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Using Topographical and State of Charge Information to Predict the Actual Range of Electric Vehicles

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Abstract

Does an electric vehicle have sufficient stored energy to reach a destination and return safely to a designated charging location without recharging? This is the central operating question for all electric vehicles. The answer depends upon a number of factors, including operating parameters of the electric vehicle, driving tendencies, topography of the route, and the current State of Charge (SOC) for the batteries. The answer is fairly simple if the starting point is also the location of the charging station, the route to be travelled is relatively flat and the batteries are fully charged. In this case, the trip should be uneventful if the destination point is no farther away than one half the range of the vehicle. The answer is more complicated if the starting point is not the charging location and the destination requires travel through congested traffic conditions and/or the terrain involves significant changes in elevation and the SOC is less than 100 %. This paper presents a methodology for predicting the actual range of an electric vehicle using the Global Positioning System (GPS), the Geographical Information System (GIS), SOC, vehicle parameters, and fundamental Newtonian equations of motion. Results are compared with experimental data obtained by operating the vehicle under controlled conditions (1) on a closed, flat test track, (2) over rolling terrain, (3) on a limited access highway used as a commuter corridor, and (4) up and down a mountainous route with a change in elevation of more than 1500 ft (2500 m) with an average grade of more than 5 %.

Keywords: electric vehicle, range, battery, state of charge

1 Introduction

Range of an electric vehicle depends upon a number of factors that include the weight of the vehicle, type and number of batteries, current state of charge for the batteries, type of drive train, regenerative braking capability, terrain and traffic conditions of the route, and personal tendencies of the driver. The influence of each of these factors can be analyzed independently using Newtonian equations of motion, coupled with experimental data to confirm the efficiencies of the various components. This is relatively straight forward for an engineer or scientist when the operating conditions are controlled. However, the motoring public is unlikely to be able to predict accurately the remaining range for an electric vehicle under "real world" conditions when an overestimation of range could result in being stranded far from a readily accessible recharging station. The following sections of this paper provide a methodology for predicting the range of an electric vehicle based on its current location as identified by an on-board Global Positioning System (GPS), distance from the normal charging station, distance to a desired destination as determined by an on-board navigation system (NAV), information on changes in elevation along the planned route as determined by the Geographic Information System (GIS), state of charge of the batteries as determined by an on-board amp hour meter, and tabulated energy consumption parameters for a particular electric vehicle obtained from Newtonian equations of motion supplemented with experimental data obtained from driving the vehicle under controlled conditions. While not implemented in this paper, a graphical interface could be integrated in the navigation system to provide the driver with an instantaneous visual indication of the geographical area that would be within the safe operating range of the vehicle, thereby eliminating a major concern for the general driving public.

2 Energy Considerations

Energy is consumed by rolling resistance and wind resistance any time an electric vehicle is moving. Additional energy is required to accelerate the vehicle and to overcome changes in elevation caused by rolling hills and mountainous terrain. Of course, considerable energy is also lost internally due to heat caused by friction and resistance to the flow of electricity in the various components that make up the energy storage and drive train of the vehicle. Some energy can be recovered by switching the electric drive motor to a generator mode during braking and while descending hills. Each of these factors has been evaluated systematically for a particular electric vehicle in order to develop a more accurate methodology for predicting driving range under various conditions.

3 Vehicle Specifications

The electric vehicle shown in Figure 1 was used to measure energy consumption under various operating conditions. This vehicle is powered by an AC Inductive Drive System with Direct-Drive and Regenerative Braking. The data logger shown in the foreground was used to record the energy restored to the vehicle during charging. Specifications for the vehicle are given in Table 1.

Figure 1 Solectria Electric vehicle

Table 1 Vehicle Specifications

Curb Weight	2460 lbs	1116 kg
Length	164 inches	4.16 m
Width	70 inches	1.78 m
Height	56 inches	1.42 m
System Power	42 kW	42 kW
Drag Coefficient	0.31	0.31
Top Speed	70 mph	112.6
Specified Efficiency At 45 mph (72.5 kph)	137 W/mi	85.1 W/km
Specified Range @ 45 mph (72.5 kph)	50 miles	80.5 km
Acceleration 0 to 50 mph (80 kph)	18 seconds	

The vehicle is powered by thirteen (13) gel-type 12 volt lead acid batteries rated at 86.4 Ah each, which results in a capacity of 13.4 kWh at 100% SOC when in new condition. Current condition of the batteries was determined to be such that a 100% SOC represents approximately 9.8 kWh of useable energy. The vehicle is equipped with an on-board charger rated at 1.5kW/110V AC.

4 Experimental Results

4.1 Test Protocol

Baseline testing was accomplished at the University of Tennessee Advanced Vehicle Test Facility which includes a paved, banked, one mile oval test track shown in Figure 2.

