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Simple Economics of Electric Vehicle Adoption

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Abstract

Increasing energy prices have led to a renewed interest in development of electric vehicles. At the same time, many customers may view an electric vehicle as an inferior alternative to the gasoline-powered car, due to limited range, length of time required to recharge the car, and limited availability of the related infrastructure. Further, commercially available and well-tested hybrid vehicle technology provides substantial fuel economy without requiring additional infrastructure investment; moreover, hybrid cars do not suffer from the range issue. This paper offers a first formal model of adoption of electric vehicles. We show that, depending on the values of the model's parameters, a situation can arise where some of the commuters purchase an electric vehicle as their second car, in addition to purchasing a regular gasoline-powered car. At the same time, improvements in fuel economy similar to development of a hybrid vehicle technology can lead to wide-spread adoption of a hybrid vehicle as household's only car. This paper will provide a framework model to analyze the question of electric vehicle adoption, which will be expanded in future research.

Keywords: electric vehicles; hybrid cars

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1. Introduction

Increasing energy prices have led to a renewed interest in development of electric vehicles. Recent auto shows feature most major auto manufacturers presenting electric powered cars; a number of models (Nissan Leaf, Tesla Roadster, etc.) are offered for sale to the general public. Nissan plans to manufacture over 250,000 Leaf vehicles annually by end of 2013, using production facilities in Japan, USA, and England. Government policies have also shifted towards supporting electric vehicles: in a number of countries, government subsidies and/or tax incentives are available to buyers of electric cars. This market segment promises to be rather profitable for the auto manufacturers, as currently electric vehicles are priced to capture the cost savings they could deliver to customers in the age of high gasoline prices. Government provided incentives are intended to help customers

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stomach the high purchase prices of electric cars: without the tax breaks, Nissan Leaf costs about $35,000 in the USA – about twice the price of Toyota Corolla, a fuel efficient gasoline-powered sedan.

Increased attention of both government and manufacturers to electric cars is understandable; however, wide-spread adoption of these vehicles is likely to encounter a number of rather difficult challenges. Limited and somewhat uncertain range, coupled with long recharge time and scarcity of charging stations may hinder adoption of electric cars by households. Additionally, development of infrastructure for charging electric vehicles (which involves both building charging stations and upgrading homes/garages to enable in-home charging of electric cars) may impose additional burden on the electric grid, potentially triggering the need to upgrade the latter as well, creating challenges for the electricity markets, and leading to increased environmental damage in the areas where coal is used to generate electricity.

Interestingly, manufacturers and government promote electric vehicles despite the existence of well-tested hybrid gasoline-electric vehicle technology, which provides substantial fuel savings as compared to the gasoline-powered vehicles. Toyota's Prius model is an undisputed leader here: this vehicle has until the launch of Chevrolet Volt been considered the most efficient gasoline-powered passenger car commercially available on the US market. Chevrolet Volt is itself a different kind of hybrid vehicle. While Prius switches between electric and gasoline power depending on the driving conditions, charging the battery as the driver applies the brake; Volt uses electric power, switching to gasoline engine once the battery has discharged. In the end, the issue of whether it is socially optimal to allocate available resources to development of hybrid cars versus electric vehicles is an important and timely problem, which this study begins to address.

In this paper, we offer a first formal model of adoption of electric vehicles. The modeling approach assumes that commuters live at different distances from their work and shopping destinations, and must use personal vehicles for both commuting and shopping needs. While all people are assumed to live within electric car's range for work commute; some commuters live too far from their shopping destination to be able to use an electric vehicle for all their travel needs. We show that, depending on the values of the model's parameters, a situation can arise where some of the commuters purchase an electric vehicle as their second car, in addition to purchasing a regular gasoline-powered car. At the same time, improvements in fuel economy similar to development of a hybrid vehicle technology can lead to wide-spread adoption of a hybrid vehicle as household's only car.

This study is not the last word in the electric vehicle debate. Quite to the contrary – we would like to start this debate. Our paper provides a framework model, which can be expanded upon in future research.

The rest of the paper is organized as follows. Section 2 gives a very brief overview of the relevant literature. Section 3 presents the modeling framework, and Section 4 extends it to analyze welfare implications of EV versus hybrid vehicle adoption by the manufacturers. Section 5 concludes with discussion of issues that can be addressed in future research.

