ARTICLE IN PRESS

Transportation Research Part C xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Electric vehicles: How much range is required for a day's driving?

Nathaniel S. Pearre [a,*], Willett Kempton [a,1], Randall L. Guensler [b,2], Vetri V. Elango [b]

[a] Center for Carbon-free Power Integration, College of Earth, Ocean, and Environment, University of Delaware, Newark, DE 19711, United States
[b] Georgia Transportation Institute, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332, United States

ARTICLE INFO

Article history:
Received 7 February 2010
Received in revised form 22 December 2010
Accepted 23 December 2010
Available online xxxx

Keywords:
Electric vehicle
Plug-in vehicle
Daily driving range
Range requirement
Trip timing
Vehicle design

ABSTRACT

One full year of high-resolution driving data from 484 instrumented gasoline vehicles in the US is used to analyze daily driving patterns, and from those infer the range requirements of electric vehicles (EVs). We conservatively assume that EV drivers would not change their current gasoline-fueled driving patterns and that they would charge only once daily, typically at home overnight. Next, the market is segmented into those drivers for whom a limited-range vehicle would meet every day's range need, and those who could meet their daily range need only if they make adaptations on some days. Adaptations, for example, could mean they have to either recharge during the day, borrow a liquid-fueled vehicle, or save some errands for the subsequent day. From this analysis, with the stated assumptions, we infer the potential market share for limited-range vehicles. For example, we find that 9% of the vehicles in the sample never exceeded 100 miles in one day, and 21% never exceeded 150 miles in one day. These drivers presumably could substitute a limited-range vehicle, like electric vehicles now on the market, for their current gasoline vehicle without any adaptation in their driving at all. For drivers who are willing to make adaptations on 2 days a year, the same 100 mile range EV would meet the needs of 17% of drivers, and if they are willing to adapt every other month (six times a year), it would work for 32% of drivers. Thus, it appears that even modest electric vehicles with today's limited battery range, if marketed correctly to segments with appropriate driving behavior, comprise a large enough market for substantial vehicle sales. An additional analysis examines driving versus parking by time of day. On the average weekday at 5 pm, only 15% of the vehicles in the sample are on the road; at no time during the year are fewer than 75% of vehicles parked. Also, because the return trip home is widely spread in time, even if all cars plug in and begin charging immediately when they arrive home and park, the increased demand on the electric system is less problematic than prior analyses have suggested.

1. Introduction

We write in the midst of a resurgence of plug-in automobiles, an accelerating movement of popular interest and industrial development that started slowly with the introduction of 'modern' electric vehicles (EVs) during the oil crisis in the

* Corresponding author. Tel.: +1 302 831 4665; fax: +91 44 4219 7763.
E-mail addresses: npearre@udel.edu (N.S. Pearre), willett@udel.edu (W. Kempton), randall.guensler@ce.gatech.edu (R.L. Guensler), vetriventhan.elango@ce.gatech.edu (V.V. Elango).
[1] Tel.: +1 302 831 0049.
[2] Tel.: +1 404 894 0405.

0968-090X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.trc.2010.12.010

1970s. For example, the Pacific Gas and Electric Company recently testified that over 70% of automakers are developing vehicles that will plug into the electric grid, and will use grid electricity for some fraction of their motive energy (PG&E, 2009).

Although electricity has many advantages as a vehicle fuel, it has two disadvantages: storing it is more bulky and expensive (batteries versus a sheet metal tank) and refueling is slow (typically 1–20 kW electric versus 5000 kW[3] gasoline). The former implies that initial electric vehicles will have less range than gasoline, and the latter implies that they cannot be quickly refueled en route. The range and refuel questions are most acute for electric vehicles (EVs), which derive motive power exclusively from onboard electrical batteries. One technical approach to range is the Plug-in Hybrid Electric Vehicle (PHEV), which can be refueled by either electricity or liquid fuels. We focus here on electric vehicles, because they present the more challenging range problem in need of this article's driving-distance analysis.

Our central question is: Are battery-range limitations compatible with our gasoline-enabled driving habits? Despite concerns about battery-range limitations, there is little published empirical analysis of driver range needs, in part due to the lack of longitudinal vehicle and household travel data collected over extended time periods. For example, one prior study of range and related questions studied a small set of vehicles sampled for few days each and suggested that more than 95% of daily driving can be accomplished with 100 miles of electric range (Gondor et al., 2007). Similarly, studies have found that about three quarters of travel miles would be powered by electricity in a plug-in hybrid with 60 miles of electric range (Graham, 2001; Denholm and Short, 2006). The problem with such studies reporting the number of limited-range trips is that car buyers are likely to want a vehicle to cover most of their own heterogeneous needs over time, not the needs of the average driver, nor even their own average travel profile. Thus we assert the importance of long-term monitoring of each vehicle studied to document the distribution of trips through a year for each vehicle, as we have done here.

