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## Measuring Range Anxiety: the Substitution-Emergency-Detour (SED) Method

Zhenhong Lin  
Oak Ridge National Laboratory, 2360 Cheralala Boulevard, Knoxville, TN 37932, USA

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### Abstract

Range anxiety has been widely recognized as a critical barrier for battery electric vehicles (BEV), but its measurement method is lacking. Such a knowledge gap makes it difficult to analyse the competitiveness of and the demand for BEVs. This study develops the Substitution-Emergency-Detour (SED) method to measure the range anxiety cost, and conducts sensitivity analysis of range anxiety cost with respect to nine factors. It is found that the most effective ways to reduce range anxiety are reducing driving intensity, increasing the vehicle range, extending the vehicle range with better charging infrastructure. Better household vehicle flexibility and less range uncertainty can also significantly reduce range anxiety. The SED method and the numerical results are expected to contribute to better understanding of the range anxiety barrier and the BEV demand.

*Keywords: EV (electric vehicle), range, market*

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## 1 Introduction

Range anxiety has been widely recognized as a critical barrier for battery electric vehicles (BEV), but has yet to be properly measured [1]-[3]. This makes it difficult to analyse the competitiveness of and the demand for BEVs. A good method to measure range anxiety could allow an improved understanding of market barriers, optimization of the BEV range, and exploration of solutions to reduce range anxiety.

This study develops the Substitution-Emergency-Detour (SED) method to monetize the range anxiety. The concept of the SED method is explained in the next section, followed by some numerical examples that illustrate how the method can be used and how range anxiety cost can be sensitive to the chosen 9 factors.

## 2 Concept and Formulation

The SED method is based on the notion that range anxiety can be theoretically compensated with no-cost, hassle-free vehicle substitution, emergency roadside service (ERS), and detours to access public chargers. In reality, these activities cost measurable money, time and inconvenience, thus providing a framework to formulate the range anxiety cost as a function of value of time, household vehicle ownership, charging infrastructure coverage and driving patterns.

$$\text{Range Anxiety Cost} = \sum \text{Costs of} \left( \begin{array}{l} \text{Vehicle Substitution} \\ \text{Emergency Roadside Service} \\ \text{Detouring for Public Charging} \end{array} \right)$$

Figure 1: the Substitution-Emergency-Detour method

For further formulation, 4 random variables are considered—the expected daily driving distance ( $x_e$ ), the unexpected deviation ( $x_d$ ) of actual daily distance ( $x$ ) from  $x_e$ , the unexpected deviation ( $r_d$ ) of the actual vehicle range ( $r$  or  $r_r$ , explained later) from the expected vehicle range ( $R_e$ ), the probability ( $P_e$ ) of using emergency roadside service as opposed to detouring to the nearest charging station under the condition that the actual vehicle range is less than the actual daily distance. When no detour is taken, the actual vehicle range ( $r$ ) is the sum of the expected vehicle range ( $R_e$ ) and the unexpected range deviation ( $r_d$ ). When a detour is taken, the actual vehicle range ( $r_r$ ) will include an additional extended range ( $R_b$ ) resulting from the detour and recharge. This detour-extended range ( $R_b$ ) is a function of the BEV range ( $R_0$ ), the detour recharge ratio ( $E_b$ ) and the wasted range ( $L$ ) in reaching and returning from the charger (5). The expected vehicle range ( $R_e$ ) is the product of the BEV range ( $R_0$ ) and the expected extension ratio ( $E$ ) that reflects the regular charging activities anticipated by the driver. The relationships among these variables are illustrated in the equations (1)—(5), with lowercase letters representing random variables and uppercase letters representing deterministic variables or constant parameters.

$$x = x_e + x_d \quad (1)$$

$$r = R_e + r_d \quad (2)$$

$$r_r = R_e + r_d + R_b \quad (3)$$

$$R_e = R_0 E \quad (4)$$

$$R_b = R_0 E_b - L \quad (5)$$

Logically, a vehicle substitution occurs when the expected daily distance exceeds the expected vehicle range (i.e.  $x_e > R_e$ ). The cost of obtaining and using a substitution vehicle ( $S_0$ ) could be as low as the daily depreciation of another vehicle in the household and as high as a daily rate of a rental vehicle plus fees of home delivery. Therefore, the annual substitution cost ( $S$ ) can be expressed in the equation (6), where  $f(x_e)$  is the probability density function of  $x_e$ .