2. Relevant Literature

Since electric vehicle adoption is in its infancy, sufficient data to allow systematic studies of EV demand have not yet been generated. Studies evaluating potential EV demand and effects are also scarce, represented by Kurani et al. (1996) and Lieven et al. (2011). Both studies use survey results to evaluate potential demand for electric vehicles, and suggest range and price as the most likely deterrents to their adoption. Lieven et al. also suggest based on their results that electric vehicles can potentially capture about 5 percent of the German car market (this would correspond to about 175,000 new electric vehicles per year). Graham-Rove et al. (2012), based on interviews with 40 owners of regular cars, who were given electric vehicles for a week, suggested limited range (along with range anxiety, which led drivers not to use all the vehicles' features to maximize the range, generally diminishing pleasure and comfort) and the likelihood of further technological developments as barriers to EV adoption.

In contrast to electric vehicles, hybrid gasoline-electric cars have been in use for a number of years, and achieved substantial degree of market penetration. The corresponding literature has appeared, focusing predominantly on quantification of the impact of incentives on sales of hybrid cars. In particular, Gallagher and

Muehlegger (2011) show that sales tax rebates increase demand by a higher magnitude than income tax incentives (the former represent an immediate discount, whereas the latter is an example of a deferred price reduction). Diamond (2009) reaches the same conclusion; however, he also suggests that higher gasoline prices is a more important driver of demand for hybrid vehicles than any of the tax incentives. Beresteanu and Li (2011) also conclude that rising gasoline prices were responsible for higher demand for hybrid cars by a larger magnitude as compared to tax subsidies. Chandra et al. (2010) estimate that tax rebates are responsible for about a quarter of all hybrid vehicles sold while rebate program was active; they also document some substitution to hybrids from both larger fuel inefficient and some smaller fuel efficient vehicles.

Our modeling framework can be considered a very simplified case of the monocentric urban model, very popular in both urban and labor economics. Origins of this model can be traced to Alonso (1964) and Mills (1972). Further theoretical research in this area has led to development of multicentric models (e.g., Wieland, 1987; Yinger, 1992). Most recently, the state of research in these employment-population location models has been described by Zenou (2009).

3. Model

3.1. Setup

Our modeling exercise centers around the notion of commuters, who need to use personal vehicles to travel to work and to a leisure destination. Commuters are uniformly distributed along a linear street of unitary length; work at the same location (i.e., a central business district, or CBD). The leisure/shopping destination is located at the distance $\alpha < 1$ from the CBD, as in Figure 1.

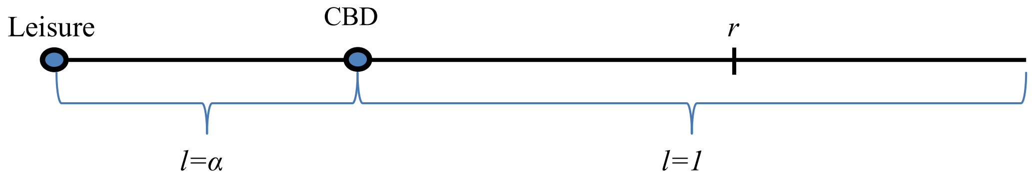

Figure 1 General Model Setup

Each commuter is then uniquely identified by its location on the street, denoted via $x \in [0,1]$. We assume that no commuter is able to walk to work, and rule out the public transit option in our model – each commuter then requires a personal car to fulfill his/her travel needs. There are two car options available to our commuters: a 'regular' car and an electric vehicle (EV). The difference between a regular and an electric car is that the single trip range of the latter is $2 < d < 2(1 + \alpha)$. This effectively means that while all commuters will be able to use the EV for work commute; for some people EV will not be a feasible option to travel to the leisure/shopping destination. We will further denote via

$$r = \frac{d}{2} - \alpha \tag{1}$$

the location of the marginal commuter that allows using EV for both work and leisure/shopping trips. That is, people located between CBD and r will be able to use EV for all their travel needs; while commuters living between r and 1 will need to keep their regular vehicle, at least for shopping trips.