The importance to automakers of the market sizes that correspond to EV-critical fuel features, such as range and recharge speed, motivates the present analysis. While there has been much discussion of the potential consumer acceptance of alternative fuels, such studies tend to focus on the required distribution infrastructure needed to mimic the convenience of the gasoline engine and filling station (Williams and Kurani, 2006; Nicolas et al., 2007). Research focused specifically on Electric Vehicle market acceptance tends to address social, market, or customer perceptions rather than needs dictated by travel patterns (Nesbitt et al., 1992; Kurani et al., 1996). From discussions with industry product managers and designers, we find little evidence that automakers have seen such travel pattern data, nor that they thoroughly understand the relationship between driving range and market segmentation.

Some of this uncertainty may be due to a poor understanding of the usage and fueling patterns of today's automobile driver. The best public information about national vehicle use is produced by the US Bureau of Transportation Statistics, in particular, the National Household Travel Survey (NHTS). The NHTS is based on a survey that asks each respondent to recall a single day's travel, and reports summed or average values. For example, the average US household owns 1.9 cars, and the average driver makes 4.1 trips/day, totaling 29.1 miles per day (USDOT, 2003a; Tables A-2, A-9 and A-17). Daily average values based on these methods are inadequate to infer marketability of vehicles with specific attributes. Kurani et al. (2007:26) argue that this information bears little or no relationship to vehicle purchase decisions. Needed information missing from the NHTS include the distribution of mileage range need across respondents and across days, the most demanding single-trip range in a vehicle's life, and the distribution of range needs across drivers. Such data could inform the vehicle designer about battery sizes needed for distinct EV market segments, but such design decisions are not possible from summarized, single-day, recall data.

From the NHTS data, range distributions are provided only for the commute trip, and these meager data appear to have informed EV design already. General Motors reportedly used NHTS commuting distance data in designing their "Extended Range Electric Vehicle", the Volt, to have 40 miles of all-electric range (Dennis, 2007). This range is claimed by GM to be enough to satisfy 78% of American commuters. GM's description is consistent with USDOT surveys of the commuter trip, showing 78% of self-reported commute trips to be less than 40 miles (USDOT, 2003b; Fig. 2: "On a typical day, how many miles one-way do you travel from home to work?"). However, according to the NHTS only 18% of US automobile trips are work-related, compared with more than 40% categorized as 'family or personal' (e.g. shopping) and nearly 30% as 'social or recreational' (USDOT, 2003a; Table A-11 Distribution of Trips by Trip Purpose, in Percent). This example suggests to us that it is not prudent for auto designers to rely on the limited NHTS data to establish needed plug-in vehicle range capabilities.

The present research is motivated by our belief that more detailed knowledge of how vehicle owners use their current gasoline cars can better inform the design of electric vehicles. In this paper, we use primary instrumented data to analyze daily driving distances, for all purposes combined, for all days in a year. Future research extending this work is discussed in Section 6.

Here we focus on daily driving range as a 'base case'. By assessing daily driving distances rather than individual trip distances, we conservatively assume that vehicle charging will be limited to a single daily charge event, probably at home and overnight, that the battery is full in the morning, and that no additional charging will take place between the various individual trips during the day. This scenario is of interest because it limits electric vehicle use based on what can be expected by

[3] SAE J1772 defines plug power ranging from 12 amp at 120 V, to 80 amp at 240 V (1.4–19.2 kW). US law (40 CFR 80.2) limits gasoline pumps to 10 gallons/min, or 37.8 l/m, thus gasoline energy transfer is 357 kWh/min, or 21.4 MW h/minute. Since electricity delivers approximately four times more travel per unit fuel into the vehicle, gasoline's comparative fueling rate is effectively 5.3 MW. Assuming a 25 MPG gasoline car and a 4 mi/kW h EV, refueling 100 miles of travel at each technology's maximum standard would require 24 s for gasoline and 1 h and 20 min for electricity. Higher-cost DC chargers, not yet standardized, could reduce 100-mile electrical refuel time to about 8 min.

the early-adopters in the initial years of production, specifically: (1) public charging infrastructure will be scarce, (2) at-home vehicle charging will be the norm, (3) many hours of charging (i.e. typically overnight) will be required due to today's low-power charger designs, and (4) batteries will be full each morning.