$$S = 365 S_0 \int_{R_e}^{+\infty} f(x_e) dx_e \quad (6)$$

When  $x_e < R_e$ , the driver would operate the BEV, hoping the uncertain actual daily distance ( $x$ ) not to exceed the uncertain actual vehicle range ( $r$ ). But once the BEV leaves home, the actual daily distance ( $x$ ) may deviate from  $x_e$  due to unplanned errands or other reasons, and the actual vehicle range ( $r$ ) may also deviate from  $R_e$  as caused by on-road speeds, use of air conditioner, congestion, and other reasons. These situations result in the possibility ( $P_{ed}$ ) of the actual daily distance exceeding the actual vehicle range (i.e.  $x > r$ ) and the need to either call for emergency roadside services or detour to a public charger. Such possibility is expressed in the equation (8), where  $g(x)$  and  $h(r)$  are the probability density function of  $x$  and  $r$ , respectively.

$$P_{ed} = \int_0^{R_e} f(x_e) dx_e \int_0^{+\infty} \int_r^{+\infty} g(x) h(r) dx dr \quad (7)$$

Let  $E_0$  and  $D_0$  respectively be the cost of one roadside service and one detour for recharging. Between these two options, the probability ( $P_e$ ) of calling for roadside services can be expressed as a function, as in the equation (8), of  $E_0$ ,  $D_0$  and the price coefficient ( $\beta$ ) that reflects the choice elasticity.

$$P_e = \frac{e^{\beta E_0}}{e^{\beta E_0} + e^{\beta D_0}} \quad (8)$$

The annual cost of emergency roadside services ( $E$ ) and detour charging ( $D$ ) can be expressed in the equation (9) and (10).

$$E = 365 E_0 P_{ed} P_e \quad (9)$$

$$D = 365 D_0 P_{ed} (1 - P_e) \quad (10)$$

### 3 Example

To apply the SED method established by the equation (1)—(10), a Base example is created based on the following assumptions.

The cost of one roadside service ( $E_0$ ) is assumed to be \$62 for each service call, based on rates of fuel delivery services by rental car companies [4].

The cost per detour for recharging ( $D_0$ ) depends on the availability of public chargers, time value and charging time. It is estimated to be \$63 based on

the assumptions of the wage rate at \$21/hour, the BEV range at 100 miles, the detour charging ratio at 100%, the charging availability at 0.5% (equivalent percentage of existing gasoline stations), and the charging power at 60 kW.

The price coefficient ( $\beta$ ) is assumed to be -0.325, based on the assumption of price elasticity at -10.

The probability density function  $f(x_e)$  is assumed to be a Gamma distribution where the driver drives 16000 miles per year and most frequently 20 miles per day. The form of distribution has been adopted for plug-in electric vehicle analysis [5][6] and validated with real-world travel data [7]. The probability density function  $g(x)$  is assumed to be a Gamma distribution with its mean at  $x_e$  and its standard deviation at 2.5% of  $x_e$ . The probability density function  $h(r)$  is assumed to be a Gamma distribution with its mean at  $R_e$  and its standard deviation at 20 miles, based on real-world BEV data. Figure 2 shows the distribution of  $x_e$  and  $r$  and the distribution of  $x$  on the days when  $x_e=70$  miles. The overlap between the distributions of  $x$  (subject to  $x_e=70$ ) and  $r$  indicates the chance of the actual daily distance exceeding the actual vehicle range, even though the expected daily distance (70 miles) is much below the expected vehicle range (100 miles).

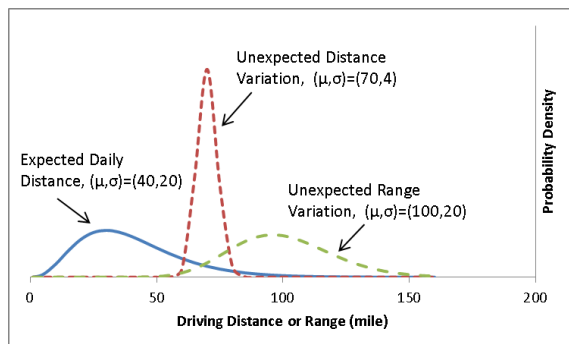


Figure 2: Variation of daily distance and range

Both the detour recharge ratio ( $E_b$ ) and the expected extension ratio ( $E$ ) are assumed to be 100%, meaning that the driver can use up to 100% of the BEV range each day and extend the BEV range by another 100% when detouring to recharge.

Based on the Base assumptions above, the range cost is estimated to be \$1309/year, 53% of which is for vehicle substitution, 28% for emergency roadside service, and 19% for detour charging.

