Rethinking FCV/BEV Vehicle Range: A Consumer Value Trade-off Perspective

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Abstract—The driving range of FCV and BEV is often analyzed by simple analogy to conventional vehicles without proper consideration of differences in energy storage technology, infrastructure, and market context. This study proposes a coherent framework to optimize the driving range by minimizing costs associated with range, including upfront storage cost, fuel availability cost for FCV and range anxiety cost for BEV. It is shown that the conventional assumption of FCV range can lead to overestimation of FCV market barrier by over $8000 per vehicle in the near-term market. Such exaggeration of FCV market barrier can be avoided with range optimization. Compared to the optimal BEV range, the 100-mile range chosen by automakers appears to be near optimal for modest drivers, but far less than optimal for frequent drivers. With range optimization, the probability that the BEV is unable to serve a long-trip day is generally less than 5%, depending on driving intensity. Range optimization can help diversify BEV products for different consumers. It is also demonstrated and argued that the FCV/BEV range should adapt to the technology and infrastructure developments. *Copyright Form of EVS25***.**

Keywords— fuel cell vehicles, electric vehicles, range, battery, alternative fuel

1. The FCV/BEV Range Problem

Fuel cell vehicles (FCV) and battery electric vehicles (BEV) are currently regarded as the two most important options to enable deep cut of petroleum use and greenhouse gases in the transport sector [1,2]. Despite many differences, both technologies face a common question: what should be the driving range? Here, the range is defined as the driving distance enabled by a full refill of onboard hydrogen for FCVs or by a fully recharged onboard battery for BEVs. This question is important for two reasons. First, simple range analogy to conventional vehicles is questionable because the onboard storage technology of either FCV or BEVs is far from being competitive with that of conventional gasoline or diesel vehicles, in terms of cost, weight or density [3]. The hydrogen refueling availability and electricity charging availability also differs greatly from gasoline or diesel availability. Second, the value of owning a FCV/BEV can greatly depend on its range [1, 2], making it crucial for automakers or market forecasters to select the proper range, or even different proper ranges for different consumers.

Yet, whether a coherent framework exists to support the determination of the FCV/BEV range behind many market and lifecycle analyses [4-7] of FCV/BEV is not clear. What is consistent is that the selected FCV/BEV ranges in these analyses are all significantly lower than the counterpart of conventional gasoline or diesel vehicles. The reason seems obvious: current or near-term technologies do not allow the “conventional driving range” under the constraints of realistic vehicle price and/or sufficient interior space. But a lower range means more frequent trips to the scarce hydrogen refueling network for the early FCV consumers or a higher level of range anxiety for the early BEV consumers. Such perceived higher level of refueling hassle or range anxiety implies some kind of extra operation cost, which may outweigh the upfront cost savings from the reduced range.

This suggests the direction of optimizing the FCV/BEV range by trading off the upfront and operating costs, as to be pursued by this study. Here, upfront cost mainly means the retail price of the vehicle, while operating cost is more general: it includes the time, hassle or other burden to be defined as resulting from limited vehicle range. The next section describes the relevant factors that cause the complexity of range determination, followed by a explanation of the range optimization approach. Some results will then be showed and discussed, leading to some conclusions that may change the thinking of the FCV/BEV range.

2. Factors and Complexity

The FCV range is largely determined by the onboard storing capacity for usable hydrogen [3], although the weight of the onboard storage system may affect the fuel economy and therefore the range. More usable hydrogen that can be extracted from the storage system enables a longer driving range, but requires a larger storage and likely more capable components. A longer driving range reduces the number of trips to refueling stations required by the same driving intensity and therefore reduces the “operating cost” associated with the stress of locating stations, time, wasted fuel and hassle from refueling travel, and the time spent at the stations [8]. But these benefits are at the extra upfront price of a larger onboard storage system.

The context becomes different for BEVs. Although the driving range of BEVs is similarly determined by the usable energy stored onboard, i.e. the usable battery capacity, the time and hassle of locating and visiting a charging station may be less relevant to what perceived by

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the BEV consumers as the "operating cost" resulting from the limited range. A BEV consumer very likely has access to home charging or alike [2, 4], as it is hard to imagine that BEV consumers will mostly depend on opportunistic public charging stations. More reasonably, the perceived operating cost resulting from the limited range, or so-called range anxiety, can be measured by the perceived probability of not being able to make the day trip because the trip distance is greater than the range or not being able to drive the BEV home due to some unexpected errands and lack of public charging points [4]. A higher range is supposed to lower such a perceived probability, but at the price of a bigger and more expensive battery.

