Developing a Move-and-Charge System for Electric Vehicles

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Abstract

A move-and-charge system for electric vehicles was developed. Through two separate experimental setups, a series of prototypes were tested for their feasibility of integration into a move-and-charge system. A single cell lithium-ion battery was tested with a level 3 charge to determine the speed at which it could be recharged. The results from this test are applicable to larger, more powerful electric vehicle batteries of the same li-ion technology which are analogous to the smaller single cell battery used in testing, albeit with a greater number of cells. The mechanical systems for transferring power from a stationary system to the moving vehicle were tested using a scale model remote control car. The prototype mechanical systems were installed on the car, which was then driven under the stationary system to simulate recharging. The two mechanical designs that were tested were: (1) a pantograph-type system with a spring loaded arm extending to a cable suspended above the car and (2) a “third rail”-type system with a small arm extending from the chassis down to a rail embedded in the road surface which supplied electricity. The results from testing suggest that, at full scale, the system would provide a possible means of extending the range of electric vehicles, thus eliminating the necessity of gasoline-electric hybrids.

Introduction

In the current oil-dependent energy economy, electric vehicle technology is a promising gasoline alternative that is a step towards a sustainable future. Fueled by electricity that can be generated by nuclear reactors, wind turbines, and solar panels, electric vehicles offer a less expensive and cleaner alternative to automobiles with an internal combustion engine.

As the electric vehicle (EV) market expands, a number of major auto manufacturers are designing and producing their own EVs. One of the most publicized is the Chevrolet Volt, an EV-gas hybrid that is due to enter the market in 2010 (Chevrolet Volt, 2009, para. 4). Tesla Motors, a startup company based in California, markets the Tesla Roadster, a vehicle powered exclusively by electricity (Tesla Motors, 2009, para. 1). Other major auto manufacturers with EV or Gas-electric hybrid prototypes include : Nissan, Renault, Audi, Honda, Toyota, and Mitsubishi (Moffett, 2009, para. 4). With large investments from corporations on electric vehicles and from governments to build a support infrastructure, the electric vehicle sector is positioned to grow as the consumers look for cheaper alternatives to gasoline.

Both purely electric vehicles and gas-electric hybrids require some form of charging to function and maintain a fuel cost advantage over gasoline-powered vehicles. When being recharged, the vehicle must always remain stationary while it is charged at the inconvenience of the owner. This wait could be avoided by implementing a system that allows an electric vehicle to continue to move while it is recharged. The purpose of this project is to design and test systems that would recharge the batteries of an electric vehicle while it is in motion.

Literature Review

Battery Systems in Electric Vehicles

There are multiple battery technologies in use today in electrically powered vehicles (EVs). Technologies are most often differentiated by the cathode, anode, and electrolyte used in the battery. A few of the most common at present are lead-acid, nickel-cadmium, nickel-zinc, and nickel-metal hydride (Chan & Chau, 2001, p.154) . Although each of these types has its own advantages, the lithium-ion battery is the technology most prevalent in EVs because of its high capacity for a relatively low number of cells and its resistance to a so-called memory effect which causes a significant loss of capacity if the battery is not fully discharged before charging or vice versa (Hodkinson & Fenton, 2001, p.113).

Lithium-ion batteries in EVs comprise a large number of cells connected in series to supply a greater voltage and hold a more substantial amount of electrical energy. Batteries are usually designed for a specific electric vehicle model, but one example gives a total of 96 cells in modules of 8 cells with each module individually controlled by its own monitoring system (Hodkinson & Fenton, 2001, p.112, fig. 5.6). Each cell has a 4V output capacity (Chan & Chau, 2001, p.165), which means that the total voltage output at full charge capacity would be 384V. The total energy capacity of a 96 cell Li-Ion battery would be 19.2 kW/h assuming that each cell has a capacity of 200 W/h (Chan & Chau, 2001, p.165).

Determining EV Battery State-of-Charge

For both the convenience of consumer EV use and for safely recharging an EV battery, accurately reading the state-of-charge (SOC) is critical. The SOC of a battery is given as the percentage of the total capacity that remains in the battery. A driver needs an accurate SOC reading to judge remaining driving distance before the batteries need to be recharged. When the batteries are being recharged, the SOC is vital in correctly charging the battery so as to avoid overcharging and subsequent damage to the battery (Westbrook, 2001, p.108).

State-of-charge can easily be measured by measuring the decline in output voltage from a battery and comparing it to a known curve. This method is very simple but not effective in most battery types because they will not show a voltage decline large enough to be accurately measured until they are very close to being fully discharged (Westbrook, 2001, p.108). The notable exception to this is the lithium-ion battery, which exhibits a relatively constant decline in output voltage as it is discharged (Hodkinson & Fenton, 2001, p.113). This allows recharging systems to accurately charge lithium-ion batteries if the SOC is communicated to the power supply regulating the recharging (Prof. A. Burke, personal communication).