We also briefly examine vehicle use by time of day. The time that EVs would be plugged into the electric grid is of concern to electric industry managers and policymakers, some of whom have predicted excessive electricity demand due to many vehicles plugging in when they get home from work (Parks et al., 2007; Kelly, 2009). Prior analysis of grid capacity and electric vehicle energy consumption has concluded that in terms of generation capacity, more than three quarters of the light vehicle fleet could be powered by the existing grid, if charged off-peak (Pratt et al., 2007; Kintner-Meyer et al., 2009). Denholm and Short (2006) found less surplus electrical capacity, enough to power only 40% of the mileage of 50% of the vehicle fleet. For 'dumb charging', Ford (1995) found that just 20% of the vehicle fleet could be electrified under then extant grid conditions in southern California.

Regardless of the exact percentage, for high penetrations of EVs, it will be important that vehicle charging become more intelligent than today's battery devices, which begin charging when first plugged in, and continue charging until full. To this end, efforts toward algorithms for charge timing are widespread, and include cost-optimized grid stabilization (Caramanis and Foster, 2009), management of grid congestion (Galus and Andersson, 2008), home energy information monitoring systems (Mets et al., 2010), charging algorithms for minimized operator cost (Lemoine et al., 2008; Lemoine and Kammen, 2009), and vehicle based predictive driving patterns to maximize time available for V2G services (Kamboj et al., 2010). Despite the existence of these smart charging algorithms, this paper conservatively assumes basic overnight charging.

To develop data needed prior to charge timing optimization, especially given the frequently expressed concern of massive simultaneous charging after work (Lemoine et al., 2008; Shao et al., 2009; Mets et al., 2010), the current article investigates parking times based upon monitored vehicle use patterns. These data will also be used to see whether simultaneous evening charging might be problematic. So, again, we test the early, simple 'base case' operational model for charging, that EVs will be plugged in when first parked at home, and will start charging right away.

2. Sampling, data collection, and analysis methods

This analysis is based on a high time-resolution database of vehicle use, previously collected in order to study traffic patterns, driver behavior and vehicle emissions (Wolf et al., 1999; Ogle et al., 2005; Schoenfelder et al., 2005). In contrast to most studies that rely on self-reporting or odometer readings, this database was generated by data acquisition hardware installed on a sample of vehicles. Vehicles were selected for the study by random stratified sampling from 13 counties in the Atlanta, Georgia greater metropolitan area (Guensler et al., 2002; Ogle et al., 2005; Schoenfelder et al., 2005). The sample captures population diversity and appears to be fairly representative of the regional population, except for an oversampling of the highest income groups and a significant under-sampling of the lowest income groups (Ogle et al., 2005).

The recruitment was based on random selection within target demographics. Respondents were told they could opt out anytime during the study. The instrument was unobtrusive, and few households did opt out, none during the 2004 study period analyzed here. It should be emphasized that the sample was taken from the general population, not those interested in alternative transportation, new technology, 'early adopters', or households likely to buy electric vehicles. The study was designed to pick drivers whose driving distances and trip timing were representative of the region of Atlanta. Below we discuss how representative Atlanta is of the nation as a whole.

The USDOT Bureau of Transportation Statistics indicates that Georgia as a whole has the 6th highest state commute duration at 27.2 min, trailing primarily densely populated Mid-Atlantic states. The national average commute duration is 25.0 min. (USDOT, 2007; Table 4-1). In annual vehicle miles traveled per capita, Georgia ranks 7th behind primarily rural states, accumulating 12,124 miles per person, 20% more than the national average of 10,067 (USDOT, 2007; Table 5-3). Georgia has 1.39 registered cars per driver, likewise ranking 7th. The national average is 1.19 cars per driver (USDOT, 2007; Table 4-2).

The sample used in this study draws from an area surrounding Atlanta accounting for roughly half of Georgia's population. Among the 30 largest urbanized areas, Atlanta has the 5th most roadway per person at 4.5 miles per thousand people. Among the same 30 urban areas, Atlanta has the second highest daily vehicle miles traveled per capita trailing only Houston, TX, and ranks 8th in daily traffic per freeway lane mile (USDOT, 2007; Table 5-4).

For a state where in some respects driving patterns resemble those of more densely populated states, Georgians also put a lot of miles on their cars. These statistics paint a picture of the Atlanta area, and Georgia, as a place where people have long commute distances and commute by car, and drive a lot of miles each year. Given that driving distances in the Atlanta area are generally higher than those in other US areas, we have no reason to expect that the data we analyze here would lead to underestimating drivers' needs for vehicle range.