Over a certain time period (e.g., a week, a fortnight, or a month) each commuter makes N trips to CBD, and one trip to leisure destination. That is, a commuter located at point x covers the distance of $2\big((N + 1)x + \alpha\big)$ each period. Total cost of commute depends on the car(s) owned by the commuter. Specifically, suppose that cost of car ownership over a period of time consists of fixed cost of p monetary units per period (e.g., a periodic loan payment) and cost of driving of $0.5t$ monetary units per mile. Using subscript C for a regular car, and E for an electric vehicle, we suppose the following relationships between these costs:

$$p_C < p_E;\ t_C > t_E \tag{2}$$

These three inequalities mean that electric vehicle is characterized by lower variable but higher fixed cost as compared to the regular car.

The set of choices a commuter faces will depend on whether he/she is capable of using an electric vehicle for all his/her travel needs (i.e., whether x is to the right or to the left of r). In the former case, the commuter's choice will be between owning a regular car or an electric vehicle. We specify total benefit (utility) from owning a regular car as

$$U_C = y - p_C - t_C\big((N+1)x + \alpha\big) \tag{3}$$

Here y denotes consumer's income. Correspondingly, benefit from owning an electric vehicle is:

$$U_E = y - p_E - t_E\big((N+1)x + \alpha\big) \tag{4}$$

A commuter located at point x will then choose an electric vehicle over a car if $U_E > U_C$. Solving this inequality gives

$$x > \frac{p_E - p_C + \alpha(t_E - t_C)}{(t_C - t_E)(N+1)} \tag{5}$$

as the condition of electric car ownership by a consumer who lives within the EV range. We can further define via x_1 the location of a commuter, living within the EV range, who will be indifferent between owning a regular car and an electric car. Clearly:

$$x_1 = \frac{p_E - p_C + \alpha(t_E - t_C)}{(t_C - t_E)(N+1)} \tag{6}$$

Now, if $x_1 \leq 0$, then all commuters living within the electric car range will own an EV; but where $x_1 > r$, no one located within the EV range will adopt an electric car. Finally, if $x_1 \in (0, r)$, then commuters located between points 0 and x_1 will not adopt an EV, while those located between x_1 and r will.

Next, consider the problem faced by commuters located in the interval $(r, 1]$. A representative commuter here faces a problem of retaining his regular car and buying an EV *in addition to the regular car*. In the latter case, EV will be used for commute to CBD, while regular car will be utilized for leisure trips. The benefit derived by consumer from ownership of two vehicles is given by:

$$U_{C+E} = y - p_E - p_C - t_E N x - t_C(x + \alpha) \tag{7}$$

This option will be preferred to owning only a regular car if:

$$x > \frac{p_E}{N(t_C - t_E)} \tag{8}$$

Similarly to what we have done above for commuters living within the EV range for all their travel needs; we can define location of a commuter indifferent between keeping his/her regular car as the only vehicle and purchasing an EV as the second car. Specifically, we define:

$$x_2 = \frac{p_E}{N(t_C - t_E)} \tag{9}$$

Then, if $x_2 < r$, all commuters living outside of the EV range will purchase an EV as their second car. On the other hand, where $x_2 > 1$, no one will buy the second car. Interestingly, location of the point x_2 does not depend on the periodic fixed cost of the regular car.

3.2. Vehicle ownership patterns

Depending on the parameters of the model, we can identify six possible outcomes resulting from the introduction of the EV. Share of households owning an EV will be determined as:

$$S_E = max\{0, min\{r - x_1, r\}\} + max\{0, min\{1 - r, 1 - x_2\}\} \tag{10}$$

We will now proceed to characterize all the possible cases.

Case 1: $x_1 > r$; $x_2 > 1$. This is a trivial outcome, where none of the commuters adopts an electric car. In this case, $S_E = 0$

Case 2: $x_1 \leq 0$; $x_2 < r$. This case represents the other extreme, with every commuter adopting an EV. However, commuters located at $x \in [0, r]$ buy EV instead of a regular car, whereas people living at $x \in (r, 1]$ buy an electric car as their second vehicle. Clearly, $S_E = 1$ here.

Case 3: $x_1 > r$; $r \leq x_2 < 1$. This is the case where some or all of the people living outside of the EV range purchase a second car. At the same time, no one living within the range adopts at electric vehicle. In this case, $S_E = 1 - x_2$.