Figure 2 UTC Advanced Vehicle Test Facility

The testing included acceleration from a standing start up to 45 mph, deceleration to a stop from 45 mph with and without regenerative braking, and range testing around the test track at constant speed of 45 mph, over a rolling terrain, on a limited access highway used as a commuter corridor, and up and down Signal Mountain which involved a change in elevation of more than 1500 ft (2500 m).

4.2 Accelerating

The energy required to accelerate a vehicle from a standing start to a given speed can be estimated to be the final kinetic energy of the vehicle plus loses due to internal friction, rolling resistance and wind resistance consumed during acceleration. The vehicle can be operated in economy, normal or power mode, depending upon traffic conditions. As expected, better acceleration times are obtained when operated in the power mode with a corresponding increase in the energy consumed as can be seen in Table 2. Note that the energy required to accelerate from 0 to 45 mph in the economy mode is actually higher than that required using the normal or power mode. This is likely to be due to the greater distance over which rolling resistance acts during acceleration.

	Econ Mode	Normal Mode	Power Mode
Time 0 to 45 mph (Seconds)	81	30.1	18.7
Energy Consumed (Watt hours)	224	150.7	179.4
Distance (miles)	0.78	0.19	0.12

Table 2 Acceleration Test Data

The final kinetic energy of the vehicle at 45 mph is 74.8 Wh which indicates an overall efficiency of the system during acceleration in the normal mode of approximately 50%. If the energy required to overcome rolling resistance (10.5 Wh) and wind resistance (0.2 Wh) are added to the kinetic energy, the net efficiency of the internal drive system (battery to wheels) would be about 57%.

4.3 Travelling at Constant Velocity

When travelling at constant velocity an electric vehicle consumes energy overcoming rolling resistance, wind resistance, and internal loses associated with friction and heat generated by the flow of electric current. Energy required to overcome rolling resistance is primarily determined by deflection of the tires and can be estimated to be equal to the weight of the vehicle multiplied by the coefficient of rolling resistance times the distance travelled. For this particular vehicle, the energy to overcome vehicle rolling resistance can be estimated to be approximately 44 lbf times the distance travelled. Likewise, the energy required to overcome wind resistance is equal to the product of the density of air, with the drag coefficient times the frontal area of the vehicle and the square of the speed of the vehicle which is approximately 14 lbf times the distance travelled at 45 mph. The balance of the lost energy can be assumed to be internal resistance caused by friction and resistance to the flow of electricity. An accounting of the energy consumed per mile from the average of 30 laps around the one mile test track at a constant speed of 45 while operating in the normal mode is given in Table 3.

Average Battery Energy Normal	Energy to Overcome Rolling Resistance	Energy to Overcome Wind Resistance	Energy to Overcome Internal Losses
202.8 Wh	87.5 Wh	27.8 Wh	87.5 Wh

Table 3 Energy Consumed per mile at 45 mph

Note that the net efficiency (battery to wheel) is again approximately 57%, indicating that the internal losses are comparable during acceleration and driving at constant speed.

A second set of tests were conducted with the vehicle operating in the economy mode. Results are given in Table 3

Average Battery Energy Consumed	Energy to Overcome Rolling Resistance	Energy to Overcome Wind Resistance	Energy to Overcome Internal Losses
155.6 Wh	87.6 Wh	27.8 Wh	40.2

Table 3 Energy Consumption per mile at 45 mph

Note that the net internal efficiency (battery to wheels) in the economy mode is approximately 74% compared to 57% in the normal mode.

4.4 Decelerating

The effectiveness of the regenerative braking was evaluated by allowing the vehicle to decelerate from to a stop from 45 mph with the regenerative braking turned on and off. Results are given in Table 4.

Speed 45 mph to 0	Time	Distance	Energy Recovered
With Regenerative Braking	25.9 sec	0.15	36.1 Wh
Without Regenerative Braking	61.1	0.55	0

Table 4 Energy Recovered while Decelerating

The ratio of energy recovered (36.1 Wh) to the kinetic energy of the vehicle at 45 mph (74.8 Wh) provides an approximation of the efficiency of the regenerative braking to be about 48%.

4.5 Changing Elevation

The energy required to climb a hill includes the usual rolling and wind resistance, internal friction and electrical loses plus the energy required for lifting the vehicle which can be estimated as the product of vehicle weight and change in elevation.

4.5.1 Ascending

For this particular vehicle, the average energy consumed in climbing 1000 feet while travelling 3.5 miles (average grade 5.4%) up a winding mountain road was found to be 1805 Wh for an average of 516 Wh per mile, compared to 202 Wh per mile for level driving. An accounting of the energy consumed is provided in Table 5.