For the duration of the study, whenever the ignition of one of the instrumented vehicles was turned on, a GPS data logger in that vehicle would record vehicle position, time and several operating variables once per second until the vehicle was again switched off. Every day the collected data were transmitted wirelessly to a server. These instrument installations were left in place for 3 years, or until the household opted out of the study. All travel during the study period is included in the resulting dataset, whether a trip to the corner store or a vacation covering many states and thousands of miles. The result of

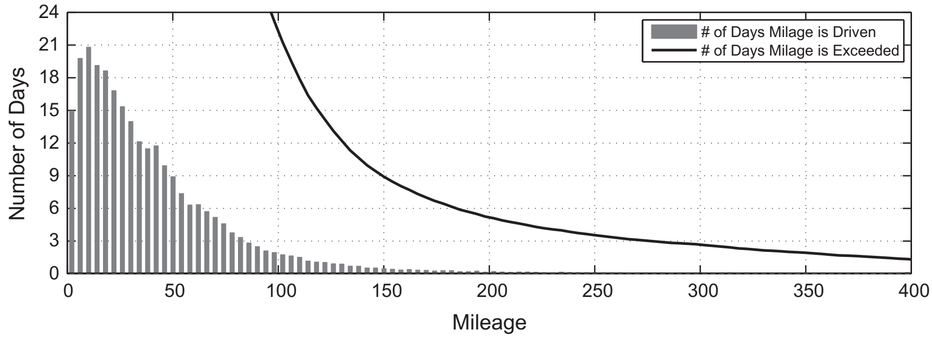

Fig. 1. Average daily mileage distribution. Histogram of daily mileage during 148,350 driving days over a year. Grey bars show 4 miles/day bins; zero daily miles is not tabulated in the histogram. The black line shows the sum of days per year that each daily mileage is exceeded.

this effort is many terabytes of second-by-second vehicle positions, covering 484 individual cars over a period of one to three years per vehicle.

Due to the detailed record of the places, times and velocities of real people going about their everyday lives, the research policies of the Atlanta study limit direct database access and require practices to reduce potential privacy concerns and liability. Per these policies, data about individual vehicles, vehicle operators and specific trips may not be transmitted outside the secure data repository, and any researchers from outside require human subjects training and must analyze the data only within strict guidelines. As a consequence, the analysis here is based on data products aggregated from second-by-second data prior to analysis. Nevertheless, the aggregated data can be used to address all the research questions we have raised here.

The analyses reported here are based upon on the portion of these data covering calendar year 2004. Second-by-second data from each trip were collapsed into individual vehicle "trips". Each trip is defined as an instance of the vehicle's ignition being turned on (key-onto key-off), and is described by a start time and location, end time and location, distance covered, vehicle make, model and year. This trip data is linked to household demographic data, based on both personal interviews conducted at the time of recruitment and follow up demographic mail surveys.[4]

Additionally, for the purposes of time of day driving pattern analysis, individual chained trips separated by less than 30 min were concatenated into single, longer trips. The reason for considering them single trips is that we were trying to understand range limits on EVs, and we considered it safest to assume that regardless of time of day or location, drivers would not plug in during short stops. By contrast, if they were parked for more than 30 min, the trips are considered two separate trips, with the possibility of plugging in between them. When we concatenate trips with short stops, the duration of each concatenated trip is the sum of the durations of the included trips plus the durations of the included intervening stops. The concatenated trip distance is the sum of the included trip distances. In most of the present article, these vehicle trips were further aggregated into daily driving distances; individual trips are used only in the final section, an analysis of how many vehicles are driving and the electrical load at each time of day.

The unit of analysis is the car. However, since we are analyzing behavior and since a single individual is likely to drive one or a small group of cars, we will as shorthand sometimes speak of "drivers" rather than "cars". Thus, our use of "driver" in this article is more precisely defined as one or more drivers operating a single car in the study.

3. Results

3.1. Daily driving distance

Within the study, 470 of the 484 vehicles were monitored for more than 50 days. For each of these vehicles, daily driving distances were subdivided into 4-mile bins, and bin frequencies were normalized by the amount of time each vehicle participated in the study. The distributions were then averaged to compute the daily distance distribution for the 148,350 driving days of the entire fleet, shown as a histogram in Fig. 1. Thus, for example, the left-most bar indicates that on average, a vehicle is driven between 0 and 4 miles about 15 days in the year. Days with no driving at all are not shown in this histogram, as explained below.

The histogram in Fig. 1 shows that the vast majority of daily range need is in the 0–50 mile range. Excluding days of zero driving, the mean daily driving range is 44.7 miles and the median is 29.9 miles. When days with no driving are included, the mean is 32.6, while the median value is 18. The survey-based NHTS data give a mean value of 29.1 miles nationwide, again

[4] Part of the ongoing analysis at the Georgia Institute of Technology is the classification of recurring trip start and end locations as "Home", "Work" and eventually other frequented locations. These characterizations are also included in the information defining each trip, but are incomplete and were not used in the present analysis.

Please cite this article in press as: Pearre, N.S., et al. Electric vehicles: How much range is required for a day's driving? Transport. Res. Part C (2011), doi:10.1016/j.trc.2010.12.010

suggesting that our Atlanta sample, with a mean of 32.6 miles may have higher range requirements than the US overall. The mode, the most common daily distance range, is 12–16 miles, the highest bar on the histogram of Fig. 1.