Case 4: $0 < x_1 \leq r$; $x_2 > 1$. In this outcome, commuters living outside of the EV range do not buy a second car; whereas some of the commuters living within the EV range adopt an EV as their only vehicle, instead of a regular car. Under these circumstances, $S_E = r - x_1$.

Case 5: $0 < x_1 \leq r$; $x_2 < r$. This is effectively case 2 with partial adoption of electric vehicles by commuters living within the EV range; $S_E = 1 - x_1$. This is the first case, for which three distinct kinds of car ownership emerge: some commuters own only a regular car, others only an EV, and all commuters living outside of the EV range own two cars – both a regular car, which they use for leisure trips, and an EV, which is used for commute to the CBD. This case is visualized in Figure 2 below.

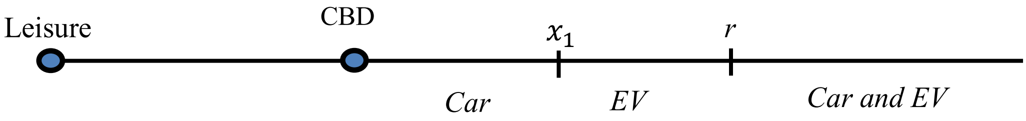

Figure 2 Car ownership pattern in Case 5

Case 6: $0 < x_1 \leq r$; $r < x_2 \leq 1$. This is the most complex case of all. Under these parameter values, some commuters living within EV range switch to an electric car; and some commuters living further away from the CBD buy an EV as their second vehicle; $S_E = 1 + r - x_1 - x_2$. This case also deserves visualization – see Figure 3 below.

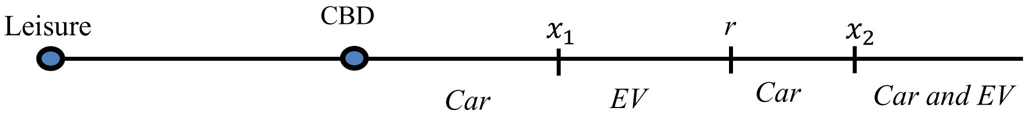

Figure 3 Car ownership pattern in Case 6

From the analysis we have performed up to now, we can see that there are certain differences in parameters which affect commuter's vehicle ownership choice, depending on whether the commuter lives within or outside of the EV range. Specifically, distance to the leisure destination and fixed periodic cost of regular car ownership do not play a role for the commuter living outside of the EV range. This is understandable, as this commuter is pre-determined to use a gasoline-powered car for trips to leisure destination. In both cases, however, EV ownership is discouraged by higher fixed and variable costs associated with EV, and encouraged by higher variable cost of driving a gasoline-powered vehicle, and larger number of trips to the CBD, other things equal. All these results are very intuitive.

3.3. Numerical example

The numerical example we develop in this sub-section demonstrates, among other things, that none of the scenarios we developed in the previous sub-section can really be ruled out. For the purpose of clarity, we will fix all the parameters except for the fixed periodic cost of ownership. Specifically, we will set $N = 30$; $\alpha = 0.8$; $r = 0.6$; $t_E = 1$; $t_C = 8$. With these values, we get:

$$x_1 = \frac{p_E - p_C - 5.6}{217} \tag{11}$$

$$x_2 = \frac{p_E}{210} \tag{12}$$

The second of the above expressions immediately leads us to deriving the range of values for p_E, for which commuters living outside of the EV range will buy an electric vehicle as the second car. Knowing that this range is defined by $r < x_2 \leq 1$, which for our parameter values turns into $0.6 < x_2 \leq 1$; we easily show that the second car will be bought by commuters living in between points 0.6 and 1 when:

$$126 < p_E \leq 210 \tag{13}$$

From expression for x_1 we can easily determine that all commuters living within the EV range will adopt an electric car if

$$p_E - p_C < 5.6 \tag{14}$$

And no one will adopt provided:

$$p_E - p_C > 135.8 \tag{15}$$

We can then determine the ranges of parameters p_E and p_C, which will correspond to each of the cases we described above. Namely:

