

## Evaluating the Urban Electric Vehicle

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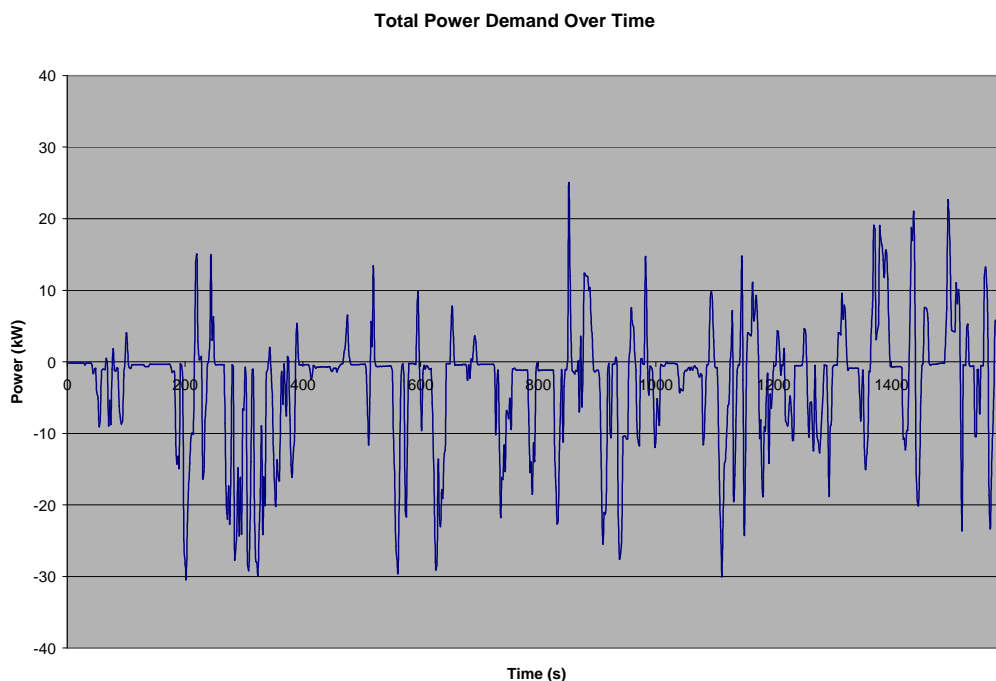
### I. Motivation

The underlying goal of the ChargeCar project is to examine the common urban commute and to determine if cars powered by managed supercapacitor-battery systems are a solution that can reduce cost of ownership for a commuter car. This is not through the development of new component technologies but by better understanding of real urban commutes and by using existing, affordable technology more intelligently.

In this paper we present power data from real-world commutes using a 2002 Rav-4 EV electric vehicle with regenerative braking. We then model the expected effects of adding an intelligently managed supercapacitor to the energy storage system.

### II. Data Analysis

The first data were captured in Pittsburgh, Pennsylvania through the use of a GPS device with a barometric altimeter. We analyzed this data using a physics model to yield statistics on power demand and regeneration. The car used to collect this data was a 2002 Toyota RAV4-EV, a plug-in electric SUV which features a regenerative braking system. The data presented below was derived from current and voltage measurements in the car. Presented here is a power demand curve and associated statistics for a typical commute in our data sets:



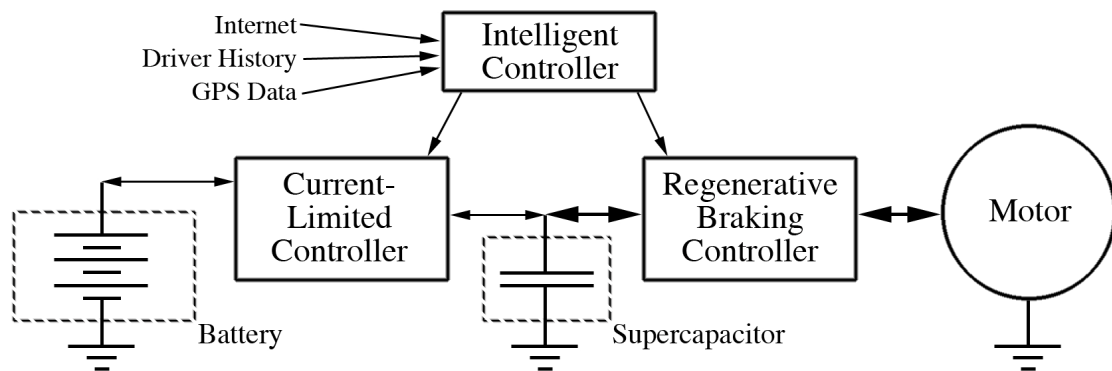
Net Energy Moved During Trip (Wh)	Total Energy Moved During Trip (Wh)	Proportion of Recharge to Discharge
-2,808	4,982	27.91%