A separate solid line in Fig. 1 shows the number of days a given mileage is exceeded, that is, the sum of all day counts (all histogram bars) to the right of that mileage.

Fig. 1 shows, for example, that on the vast majority of days, daily mileage is below 100 miles. The solid black line shows that 100 miles or more of daily driving occurs on average only 23 days in the year (on average, once every 16 days). This finding is within the 95% confidence interval (2.55%) of Gondor et al. (2007), that found less than 5% of daily driving (18 days of 366) exceeds 100 miles. Similarly, the figure shows that 150 miles or more of driving is rare, occurring on average fewer than nine times in the year (about once every 6 weeks). Long distance travel by automobile is a fairly rare event in the sample households (Xu et al., 2009). We call out 100 and 150 miles in Fig. 1 because mass-produced electric vehicles with 100 miles range are becoming available for retail sale as we write this article, and vehicles with 150 mile or more are already available in smaller quantities.

The average vehicle in the study is not driven at all on 27% of individual days, thus if zero daily range were not excluded from Fig. 1, zero miles per day would be the mode with 99 instances per year. In the Atlanta study, the goal was to instrument all household vehicles operated more than 3000 miles per year. Hence, the sample included the primary commute vehicle, secondary service vehicles, etc., but excluded any vehicles with minimal use at the time of the sample. Few of the households participating in the study had a viable commute option by bus or rail (Zuehlke, 2007), so few zero-range days in this sample are likely to be due to commuting by transit. However, regular automobile commuters are occasionally ill or elect to work at home, households may not use secondary vehicles on many days, and the sampling includes weekend days, when one primary vehicle is typically shared by the household and secondary vehicles sit idle. Because zero daily mileage is so common, it was omitted from the graph in Fig. 1; otherwise, the scale would be expanded so much as to render unreadable the distinctions within 0–24 days.

Fig. 1 can be thought of as addressing the question; "How many days per year would the average driver have to adapt his behavior by, for instance; (1) switching to a gasoline car, (2) charging during the day, or by (3) planning the day's trips to cover less total distance?" Thus, re-phrasing the prior observation of the intersection of the line at 150 miles, from Fig. 1 we would conclude that an electric vehicle with 150-mile range, and no recharging during the day, would meet the unmodified driving need of the average driver all but 9 days in the year. It is important to note that the data include days in which the household is conducting long distance tours. If we assume that electric vehicles would not likely be used for long distance travel (i.e. a gasoline vehicle would be rented or a secondary household vehicle would be employed), limited range electric vehicles would be inadequate on an even smaller number of days.

We will refine this initial graph by examining distributions among drivers and among trips, but Fig. 1 illustrates the basic distribution of driving distances across all cars in the sample.

3.2. Days of vehicle use and mileage

The next analysis compares how many days the vehicle is used with daily distance driven. As in Section 3.1, the fleet was again limited to the 470 vehicles observed 50 days or more, and as before results were normalized by the amount of time each vehicle was under observation. In this analysis, each vehicle is characterized by two parameters: the number of days on which that vehicle was used during the year and the average mileage driven on those days when it was used.

Fig. 2 is a graph of the 470 vehicles. Here, vehicles are arbitrarily grouped into subsets of 30.5 days, thus 12 groups are shown for the year (the first subset is used between 0 and 30.5 days during the year, the second between 30.5 and 61, etc.). In the top graph of Fig. 2, for each subset, the sample mean is indicated with a square marker, and 95% confidence limits of the mean are indicated with error bars. In the bottom graph of Fig. 2, the population of each subset is shown, as a percentage of the 470 vehicles.

Fig. 2 reveals little relationship between the frequency of use of a vehicle and its average daily miles of travel. The correlation coefficient (r) between these variables using the disaggregated data is 0.18. Vehicles that are used 30.5 days per year or fewer, on average, travel only 10 miles per day when they are used. Excepting this lowest group, there is little variation in average daily travel (the square boxes in the top graph of Fig. 2) between the least-frequently used and most-frequently used cars. The low r coefficient shows that there is little linear relationship between how many days a vehicle is driven, and how far it is driven on the days it is used.

The finding that frequency of use is not strongly related to distance per day motivates further analysis in that it indicates the existence of a population of vehicles that are used frequently, yet that on average drive short distances relative to national average driving patterns. This population could be one early target market for EV sales, because for these households, a limited-range vehicle could be their primary vehicle, in daily use.