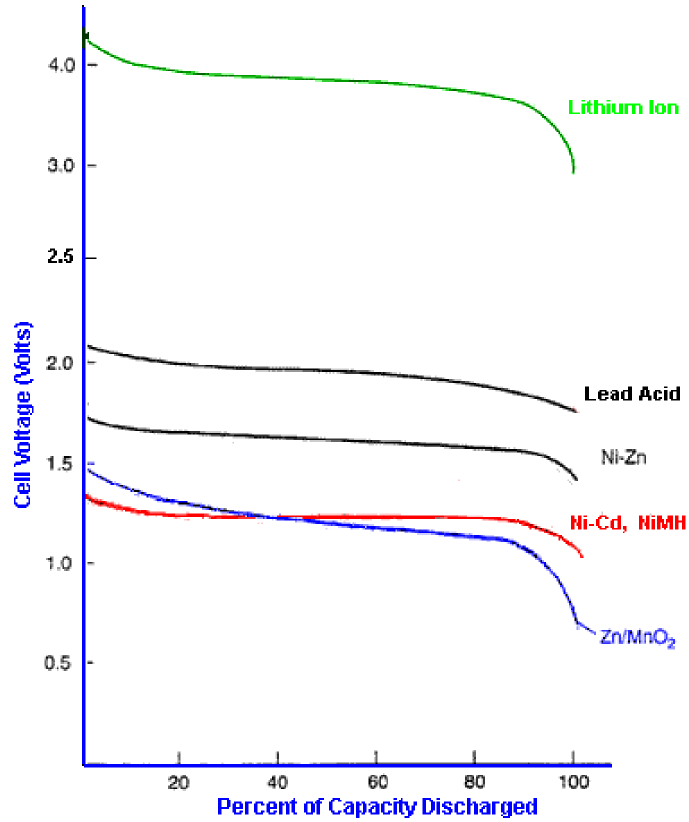

Figure 1. Discharge curves for various types of batteries. Note that the lithium-ion curve shows a larger decline in voltage in the middle of the curve, where other battery types remain relatively constant (Woodbank Communications, 2005).

Recharging Electric Vehicles

There are multiple methods of recharging an electric vehicle. The method used in the case of the Tesla Roadster is known as a Level 1 charge (Chan & Chau, 1996, p.2). This type of charge is the only one feasible for a typical consumer to utilize at home, where the electricity supply is relatively limited. Although there is an intermediate level of charging, Level 2, the most desirable method of recharging an EV is a Level 3 charge. When a purpose-built charging station (akin to a gas station for electric cars) is constructed, it is often given access to a much greater supply of electricity from the power grid and can use that to charge vehicles at a much greater rate. With a larger amount of electricity available, a Level 3 charging station can complete a full charge in as few as 10-15 minutes depending on the EV and the battery being charged (Chan & Chau, 1996, p.2).

Recharging an EV requires an electrical connection with the vehicle to transmit electricity to the battery. Because all charging stations at present are for stationary vehicles only, the connections are most often simple contact connections of two conductive materials (Westbrook, 2001, p.111). Various designs for a move-and-charge (MAC) system that would allow the vehicle to remain in motion while charging have been proposed, but such a system has never been successfully implemented in a commercial application. There are both technical and business-related reasons for this. A MAC system must circumvent environmental issues such as contamination of the conductive surfaces by oil, water, and ice as well as regulate the charging when the supply of electricity is interrupted by electromagnetic interference from sparking at the point of electrical contact between the moving vehicle and the fixed recharging system (Westbrook, 2001, p. 111). From a business standpoint, a system that requires a large investment but caters to a relatively small customer base of electric vehicle owners does not make sense. Until electric vehicles become commonplace in the transportation industry, move-and-charge systems are unlikely to become economically viable.

Existing Electric Vehicle Designs

The Chevrolet Volt is a well-known gas-electric hybrid that requires a recharge to avoid prolonged use of the gasoline engine to generate electricity and thus avoid a loss of efficiency. Without the use of a gasoline engine to recharge the batteries, the Volt has a maximum range of approximately 64km ("Chevrolet Volt", 2009, para. 1). This range is farther than the daily commute of more than 75% of Americans who drive to work ("Chevrolet Volt, 2009", para. 3), which would allow these commuters to drive exclusively using battery power if the batteries were recharged overnight. The Tesla Roadster is powered by electricity only and thus has more room and weight on the chassis to devote to batteries than the Volt because it does not have an internal combustion engine. The Roadster boasts a maximum range of 393 kilometers on a single charge ("Tesla Motors", 2009, table 1). If a customer were to recharge the Roadster's batteries from the typical household electricity supply, a full recharge would take approximately 3.5 hours at 240 volts and 70 amps ("Tesla Motors", 2009, table 1).

Although weight is a very important factor to be minimized in electric vehicles, the integration of a MAC system into the car would result in a relatively small weight increase for the advantages it would provide. The circuitry for recharging the batteries is already integrated into the design of the Tesla Roadster ("Tesla Motors", 2009, table 1) such that the only additional part of the MAC that would need to be added on would be the mechanical device for connecting to the MAC system. At a curb weight of 1238 kgs. ("Tesla Motors Technical Specifications", 2009, table 1), a mechanical MAC system weighing a maximum of 25 kgs. would be approximately a 2% increase in weight.

