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# BEV Consumer Household Travel Behavior Decisions in Multi-Vehicle Households: Do They Get the Maximum Out of Their Nissan LEAF?

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**Summary**

This paper analyses the travel behaviour of early Leaf adopters based on GPS tracking data. Heterogeneity between households that own a Leaf and do not own a Leaf was found in terms of their travel demand and how they assign multiple vehicles for different trips. Within a Leaf household, medium trips are more often assigned to the Leaf maximizing its usage while short trips are assigned to both the Leaf and the ICE and long trips are assigned to the ICE. This also suggests that Leaf households self-select if these beneficial travel patterns match their household. However, Leaf households do not completely optimize their travel as household eVMT can theoretically increase by 10% if drivers in the household swap cars more

*Keywords: BEV household, mix vehicle household, eVMT, GPS data*

## INTRODUCTION

Studies show homogeneity among early BEV adopters, including the likelihood of living in a single-family house and owning their house [1], the likelihood of having more vehicles in their household [2, 3], the higher likelihood of buying new vehicles [1], and the express the intention of buying a BEV [4]. Based on survey data about consumer preference toward vehicle type and commute distance, BEV buyers are a self-selected group [3].

A study of early Mini-E adopters [5] shows that multi-vehicle households (MVHHs) have higher satisfaction with EV and less dependence on charging away from home. Other studies [6-8] based on travel diary data of internal combustion engine (ICE) vehicles also indicate that MVHHs are able to adopt a BEV with less inconvenience compared to single-vehicle households. Tamor and Milačić [6] assume that BEVs will be the primary choice in MVHH for trips within the BEV range, and the analysis shows that BEV can electrify nearly 55% of travel. Khan and Kockelman [7] shows that if a BEV replaces the less-used vehicle, 80% MVHHs would need to change their travel activities less than four days per year. Jakobsson et al [8] also finds that the second car in MVHHs require less adaption and are better suited for BEV adoption compared to the first car in MVHHs, as well as single-vehicle households.

Most of these studies are based on travel activities of ICE vehicles to see how BEVs will fit those travel demand. But as mentioned above, a BEV purchase might be self-selection so that the travel demand of the household with BEVs can be different from others. There are very limited studies about BEV adoption based on real driving behavior after they own a BEV. By comparing the travel behavior of households owning and not owning a BEV, we can see if there is heterogeneity between these two groups of people. This helps determine whether a BEV purchase is self-selection.

Additionally, since a BEV is usually not the only car in the household [2, 3], we can determine how vehicles are assigned among different household trips, whether they maximize the usage of BEVs, and what factors affect the household eVMT.

## DATA

There are two datasets used in this study. One is the 2012 California Household Travel Survey (CHTS) dataset [9] which consists of socio-demographic information of sample households and individuals, their vehicles, and a one-day travel diary including place information, travel distance, and activities at each location. Among the CHTS sample households, a subsample of first generation Leaf owning households was recruited, and GPS loggers were installed all vehicles of the sample household to get accurate record about their travel activities. In total, there were a total of 78 households who reported valid data, and 39 out of the 78 households have one Leaf and one ICE. Other households in the GPS dataset only had ICE vehicles and provide a comparison to Leaf owning households. The Leafs in this analysis were all rated by the EPA at a range of 73 miles.

The original GPS point dataset contains second-by-second location information (longitude & latitude). Those GPS points data was also aggregated into trip information such as trip duration, trip distance, average and maximum speed, and acceleration/deceleration during a trip. Because the GPS dataset doesn't contain any information about the drivers, effort was made to match GPS trip data with the activity-based travel diary from CHTS Dataset in order to find out the driver of each GPS trip. The matching process is based on the origin and destination location and the start and end time of each trip. However, few pieces of GPS trip data can be matched because the travel diary in CHTS Dataset doesn't have date information and there are noticeable spatial and temporal differences between GPS trips and the travel diary. Therefore, only socio-demographic data of households and models of vehicles were used in this study.