3.3. Maximum daily travel distance

The next analysis is similar to Section 3.1, but tabulates only one day of the year for each vehicle; the day on which that vehicle drove the furthest. The analysis gives an indication of the "worst case" for limited-range EVs, a situation of interest for households having no alternatives to their EV. Due to the importance of statistical outliers to this analysis, we have

Please cite this article in press as: Pearre, N.S., et al. Electric vehicles: How much range is required for a day's driving? Transport. Res. Part C (2011), doi:10.1016/j.trc.2010.12.010

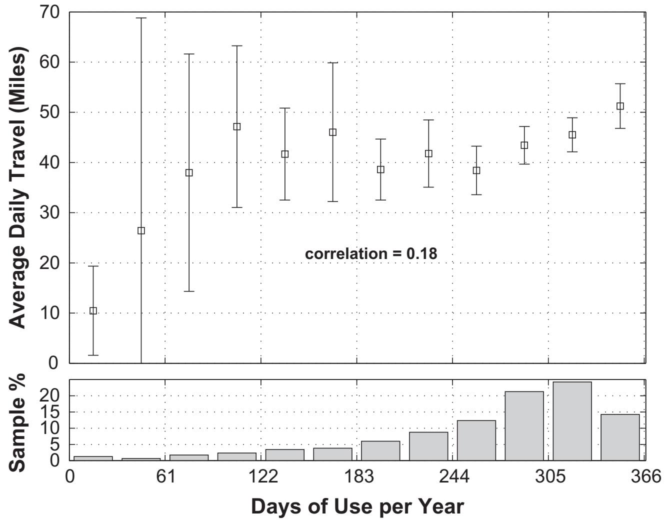

Fig. 2. Daily travel in miles vs. days of vehicle use. Vehicles are divided into 12 subsets, by days of use in the year. *Top*: Average daily mileage on the days they are driven for each subset. Squares indicate the sample mean values for each subset, error bars indicate 95% confidence limits in the mean. *Bottom*: Subset population, as a percentage of the 470 vehicles examined.

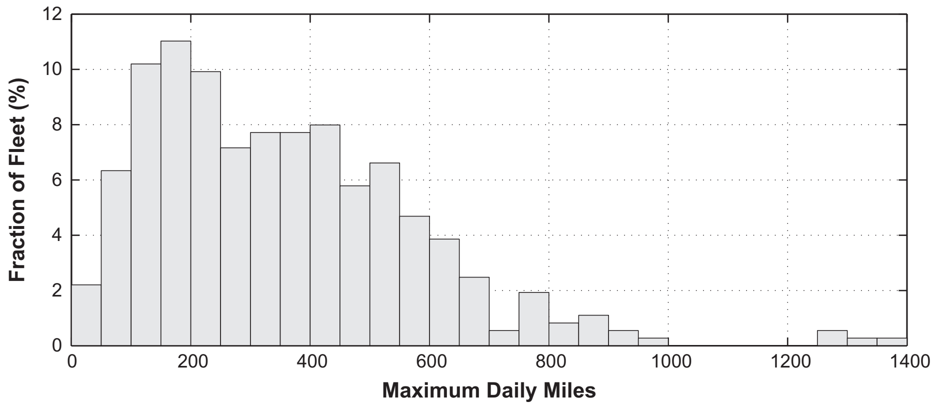

Fig. 3. Maximum daily mileage distribution. For each of the 363 vehicles, the day of maximum travel distance is identified, and that day's distance is tabulated and sorted into 50-mile bins.

restricted it to vehicles that participated in the study at least 75% of the year (274.5 days out of 366).[5] This reduces the sample to 363 vehicles.

In Fig. 3, the distribution of maximum daily mileage for the 363 vehicles is shown as a histogram with bin sizes of 50 miles. No adjustments have been made for vehicles with less than a full year of data, but these vehicles were in the study an average of 357 days, so any bias from missing data should be small. Note that, unlike the all-data histogram of daily driving in Fig. 1, the distribution of the fleet's maximum travel in Fig. 3 shows 2% or more of the fleet in each bin from zero to 700 miles. Few cars exceed a daily travel maximum of 650 miles, which corresponds to 10 h spent driving at an *average* speed of 65 mph. Only four vehicles (1.1%) exceed 1000 miles, none exceed 1400 miles. The diminution of driving from 650 to 1000 miles can be interpreted as a physical limit imposed by road speed limits and human exhaustion. The mean value in this distribution is 355 miles, and the median is 312 miles. This is arguably an overly severe test for electric vehicles, as most of these trips are long distance trips outside of the region, for which most households could select or rent an alternative vehicle.

Fig. 4 is the cumulative distribution of the maximum daily mileage for the same 363 vehicles. The cumulative distribution, for a given value of daily driving, is defined to be the fraction of the fleet that never exceeds that distance in the study

[5] If the fleet driving distance distribution found in Fig. 1 can be extrapolated to individual vehicles, the mileage on the worst of 50 studied days would only be 46% that of the mileage on the worst of 366 studied days. In contrast, the mileage on the worst of 274.5 studied days would be 93% of the mileage on the worst of 366.