Research Plan

At present, electric vehicles can only be charged with electricity from the power grid while they are stationary and connected to a charging station. The need to stop and wait for a charge wastes valuable travel time and causes an inconvenience for the driver. There is no currently implemented system that can recharge electric vehicles with power from the grid that allows the vehicles to remain in motion.

This project comprises the design and construct a proof-of-concept model of a system for recharging an electric vehicle while it remains in motion.

The test vehicle for the mechanical system will be a Radio Shack xMods remote control car (1:64 scale Toyota Supra). Two lithium-ion batteries will be installed on the car (3.7V, 350 mAh each). A lithium-ion laptop battery will be used for the battery testing.

The design criteria for the prototype designs are minimum battery recharge time (to 100% SOC), minimum length of recharge lane required, and feasibility of integration into electric vehicle. Criteria for electrical requirements, maximum travel speed allowed, and cost efficiency were also included but not weighted as heavily.

Two separate test scenarios will be used:

In the first setup, the remote control car will be tested on a typical road surface. The prototype mechanical systems will be installed on the car. Lithium-ion batteries powering the car will be recharged with electricity supplied by the stationary system and transferred through the mechanical prototypes. Sensors will measure the temperature of the batteries, the state-of-charge of the batteries, and the velocity of the vehicle over time.

The second procedure will involve a lithium-ion laptop battery as a scale model of a full size EV battery. The battery will be charged with varying amounts of voltage and amperage to determine how quickly the battery can safely be charged.

The data from the tests with the remote control car will be used to assist in assigning each design a value for criteria 1-5 on the design criteria matrix. This will be done by taking the available data and extrapolating to a full-scale test. For example, if the battery regained 2% of full capacity for every meter the car traveled at 2 m/s with 2 amps of electrical current at 10v, a full-scale charging lane would need to be at least 50 m in length and a full recharge could take as long as 25 seconds.

The data from the laptop battery tests will be used to determine the maximum amount of power that can be supplied to the battery while maintaining safe temperatures without any special cooling. Full-scale results can again be extrapolated because EV batteries are simply a larger number of li-ion cells in series, the same cells that make up the laptop battery. Determining values for criterion 6 for each design will require estimations of cost that can be made after the designs have been finalized and tested so that accurate predictions for materials and power needs can be made.

Methodology

Lithium-Ion Battery

The procedure was conducted at a constant ambient air temperature (recorded with a Vernier stainless steel temperature probe). The test instruments (standard chronometer, ExTech DM110 digital multimeter) were set up in a safe location such that the displays could be recorded on video (using a Sony HandyCam DCR-SR40 video camera). The battery (Lithium-Ion 3.7C 350mAh model LC-10440) was connected to the power supply (Sorensen XTS 20-3M7). A (10 cm cube inside dimensions) Lucite box was placed around the battery such that it could have safely contained any debris in the event of a battery explosion. The thermocouple probe was inserted into middle of the battery so that it was in contact with the only battery cells, not any of the plastic casing that held the cells together.

The power supply was connected to the battery and plugged into an electrical outlet (standard 120v). The video camera was powered on and video recording commenced. All other instruments were turned on such that they were showing readings and the standard chronometer was set to display a running time for reference on the video. Charging began as the power supply was switched on (4.0V, 3.0A limit). It continued until the state-of-charge of the battery was 100%. The maximum internal temperature of the battery was limited to 90°C.

The video recording was stopped, and the file saved. The instruments were turned off. After cooling to approximately the ambient air temperature, the battery was discharged by connecting it to a circuit with 12 ohms of resistance. After the state-of-charge of the battery reached 0%, the charging procedure in paragraph 2 was repeated using settings 8.0V, 12.0V, 16.0V, 20.0V; for 15 tests at each setting.

Scale Model Remote Control Car

The stationary system for supplying power was constructed. Two 10 cm-long pieces of standard 2x4 boards were connected to each end of a (2.24 m long) standard 1x3 board such that the 8 cm length was perpendicular to the 1x3 10 cm long pieces of standard 1x3 boards were screwed into the tops of the 8 cm 1x3 pieces such that the 10 cm length was perpendicular to the 8 cm piece of 1x3. 1 cm diameter holes were drilled in the center of each of the 10 cm 1x3 pieces. The (3.0 m length) stainless steel cable was threaded through the holes. The cable was secured with 4 standard cable clamps such that it had enough tension to prevent sagging more than 2 cm from its initial height at each end. A standard wire clamp was connected to the stainless steel cable, and the power supply such that it could conduct electricity from the power supply to the cable.

Figure 2. The stationary recharging system. The 3 m stainless steel cable is suspended approximately 10 cm above the floor. The RC car can be seen traveling under the system.

The mechanical arm was attached to the remote control car (Radio Shack X-Mods, catalogue number 60-8006). The mechanical arm and the ground arm were connected with a wire such that electricity could flow through them from the stationary system to the ground.