## COMPARISON OF VEHICLE USAGE IN LEAF AND NON-LEAF HOUSEHOLDS

Surveys of early BEV adopters show that their access to Level 2 chargers is significantly higher than for current buyers [10]. This combined with the fact that few chargers existed at the time of the data collection allows us to make the simplifying assumption that the home is the center of the subjects' daily pattern and the primary charging location of the Leaf drivers, and home-based tours are more meaningful than trips. All trips that were made after respondents left their home and before they came back home belong to the same tour. A tour-based analysis allows us to further understand how Leaf households use different vehicles, so travel activities are aggregated as tour-based for later analysis.

By comparing the usage strategies of households owning a Leaf to those not owning a Leaf we investigate if there are significant differences between households. Considering households with more than two vehicles has more complexity and variability when they assign vehicles for different travel demand, so we choose households with only two vehicles for our analysis. 39 Leaf households that have one Leaf and one ICE vehicle were selected. The 518 households that have only two ICE vehicles but no Leaf were selected as representing ICE usage.

As Table 1 and Figure 1 indicate, in terms of the average daily driven duration and the average daily travel distance, the Leaf is used more than the ICE in those households. For daily travel demand between 20 miles to 70 miles, Leaf households use the Leaf the same or more intensity as non-Leaf households use their most used ICE vehicle. However, Leaf households use their ICE vehicle for long distance travel while non-Leaf households continue using the most used ICE as the primary choice for long distance travel. The average daily distance of the two vehicles added together is similar between Leaf and non-Leaf households, but the vehicle usage in Leaf household is more evenly distributed.

Although the ICE vehicle is used for longer tours in Leaf households, the average travel distance per tour and the average speed of Leaf households' ICE vehicle is lower than the most used ICE vehicle of non-Leaf households. Interestingly, the maximum travel distance of the second most used ICE vehicle in non-Leaf households is longer than that of ICE vehicle in Leaf households, as Table 1 shows. Figure 1 also indicates that long distance travel (longer than 120 miles per day) accounts for significantly more of the total travel demand of non-Leaf households than Leaf households. Based on our sample, Leaf households have a shorter daily travel pattern and they are less likely to make long-distance travel.

Those travel patterns indicate that the Leaf purchase could be a result of self-selection. Households with daily routine commute demand within the range of Leaf are more likely to buy Leaf, and the ICE vehicle in those households are used for shorter trips and occasional long distance trips. In that case, Leaf helps to achieve higher fuel efficiency. While households with commute distance exceeding the Leaf range or with frequent long distance travel demand are less likely to buy a Leaf.

**TABLE 1** Day-based Comparison of Driving Behavior of household owning or not owning Leaf

| | Leaf HH | | Non-Leaf HH | |
|---|---|---|---|---|
| | ICE | Leaf | Most Used ICE | Less Used ICE |
| Avg. Daily Travel Time (min) | 66.4 | 70.7 | 82.2 | 52.0 |
| Max. Daily Travel Time (min) | 289.8 | 173.8 | 790.4 | 358.9 |

| | | | | |
|---|---|---|---|---|
| Avg. Travel Time Per Tour (min) | 38.7 | 43.7 | 48.5 | 32.7 |
| Max. Travel Time per tour (min) | 281.0 | 173.8 | 789.2 | 357.6 |
| Avg. Daily Travel Distance (mile) | 35.2 | 37.5 | 48.2 | 25.8 |
| Max. Daily travel Distance (mile) | 255.0 | 123.3 | 851.6 | 215.3 |
| Total Travel Distance (mile) | 6,157.4 | 8,029.4 | 109,216.2 | 4,4440.9 |
| Avg. Travel Distance per tour (mile) | 21.5 | 22.7 | 28.4 | 16.2 |
| Max. Travel Distance per tour (mile) | 249.4 | 123.3 | 851.5 | 215.3 |
| Avg. Speed (mph) | 28.8 | 29.9 | 30.8 | 26.7 |
| Weighted avg. speed (mph) | 24.8 | 26.8 | 27.1 | 24.3 |
| Max. Speed (mph) | 89.5 | 88.4 | 103.9 | 107.7 |