3. The Range Optimization Method

In this study, the FCV/BEV range is optimized by trading off the upfront cost with the operating cost as associated with the range and minimizing the total range cost, sum of the upfront cost and the operating cost associated with the vehicle range.

3.1. FCV

For a FCV, the total range cost (C in USD) is seen as a function of the driving range (x in km) and includes five components: the upfront storage cost (S in USD), the upfront loss (I in USD) due to reduced interior space, the travel time and hassle (T in USD), the wasted fuel cost (W in USD) from searching and traveling to stations, and the pumping time cost (P in USD) at the station, as expressed by the equation (1).

$$C = S + I + T + W + P \qquad (1)$$

Assume that S and I are proportional to x and that T, W and P are inversely proportional to x. Thus, the equation (1) can be converted into the equation (2), where S_0, I_0, T_0, W_0 and P_0 are the corresponding cost components at any arbitrary reference point x_0.

$$C = \frac{S_0}{x_0}x + \frac{I_0}{x_0}x + T_0 x_0 \frac{1}{x} + W_0 x_0 \frac{1}{x} + P_0 x_0 \frac{1}{x} \qquad (2)$$

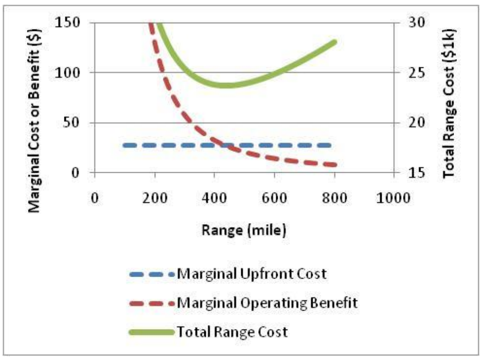

Figure 1: Illustration of Range Optimization Approach Showing the Marginal Cost and Benefit of Driving Range

From the equation (2), additional range increases the upfront components S and I, but decreases the operating components T, W and P. The decrease in the operation costs can be equivalently seen as increases in operating benefits. Therefore the tradeoff can be made where the marginal cost equals the marginal benefit (Figure 1). Therefore, the optimal range is obtained by minimizing the range cost C. By solving the equation (3) for x, the optimal range x* can then be obtained through the equation (4).

$$\frac{\partial C}{\partial x} = 0 \qquad (3)$$

$$x^* = x_0 \sqrt{\frac{T_0 + P_0 + Y_0}{S_0 + I_0}} \qquad (4)$$

Several important parameters need to be specified for the FCV range optimization. Onboard storage system cost and space cost are cited from published information [9-11]. The relationship between per-trip refueling travel time and fuel availability is based on station location optimization [8, 12]. Costs of travel time and hassle, wasted fuel and pumping time are estimated by assuming the FCV fuel economy at 64 mile/kg, 1.5 cost mark-up factor, time value at 50% of salary rate, 10-year vehicle lifetime, and 7% discounting rate.

Particularly, the travel time and hassle cost is calibrated to design data of 5830 gasoline and diesel vehicles with careful adjustment on fuel availability and storage cost. Without the calibration, the conventional analytical method that considers only travel time cost tends to have a lower estimate of fuel availability cost, compared to what are revealed by consumer surveys [13]. Our calibration reveals a significant portion of fuel availability cost that cannot be explained by regular travel time cost and appears to explain the estimation gap between the conventional analytical results and the survey results (Figure 2).

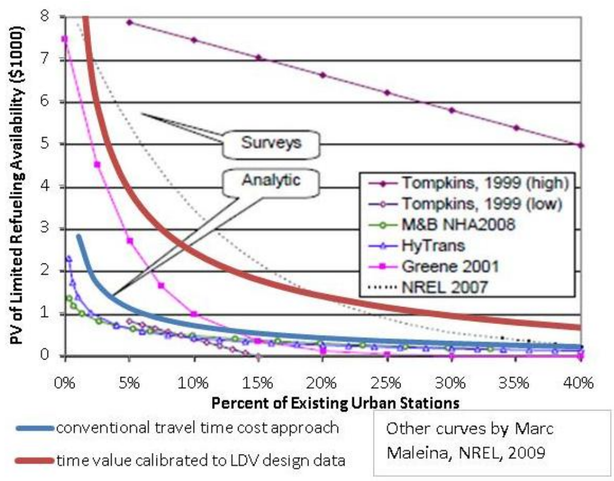

Figure 2: Consumer Cost of Limited Fuel Availability Calibrated to Real Vehicle Data and Compared to Other Estimates