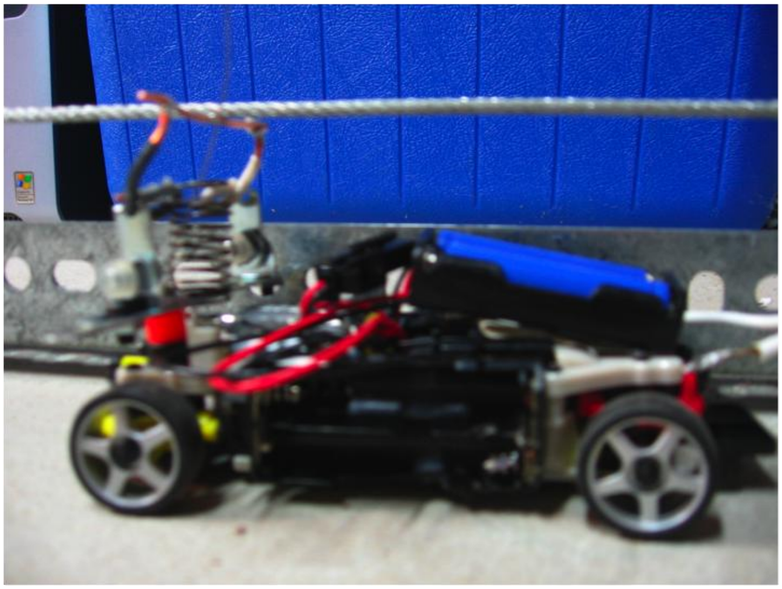

Figure 3. The RC car with the prototype pantograph system installed. The top of the pantograph is touching the stainless-steel wire that supplies electricity to the system.

The video camera was set up to show the entire length of the test run and aligned on a plane parallel to that in which the vehicle would be moving such that video analysis could be performed if needed. The multimeter was connected to the ground system in order to measure the voltage output of the system for comparison to the voltage input to the system. The power supply was connected to the stainless steel wire with standard wire clamps and set to (4.0V, 2.0A output). A scale reference of known length was included in the video frame for video analysis. The power supply was switched on and video recording began. Starting 2 meters away from the front of the stationary system, the car was accelerated until it reached a predetermined velocity. The vehicle was driven at this constant velocity throughout the length of the stationary system as data was recorded. After passing the stationary system, the car was safely brought to a halt. Video recording was stopped and the file saved. All instrument data was saved for later analysis.

The test procedure described above was repeated using velocities in 0.5 m/s increments from 0-5 m/s. The test procedures in this paragraph and the previous paragraph were repeated with the 3rd Rail system (short mechanical arm extending from the bottom of the car) implemented as the mechanical portion of the system on the remote control car.

Results/Data Analysis/Discussion

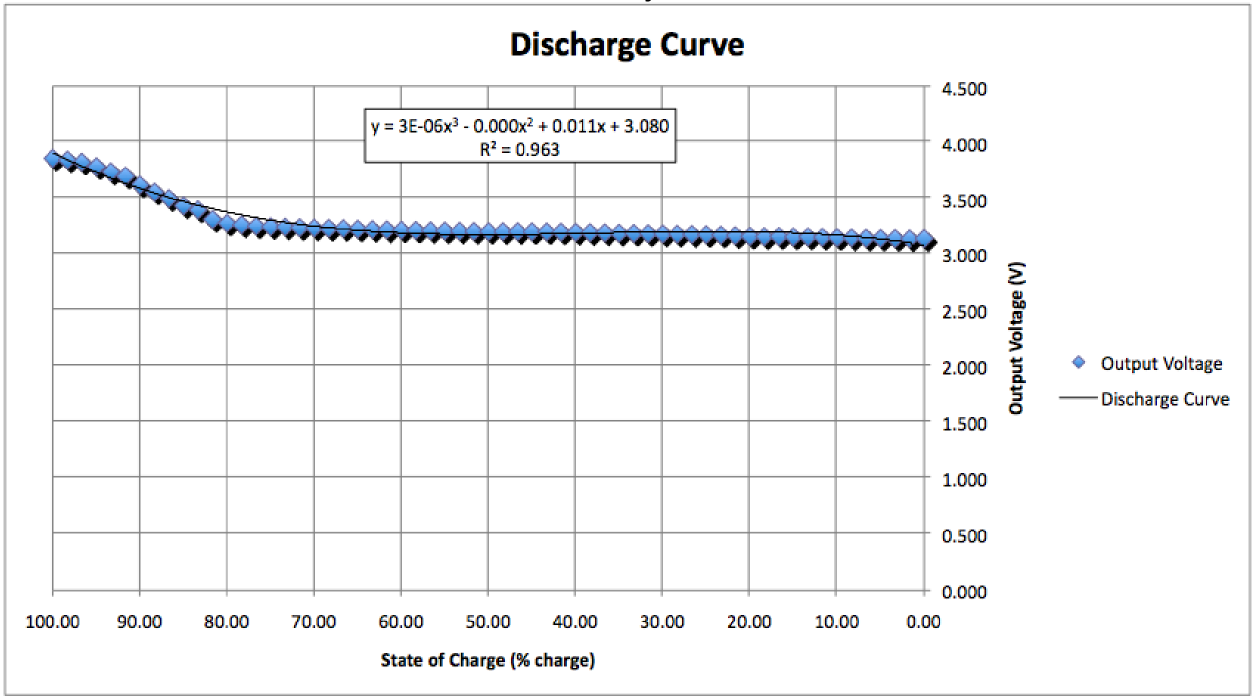

Figure 4. Discharge curve for single-cell lithium-ion battery. The cell was rated at 3.7V, 350 mAh. The curve indicates a 100% state-of-charge close to 4V and full discharge between 3.1V and 3.2V. The source data for this graph can be found in appendix C.