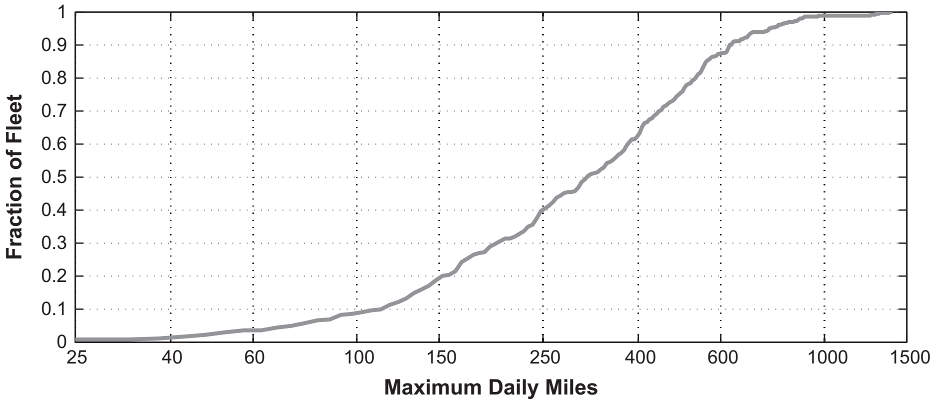

Fig. 4. Maximum daily mileage CDF. The cumulative distribution function of each of the 363 vehicles' maximum daily driving distance over a year. For each value of distance on the *x*-axis, the curve indicates the fraction of the fleet that never travels more than that distance during the year.

year. For example, an electric vehicle with a range of 100 miles, charged only once per day, could substitute for 9% of the fleet. Conversely, for the remaining 91% of the fleet, that same 100 mile EV would have failed to address the driver's range needs on at least one day during the year.

Similarly, looking at the 50% mark, an EV would require 313 miles of range to fully substitute for half of the vehicle fleet. Again, by "fully substitute" we mean that for 9% and 50%, of drivers, an electric vehicle with 100 and 313 miles range, respectively, would satisfy all driving needs, every day of the year, with no change from their gasoline vehicle habits. It should again be noted that this is a stringent test, as it includes vacation driving and other long trips for which vehicle substitution might be expected.

3.4. Days requiring adaptation

The previous analyses examined the distance travelled and the number of days each vehicle was used. Drivers who never exceed a given range in a day are potential users of limited-range vehicles without adaptation. In this section, the data are analyzed based on the notion that a driver might be willing to adapt their driving behavior on some number of days. By "adapt driving behavior" we mean either (1) substituting a liquid fuel vehicle (use another car in the household or rent a gasoline car), (2) recharging during the day or en route, (3) delaying part of the travel until the next day (e.g. instead of three side errands after work, two are done one day and the third the next day), or (4) choosing a different mode of transport (commuter rail, bus, air, etc.). Even though vehicle sharing within a household might be seen as so simple as not to qualify as an "adaptation", we include it in order to tabulate without judgment all changes required to adapt to limited range.

The need for adaptation is assessed in terms of three factors: Given a vehicle with *X* miles of range, *Z*% of the study drivers would find that vehicle fully satisfies their current driving patterns on all but *Y* days of the year. On those *Y* days, they have to make some form of adaptation, as itemized above. In these terms, the analyses for Figs. 3 and 4 set *Y* to zero, whereas, in the following analysis, the implication is that a person might be willing to adapt a few days a year.

The information needed to answer this question is a three-dimensional surface. In Fig. 5, "Vehicle Range" (*x*-axis) is the distance a given EV can travel in a day, "Days Requiring Adaptation" (*y*-axis) is the number of times during the year that range would not be sufficient, so the driver would have to adapt by one of the four methods above. The lines (the surface or *z*-axis) then describe the fraction of the fleet that would require adaptation on this number of days. Because this analysis, like Section 3.3, is susceptible to statistical outliers, we again use only the 363 vehicles monitored at least 274.5 days during the year. In addition, the failure rates have again been normalized to failures per year, so the *y*-axis is correspondingly "Days Requiring Adaptation" per year.

To help interpret Fig. 5, a "crosshair" (the cross and circle target) has been included near the lower left-hand corner. On the "Vehicle Range" axis, the crosshair is aligned with 125 miles, and on the "Days Requiring Adaptation" axis the crosshair is aligned with 2 days. Aligned on the axes in this way, the crosshair falls on the 0.25 line. This may be interpreted as follows: If an electric vehicle has a range of 125 miles, and the owners of these vehicles are willing to adapt their travel behavior no more than two days per year (e.g., switching vehicles or charging during the day), then that vehicle would be compatible with the current driving patterns of 25% of current gasoline vehicle drivers. Put another way, 25% of the monitored vehicles traveled no more than 125 miles per day, except on two or fewer days per year.