- Case 1 (no one adopts an EV) will occur if $p_E > 210$ and $p_C < 74.2$
- Case 2 (everyone adopts) will take place for $p_E \leq 126$ and $p_C < 120.4$ and $p_E - p_C < 5.6$
- Case 3 (no one within the range adopts, while some outside buy second car) is what we will have for $126 < p_E \leq 210$ and $p_C < 74.2$
- Case 4 (only some of the commuters within the EV range adopt the electric vehicle) will happen for $p_E > 210$ and $p_E - 135.8 \leq p_C < p_E - 5.6$
- Case 5 (partial adoption by commuters within the EV range and full adoption outside of the range) will be the outcome for $p_E \leq 126$ and $p_E - p_C < 5.6$
- Case 6 (partial adoption of EV both within and outside of the range) is the outcome for $126 < p_E \leq 210$ and $p_E - 135.8 \leq p_C < p_E - 5.6$

Overall, every case we have outlined previously is possible for some combination of our model's parameters. We can thus claim that, based on this simple example, none of the six cases outlined above can be ruled out based on the structure of our model.

4. Extension – electric car versus hybrid

In this section, we will consider one simple extension of our model, of multiple possible ways to expand this analysis. Specifically, let us suppose that the society has certain resources, which can be devoted to developing either an electric vehicle, or a "hybrid" car, which in the language of our model will mean that a type H vehicle is created, so that:

$$p_C < p_H < p_E; \; t_C > t_H > t_E \tag{16}$$

The corresponding benefit (utility) associated with the hybrid car ownership is given by:

$$U_H = y - p_H - t_H\big((N+1)x + \alpha\big) \tag{17}$$

Since hybrid vehicle will have no range restrictions associated with it; the commuter's problem is simplified to that of choosing between an regular and a hybrid car (note that we supposed that we can develop either an EV or a hybrid, but not both, so that all three alternatives will never be available to the commuter). The location of a commuter indifferent between a car and a hybrid is then given by:

$$x_H = \frac{p_H - p_C + \alpha(t_H - t_C)}{(t_C - t_H)(N+1)} \tag{18}$$

Commuters located to the right of x_H will be buying hybrid vehicles, and commuters located between x_H and the CBD will purchase regular cars. Clearly, if $x_H < 0$, everyone adopts a hybrid vehicle; and all commuters will stick to the regular cars if $x_H > 1$.

Taking prices as given (we will return to this issue when discussing the model's implications); the issue of social desirability of developing an electric vehicle or a hybrid car can be addressed by comparing the values for the consumer surplus in these two cases. Technically, a more complete analysis would also take into account the profit of the car manufacturers involved in the game; however, we leave this issue outside of the scope of our analysis, due to potential multitude of the possible market structures to be considered (an issue for a potentially fruitful future research agenda). Specifically, in the regular versus hybrid car problem, the consumer surplus is given by:

$$CS_H = \int_0^{\max\{0,X_H\}} U_C dx + \int_{\min\{X_H,1\}}^1 U_H dx \tag{19}$$

For the case where $X_H \in (0,1)$ – we can call this an interior solution – we have:

$$CS_H = y - p_H - t_H\left(\alpha + \frac{1}{2}(N+1)\right) + x_H\big(p_H - p_C + \alpha(t_H - t_C)\big) + x_H^2\frac{1}{2}(N+1)(t_H - t_C) \tag{20}$$

Using (18) and after some algebraic transformations, (20) can be simplified to:

$$CS_H = y - p_H - t_H\left(\alpha + \frac{1}{2}(N+1)\right) + \frac{1}{2}\frac{[p_H - p_C + \alpha(t_H - t_C)]^2}{(t_C - t_H)(N+1)} \tag{21}$$

Consumer surplus in the case where commuters have the choice of a regular car and an electric vehicle is a more complicated issue to examine, due to the sheer number of possible patterns of car ownership, as discussed in the previous section of this paper. The most interesting cases for our purpose, however, are those involving some or all of the households purchasing an EV as their second car (i.e., cases 2, 3, 5, and 6). Let us elaborate on those scenarios.