3.2. BEV

For BEVs, the total range cost (C_b in USD) can also be seen as a function of the driving range (x_b in km), but include different cost components: the upfront battery cost (B in USD), the loss (R in USD) due to reduced interior space, and the range anxiety (H in USD), i.e. perceived cost and hassle of not being able to use the BEV for some long-trip days, as expressed by the equation (5).

$$C_b = B + R + H \quad (5)$$

Similarly, B and R can be assumed to be proportional to the driving range x_b. The relationship between the range anxiety H and the driving range x_b is more complicated. Assume the consumer perceives her daily driving distance y as a random variable following the probability density function p(y) and being capped at the maximum M. That is,

$$\int_0^M p(y)dy = 1 \quad (6)$$

It is possible that x_b is larger than M and then H becomes zero, meaning there is no range anxiety. But for most consumers with the near-term BEV technology, it is most likely that x_b is less than M. Thus, the range anxiety cost H can be expressed with the equation (7), where U is the perceived cost each day the BEV range is lower than the daily trip distance and D is the discounted lifetime factor to represent both the vehicle life and the discounting effect.

$$H = 365 \cdot U \cdot D \cdot \int_{x_b}^{M} p(y)dy \quad (7)$$

The optimal BEV range is obtained by minimizing the range cost C_b. Take the derivative of C_b with respect to x_b and solve for equation (8) and (9).

$$\frac{\partial C_b}{\partial x_b} = 0 \quad (8)$$

$$\frac{\partial^2 C_b}{\partial x_b^2} > 0 \quad (9)$$

The optimal BEV range x_b^* can then be obtained via the equation (10).

$$x_b^* = p^{-1}\left(\frac{B_0 + R_0}{365 \cdot U \cdot D \cdot x_{b0}}\right) \quad (10)$$

Several parameters need to be specified to optimal the BEV range. The space cost R_0 is estimated in a similar manner based on published information [11]. The battery price is assumed to be $500/kWh, a number that is informally estimated for the Nissan Leaf [14], though it is acknowledged that this estimate is much more optimistic than the conventional estimates [4, 6, 15]. For each day of the BEV not meeting the distance demand, the cost is assumed to be $50, an arbitrary value to represent the rental car cost. A 10-year vehicle lifetime and a 7% discounting rate are assumed.

Probably the most important parameters are the specifications of the daily distance density function p(y). For simplicity, three gamma distributions (Figure 3) representing three driving intensities among the U.S. household drivers are generated based on the U.S. National Household Travel Survey data [16, 17]. The Modest Driver, Average Driver, and Frequent Driver drive an average of 40km, 70km, and 124km daily, respectively. The Frequent Driver is more likely to have daily driving distance over 150km and the Modest Driver is least likely.

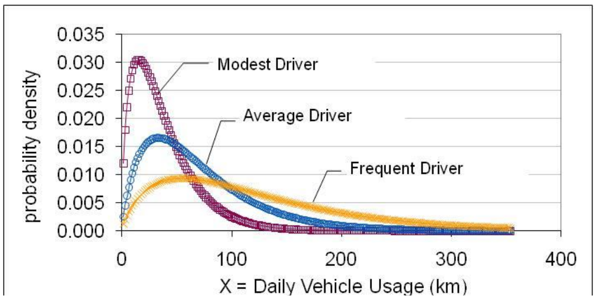

Figure 3: Three Daily Vehicle Usage Distributions Representing the U.S. Household Drivers

4. FCV Range Optimization Results

In the baseline case that represents the near term characterized by very limited hydrogen station deployment and current technology status for onboard storage, the optimal FCV range is estimated to range 457-870 km, depending on up to 10% variation on key parameters. In the baseline case, hydrogen availability, the percentage of stations providing hydrogen is assumed to grow from 1% at the present to 10% in 10 years. Onboard storage technology is assumed to be available at $15.6/kWh and 0.6 kWh/L.

The relationship between optimal range, storage cost, storage density, and fuel availability is quantified (Figure 4). In general, the optimal range is found to increase with lower storage cost or higher storage density, but decrease with better fuel availability.