The discharge that was determined through experimentation is very similar in shape to the normal lithium-ion discharge shown in figure 1. It exhibits the sharp decline in output voltage from 100% charge to approximately 80%, where it flattens at shows little decline until nearing 0% charge. The decline in output voltage is not as sharp as is given in figure 1, but the curve shows the start of a downward trend that likely would have continued had testing continued to lower than 3.0V output (it was stopped because of the manufacturer's warning that the battery cells not be discharged any lower than 3.0V).

Table 1. Efficiency of the mechanical move-and-charge system based on input versus output voltage. Values are averages based on results from 15 trials at each setting. Full tables of this data can be found in Appendix A.

RC Vehicle Velocity	0 m/s	0.5 m/s	1.0 m/s	1.5 m/s	2.0 m/s	2.5 m/s	3.0 m/s	3.5 m/s	4.0 m/s	4.5 m/s	5.0 m/s
Input Voltage	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	3.62	3.57	3.54	3.53	3.53	3.52	3.52	3.49	3.46	3.41	3.32
Voltage Lost	0.38	0.43	0.46	0.47	0.47	0.48	0.48	0.51	0.54	0.59	0.68
% Input Voltage Lost	9.50	10.75	11.50	11.75	11.75	12.00	12.00	12.75	13.50	14.75	17.00

The RC car testing returned relatively linear results. As the velocity increased, the voltage loss increased as well. With each increment of 0.5 m/s in velocity, approximately 0.3 volts of current were lost. The percentage of input voltage lost is somewhat high, especially at higher velocities such as 5.0 m/s, where nearly 20% of the input voltage was lost. This was most likely caused by the relatively low input voltage rather than a significant amount of actual current loss: 0.68V lost is a large percentage of a 4.0V input but not of consequence at input voltages in hundreds of volts that would be used in full-scale versions of the system.

Table 2. Recharge time for 3.6V lithium-ion cell for varying levels of electrical current supplied. Values are the average of 15 trials per setting. Full data tables can be found in Appendix B.

Recharge Current (Voltage, Amperage)	4.0 V, 1.5 A	4.0 V, 3 A	8.0 V, 1.5 A	8.0 V, 3 A	12.0 V, 1.5 A	12.0 V, 3 A
Charging Time (sec.)	432	356	407	329	376	291
Percent State of Charge Gained (from 0%)	100	100	100	83	100	76
Projected 0-100% Charge Time (sec.)	432	356	407	396.385542168675	376	382.89473684210 5
Initial Temperature (°C)	20	20	20	20	20	20
Temperature at End of Test (°C)	64	71	68	80	70	80

In table 2, temperature before and after is given to indicate when testing was stopped as the battery cells reached temperature safety limits. Projected 0-100% charging time assumes that the batteries would be cooled such that they would not overheat and charging could continue unimpeded.

The test results show a marked decrease in recharging time, predicted or observed, as electrical current supply increases. Although safety concerns forced testing at higher current supplies to be stopped before reaching 100%, the predicted recharge time decreased in most cases. The one exception to this trend is the data from tests at 4.0V, 3.0A of current which actually recharged the battery in the shortest amount of time. This suggests that the test results at that setting were skewed by some outside factor that was not present in testing at all of the other settings.

Conclusions

The test results suggest that a move-and-charge system would be feasible. Extrapolating from the single-cell battery testing to a larger battery, assuming it would have the same recharge characteristics, shows that a battery could be recharged in six or seven minutes. This is more than short enough so as to be convenient for a consumer to use a recharging lane. Results from tests of the mechanical system show that the scale system lost very small amounts of current as velocity increased. This evinces that a full-scale system would also exhibit diminutive current losses even at high velocities.

At 1:28 scale, a velocity of 5.0 m/s caused a loss of only 0.7 V, a nearly 20% loss at the low input voltage of 4.0V, but an insignificant loss at the 100+ volt currents that would be used in full-scale systems. Furthermore, a velocity of 5.0 m/s at 1:28 scale translates to 140.0 m/s at a 1:1 scale, easily fast enough to accommodate typical highway speeds. The test results suggest that every aspect of the system would be feasible to implement at full scale and that this system would be suitably convenient for consumers to use.