We will start from Case 2, as this is the simplest one to tackle. Recall that in this case, all commuters adopt an EV. The consumer surplus will in this case be:

$$CS_2 = \int_0^r U_E dx + \int_r^1 U_{C+E} dx \tag{22}$$

From this point on, in notation used for consumer surplus in cases involving electric vehicles, we will use subscript corresponding to the number of possible vehicle ownership scenario outlined in the corresponding sub-section of this study. Simplifying and rearranging yields the following expression for the consumer surplus:

$$CS_2 = y - p_E - (1-r)p_C - \alpha(r(t_E - t_C) + t_C) + \frac{r^2}{2}(t_C - t_E) - \frac{1}{2}(Nt_E - t_C) \tag{23}$$

Comparing the two expressions for consumer surplus is not an analytically feasible exercise. We will therefore resort to providing a numerical example to demonstrate that depending on parameter values of the model, consumer welfare can be higher with in either of the two cases (recall that we have set out to evaluate whether commuters will be better off when facing the choice between an EV and a regular car or a hybrid vehicle and a regular gasoline car).

As before, suppose $N = 30$; $\alpha = 0.8$; $r = 0.6$; $t_E = 1$; $t_C = 8$. Further, setting $p_E = 120$ and $p_C = 115$ results in universal adoption of electric vehicles. Let us now vary p_H and t_H in between the bounds set by (16). Suppose $p_H = 117.5$. Simple numerical analysis then shows that development of a hybrid car rather than an EV results in higher consumer surplus for t_H lower than approximately 2.6. Once this value is exceeded, EV is a preferred choice by the consumers. Generally, values of t_H lower than 2.4 will result in a hybrid car being the preferred option for consumers for any feasible values of p_H within the range stipulated by our numerical exercise. On the other hand, for any feasible values of p_H, values of t_H higher than 2.7 will imply higher benefits for commuter from development of an EV. These results suggest that a fairly intuitive trade-off between the fixed and variable cost of car ownership. Further, in our example variable cost appears to play a more important role in defining which of the cases will result in higher welfare for the commuters.

Vehicle ownership patterns implied by cases 5 and 6 are actually fairly similar in terms of welfare implications to case 2 we have just considered. Case 5 results in partial adoption of an EV by commuters living inside of the EV range. Case 6 involves partial adoption both within and outside of the range. We can safely suggest that if full adoption of EV outside of the electric vehicle's range (e.g., everyone outside of the range owning two cars) can be beneficial to commuters, same is probably true for partial adoption. Let us however pay closer attention to Case 3 – an ownership pattern involving some commuters outside of the EV range buying the second car, and no one switching within the range. Consumer surplus in this scenario is calculated as follows:

$$CS_3 = \int_0^{X_2} U_C dx + \int_{X_2}^1 U_{C+E} dx \qquad (24)$$

This simplifies to the following rather complex expression:

$$CS_3 = y - p_C - \alpha t_C - \tfrac{1}{2}(Nt_E - t_C) + \frac{p_E}{N^2(t_C - t_E)^2}\left[t_E\left(\tfrac{1}{2}p_E(N-1) - N\right) - Nt_C - p_E\right] \qquad (25)$$

For the numerical example, we are taking the following parameters: $N = 30$; $\alpha = 0.8; r = 0.5$; $t_E = 1$; $t_C = 8$ (we have only changed the range here). We set $p_E = 175$ and $p_C = 60$, which yields $x_1 = 0.504$ and $x_2 = 0.833$. Comparison of consumer surpluses suggests a very limited set of combinations of plausible values for p_H and t_H, which result in higher consumer surplus for with the hybrid vehicle than with the car. This outcome is possibly stipulated by limited adoption of EV as the second car.

We have thus shown that in general the answer to the question of social desirability of development of an electric vehicle (which we defined as a car with high fixed but low variable cost of ownership, but a limited trip range) versus improving the existing technology to reduce variable cost of ownership at the expense of higher fixed cost, but without sacrificing the trip range depends on the model's parameters. Even where adoption of an electric vehicle results in some commuters purchasing their second car instead of substituting the regular gasoline car for an EV; the resulting decrease in variable cost of ownership can justify the inconvenience of limited range and additional fixed cost. Of course, the numbers we have chosen for our numerical exercise are somewhat arbitrary, selected to suit the vehicle ownership scenarios we have analyzed. Further studies can make an effort at calibrating this setup to more realistic parameter values.

5. Discussion and conclusions

What we have developed here can be thought of as a framework for modeling adoption of an electric vehicle. A great number of issues remained outside of the scope of our analysis for now, and present an opportunity for future inquiry. In particular, we can identify the following opportunities for extending the model's scope and subsequent applications.