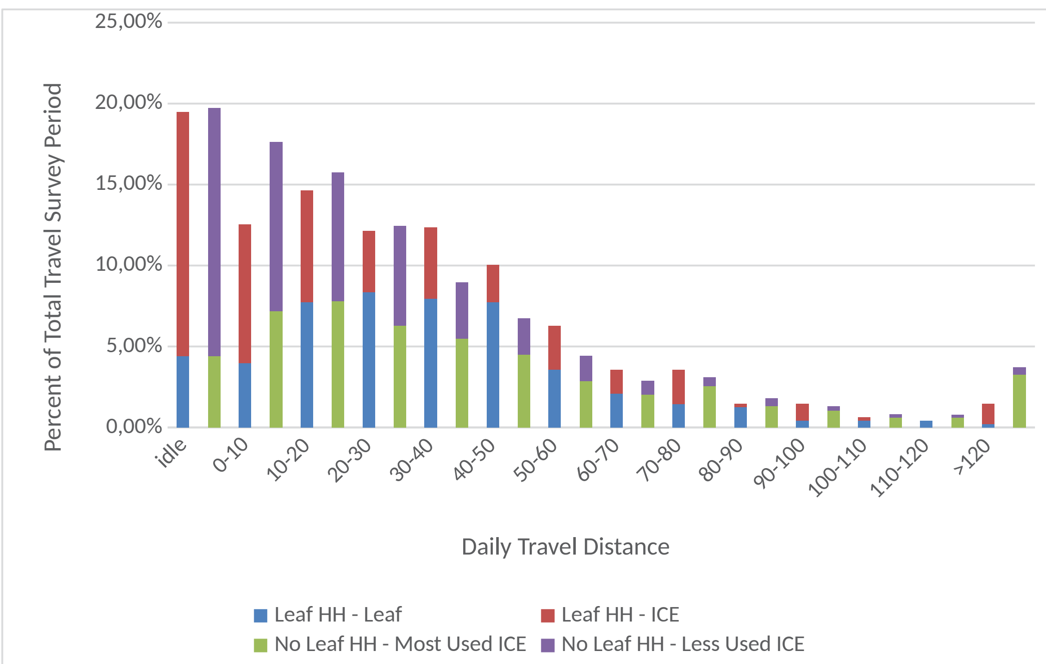


**FIGURE 1 Daily Travel Distance and Vehicle Usage Comparison**

## COMPARISON OF LEAF AND ICE VEHICLES USAGE IN THE SAME HOUSEHOLD

In terms of the maximum number of tours, maximum travel time, and maximum distance, ICE vehicles have more extreme values than Leaf in Leaf households. This indicates respondents prefer to use an ICE vehicle for long tours. The maximum observed tour distance of a Leaf is 123.3 miles (Table 1) which is shorter than twice the Leaf's range which could be up to 146 miles assuming a 73-mile one-way range. This indicates many people won't drive a Leaf if that tour requires more than one charge in per day, which is consistent with a previous survey study [11] which found that people's willingness to choose a BEV for a trip decreases as the number of charging events necessary to complete the trip increases.

Both average speed and weighted average speed was calculated in Table 2. Average speed is calculated as total travel distance divided by total travel time. Weighted average speed is the arithmetic mean of average speeds of the vehicles' daily travel. For a longer travel distance, the drivers are more likely to use freeways, and the average speed will be higher as a result. Thus, the average speed of tours with shorter distance will have relatively higher weight than the average speed of tours with longer distance. If there are three tours in one day: one tour contains long-distance travel on a freeway and two other tours are low-speed, the average speed of tours on that day could be high while the weighted average speed could be lower than the average speed.

Based on numbers in Table 2, ICE vehicles have high average speed but lower weighted average speed which means the drivers took fewer freeway tours than local tours. The higher average speed on weekends might be caused by less congestion, different travel purposes, and better level of service on weekends. However, the Leafs have a relatively higher average speed and weighted average speed on weekdays compared with on weekends. Additionally, the weighted average speed of Leafs on weekdays is higher than ICEs although the average speed of Leafs on weekdays is lower than ICEs. It could mean that drivers travel at lower speed when they drive a Leaf in general, but ICEs are used more for shorter trips on local roads, especially on weekdays, which causes the difference between average speed and weighted average speed.

