed for any given vehicle. At low speed the drag force is negligible. At high speed, the drag becomes a significant factor. For simplicity, a semi-empirical model is used here [6]

$$D_A = \frac{1}{2}\rho V^2 C_D A \quad (2)$$

where V is the vehicle speed (ft/sec), A is the frontal area of the vehicle (ft^2), C_D is the aerodynamic drag coefficient, D_A is the aerodynamic drag (lb), ρ is the air density (lb-sec^2/ft^4). A nominal value of ρ = 0.00236 (lb-sec^2/ft^4) is used in this paper. An estimated value of 0.45 for C_D is used for a late model Ford F-150 [6].

The rolling resistance

Rolling resistance of the tires is a major vehicle resistance force. It is the dominant motion resistance force at low speed (<50 mph). The rolling resistance can be modeled as the vehicle static weight W multiplied by the coefficient of rolling resistance f_r:

$$R_x = f_r W \quad (3)$$

The coefficient of rolling resistance is affected by tire construction, tire temperature, vehicle speed, road surface, and tire pressure. For instance, the rolling resistance coefficient changes as the temperature changes. To simplify our analysis, we make the following assumptions:

- The tire pressure is maintained at the value specified by the OEM;
- The tire temperature is above 50 ^{o}F;
- The vehicle is driven on a dry concrete surface at a speed below 60 mph.

With these assumptions, the coefficient of rolling resistance can be assumed constant. Typical values for the coefficient of rolling resistance f_r are between 0.01 and 0.02 under the above assumptions. We use 0.015 as the nominal value.

Dynamic weight transfer and the aerodynamic lift force have negligible effects on the coefficient of rolling resistance.

Power required

Based on the above analysis, the power required to drive the vehicle at a given speed V (mph) is given by the total road load forces multiplied by the vehicle speed, i.e.,

$$HP = 0.00267(D_A + R_x + W_x)\, V \quad (4)$$

where W_x can be calculated using (1), D_A is given by (2), R_x can be calculated using (3) with f_r = 0.015, and 0.00267 is the conversion factor to horsepower, HP. To calculate these quantities, we need the following inputs:

- vehicle speed (mph);
- vehicle weight (including trailer if there is one) (lbs);
- frontal area of the vehicle, (including trailer if there is one) (ft^2);
- aerodynamic drag coefficient (including trailer if there is one) (approximately 0.45 for F-150.);
- coefficient of rolling resistance (approximately 0.015 for F-150);
- surface incline angle (degree).

Energy required

Energy is power integrated over time. If the total distance traveled is long enough, the initial acceleration and final deceleration have negligible effect on the total energy calculation. Also, since this is a steady state analysis the aerodynamic drag is constant. Noting that $W_x = Wsin(\theta)$ and $V = dx/dt$, it follows that

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$$\int W_x \frac{dx}{dt} dt = \int W sin(\theta) dx = W \int sin(\theta) dx = W \Delta h$$

where Δh is the change in elevation between the starting and ending points. Thus, the energy required to move a vehicle for a distance of d (miles) at a speed V (mph) with a change in elevation of Δh (miles) is given by

$$E\ (kWh) = 0.00267[(D_A+R_x)d + W\ \Delta h] \times 0.746\ (kW)/Hp$$
$$=0.002\,[(D_A + R_x)d + W\Delta h]. \quad (5)$$

Define θ^* as the average slope; i.e.,

$$sin\ \theta^* = \Delta h/d$$

and

$$W_x^* = W\ sin\ \theta^*$$

Then the trip energy becomes

$$E\ (kWh)= 0.002(D_A + R_x + W_x^*)d. \quad (6)$$

At first glance, the energy calculation in (6) appears to be independent of the speed. A closer look reveals that the energy is dependent on the speed since the aerodynamic drag D_A is dependent on the vehicle speed. If speed is not constant, equations (5, 6) do not apply and the power consumed to overcome drag must be evaluated as an integral.

The energy calculations in (6) can be converted to MJ (1 kWh = 3.6 MJ):

$$E\ (MJ) =0.0072(D_A + R_x + W_x^*)d. \quad (7)$$

Battery specific energy

The total energy required for driving a vehicle at constant speed over a given range can be used to derive the requirement on battery specific energy D_{se} (MJ/kg).