The most interesting features of these statistics are that:

- There is a substantial amount of power recovered on this trip: we recoup more than a quarter of our power discharge through regenerative braking!
- The difference between battery duty and net power is quite high, nearly 4000 kW. This extra duty is from the regenerative braking, and produces extra heat in the battery. If we model a supercapacitor-battery system, accounting for the low internal resistance of the supercapacitor, we can reduce the extra duty on the battery, reducing the heat loss, saving energy, and extending battery longevity. Because the maximum current demands on the battery are reduced, this system also allows us to use less expensive batteries, which further reduces the cost of the car.

### III. Architecture:

Here is a simplified diagram of our system:



The battery in this system is the primary power reservoir of the car. The supercapacitor serves as a cushion for the battery, which handles as much of the current demand as possible. The motor represents the motors of the car and their regenerative brakes. The current-limited controller and regenerative braking controller allocate the current needed to power the car and any regenerated current. The intelligent controller sits in the middle of all of these components, using a variety of inputs to handle present and future current demands as effectively as possible.

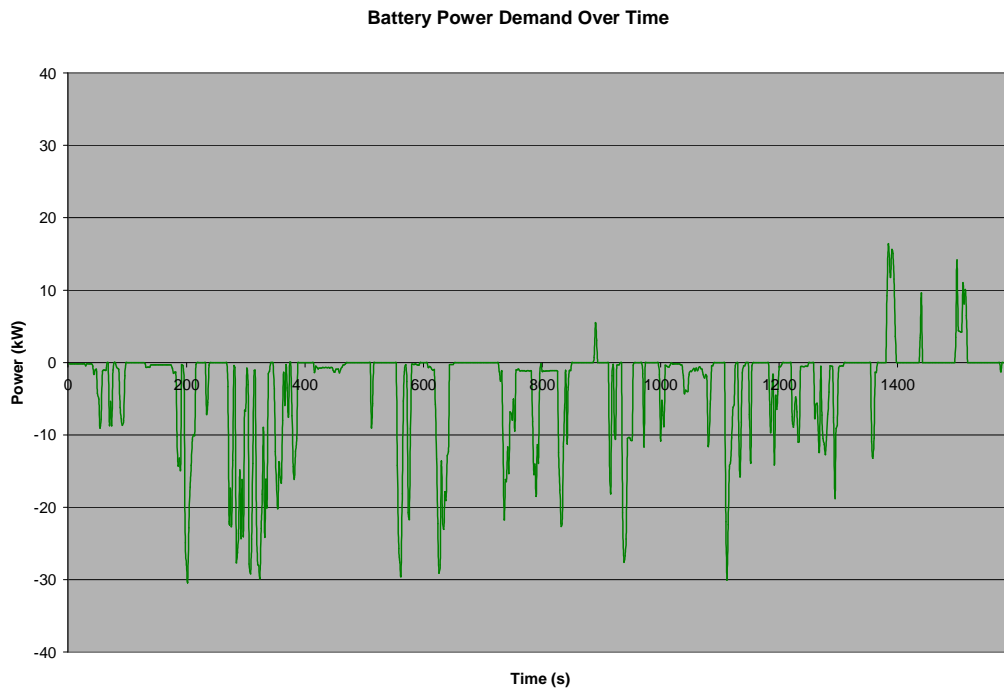
By using this system and utilizing the supercapacitor as much as possible, we are able to reduce the amount of work the battery does substantially. We seek to reduce the amount of duty that the battery does to the bare minimum: the net energy it takes to make the trip, minimizing waste heat produced in the battery. This saves energy and preserves the longevity of the battery, reducing the total cost of ownership.