The median value of travel distance of ICE vehicles is lower than Leafs, but the average travel distance of ICEs is higher than Leafs are similar on the weekend, and the Leaf has higher travel distance on weekdays. If travel patterns on weekdays are relatively fixed compared with on weekends, figures in Table 2 could indicate that Leaf drivers have set predictable routes. When they go to a location they are not familiar with, they may worry about exceeding the range of their Leaf, so they may prefer to use an ICE vehicle over a Leaf. In other words, they may be more confident driving a Leaf to places close to their home and likely to keep their travel distance short on weekends.

**TABLE 2** Daily tour-based comparison of driving behavior of Leaf vs. ICE vehicle belonging to the same household

| | ICE Vehicle | | Leaf | |
|---|---|---|---|---|
| | **Weekday** | **Weekend** | **Weekday** | **Weekend** |
| Max No. Tour | 25 | 12 | 18 | 21 |
| Avg. No. Tour | 5.0 | 4.4 | 5.7 | 5.8 |
| Median No. Tour | 4 | 4 | 5 | 4 |
| Max. Travel Time (min) | 289.8 | 256.6 | 173.8 | 166.4 |
| Avg. Travel Time (min) | 68.1 | 59.8 | 76.3 | 55.7 |
| Median Travel Time (min) | 53.5 | 36.8 | 75.0 | 49.0 |
| Max. Daily Distance (mile) | 255.0 | 183.9 | 123.3 | 107.9 |
| Avg. Daily Distance (mile) | 37.1 | 35.8 | 40.0 | 28.2 |
| Median Daily Distance (mile) | 24.6 | 17.0 | 36.6 | 21.8 |
| Max. Speed (mph) | 88.7 | 89.5 | 87.6 | 88.4 |
| Avg. Speed (mph) | 32.7 | 35.9 | 31.5 | 30.4 |
| Weighted Avg. Speed (mph) | 28.5 | 29.9 | 30.8 | 27.3 |
| Max. No. Stop | 23 | 11 | 13 | 12 |
| Avg. No. Stop | 5.3 | 4.5 | 4.8 | 5.0 |
| Median No. Stop | 5 | 4 | 4 | 5 |

Analyzing second-by-second GPS point data can reveal some other differences in the driving behavior when a household using a Leaf versus an ICE vehicle. As Figure 2 indicates, respondents spent most of their time driving the Leaf at around 31 mph to 40 mph. However, they spent more time driving at a speed of 60 miles per hour or higher when they drove an ICE vehicle. Additionally, there is more time spent in stop-and-go conditions when they drove a Leaf compared with an ICE vehicle. Taking the speed limit of 65-70 mph for a freeway and 25-45 mph for a local street into consideration, the different speed distribution could indicate that respondents traveled longer on the freeway when driving an ICE vehicle, and they traveled longer on local streets when driving a Leaf.

