Development and Evaluation of Decision Support Tools for Promoting Electric Vehicles

A final report to Institute of Sustainability and Energy at Northwestern

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1 Introduction

The growing concerns about energy security and global climate change have stimulated the transition to alternative fuel vehicles (AFV), widely considered an important ingredient in sustainable transportation (1). Of the many competing technologies, plug-in electric vehicles (PEV) have received much attention thanks to their high energy efficiency (2), the ability to substitute electricity for petroleum and the potential to reduce carbon footprint (3). However, the adoption of PEVs is hurdled by several critical factors: the relatively high retail price, the short range of batteries, and the lack of supporting infrastructure, especially charging stations (4). In the US, policy makers have created various incentive program aiming to overcome some of these barriers. The American Recovery and Reinvestment Act of 2009 (ARRA) signed into law a provision that will offer up to $7,500 of tax credit for each new PEV purchase starting from 2010. The state governments in the US have also implemented various policies to encourage the ownership of PEVs and installation of charging stations. In Illinois, for example, Electric Vehicle Initiatives provide a rebate up to $49,000 toward the installation of Level II charging stations and a rebate up to $ 4000 for the purchase of a new alternate fuel vehicle. It is clear that the public investment on these incentive programs is a scarce resource that should be carefully allocated to maximize its impact.

Funded by Institute for Sustainability and Energy at Northwestern (ISEN), our project aims at developing mathematical models that support resource allocation in this process. When fully implemented, the models created in this project may help the policy makers decide (1) when and how much money should be invested on what incentive programs in order to achieve a desired goal (e.g. reduced greenhouse gas emissions, reduced dependence on petroleum); and (2) how to plan the charging infrastructure in order to meet the demand for intercity trips made using PEVs. In what follows, we briefly explain the progress we were able to make with the resources provided by ISEN. The first part focuses on the optimization of incentive policies, and the second deals with the problem of locating charging stations along heavily traveled corridors.

2 Optimization of PEV incentive policies

2.1 Modeling framework

The adoption of PEV is modeled over a fixed analysis period in this study. Each year, a certain number of consumers need to purchase a new vehicle from a discrete set of vehicles, of which a subset are PEVs.
Table 1: Characteristics of the different types of vehicles

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Price</th>
<th>Electric range</th>
<th>Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Vehicle</td>
<td>20000</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Plug-in Hybrid Electric Vehicle</td>
<td>35000</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>Electric Vehicle</td>
<td>31000</td>
<td>80</td>
<td>10</td>
</tr>
</tbody>
</table>

The choice of vehicles is affected by, among other things, the purchase price and charging availability, which affects the operating cost of PEVs. The government offers two incentives over the entire analysis period: purchase rebates and publicly funded charging stations, with the objective of promoting PEVs and/or minimizing social cost of travel (potentially including the environmental impacts). The question addressed in this project is how these resources should be allocated to each of the incentives over the analysis period to optimize the intended objective.

The proposed modeling framework in this study consists of a travel model, a vehicle choice model and an optimization model. Travel is represented using a simple linear model considering inter and intra-city trips using the electric range of a given vehicle and the city boundary. A trip shorter than the radius of the outer circle is considered “within-city”; otherwise it is considered an intercity trip. The vehicle choice model calculates the consumer utility considering the purchase price of vehicle (with a subsidy and salvage value), the total estimated fuel cost, the total estimated refueling time cost and the total carbon footprint cost. Finally, the optimization problem is formulated as a nonlinear program whose objective function is the total user cost inclusive of fuel, charging time and CO2 costs - note that the vehicle price is not included because it is not considered a societal cost.

2.2 Case Study and findings

The case study considers three types of vehicles and three user classes. The three types of vehicles are conventional vehicles (CVs), battery electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Conventional vehicles are regular gasoline vehicles with an internal combustion engine. Electric vehicles have an electric motor with a rechargeable battery, and the only fuel they use is electricity. Plug-in hybrid vehicles have both an internal combustion engine and an electric motor, and thus, use both gasoline and electricity as fuel. Plug-in hybrid vehicles typically have lower electric range compared to EVs, and are more energy efficient than CV, without the range anxiety of electric vehicles. The main characteristics of these vehicles are given in Table 1.