### IV. Supercapacitor Effectiveness

When we consider using a supercapacitor-battery system, it is useful to consider the amount of possible savings we could realize. Looking at the sample trip statistics shown above, we can see that there is significant room to improve with regards to battery

duty. Similarly, we can improve heat loss greatly by removing peaks, and could theoretically reduce waste heat by 50 to 90 percent, which would yield additional substantial benefits. We present an example trip with a simple management algorithm to demonstrate the potential improvements from a supercapacitor-battery system.

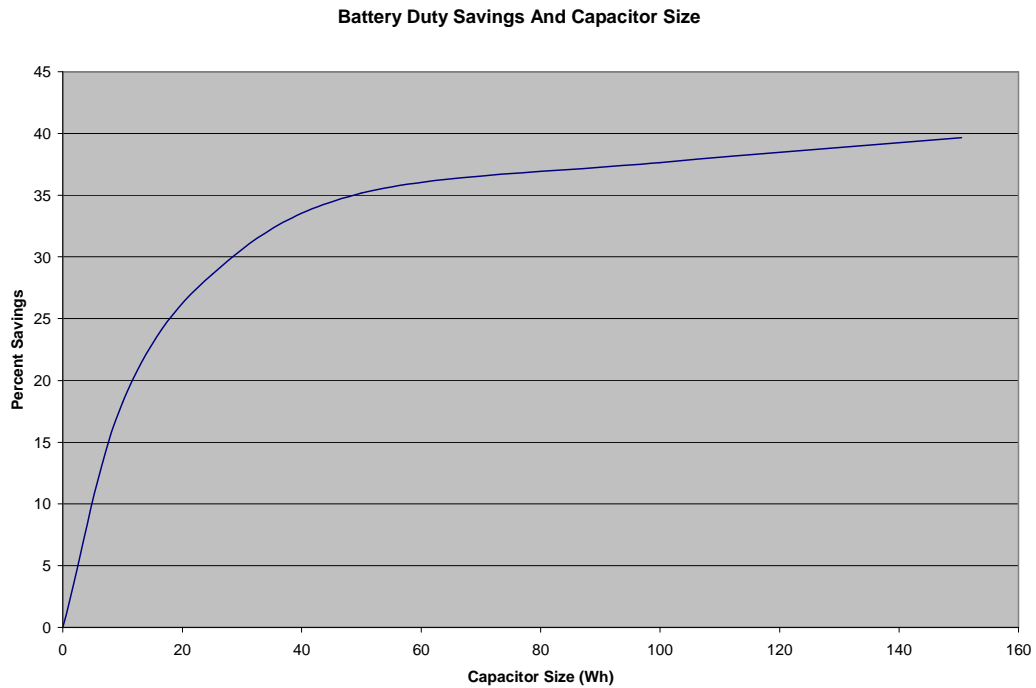
In this example we have modeled the most basic algorithm to manage the capacitor-battery system as the opportunistic, “buffer” capacitor system. This capacitor simply takes all regeneration if it can, and discharges if it can, and otherwise those demands are routed to the battery. This is far from ideal, since the capacitor is often empty, leaving the battery to do all of the work, but it is a good baseline to illustrate the potential of a supercapacitor-battery system. Consider our sample trip, whose power demand schedule is shown above. It is very volatile, with many rapid changes in charging and discharging, along with high peaks. If we apply the modeled supercapacitor-battery system to this trip using a 50 Watt-hour supercapacitor, this is what the battery would be doing:



Much of the smaller activity is gone, so the battery does much less than it did before. In fact, the battery duty is reduced by 35%, and the wasted energy due to battery heating is reduced by nearly a third. This indicates that there is great improvement to be had by even simply employing a supercapacitor-battery system.