Energy for Rolling Resistance	306 Wh
Energy for Wind Resistance	56
Energy for Elevation Change	1077
Subtotal	1439
Battery Energy Consumed	1805
Estimated Internal Losses	366

Table 5 Energy Consumed while Ascending

4.5.2 Descending

As expected, regenerative braking while descending the above described route results in energy being returned to the battery that exceeds that required to overcome rolling, wind and internal resistance plus the change in kinetic energy due to the vehicle velocity at the bottom of the mountain. Table 6 shows the distribution of energy while descending.

Energy for Rolling Resistance	306 Wh
Energy for Wind Resistance	76
Energy for Change in K.E.	59
Potential Energy Lost	1077
Subtotal	1518
Energy Restored to Battery	304

Table 6 Energy Recovered while Descending

Note that 304 Wh are restored to the battery, representing approximately 28 % of the potential energy lost by the drop in elevation. This is naturally less than the efficiency observed during regenerative braking at the test track because of the need for some frictional braking to keep the vehicle safely under control while descending.

4.6 Driving in the “Real World”

With test data obtained from the test track, the next step in development of a method for predicting actual range was to operate the vehicle on city streets, over rolling terrain, on the open highway and up and down a mountain. Results are shown in Table 7.

Route	Wh/mile
Test Track @45 mph	202
Rolling Countryside @ 40 mph	175
Limited Access Hwy @ 55 mph	211
Mountainous Ascent (>5% Grade)	516
Mountainous Descent (>5%Grade)	-87

Table 7 Energy Used in “Real World” Driving

As expected, change in elevation has the greatest effect on energy consumption, with speed accounting for the remainder of the differences observed.

5 Range Prediction

The range of an electric vehicle can be predicted by accounting for all the energy consumption as a vehicle passes through all the waypoints between the starting location and the final destination which must always be the preferred charging station. This is accomplished by application of the first and second laws of thermodynamics [1] combined with Newtonian laws of motion [2], accurate information on the elevation of all significant waypoints obtained from GPS and GIS, with street maps and distances derived from the on-board NAV system, knowledge of vehicle specifications and performance characteristics from road testing, and the current SOC of the battery deduced from an on-board Ah meter. The task is simplified by use of a topographical inertial simulator [3] that integrates the data and handles all the energy calculations.

An example of range prediction is given in Table 8 which assumes the route begins and ends at the charging station and the batteries are fully charged with 9.8 kWh, of which 80% can be used before the vehicle automatically goes into a "limp back" mode.

Route	Range (miles)
Test Track @45 mph	38.8
Rolling Countryside @40 mph	44.8
Limited Access Hwy @ 55 mph	37.1
Mountainous (Up and Down)	18.2

Table 8 Range Estimates for Various Routes

It is important to note that the "useful" range for the vehicle is actually one half of the values shown in Table 8 because of the need to always return to the charging station.

6 Summary

It has been shown that the range of an electric vehicle can be predicted with precision if the driving conditions can be accurately modelled and the operating parameters of the vehicle, including SOC for the batteries is known. What remains to be done is to integrate this method for predicting range into a modified on-board navigation system that can display not only the current location and destination of the vehicle, but also the dynamically changing range of the vehicle as the SOC decreases and the vehicle moves in relation to the charging station, which must be the final destination. This work is under development. A preliminary example is provided in Figure 1 which shows the limitations on destinations that the driver of an electric vehicle would have when the SOC is 50% and the vehicle is approximately 10 miles from the recharging station. Note that the vehicle can be driven less than 3 miles if the destination is up Signal Mountain and away from the charging station, while it can be driven more than 15 miles if the direction is toward the charging station and beyond.

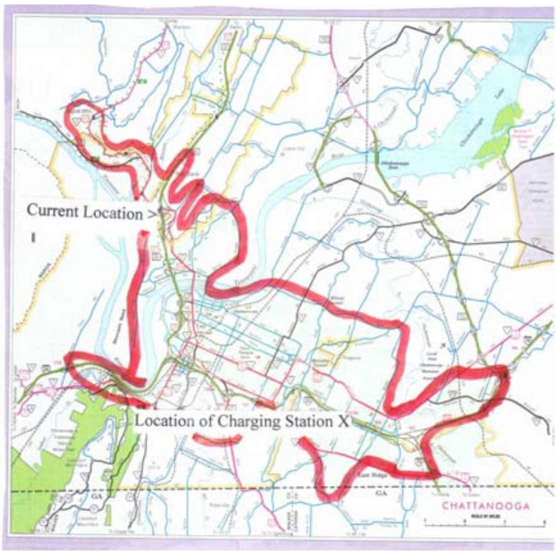

Figure 1 Predicted Range with 50% SOC

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