## 4 Sensitivity Analysis

Sensitivity of the range anxiety cost is analysed with respect to the following 9 factors, each changed by 50% up and down.

- Vehicle Substitution Cost (\$/each)
- Emergency Roadside Service Cost (\$/each)
- Value of Time (\$/hour)
- Daily VMT Mode (miles)
- Annual VMT (miles)
- Vehicle Range (miles)
- Expected Extension Ratio (100%)
- Range St.D. (miles)
- Charger Availability (100%)

### 4.1 Vehicle Substitution Cost

Vehicle substitution cost indicates the easiness to obtain a backup vehicle when the expected daily distance exceeds the expected vehicle range. It depends on household vehicle flexibility and can range from \$15 to \$50, where the lower bound reflects the cost of using an easily available vehicle in the household by considering vehicle depreciation and the upper bound reflects the cost of a delivered rental vehicle. As shown in Figure 3, the vehicle substitution cost only affects the Substitution component of range anxiety. Higher vehicle substitution cost leads to higher range anxiety cost. High-income consumers are more likely to have high vehicle ownership and thus better vehicle flexibility. Because of this, they may perceive less range anxiety. However, they may have higher value of time and perceive a higher cost for detour recharges.

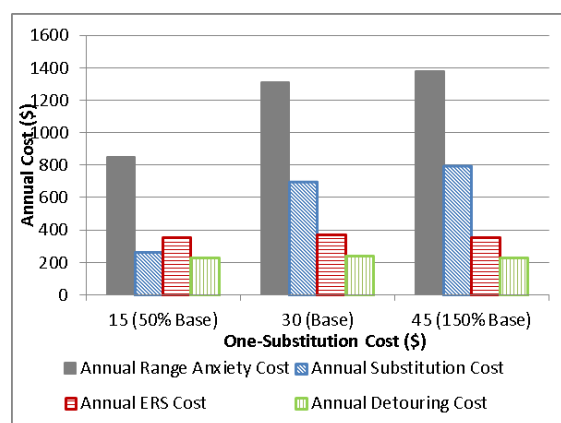


Figure 3: Range anxiety sensitivity to vehicle substitution cost

### 4.2 Emergency Roadside Service Cost

The ERS cost rate indicates the penalty each time a BEV is out of range on the road and the driver

calls for ERS. Higher ERS cost would motivate the driver to make greater efforts in detouring for recharges, but would nevertheless increase the range anxiety cost. As shown in Figure 4, the 50% increase in the ERS cost results in very little increase in the range anxiety cost, but it causes the driver to almost completely rely on detour recharging in the event of insufficient range on the road. As a result, the annual Detouring cost increases substantially. The 50% reduction in the ERS cost causes the driver to call for ERS whenever being stuck on the road, but the annual Emergency cost surprisingly decreases. This is because the reduction in the ERS cost offsets the effect of increased ERS frequency. The net effect is nearly 25% reduction in the range anxiety cost.

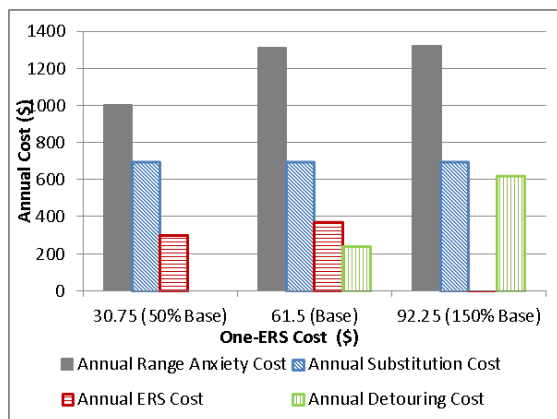


Figure 4: Range anxiety sensitivity to ERS cost

### 4.3 Value of Time

A higher-income consumer is expected to perceive higher value of time and thus be more averse to detour charging. In the Base case, the driver uses both ERS and detour recharging (Figure 5). When the value of time increases by 50%, the driver is predicted to almost completely rely on ERS. If the value of time decreases by 50%, detour charging would almost always be preferred over ERS.