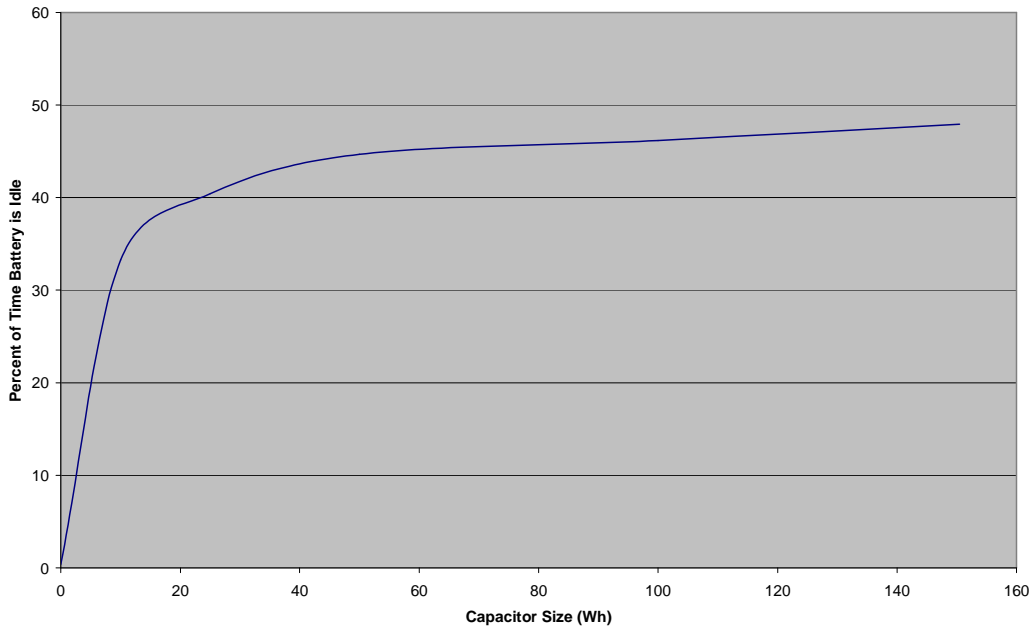
Choosing the supercapacitor size is a matter of trading off between cost and total battery duty. Currently available supercapacitors are very limited in energy density, and while it is tempting to use the largest supercapacitors possible, that would increase cost. Going to the other extreme, using a smaller supercapacitor reduces the benefit substantially, making a small supercapacitor of little benefit to the performance of the car. We have selected a 50 Watt-hour supercapacitor for our model, which is a commercially available medium size which reaps most of the benefit without an unwieldy

cost. Below is the curve which illustrates the relationship between capacitor size and battery duty savings for our sample trip.



Another way to demonstrate the level of battery duty savings with this management system is to examine the amount of time that the battery is idle and the supercapacitor is doing all of the charging and discharging. This curve shows the change in idle battery time with varying supercapacitor sizes.

Idle Battery Time and Capacitor Size



While battery duty is important, the most important quantity to consider when looking at the supercapacitor-battery systems is current<sup>2</sup> ( $I^2$ ). This is roughly proportional to the heat wasted in the battery, and minimizing this value could increase the longevity of the battery substantially. Heat exposure degrades the battery and reduces its capacity over the course of many trips, and reducing this prolongs the time before the battery needs to be replaced, which is a significant cost of ownership of an electric vehicle. To illustrate the magnitude of the potential benefits of using a supercapacitor-battery system, consider these statistics:

Algorithm	Total Energy Lost to Heat (Wh)
No Capacitor	95.137
Buffer Capacitor	63.021

The above data is based on commute data only in Pittsburgh, and furthermore the "buffer capacitor" management strategy is not at all optimal. But these are hopeful results: we can see that an urban commute may include very volatile power demands, and therefore a regular electric car may be quite inefficient compared with what might be possible. We are also finding that reasonably sized supercapacitors can have major impact on battery duty, idle time and current. To truly innovate for low-cost-of-ownership electric vehicles, there are several important next steps. We must collect and examine widespread urban commute data so that we can compute just how much volatility there is in urban commutes across the United States. We also need to investigate intelligent power management systems that actively control the amount of charge in the supercapacitor specifically to minimize battery current squared. Such intelligent control could take everything into account: whether there is an uphill or

downhill stretch in the next quarter mile; where the next stop sign is; whether the driver typically stops for coffee here; etc. This project invites you to participate, by sharing and analyzing your own commute data and by designing the best power management system possible. We truly believe a community-based approach to innovation for electric cars has the chance to revolutionize the electric car industry.