Limitations and Assumptions

The experimentation involved many assumptions that were necessary to conduct the experiments within the time, budget, and resources available. In testing the RC car, it was assumed that the system had no loss of electrical current other than inefficiencies in the pantograph or 3rd-rail system that was being tested. Tests revealed that there was a slight inefficiency in the system even when the vehicle was stationary. This means that there was a small amount of electrical current lost when it flowed through the system. It was assumed that this same inefficiency was present in tests while the vehicle was moving.

During the experimentation, there were few variables that needed to be controlled because of their potential to affect results. The stationary system was controlled throughout testing. No modifications were made to it between tests. Most importantly, the tension and the length of the wire were kept constant. The RC car was not changed in between tests, other than necessary modifications made to implement the prototype pantograph and third rail systems.

In the lithium-ion battery testing, it was assumed that the batteries did not lose any capacity over the length of testing. The charging curve that was generated at the beginning of testing was assumed to be accurate for all tests, that is, that the batteries were not overcharged or overheated to the point that their charging characteristics were damaged. The analysis and conclusions drawn from the battery testing assume that the results from a single battery cell can be scaled to a larger number of cells connected in parallel. If one cell could charge in a certain amount of time, it was assumed that x number of cells would charge in the same amount of time as the single cell as long as the electrical current supply was x times as powerful as the single-cell tests. This allowed for predictions of the characteristics of full-scale electric vehicle batteries based upon the test results of a single-cell battery.

Testing was completed with two different batteries, but it was assumed that both of them had identical charge/discharge characteristics because they were the same model of battery (LC-10440 3.7V 350 mAh). Conclusions and analysis of the results assume that the cells of a larger-scale lithium-ion battery would comprise multiple cells in parallel, with each cell identical to the single-cell lithium-ion batteries that were tested.

While testing the battery, it was assumed that ambient air temperature remained within a small enough range so as to be insignificant in affecting the temperature of the battery during testing. This assumption was made because the range of the ambient air temperatures was relatively small in relation to the temperature range that was measured in the battery as it was charged.

Applications and Future Experiments

This system has strong potential for future applications as the electric vehicle market expands. As emissions regulations force manufacturers and consumers towards more efficient vehicles, electric and hybrid automobiles will certainly gain more market share over traditional, gas-powered cars. A greater number of electric vehicles on the roads will exacerbate the need for convenient methods of recharging. The move-and-charge system is perfectly suited to fulfilling this need.

Recharging lanes of 1-2 km. built every 65 km would provide sufficient recharging capability for electric vehicles such as the Chevrolet Volt and the Tesla Roadster to drive indefinitely on the highway without stopping to charge. A distance of 65 km is proposed only because that is roughly the maximum range of the Chevrolet Volt, used here as approximation for the shortest maximum range of an electric vehicle. The spacing of 65 km requires relatively little extra land alongside highways, and the leeway to build systems at 60 km or 70 km apart instead means that locations could be chosen to avoid cities or other areas where it may not be cost-effective to purchase and build on land alongside the highway.

If the electric vehicle market does become a popular, widespread alternative to gasoline-powered cars, move-and-charge systems could facilitate further growth in the sector as they would make it more convenient for electric vehicle owners to travel long distances. This situation is somewhat circular, because the widespread adoption of electric vehicles depends, among other things, on convenient methods of recharging, and the viability of convenient methods of recharging such as a move-and-charge system depends on the widespread adoption of electric vehicle technology. The critical number of electric vehicles needed to facilitate move-and-charge systems is most likely to come as a result of government regulations on vehicle emissions and consumption of fossil fuels, which would make electric vehicles an attractive alternative to cars with internal combustion engines.

The spread of move-and-charge systems also depends on the fact that the system can sufficiently recharge vehicles within a reasonable distance and time such that consumers would actually choose to use it. Although the results from this study suggest that it would be feasible, the only way to ensure the proper functionality of the system for full-size electric vehicles would be to conduct full-scale testing. This would require funding for the construction of a system and the modification of (a) prototype vehicle(s). Testing at this scale would provide results closer to the probable performance of a system when commercially implemented.

Another possibility for future experimentation exists in the design of electric vehicle batteries. Current lithium-ion designs are not optimized for level 3 charging, because there are very few charging systems that can take advantage of this capability. Developing a battery specifically well-suited to expedited recharging would likely make a move-and-charge system more feasible for commercial use.

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Appendices

Appendix A.
RC Car Test Results

Velocity	0 m/s									
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.63	3.62	3.62	3.62	3.62	3.63	3.62	3.62	3.61	3.62
Voltage Lost	(V)	0.37	0.38	0.38	0.38	0.38	0.37	0.38	0.38	0.39	0.38
% Input Voltage Lost	(%)	9.25	9.5	9.5	9.5	9.5	9.25	9.5	9.5	9.75	9.5

10	11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.0	4.00
3.62	3.62	3.62	3.61	3.62	3.62	3.62
0.38	0.38	0.38	0.39	0.38	0.38	0.38
9.5	9.5	9.5	9.75	9.5	9.5	9.50

Velocity	0.5 m/s									
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.57	3.57	3.57	3.57	3.57	3.57	3.56	3.57	3.57	3.56
Voltage Lost	(V)	0.43	0.43	0.43	0.43	0.43	0.43	0.44	0.43	0.43	0.44