Let the battery weight be W_b (lb) and the delivery efficiency be η. The total available energy $E_T(MJ)$ from the battery/electric motor is determined by

$$E_T\ (MJ) = 0.455\ (kg/lb) \times D_{se}\ (MJ/kg) \times Wb\ (lb) \times \eta. \quad (8)$$

This amount must be greater than or equal to the total energy required as given in (7), i.e.,

$$0.0072(D_A D_A + Rx+Wx^*)d \le 0.455\eta D_{se} W_b. \quad (9)$$

From this one can solve for D_{se} required to travel a given distance

$$D_{se} \ge 0.0158 \frac{D_A+R_x+W_x^*}{\eta W_b} d. \quad (10)$$

Alternatively, we can calculate the maximum distance d_{max} the vehicle can travel when the specific energy is given

$$d_{max} = 63.29 \frac{\eta W_b}{D_A+R_x+W_x^*} D_{se}. \quad (11)$$

Note that the battery weight W_b is part of the vehicle weight W, which is used in the calculation of R_x and W_x. Denoting the vehicle weight without the battery by W_0 (lb), we have

$$W = W_0 + W_b. \quad (12)$$

Combining (9) and (12), we get

$$W_b[63.29\eta D_{se} - d(sin\theta^* + f_r)] \ge d[D_A + (sin\theta^* + frW0. \quad (13)$$

Since the right hand side is positive, and the battery weight must be positive, we must have

$$d < \frac{63.29\eta D_{se}}{sin\theta^* + f_r} \quad (14)$$

The right hand side of (14) provides a theoretical upper bound for the distance a vehicle can travel with infinite battery weight (energy) regardless of the speed, vehicle weight, and aerodynamic drag.

Under the assumption that (14) holds, one can determine the weight of a battery in order to travel a distance d

$$W_b \ge d \frac{D_A + (sin\theta + f_r)W_0}{63.29\eta D_{se} - d(sin\theta + f_r)} \quad (15)$$

One can conclude that, as long as (14) holds, a sufficiently heavy battery would always enable the vehicle to travel a given distance d. In practice, there are other constraints such as the volumetric limitation for the battery and vehicle load capacity.

Using (12) in (10) yields

$$D_{se} \ge 0.0158 \left[\frac{D_A}{W_b} + (f_r + \sin(\theta^*))\left(1 + \frac{W_0}{W_b}\right)\right] \frac{d}{\eta} \quad (16)$$

Using the Ford F-150 parameter values, the relationship between minimum battery weight and specific energy is plotted in Figure 2 for different values of driving range. The efficiency for battery and motor is assumed to be 75% [4] and the speed is 40 mph. For a given driving range, the battery weight and specific energy must be chosen so that the point is above the curve corresponding to the driving range.

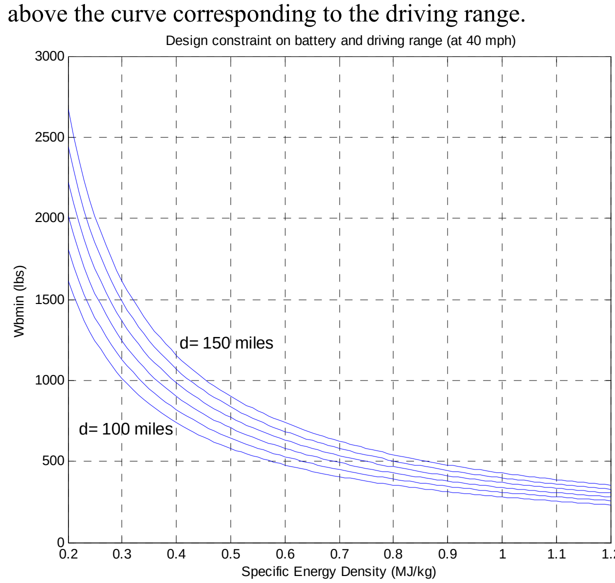

Figure 2. Design constraint among specific energy, driving range, and battery weight

Maximum cruise speed

The maximum cruise speed that the vehicle is required to maintain imposes requirements on the power delivered by the motor and batteries. The example below is for a cruise speed of 80 mph.

Using the following vehicle parameters in the steady state model:

- vehicle speed: 80 mph,
- vehicle weight (including motors, but w/o engine, transmission, battery): 4000 lbs,
- frontal area of the vehicle: 34 ft^2,

- air temperature: 59 °F,
- atmospheric pressure: 29.92 in-Hg,
- aerodynamic drag coefficient: 0.45,
- coefficient of rolling resistance: 0.015,
- efficiency = 75%,
- surface incline angle: 0 degree,
- battery weight: 1000 lbs,

one can calculate the requirement on motor power for a maximum cruise speed of 80 mph to be greater than 52 kW. The power requirement on the motor is plotted as a function of maximum cruise speed in Figure 3. If two motors are used, then each motor should have rated power greater than 26 kW. The corresponding power requirement on the batteries can be derived by dividing the motor power by the efficiency. With a maximum cruise speed of 80 mph, the battery power can be calculated as greater than 69 kW. This can be translated to the current/voltage requirements on the batteries. For example, if the voltage output is 300 V, then the current must be greater than 69000/300 = 230 A.