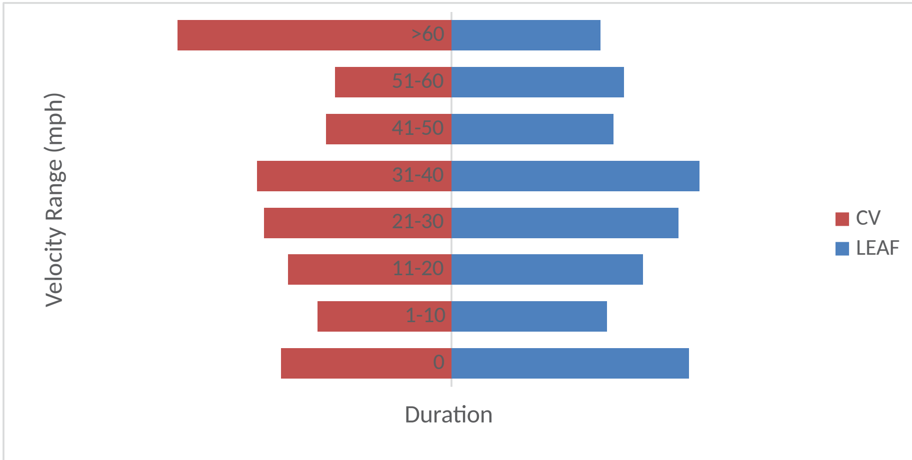


**FIGURE 2** Distribution of Travel Duration at Different Velocity

Similar results can be concluded from derived GPS trip data. The charging time for a Leaf from zero to full is about 16 hours for an AC Level 1 charger and 7 hours for an AC Level 2 charger. Although there are no data about charging activities, it is reasonable to assume that people will charge their Leaf at home as access at home is likely and the dwell time is long. If home is the center of a respondents' daily travel pattern, then the Euclidean distance between a respondent's home and the farthest stop he/she reached in one day is one way to determine the radius of his/her travel pattern. As Table 3 and Figure 3 show, the largest travel radius of for Leafs is 78.54 miles which is much shorter than that of ICE vehicles which is 94.48 miles. Additionally, the median value of a travel radius is 11.87 miles with a standard deviation of 12.24 for Leaf but for ICE vehicles, 7.71 miles with a standard deviation of 14.65. These data indicate respondents have a medium travel radius when driving Leaf, and they prefer ICE for very short or extreme long distance trips.

However, a shorter radius of travel doesn't necessarily mean shorter daily travel distance. As Table 3 and Figure 1 show, the mean value of total travel distance per day for Leafs is 37.51 miles with a standard deviation of 25.18 while the median value of total travel distance per day for ICE vehicles is 35.15 miles with a standard deviation of 41.21. This means the average daily travel distance is longer when respondents drive a Leaf rather than an ICE vehicle, and there is less variation in daily travel distance when they drive a Leaf. Although the Leaf is apparently driven more, the standard deviation of ICE daily travel distance is much higher indicating that there is great variability in how ICE vehicles are driven.

The 2011 and 2012 Leafs in this analysis were all rated by the EPA at a range of 73 miles and over 90% tracked daily travel by Leafs is shorter than the range of Leaf. Considering the lower variation in daily travel distance, this indicates that most drivers control their daily driving distance within the range of Leaf without needing an extra charging event, although most drivers report access to chargers at their work location and home. One possible reason for this limited driving distance is that most Leaf drivers charge only once per day, or at least cannot dependably count on charging outside of home.

**TABLE 3** Comparison of travel radius distribution of Leafs vs. ICE vehicles belonging to the same households

| | | Travel Radius (mile) | | Daily Travel Distance (mile) | |
|---|---|---|---|---|---|
| | | **ICE Vehicles** | **Leaf** | **ICE Vehicles** | **Leaf** |
| Quartile | 100% | 94.48 | 78.54 | 254.98 | 123.29 |
| | 90% | 22.16 | 25.06 | 77.97 | 70.30 |
| | 75% | 8.33 | 16.51 | 47.38 | 49.39 |
| | 50% | 3.20 | 7.70 | 22.65 | 32.90 |
| | 25% | 0.00 | 3.66 | 9.48 | 18.85 |
| | 0% | 0.00 | 0.00 | 0.00 | 0.00 |
| | Mean | 7.71 | 11.87 | 35.15 | 37.51 |
| | Std. Dev | 14.65 | 12.24 | 41.21 | 25.18 |
| | Std. Err Mean | 1.13 | 0.94 | 3.83 | 2.02 |
| | Upper 95% Mean | 9.94 | 13.74 | 42.73 | 41.51 |
| | Lower 95% Mean | 5.48 | 10.01 | 27.57 | 33.52 |