% Input Voltage Lost	(%)	10.75	10.75	10.75	10.75	10.75	10.75	11	10.75	10.75	11

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.56	3.56	3.57	3.58	3.57	3.57
0.44	0.44	0.43	0.42	0.43	0.43
11	11	10.75	10.5	10.75	10.80

Velocity	1.0 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.54	3.54	3.52	3.54	3.54	3.54	3.54	3.55	3.54	3.54
Voltage Lost	(V)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
% Input Voltage Lost	(%)	11.5	11.5	12	11.5	11.5	11.5	11.5	11.25	11.5	11.5

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.53	3.54	3.54	3.54	3.54	3.54
0.5	0.5	0.5	0.5	0.5	0.46
11.75	11.5	11.5	11.5	11.5	11.53

Velocity	1.5 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.53	3.53	3.53	3.54	3.54	3.53	3.53	3.53	3.53	3.53
Voltage Lost	(V)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
% Input Voltage Lost	(%)	11.75	11.75	11.75	11.5	11.5	11.75	11.75	11.75	11.75	11.75

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.52	3.53	3.53	3.53	3.53	3.53
0.5	0.5	0.5	0.5	0.5	0.47
12	11.75	11.75	11.75	11.75	11.73

Velocity	2.0 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.53	3.52	3.53	3.53	3.53	3.52	3.53	3.53	3.53	3.52
Voltage Lost	(V)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
% Input Voltage Lost	(%)	11.75	12	11.75	11.75	11.75	12	11.75	11.75	11.75	12

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.53	3.53	3.53	3.52	3.53	3.53
0.5	0.5	0.5	0.5	0.5	0.47
11.75	11.75	11.75	12	11.75	11.82

Velocity	2.5 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.52	3.53	3.53	3.54	3.52	3.52	3.52	3.52	3.52	3.52
Voltage Lost	(V)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
% Input Voltage Lost	(%)	12	11.75	11.75	11.5	12	12	12	12	12	12

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.52	3.52	3.55	3.52	3.52	3.52
0.5	0.5	0.5	0.5	0.5	0.48
12	12	11.25	12	12	11.88

Velocity	3.0 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.50	3.51	3.52	3.52	3.52	3.52	3.50	3.52	3.52	3.52
Voltage Lost	(V)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
% Input Voltage Lost	(%)	12.5	12.25	12	12	12	12	12.5	12	12	12

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.52	3.51	3.52	3.52	3.52	3.52
0.5	0.5	0.5	0.5	0.5	0.48
12	12.25	12	12	12	12.10

Velocity	3.5 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.49	3.49	3.48	3.49	3.49	3.49	3.49	3.49	3.49	3.49
Voltage Lost	(V)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
% Input Voltage Lost	(%)	12.75	12.75	13	12.75	12.75	12.75	12.75	12.75	12.75	12.75

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.49	3.49	3.50	3.50	3.50	3.49
0.5	0.5	0.5	0.5	0.5	0.51
12.75	12.75	12.5	12.5	12.5	12.72

Velocity	4.0 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.46	3.46	3.45	3.46	3.46	3.46	3.42	3.46	3.46	3.46
Voltage Lost	(V)	0.5	0.5	0.6	0.5	0.5	0.5	0.6	0.5	0.5	0.5
% Input Voltage Lost	(%)	13.5	13.5	13.75	13.5	13.5	13.5	14.5	13.5	13.5	13.5

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.47	3.46	3.46	3.46	3.46	3.46
0.5	0.5	0.5	0.5	0.5	0.54
13.25	13.5	13.5	13.5	13.5	13.57

Velocity	4.5 m/s																
	Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.00
Output Voltage	(V)	3.40	3.40	3.40	3.40	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.42	3.42	3.41	3.41	3.41
Voltage Lost	(V)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.59
% Input Voltage Lost	(%)	15	15	15	15	14.75	14.75	14.75	14.75	14.75	14.75	14.75	14.5	14.5	14.75	14.75	14.78

Velocity	5.0 m/s										
	Trial	1	2	3	4	5	6	7	8	9	10
Input Voltage	(V)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Output Voltage	(V)	3.32	3.32	3.32	3.32	3.32	3.33	3.33	3.33	3.33	3.32
Voltage Lost	(V)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
% Input Voltage Lost	(%)	17	17	17	17	17	16.75	16.75	16.75	16.75	17

11	12	13	14	15	Average
4.0	4.0	4.0	4.0	4.0	4.00
3.32	3.32	3.32	3.32	3.32	3.32
0.7	0.7	0.7	0.7	0.7	0.68
17	17	17	17	17	16.93

Appendix B
Battery Test Results

4.0V	1.5A										
Trial		1	2	3	4	5	6	7	8	9	10
Charging Time	(sec.)	430	429	428	425	431	419	430	433	433	437
Percent Charge Gained	(from 0%)	100	100	100	100	100	100	100	100	100	100
Projected Recharge Time	(sec.)	430	429	428	425	431	419	430	433	433	437
Initial Temperature	(°C)	20	20	20	20	20	20	20	20	20	20
Temperature at End of Test	(°C)	66	67	66	66	67	65	66	64	63	62