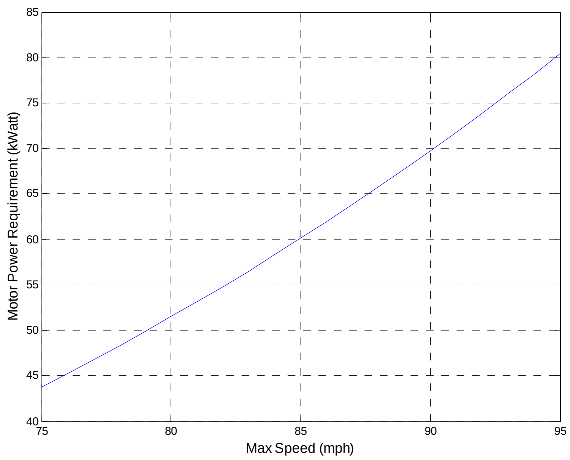

Figure 3. Motor power as a function of max vehicle speed

Figure 3 shows that the power is very sensitive to the maximum cruise speed. Naturally, one would also like to know if the battery weight has significant impact on the power requirement based on cruise speed.

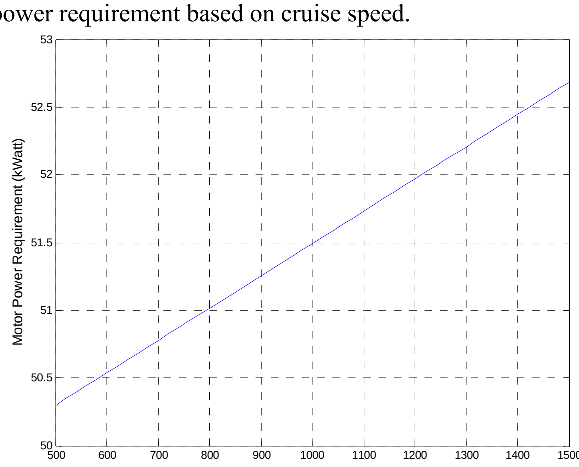

Figure 4. Motor power as a function of battery weight

Figure 4 shows the motor power requirement at 80 mph with different battery weights. Notice that a 200% increase of battery weight from 500 lbs to 1500 lbs only results in about 5% change in the battery power requirement. A 53 kW total motor power can cover all realistic battery weights. One can plot a similar graph of battery power requirement vs. battery weight. The result is also similar: the impact of the battery weight on the power requirement based on maximum speed is insignificant. It can be calculated that a 71 kW battery power is sufficient for any realistic battery weight for an 80 mph cruise speed.

The maximum cruise speed scenario is used to determine the rated power for batteries and motors. In other words, the battery and motor are required to provide the power over a long period of time.

III. DYNAMIC ANALYSIS

When the vehicle is driven over a short period of time or the time spent in accelerating/decelerating is a significant portion of the total time, steady state analysis is not adequate. Instead, dynamic analysis is needed. The dynamic model developed in this section will be used to derive requirements on motor and battery outputs.

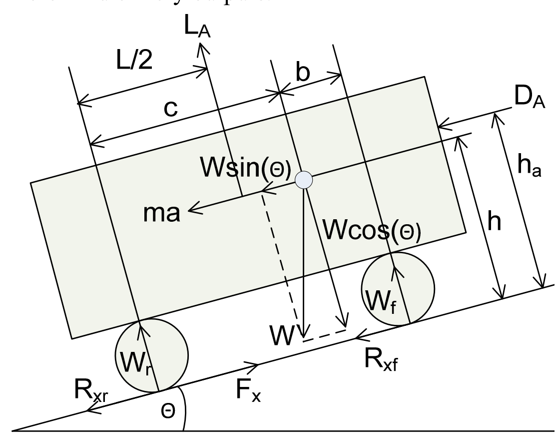

Figure 5. Vehicle dynamics model

The forces acting on the vehicle are illustrated in Fig. 5.