The users are distinguished exclusively by their travel pattern. Following (5), we divide the users into three classes based on their daily travel distance distribution, which are assumed to follow the Gamma distribution. Figure 1 shows the

![Figure 1: Daily trip length, probability density functions for different groups of users (User1: Modest traveler, User2: Average traveler, User3: Frequent traveler)](image-url)
probability density functions of the distribution for the three classes: namely modest drivers (User 1), average drivers (User 2) and frequent drivers (User 3). We assume that the ratio between of the populations of the three users is 3:6:1. Without loss of generality, the total population of all drivers is assumed to be 10,000 in year 0. Since all vehicles have a life expectancy of 10 years, in year 1, 1,000 drivers will need to replace their cars. The total population, as well the demand for new cars, is assumed to grow at constant rate of 2% rate compared to the base year.

Figure 2 shows the cumulative number of different types of vehicles adopted by different classes of users, when an optimum incentive policy portfolio is adopted. The main findings from the case study are summarized as below

- EVs are a better option for shorter daily trips, while frequent drivers with longer average daily driving distance are more likely to choose PHEVs to avoid the range anxiety.
- Building charging stations is found to be a better incentive for adoption of PEVs, compared to providing purchase rebates.
- As the gasoline prices rise, EVs will become more desirable, and more charging stations should be built in intracity areas.
- As the cost of acquiring alternative transportation (when EV users cannot use their car for certain trips due to the lack of charging facilities) rises, the optimal number of intercity charging station increases.

3 Locating charging stations for inter-city travel

3.1 Modeling framework

One of the most important barriers in adoption of EVs is the range anxiety due to the limited range of current EV batteries and limited number of recharging facilities. Availability of recharging infrastructure can help the adoption of EVs either in inter-city trips or in intra-city trips. The optimum allocation of these infrastructure can speed up the adoption while minimizing the system costs.

Nie and Ghamami (6) developed a conceptual corridor model to analyze travel by EVs along a long corridor. Their model aims to select the battery size and charging capacity (in terms of both the charging power at each station and the number of stations needed along the corridor) to meet a given level of service in such a way that the total social cost is minimized. This study generalizes Nie and Ghamami’s model in the following important aspects. First, it considers realistic spatial profile of EV demands along the corridor. Second, it relaxes the restrictive assumption that the
charging stations must be evenly spaced along the corridor. Third, it allows the EV users to choose recharging points as they plan their trip, rather than forcing them to charge only when the battery is completely depleted. The resulting problem is formulated as a mixed integer program and solved using a specialized heuristic algorithm.

### 3.2 Case study and main findings

The Chicago-Madison-Minneapolis corridor is used in our case study to analyze intercity travel. The spatial demand profile is estimated using a tool developed by our research team, as shown in Table 2. Electric vehicles are assumed to have an average range of 100 miles with a 40(kwh) battery.

The improved corridor model suggests charging stations to be located at miles 75, 155, 225, 290 and 360 (measured from Chicago), each with a capacity of 5 charging spots. This reduces the construction cost by 48 percent compared to the conceptual corridor model of (6). Overall the results of the case study shows the potential of the improved as a decision-support tool for planning the location of intercity charging stations.

### References


### Table 2: Characteristics of the different types of vehicles

<table>
<thead>
<tr>
<th>Origin Destination Pair</th>
<th>Chicago-Madison</th>
<th>Madison-Minneapolis</th>
<th>Chicago-Minneapolis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>150</td>
<td>270</td>
<td>420</td>
</tr>
<tr>
<td>Electric Vehicle Demand*</td>
<td>937</td>
<td>487</td>
<td>1588</td>
</tr>
<tr>
<td>Frequency (trip per year)</td>
<td>2.99</td>
<td>1.72</td>
<td>1.84</td>
</tr>
</tbody>
</table>

* Considering 0.5 percent adoption rate of electric vehicles. (7)