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Online routing and battery reservations for electric vehicles with swappable batteries

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ABSTRACT

Electric vehicles are becoming a more popular form of transportation, however their limited range has proven problematic. Battery-exchange stations allow the vehicles to swap batteries during their trip, but if a vehicle arrives at a station without a full battery available it may have to wait an extended period of time to get one. The vehicles can be routed so that they avoid stations without available batteries or to keep batteries available for other vehicles that need them in the future. The batteries can also be reserved during the routing process so that each vehicle is ensured the battery it plans to use is available. This paper provides a method of online routing of electric vehicles and making battery reservations that minimizes the average delay of the all vehicles by occasionally detouring them to the benefit of future ones. The system is modeled as a Markov chance-decision process and the optimal policy is approximated using the approximate dynamic programming technique of temporal differencing with linear models. The solution algorithm provides a quick way for vehicles to be routed using onboard vehicle software connected to a central computer. Computational results for the algorithm are provided using data on the Arizona highway network.

1. Introduction and system operation description

Lowering the use of petroleum products is one of the major goals of the twenty-first century. Gasoline-powered vehicles account for a large amount of the world's petroleum use, and so electric vehicles are being considered as a possible replacement technology. These vehicles have an electric motor rather than a gasoline engine, and a battery to store the energy required to move the vehicle. Governments and automotive companies have recognized the value of these vehicles in helping the environment (Hacker et al., 2009), and are encouraging the ownership of electric vehicles through economic incentives. For many electric vehicles, such as the Nissan LEAF or Chevrolet VOLT, the method of recharging the vehicle battery is to plug the battery into the power grid at places like the home or office (Bakker, 2011). Because the battery requires multiple hours to fully recharge, this method has the implicit assumption that vehicle will be used only for driving short distances. Electric vehicle companies are trying to overcome this limited range requirement with fast charging stations; locations where a vehicle can be charged in less than an hour to near full capacity. Besides being much more costly to operate rapid recharge stations, the electric vehicles still take more time to recharge than a standard gasoline vehicle would take to refuel (Botsford and Szczepanek, 2009). These inherent problems, combined with a lack of refueling infrastructure, are inhibiting a

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wide-scale adoption of electric vehicles. The problems are especially apparent in longer trips, or inter-city trips. *Range anxiety*, when the driver is concerned that the vehicle will run out of charge before reaching the destination, is a major hindrance for the market penetration of electric vehicles (Yu et al., 2011).

Another electric vehicle recharging method is to construct *battery-exchange stations*. These stations will remove a battery that is nearly depleted from a vehicle and replace the battery with one that has already been charged (Shemer, 2012). Once the depleted battery is dropped off at the station it is charged until full so that a different vehicle can use it in the future. This method of refueling electric vehicles has the advantage that it is very quick for each vehicle since the driver only has to wait for the battery to be swapped and not for the battery to be charged. An issue with this approach is that all of the vehicles serviced by the battery-exchange station are required to use the identical batteries. As with other new technologies introduced into the market, it is likely that the developers of these batteries will coalesce around a single common standard, as has been the case for other car parts such as tires and wipers. Additionally, the infrastructure of battery-exchange stations is expensive to build, since each station requires battery swapping machines, battery chargers, and many extra batteries on hand. In conjunction to the battery-exchange concept, it is assumed that there exists a viable business model that provides a reasonable profit for companies that establish battery-exchange facilities for the public. Battery-exchange stations have been implemented in the countries of Israel and Denmark by the company Better Place (2013), but unfortunately they have yet to be profitable (Kershner, 2013) and this has forced the company into bankruptcy. The electric vehicle company Tesla Motors Inc., which currently sells plug-in electric vehicles, has recently shown a prototype vehicle with battery-exchange technology (Motavalli, 2013).

Since the construction of battery-exchange stations and their infrastructure is very expensive, they have only been placed in a limited number of locations so far. In addition, the extra batteries that are stored in the station are also expensive, so to keep inventory costs low it is best to stock the stations with as few batteries as required. The number of batteries needed by vehicles visiting the station throughout the day depends on the location of the station, the day of the week, the weather, and many other variables. Further, the manner in which the vehicles arrive affects the number of batteries needed; if the vehicles all tend to arrive around the same time then more batteries are needed since there will not be enough time for them to recharge after being dropped off. Since the exact distribution of cars that will pass through a station is unknown when the stations are constructed, each station has to be designed to handle near the maximum demand that station is expected to receive at any given time. In the event that no full batteries are available at a station, an arriving vehicle will have to wait until a battery is charged before it can leave the station. If a driver of a vehicle is informed in advance that there will be no available batteries at a station they planned to stop at, then that station could be avoided by taking a circuitous route. The decision on how many batteries to place at a station has to balance the company's desire to minimize costs with need for drivers to not have to wait when there are no batteries available. It is possible that by balancing the vehicles across many stations, fewer vehicles would arrive at stations when no batteries are available which would improve the service they receive.

The goal of this paper is to devise an algorithm for real-time routing of electric vehicles with swappable batteries that balances the desire for drivers to have quick trips with the need for the operating company to control the battery swap loads across stations. Further, the algorithm will make reservations for each vehicle at all of the battery-exchange stations on the desired routes. Making reservations will remove the possibility that the batteries the vehicle expect to receive are unavailable due to other vehicles taking them. The objective of the routing and reservation algorithm is to minimize the total expected travel times of not only the vehicle being routed, but of future vehicles as well. Because of this objective, part of the routing and reservation process is to understand how a set of battery reservations could affect future arrivals into the system.

This paper assumes that there is a viable business model for the development and operation of a network of battery-exchange systems. Thus, for our purposes we assume that the stations have already been located and built to hold a set number of batteries that are constantly being charged. In practice, an algorithm like this would require onboard computer units in each vehicle that communicated with a central server that does the routing and reservations. When a fleet of cars is produced to be compatible with a set of battery-exchange stations, the operating company of the stations will likely be involved in the design and production of the vehicles. In the case of the company Better Place, they collaborated with Renault Fluence Z.E. so that their vehicles could be used in the network (Kershner, 2013). Because of this involvement, the operating company can ensure that each vehicle has a compatible unit installed that communicates with the operating company's central server. The operating company could implement a robust routing and reservation software system that provides to each vehicle a route from its origin to its destination, along with where to stop to swap the battery so the vehicle does not run out of charge. At the time the system provides a route, the system would also make reservations at the battery-exchange stations for the batteries needed by the vehicle.

The routing and reservation system would make the route suggestion based on the current battery charge levels at each station along with the pre-existing reservations made by earlier vehicles, which would be stored in the central server. The model in this paper assumes that when the vehicle turns on it will be provided with a single route from the routing and reservation system, and that the driver will take the given route exactly. The steps in this routing and reservation process for each vehicle would be:

1. When the electric vehicle is turned on, the driver would input a destination into the vehicle's computer unit. This, combined with the origin of the trip determined by the GPS location of the vehicle, would be sent to the central server.