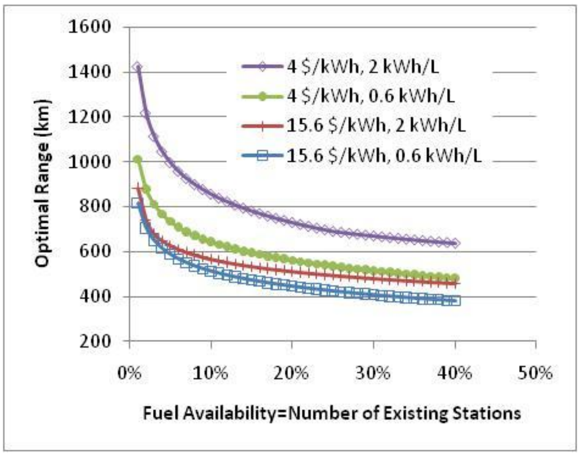

Figure 4: Optimal FCV Range Decreases with Better Fuel Availability, Higher Storage Cost or Lower Storage Density

Sensitivity analysis demonstrates the robustness of the optimization (Figure 5). A 10% variation on each of 16 key parameters results in -5.7% - +6.2% change in the optimal range and the optimal onboard usable fuel capacity.

The FCV driving range needs to be properly determined for accurately assessing the market barrier and cost-effectiveness of this vehicle technology. While an overestimated range means an overestimated cost of onboard storage, an underestimated range leads to exaggeration of refueling hassle especially in the early transition period when fuel availability is very limited. Either overestimation or underestimation of the driving range leads to exaggeration of commercialization barrier for FCV and could mislead policies.

The barrier overestimation by non-optimal range design can be significant. Compared to the optimal range, the standard range assumption leads to an overestimate of range cost by over $8000 per vehicle (Figure 6). Such a significant overestimate of barrier can seriously mislead policy making and should be corrected by range optimization.

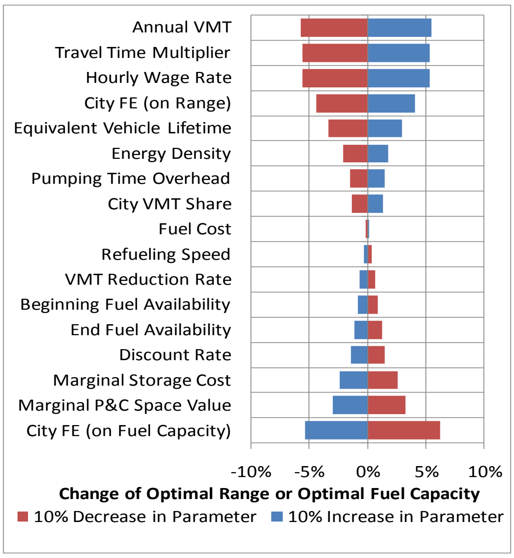

Figure 5: Robustness of Range Optimization Demonstrated by Results of 10% Sensitivity Analysis

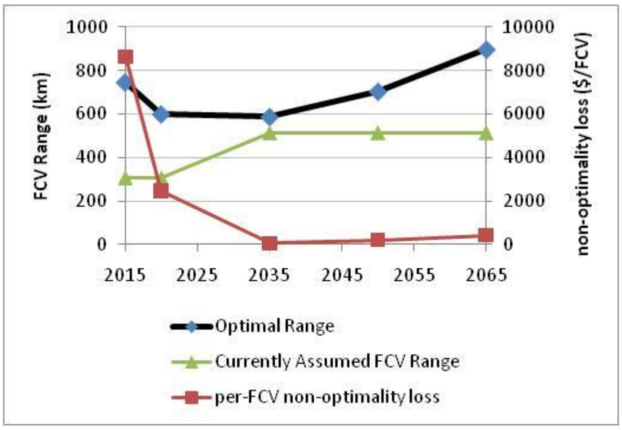

Figure 6: Significance of Range Optimization Demonstrated by Possible Non-Optimality Loss during Early Market.

The scenario analysis assuming aggressive hydrogen penetration [18] shows that the FCV range does not necessarily exhibit a monotonic increase or decrease over time. It decreases initially and grows later in response to the relative development pace of storage technology and infrastructure (Figure 6). In reality, product design constraints and consumer expectation set by previous products may prevent the designed range from significantly decreasing. However, what is important is that by reaching the initial critical level of fuel availability, the FCV range can be reduced to save storage costs if little progress is made on onboard storage. It also suggests that after the critical fuel availability level, a higher FCV range is realistic if onboard storage is significantly improved.