11	12	13	14	15	Average
438	442	432	436	435	431.87
100	100	100	100	100	100.00
438	442	432	436	435	431.87
20	20	20	20	20	20.00
63	63	62	61	61	64.13

4.0V	3.0A																
Trial		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
Charging Time	(sec.)	353	362	351	353	353	356	354	352	360	359	358	355	359	358	351	355.60
Percent Charge Gained	(from 0%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100.00
Projected Recharge Time	(sec.)	353	362	351	353	353	356	354	352	360	359	358	355	359	358	351	355.60
Initial Temperature	(°C)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20.00
Temperature at End of Test	(°C)	74	73	73	72	74	68	70	69	72	71	69	73	72	72	70	71.47

8.0V	1.5A																
Trial		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
Charging Time	(sec.)	400	401	410	411	41 2	411	409	408	409	409	405	408	407	406	406	407.47
Percent Charge Gained	(from 0%)	100	100	100	100	10 0	100	100	100	100	100	100	100	100	100	100	100.00
Projected Recharge Time	(sec.)	400	401	410	411	41 2	411	409	408	409	409	405	408	407	406	406	407.47
Initial Temperature	(°C)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20.00
Temperature at End of Test	(°C)	68	68	67	67	67	68	67	68	68	68	69	68	69	68	69	67.93

8.0V	3.0A																
Trial		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
Charging Time	(sec.)	330	328	329	329	323	330	332	328	328	329	328	328	329	331	326	328.53
Percent Charge Gained	(from 0%)	83	83	82	81	84	84	84	85	83	83	82	81	81	81	81	82.53
Projected Recharge Time	(sec.)	397	394	397	404	384	392	398	382	395	396	395	401	404	406	401	396.40
Initial Temperature	(°C)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20.00
Temperature at End of Test	(°C)	79	79	79	79	80	80	80	80	83	80	80	79	80	79	80	79.80

12.0V	1.5A										
Trial		1	2	3	4	5	6	7	8	9	10
Charging Time	(sec.)	377	368	370	378	376	377	380	381	379	376
Percent Charge Gained	(from 0%)	100	100	100	100	100	100	100	100	100	100
Projected Recharge Time	(sec.)	377	368	370	378	376	377	380	381	379	376
Initial Temperature	(°C)	20	20	20	20	20	20	20	20	20	20
Temperature at End of Test	(°C)	71	73	73	73	74	68	70	67	68	68

11	12	13	14	15	Average
377	379	378	376	375	376.47
100	100	100	100	100	100.00
377	379	378	376	375	376.47
20	20	20	20	20	20.00
72	76	72	74	70	71.27

12.0V	3.0A																
Trial		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
Charging Time	(sec.)	288	293	287	289	288	290	291	294	293	294	290	289	291	290	291	290.53
Percent Charge Gained	(from 0%)	75	75	75	75	74	75	75	76	80	77	77	77	76	77	77	76.07
Projected Recharge Time	(sec.)	384	393	383	386	390	387	389	388	366	382	377	376	384	377	378	382.67
Initial Temperature	(°C)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20.00
Temperature at End of Test	(°C)	82	80	79	77	77	78	79	78	81	84	79	80	80	79	80	79.53

Appendix C
Discharge Curve Testing

TimeElapsed	Ouput	% Charge	(cont'd.)		
(sec.)	(V)		300	3.203	50.00
0	3.856	100.00	310	3.203	48.33
10	3.841	98.33	320	3.203	46.67
20	3.822	96.67	330	3.202	45.00
30	3.782	95.00	340	3.201	43.33
40	3.736	93.33	350	3.199	41.67
50	3.698	91.67	360	3.197	40.00
60	3.620	90.00	370	3.194	38.33
70	3.556	88.33	380	3.192	36.67
80	3.498	86.67	390	3.189	35.00
90	3.434	85.00	400	3.187	33.33
100	3.397	83.33	410	3.185	31.67
110	3.311	81.67	420	3.182	30.00
120	3.278	80.00	430	3.180	28.33
130	3.263	78.33	440	3.178	26.67
140	3.252	76.67	450	3.176	25.00
150	3.247	75.00	460	3.172	23.33
160	3.244	73.33	470	3.167	21.67
170	3.238	71.67	480	3.160	20.00
180	3.235	70.00	490	3.158	18.33
190	3.232	68.33	500	3.159	16.67
200	3.230	66.67	510	3.155	15.00
210	3.225	65.00	520	3.155	13.33

220	3.222	63.33	530	3.152	11.67
230	3.219	61.67	540	3.149	10.00
240	3.216	60.00	550	3.148	8.33
250	3.214	58.33	560	3.144	6.67
260	3.211	56.67	570	3.143	5.00
270	3.209	55.00	580	3.141	3.33
280	3.207	53.33	590	3.139	1.67
290	3.205	51.67	600	3.141	0.00