Perhaps most importantly, our framework does not currently examine the role of markets – indeed, both fixed and variable costs are exogenous to our model. Variable cost is less of a problem here, as we can safely assume that a commuter purchases gasoline and maintenance on competitive markets – then, variable cost of car ownership will simply reflect the marginal cost of providing these services (i.e., price of gasoline and oil changes), and can to a large degree be assumed exogenous. Same cannot however be assumed about the fixed costs, as car manufacturers are known to operate in imperfectly competitive markets. Therefore, extending our framework to models of oligopoly offers a fruitful extension for future research. Moreover, one can consider different market setups: a monopolist producing both regular and electric vehicles; a duopoly with one manufacturer offering regular cars, and a competitor selling electric vehicles only; and a more realistic oligopoly model, with two or more firms present in both market segments. The important problem will then be to consider which market structure delivers higher total market welfare. To bring our modeling exercise closer to reality, further studies can consider scenarios involving markets producing regular, hybrid, and electric vehicles, and commuters differentiated not only by their location, but also by socio-demographic characteristics, such as income. Further, commuters living outside of the EV range can choose to utilize services of car rental or car sharing industries for their trips to the leisure destination, and these industries can themselves respond to adoption of electric vehicles by commuters by changing their strategies.

An important rationale used to justify government support for electric vehicle is reduction in pollution such a development can bring. The concept of negative externalities is invoked; suggesting that commuters will not account for the environmental harm their decision to purchase a gasoline-powered vehicle will create. This argument can be used to justify both subsidies to buyers of electric vehicles, and fuel taxes, or a combination of the two. Our study however points to another potential externality associated with electric vehicle manufacturing.

Namely, environmental harm is also created during the car manufacturing process, and some of the vehicle ownership patterns emerging in our model imply that introduction of an electric vehicle will result in more cars being produced, which will impact calculation of social welfare implications of EV introduction.

Our model assumes otherwise homogeneous consumers living in fixed locations at different distances from the CBD. This stylized setup differs from reality in several important ways. First, commuters' location is not fixed in the long run – people move closer to where they work, and availability of an electric vehicle may change commuters' incentives with respect to how far from the CBD they are willing to live. Property prices may also be affected. Future modeling exercises can tackle this issue. Second, commuters' location can be linked to people's demographic characteristics. For instance, what if higher-income commuters choose to locate further away from the CBD, and we allow demand for travel to depend on commuter's income? Our framework is well amenable to incorporating such scenarios. The third important limitation of our model relates to our assumption of fixed travel demand – among other things, this means that the issue of road congestion is left out of our framework. In fact, increased fuel efficiency leads to an increase in vehicle miles driven – a well-documented phenomenon known as the rebound effect (Small and van Dender, 2007). Making miles driven endogenous will also open door to analyzing implications of electric vehicle development and adoption for road congestion.

We have indicated earlier in this paper that long-term establishment of electric vehicles will require certain infrastructure investment. This is an issue that can be incorporated into our framework as well. For instance, construction of a charging station at the leisure destination will increase the EV's range (moreover, for $\alpha < 1$ and assuming the vehicle can be fully charged while the customer is at the leisure destination, such a charging station will place every commuter within the EV range, greatly simplifying our analysis). At the same time, for certain combinations of parameter values, a charging station will *not* increase the level of EV adoption in our framework; and it will not be impossible to come up with examples, where the cost of building and maintaining the charging station will not justify the benefits in the form of higher consumer surplus.

We have also mentioned in the literature review that our modeling exercise resembles an over-simplified monocentric urban model. The urban location models have evolved since the first monocentric one was developed; thus, future studies can put our framework into the context of those models, further bringing future modeling exercises closer to reality.

Last but not least, our modeling framework suggests clear and intuitive hypotheses for future empirical studies of EV adoption. Our model effectively predicts higher level of electric vehicle adoption in more densely populated areas, other things equal.

Notwithstanding the above-listed possible extensions of our framework; we hope to see future studies calibrating the model we propose here, to enable practical applications of this framework to predicting demand for electric vehicles, as well as to evaluating effects of any proposed incentives to buyers of those vehicles.

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