5. BEV Range Optimization Results

The BEV range is optimized at the $500/kWh battery price level for the three driver types (Figure 7). It is observed that the Nissan Leaf's 100-mile driving range seems to be a good design for the Modest Driver, considering the battery cost and the possible variation of usable range under different operation circumstances. The majority of the U.S. household drivers, if they want a BEV, would prefer a BEV with the range longer than the Leaf's even though such a BEV would be more expensive. However, when BEV penetrates into the majority market, two factors will counteract to affect the optimal BEV range. On one hand, the continued decrease in battery cost will justify more range in order to further cut the range anxiety cost. On the other hand, easier access to workplace or public charging stations in addition to home charging will be likely, making more long-trip days servable by BEV. This reduces the range anxiety cost and therefore allows less driving range in order to save on battery cost.

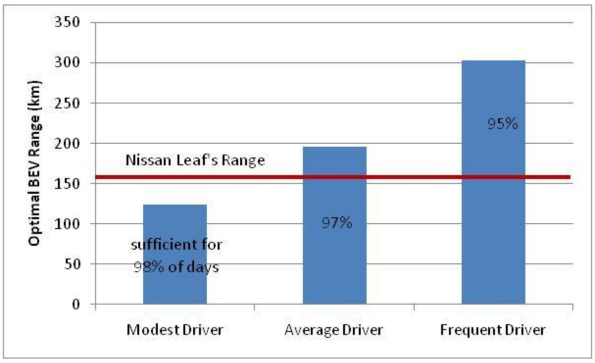

Figure 7: Optimal BEV Range by Vehicle Usage Intensity

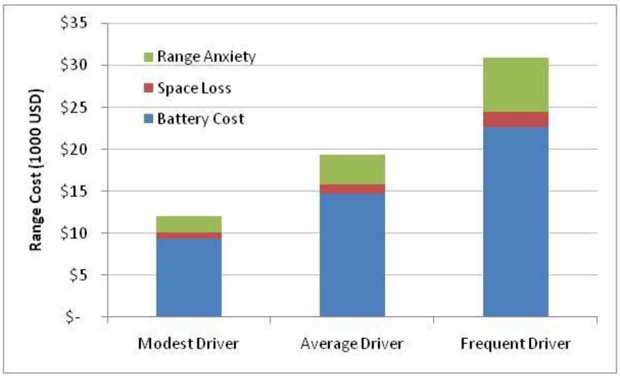

Figure 8: Cost Components from Optimal BEV Range by Vehicle Usage Intensity

The expected probability that the daily driving demand can be served by BEV with the optimal range is very high, 98% for the Modest Driver down to 95% for the Frequent Driver (Figure 7). The optimal range does not cover all days because it is not worthwhile, from the consumer value perspective, to buy additional battery capacity to serve the driving demand of those very few longest-trip days.

However, the small percentage of unserved longest-trip days does not suggest that they as a market barrier should be ignored. Although the battery cost is still the dominant part of the total range cost, the range anxiety cost is still very significant, over $2000 for the Modest Driver based on our calculation. For the Frequent Driver, the range anxiety resulting from the optimal BEV range is estimated to be over $6000, indicating a substantial market barrier for today's BEV technology even if the optimistic $500/kWh battery price level is real.

6. Conclusions

This study proposes a coherent framework for optimization of the driving range for fuel cell vehicles (FCV) and battery electric vehicles (BEV). The FCV range is optimized by trading off between less storage cost, more interior space and less refueling time and hassle. The BEV range is optimized by trading off between less battery cost, more interior space and less range anxiety. Several observations can be made from the preliminary results.

- Both FCV and BEV ranges should be viewed as an adaptive specification in response to technology development and infrastructure deployment during the transitional period.
- Generally, the FCV range should increase with lower storage cost or higher storage density but decrease, subject to business constraints, with better fuel availability.The BEV range should increase with higher driving intensity or lower battery cost, but decrease with better charging availability.
- Without range optimization, the market barrier of FCV can be seriously overestimated, resulting in less informed policies.
- BEV range optimization provides guideline for diversification of BEV products among market segments with different driving intensity and behavior.

7. Acknowledgement and Disclaimer

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