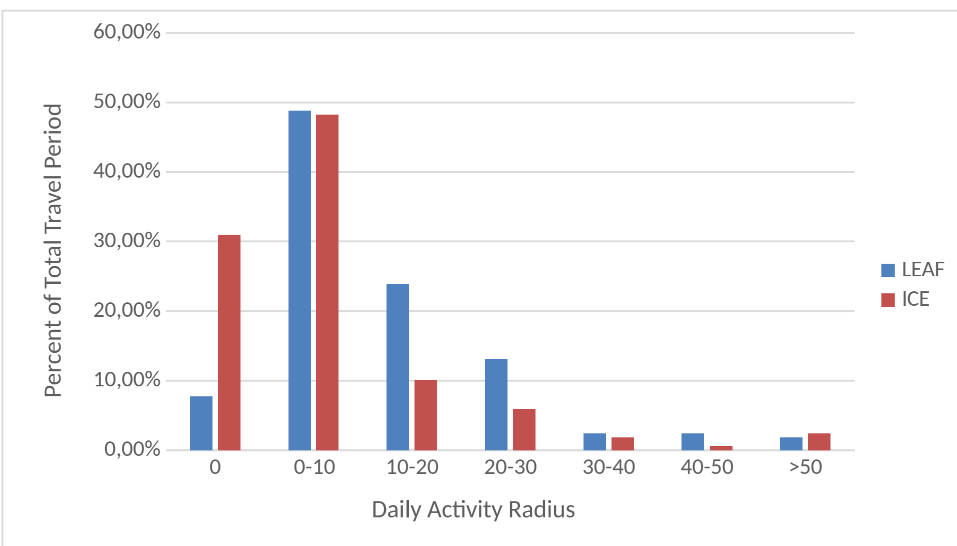


**FIGURE 3** Distribution of Daily Activity Radius

Additionally, we found that ICEs were driven only about 80% as many days as Leafs as shown in Figure 4. These idle days point to several possibilities. One, the leaf is bought for a commute and the commute is more regular than other travel. Alternatively, travel in non-commute households is shifted to the Leaf leaving the ICE idle.

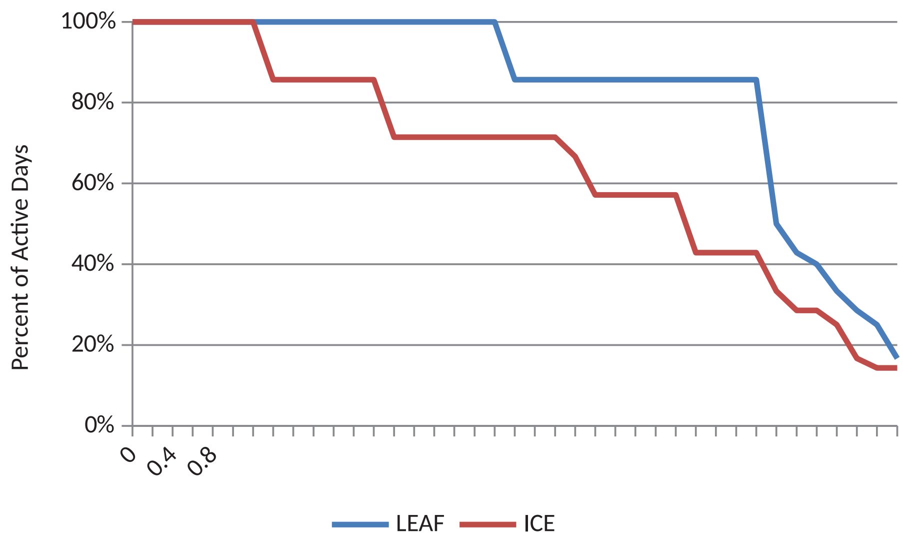


**FIGURE 4** Percent of Days Active within Data Collection Period

## HOUSEHOLD EVMT OPTIMIZATION POTENTIAL

For households that have both Leaf and ICE vehicles, we constructed scenarios to determine how many times the Leaf was idle when the ICE vehicle was used and the leaf had the range and time to complete the travel. Although the Leaf has a range limitation, there is still room for those households to maximize their usage of Leaf.