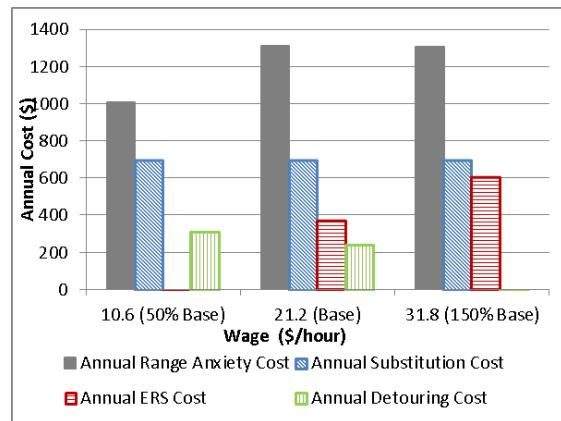


Figure 5: Range anxiety sensitivity to wage rate

### 4.4 Daily VMT Mode

Given the same annual VMT, a lower daily VMT mode would mean more long-distance days. This could cause more days of insufficient expected range. As shown in Figure 6, the most significant effect of daily VMT mode is on the Substitution component of the range anxiety cost.

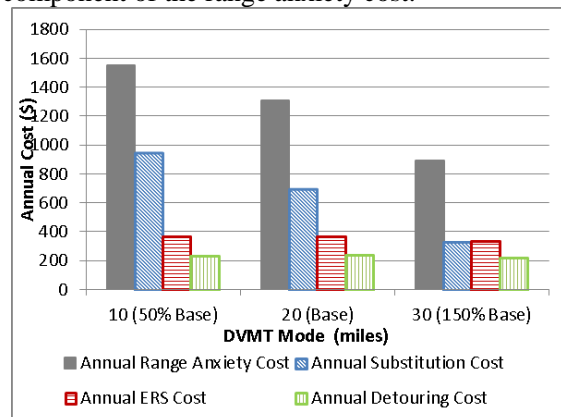


Figure 6: Range anxiety sensitivity to the typical daily distance

### 4.5 Annual VMT

For the same typical daily distance that is far below the BEV range, an increased annual driving distance very likely means more days of daily distance exceeding the BEV range. As shown on Figure 7, all cost components, especially the Substitution cost, are very sensitive to the annual driving distance. Higher driving intensity simply means greater range anxiety.

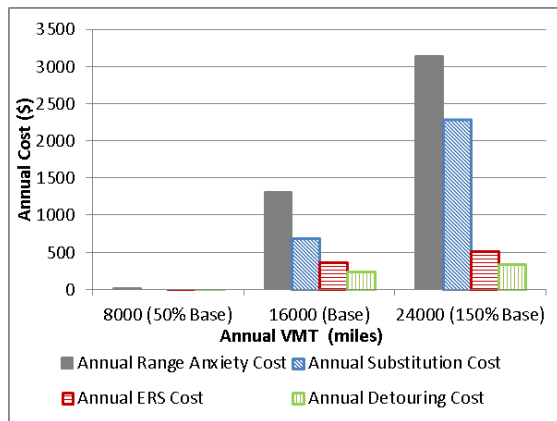


Figure 7: Range anxiety sensitivity to annual VMT

#### 4.6 Vehicle Range

Obviously, more vehicle range means less range anxiety. Figure 8 shows how the range anxiety cost changes with the vehicle range. The Substitution cost becomes a more dominating component when the vehicle range is reduced. Less vehicle range also causes the Detouring component to increase more rapidly than the Emergency component, because less range means less charging time, which makes the detour option more competitive than the ERS option.

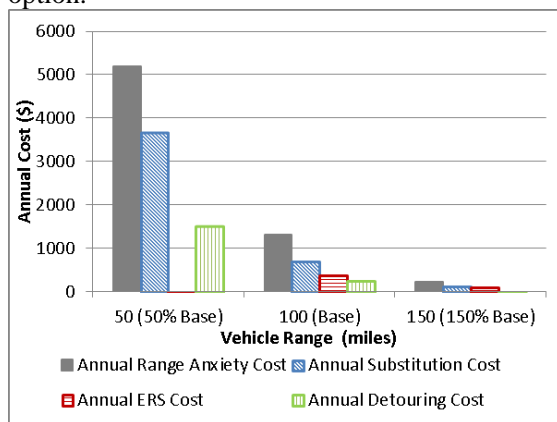


Figure 8: Range anxiety sensitivity to vehicle range

#### 4.7 Expected Extension Ratio

A 50% expected extension ratio means that only half of the 100-mile BEV range is usable. Therefore, the expected extension ratio has a similar effect on the range anxiety cost as the vehicle range, as shown in Figure 9. The only difference is that with a larger battery, the recharging time at detours is longer than the situation of 50-mile vehicle range (Figure 8). This makes ERS relatively more attractive.