- W is the gravity force.
- R_{xf} and R_{xr} are front and rear rolling resistant forces and $R_{xf} + R_{xr} = R_x$.
- W_f and W_r are front and rear normal forces.
- D_A is the aerodynamic drag.
- L_A is the aerodynamic lift.
- F_x is the tractive force (rear wheel drive is assumed).

Compared to the vehicle forces and inertia, the dynamics of the motor and wheels are not significant and hence not considered here.

Newton's Second Law is applied in the direction of the vehicle movement and the direction perpendicular to the road surface.

$$F_x - W\sin\theta - D_A - \frac{W}{g}a - R_x = 0 \quad (17)$$

$$W_f + W_r + L_A - W\cos\theta = 0 \quad (18)$$

where the aerodynamic lift force is given by

$$L_A = \frac{1}{2}\rho V^2 C_L A \quad (19)$$

Typical values for aerodynamic lift coefficient is C_L = 0.3-0.5 [6]. The lift force is applied at the center of the wheel base.

A moment equation about the contact point at the front wheels can also be written.

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$$W_r(b+c) - D_A h_a - \left(\frac{W}{g}a + W\sin\theta\right)h + \frac{L}{2}L_A - W\cos(\theta)b = 0 \qquad (20)$$

There are two scenarios for the traction force F_x:
1) limited by the motor output (power limited);
2) limited by the road surface friction coefficient (traction limited).

These two cases are discussed separately.

Power Limited

Ignoring the wheel dynamics, we have

$$F_x = \frac{T_m}{r} \qquad (21)$$

where T_m is the torque applied to the wheel from the motor and r is the radius of the tire.

Traction limited

In this case, the motor torque calculated by (21) exceeds the maximum tractive force the road surface and the tire can generate, which is determined by

$$F_x = \mu W_r \qquad (22)$$

where μ is the surface friction coefficient. For truck tires, on dry asphalt, μ is approximately 1.

From (17), (20), (22), we can solve for the maximum tractive force F_{xmax}

$$F_{xmax} = \frac{\mu}{b+c-\mu h}\left[D_A h_a - (D_A + R_x)h - \frac{L}{2}L_A + Wb\cos\theta\right] \qquad (23)$$

In the MATLAB/Simulink model, these two cases can be combined by calculating the minimum of the two forces in (21) and (23). A flag can be created in the model to show when the vehicle is traction limited.

0-60 mph

The requirement on 0-60 mph time determines the maximum outputs from the batteries and the motors. A 10 second 0-60 mph time is used as a vehicle acceleration requirement. During the 10 seconds while the vehicle accelerates to 60 mph from a standing start, the maximum power generated by the motor and battery can be significantly higher than the rated values.

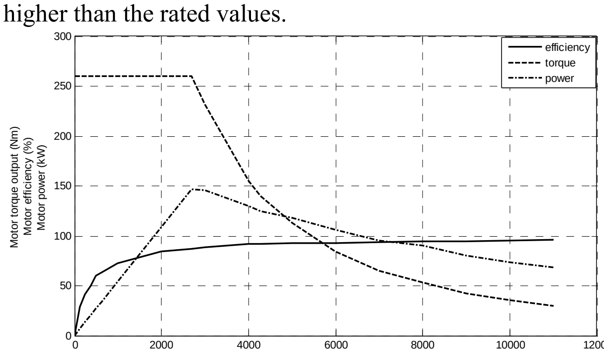

Figure 6. AC induction Motor power, torque, and efficiency as a function of speed

Figure 6 shows the characteristic of a typical AC induction motor. This can be used together with the vehicle dynamics model, as shown in Figure 7, to derive the maximum power requirements on the motor and battery. The Simulink model can be used to determine the 0-60 mph time. Based on the simulation result, one can find if a specific motor/battery combination will meet the requirement on 0-60 mph time. In addition to the parameters used in the derivation of power requirements for maximum speed, the following parameters are needed

- Aerodynamic lift coefficient: 0.4;
- Gear ratio: 10;
- Wheel base (L): 126 in;
- CG height (h): 1m;
- Height of aerodynamic drag (h_a): 1.1m;
- Radius of loaded wheel: 0.351m;
- Weight percentage on front wheels: 55%;
- Motor torque curve;
- Motor efficiency curve;
- Battery power limit;
- Surface mu: 0.95;

where the gear ratio is the ratio between the angular velocities of the motor and the driven wheels.