To optimize the usage of Leaf, there are several rules for scenario testing:

1. Based on previous discussion, drivers prefer to limit their daily travel distance to the range of Leaf which is 73 miles based on EPA's estimate. Therefore, the maximum daily travel distance of a Leaf is set to be 73 miles. Based on GPS data, there are some Leafs that traveled farther than 73 miles in one day which means there should be an extra charge for those Leafs. However, in order to simplify the optimization process, the remaining range of those Leafs which travels longer than 73 miles is zero.

2. For each household, if there is an ICE vehicle tour during that period of time Leaf was idle and the tour distance is shorter than the remaining range of Leaf on that day, that tour will be reassigned to Leaf which means that the Leaf will be assigned that travel of the ICE vehicle. When there are multiple ICE vehicle tours eligible for reassign-ment, the longest tour will be reassigned first, then the remaining range of Leaf will be

refreshed and the next longest eligible tour will be reassigned until there are no more tours eligible for reassignment.

3. For each household, the Leaf travel can be switched entirely with the ICE vehicle. If there are ICE vehicle tours whose period is overlapped with Leaf tours, the total distance of the overlapped ICE vehicle tours in one day is longer than the corresponding overlapped EV tours on that day, and after exchanging those tours, the total distance of Leaf on that day won't exceed its range, those tours will be exchanged.

Table 4 contains three assumed tours for both ICE vehicles and Leafs and it will be used to further explain these rules. Based on rule 1, the remaining range of the Leaf is 23 miles. Based solely on rule 2, the first ICE vehicle tour will be reassigned to a Leaf because there is only an ICE vehicle being used during 8:00-9:00 and the remaining range of the Leaf after the reassignment will be 13 miles. Based solely on rule 3, the second and third ICE vehicle tours and Leaf will be exchanged because they overlap. The total tour distance of the ICE vehicle is longer than that of the Leaf, and the remaining range of the Leaf after exchange will be 8 miles.

**TABLE 4** Sample Tours

| Tour ID | ICE Vehicle Tours | Leaf Tours |
|---|---|---|
| 1 | 8:00 – 9:00, 10 miles | 10:00-12:00, 20 miles |
| 2 | 13:00 - 15:00, 20 miles | 14:00-15:30, 15 miles |
| 3 | 16:00 - 18:00, 30 miles | 17:00-20:00, 15 miles |

Four cases were built to optimize Leaf usage by different strategies

- In case 1, only rule 1 and rule 2 were implemented
- In case 2, only rule 1 and rule 3 were implemented
- In case 3, rule 2 was implemented followed by rule 3 and rule 1 was followed through the process.
- In case 4, rule 3 was implemented followed by rule 2 and rule 1 was followed through the process.

In some scenarios, case 3 and case 4 can have different results. Taking tours in Table 4 as an example, in case 3 after implementing rule 2, the first ICE vehicle tours will be reassigned to the Leaf and the remaining range of Leaf will be 13 miles, and when implementing rule 3, although there are overlapping ICE vehicle tours which are longer than Leaf tours, they won't be exchanged because the remaining range of the Leaf doesn't allow such action. Similarly, in case 4, after exchanging the overlapped tours, the reaming range of the Leaf doesn't allow reassignment of the first ICE vehicle tour to Leaf.

Optimization results are listed in Table 5. As the results indicate, optimization achieved by rule 2 is larger than rule 3, and the sequence to implement rule 2 and rule 3 doesn't influence the final result significantly.

One potential drawback of rule 2 is that it might not always be the best choice to reassign the longest eligible tour. For example, there are three eligible tours with distance of 6, 8, and 10 miles, and the remaining range is 15 miles. Based on rule 2, only the 10-mile tour will be reassigned, but a better strategy is to reassign both 6-mile and 8-mile tours. The sensitivity of this interaction will be left to future analyses.