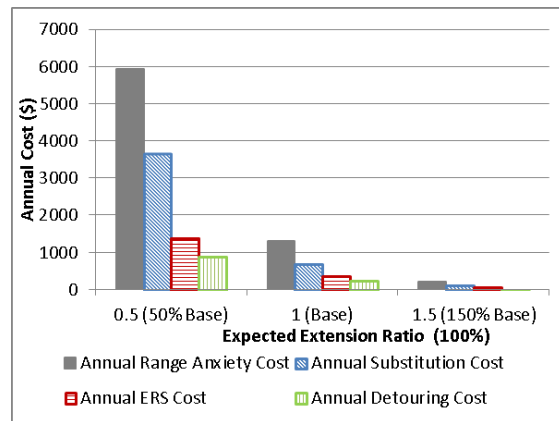


Figure 9: Range anxiety sensitivity to expected extension ratio

#### 4.8 Range Standard Deviation

Figure 10 shows that with more uncertainty of the vehicle range, the Substitution component remains constant, but both the Emergency and Detouring components increase. This is because with a larger range standard deviation, the actual vehicle range has a higher probability of falling below the actual daily distance. That is, the driver is more likely to use the BEV and be stuck on the road.

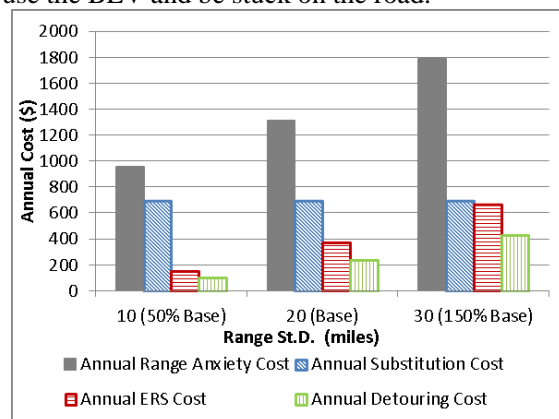


Figure 10: Range anxiety sensitivity to range standard deviation

#### 4.9 Charger Availability

Charger availability is defined as the equivalent percentage of existing gasoline stations to be installed with public chargers. Better charger availability reduces the distance from where a detour recharge is needed to the nearest charger. As shown in Figure 11, better charger availability does not affect the Substitution component; it results in more detours and fewer calls for ERS. The result in Figure 11 should not be misinterpreted as that improved charger availability reduces little range anxiety. Better charger availability would likely increase the



expected extension ratio and reduce the range anxiety cost by reducing the Substitution component. This part of effect is not reflected in Figure 11, which is used to isolate the effect of charger availability on detour charging.

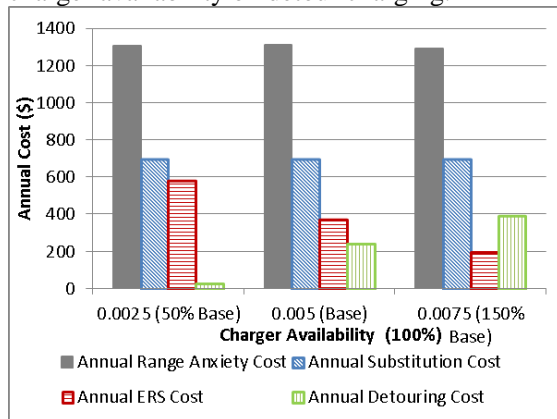


Figure 11: Range anxiety sensitivity to charging availability

## 5 Summary

This study develops a SED method to measure range anxiety associated with BEV ownership. Range anxiety is measured in terms of range anxiety cost, which is assumed to be just enough for compensating for vehicle substitution, emergency roadside services, and detour charging that altogether are assumed to erase range anxiety. Thus, the range anxiety cost is formulated as the sum of three cost components—Substitution, Emergency, and Detouring.

A Base case example is set up to illustrate the SED method, followed by a sensitivity analysis of the range anxiety cost with respect to 9 factors. It is found that the most effective ways to reduce range anxiety are reducing driving intensity, increasing the vehicle range, extending the vehicle range with better charging infrastructure. Better household vehicle flexibility and less range uncertainty can also significantly reduce range anxiety.

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## Authors



Zhenhong Lin received the Ph.D. degree in Civil and Environmental Engineering from the University of California, Davis. He is currently a research staff member at the Oak Ridge National Laboratory. His specialty research areas include energy and environmental policy analysis, simulation and optimization, and vehicle technologies.