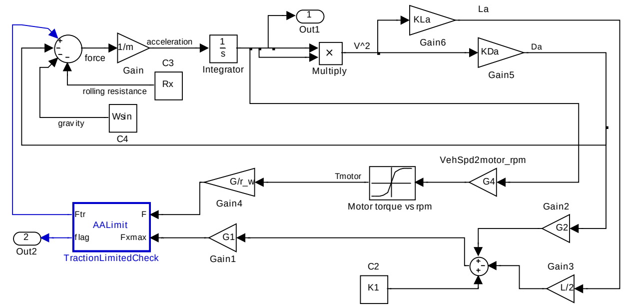

Figure 7. Vehicle dynamics model with motor characteristics

The model parameters are defined as

- m: vehicle mass;
- $Wsin = W\sin(\theta)$;
- $KLa = \frac{1}{2}\rho V^2 C_L A * 9.8 * 3.28^2/2.2$;
- $KDa = \frac{1}{2}\rho V^2 C_D A * 9.8 * 3.28^2/2.2$;
- L: wheel base;
- $G_1 = \mu/(b+c-h\mu)$;
- $G_2 = h_a - h$;
- r_w: ratius of tire;
- G: gear ratio;
- $G_4 = G * (\frac{60}{2\pi})/r\_w$.

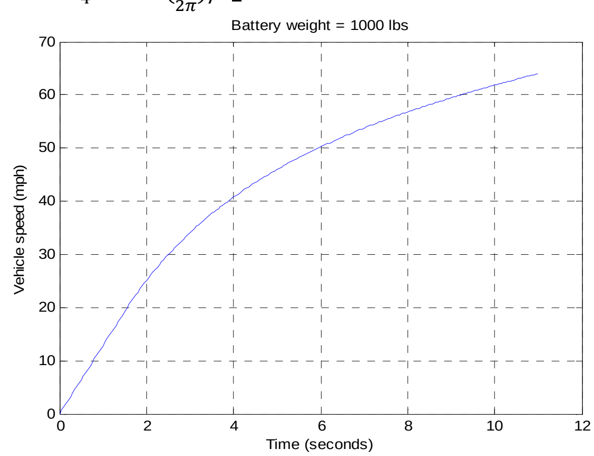

Figure 8. Maximum vehicle acceleration

With the motor characteristic given in Figure 6 and a

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maximum battery power of 140 kW, the simulation result in Figure 8 shows that the vehicle can accelerate from 0 to 60 mph in 9.2 seconds.

By varying the battery weight and repeating the simulation, the 0-60 mph time as a function of the battery weight is plotted in Figure 9. It can be seen that the battery weight has a significant impact on the 0-60 mph time.

It is worth noting that the results in Figures 8 and 9 are highly dependent on the motor and battery characteristic. The model can be used to conduct trade-off studies for motor, battery, gear ratio, cost, and other design parameters.

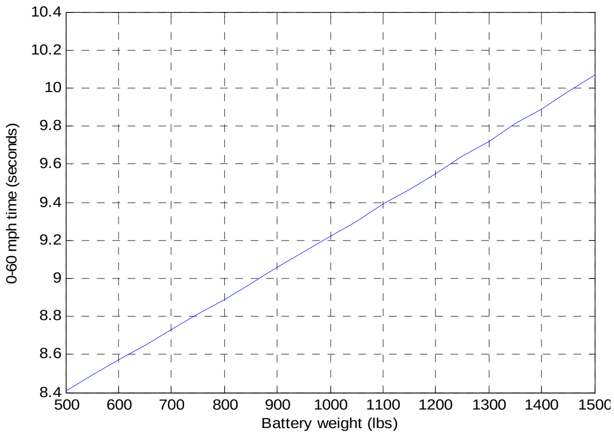

Figure 9. Impact of battery weight on maximum acceleration

IV. Conclusion

Several design requirements for conversion to electric vehicles are discussed in this paper. System level design requirements are used to derive requirements on motor power and torque and battery power, weight and specific energy based on simulation tools developed using first principle models. A design constraint involving battery weight, specific energy, and driving range is derived. The maximum cruise speed requirement results in requirements on the rated motor torque, power, and battery power. For a given motor and battery, the maximum acceleration can be simulated to see if the 0-60 mph time requirement is met. The steady state simulation model can also be created in Excel. The dynamic model requires the use of Simulink. The simulation tools allow further investigation of design trade-offs among different parameters. Future research includes the optimization of vehicle performance and cost using the simulation tools developed in this paper, sensitivity studies for the design parameters in the simulation model, and incorporating motor dynamics [5] into our model. Also, energy instrumentation could be a possible research area investigating replacement of fuel gauge and engine temperature by corresponding parameters in the electric domain [11]. Associated with this instrumentation is the fault indication capability of the system that needs further investigation too.

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