This analysis shows that BEV range might not be the primary factor that causes failure to maximize the household eVMT since over 90% of sample days have daily travel distance within the range of Leaf (Table 3), and the average daily travel distance after the optimization process is still far below the Leaf range. Instead, how vehicles are assigned among house members can significantly influence the household eVMT. Although there is lack of information about drivers, it is reasonable to assume that house members won't exchange vehicle during the day. In another word, for households with two drivers and two vehicles, each driver use one car per day without switching to the other car. Based on that assumption, optimization case 2 indicates that the person with longer travel distance uses the Leaf in most Leaf households since the rule 2 to exchange drivers with overlap tours doesn't help to improve the household eVMT greatly. However, optimization case 1 suggests that the person with shorter travel distance didn't use the Leaf even when Leaf is idle at home and he/she will come back home before the other driver needs to leave home, which helps to validate the assumption about no vehicle exchange during the day.

**TABLE 5** Leaf Usage Optimization Results

| | **Avg. Daily Travel Distance (mile)** | | **Total Travel Distance (mile)** | |
|---|---|---|---|---|
| | **Leaf** | **ICE Vehicle** | **Leaf** | **ICE Vehicle** |
| Original | 37.51 | 35.15 | 8029.47 | 6157.45 |
| Case 1 | 40.35 | 32.85 | 8801.88 | 5385.03 |
| Case 2 | 38.79 | 33.87 | 8376.00 | 5810.91 |
| Case 3 | 41.59 | 31.58 | 9137.13 | 5049.79 |
| Case 4 | 41.57 | 31.59 | 9132.92 | 5054.00 |

## CONCLUSIONS

The comparison of vehicle usage between non-Leaf households and Leaf households shows that households who buy the Leaf self-select based on their travel patterns. Leaf households use the Leaf and ICE vehicle more evenly: Leafs for medium distance tours and ICEs for short and long-distance tours, while non-leaf households primarily use one vehicle over the other. Also, households owning a Leaf have less variation in their travel pattern and are less likely to make long-distance travel than non-Leaf households based on GPS tracking data, so that Leafs can satisfy most of their travel demand. Non-Leaf households have significantly more long-distance travel demand which might lead to self-selection of not buying a Leaf.

For the same households that own both a Leaf and an ICE vehicle, drivers have a smaller travel radius and are less likely to take freeways when they drive a Leaf compared with an ICE vehicle. Limited range and long charging time may be key factors that determine Leaf driver behavior. Most drivers limited their total daily travel distance within the range of the Leaf even though most of them reported having access to chargers at both home and work locations. Based on GPS tracking data, none drove a Leaf for long-distance travel that required more than two charges in one day. However, a small travel radius doesn't necessarily mean significantly fewer miles in a Leaf. For short-to-median distance travel, people are more likely to use a Leaf than an ICE vehicle.

Although Leaf households use their Leafs as frequently as non-Leaf households use their most used vehicle for medium-distance trips, there is still room to maximize the use of the Leaf compared to the ICE vehicle. Based on two simple optimization rules, the total travel distance by Leaf can theoretically increase by up to 10% if drivers in the household swap cars more often. Finally, ICEs were idle more days than Leafs in this dataset. This may represent a shift in travel in the household, or a self-selection of households who can best use a Leaf consistently.

This dataset is composed of first generation Leafs with early buyers. Early buyers of Leafs may not represent exactly the buyers of future Leafs and further analysis is needed to determine their representativeness. There may be income differences and as a result, differences in vehicle fleet sizes and options for travel. Additionally, only 2 vehicle households were analyzed. Further, this dataset is at most one week and in some cases shorter time periods. Longer time periods may better capture travel that occurs infrequently or trends that only are apparent with more observation time such as seasonality.

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Dr. Tal is one of the leading researchers in the field of electric transportation in the USA and globally. His work in the Plug-in Hybrid & Electric Vehicle Research Center at the Institute of Transportation Studies contribute to the development of policies and planning tools in California and the US focusing on the role of incentives in the EV market and on siting and design of electric vehicle (EV) charging infrastructure. He is currently working on projects for the California air resources board, The California energy commission, the Department of Energy, car companies and utility companies. As part of this research, Dr. Tal has produced methodological innovations in on-line travel surveys and EV charging location modeling that include GIS-based mapping that have been published. Dr. Tal published more than forty articles and peer-reviewed conference proceedings, and presented his work to policy makers decision makers in the US, China and Europe.