As another example use of Fig. 5; Three quarters of drivers (75%) could substitute an EV with 155 miles range for their current gasoline-fueled vehicles if they made some adaptation to limited range on 10 days per year. (Again, with "adaptation" meaning using a second household vehicle, renting, stopping to charge en route, etc. on those 10 days.)

Looking at the effect of each axis in Fig. 5, as the EV battery range increases (moving to the right), the fraction of drivers whose travel patterns can be accommodated increases. Considering the *y*-axis, if drivers are willing to accept more days of

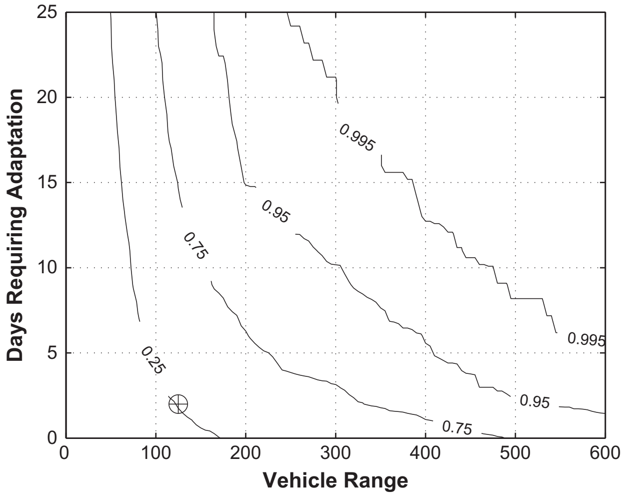

Fig. 5. Driving success surface. The fraction of the 363 vehicle fleet (numbers on lines) which would be suitable for an EV with the shown vehicle range (*x*-axis), on all but a given number of days requiring adaptation (*y*-axis).

adaptation (moving upward), the fraction that could substitute a vehicle with that range likewise increases (and vice versa with smaller batteries and lower driver tolerance for making adaptation).

Fig. 6 shows another view of the data surface in Fig. 5. Fig. 6 moves the fleet fraction values to the *y*-axis and picks four representative numbers of days of adaptation to describe the surface. The four lines represent zero, two, six, and 25 days of required adaptation. The "No adjustment days" line depicts the same information as the cumulative distribution function in Fig. 4, though the axes scale has changed. In Fig. 6, if we start with 125 miles on the *x*-axis, move up to the light dotted line (2 adaptation days), then look left to the *y*-axis, we see that 25% of drivers have driving patterns consistent with this EV range, if they would tolerate 2 adaptations per year. These are the same conditions used for the cross-hairs example in Fig. 5.

As shown earlier, EVs with 100 miles range could replace about 9% of all cars with zero driver adaptations. Fig. 6 shows that, if the drivers were willing to adapt on 2 days in the year, those 100-mile EVs would meet the needs of 17% of drivers. Or, if owners were willing to adapt six days per year, the same 100-mile EV would meet the needs of 32% of drivers.

3.5. Segmenting by average daily driving distance

We have found that a substantial fraction of vehicles travel few miles on those days when they are driven, largely independently of how many days they are used (Fig. 2). We now segment the data into four groups, based on their average daily

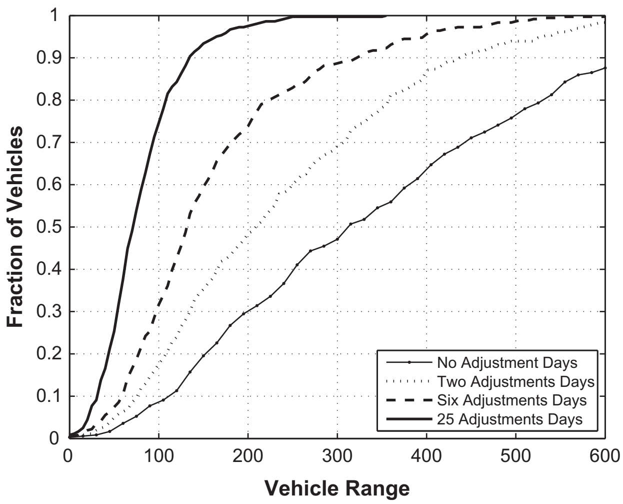

Fig. 6. Driving success surface by adaptation days. Fraction of the 363 vehicle fleet appropriate for varying vehicle ranges, with the four lines representing vehicle owners willing to make adaptations 0, 2, 6, and 25 days in the year.

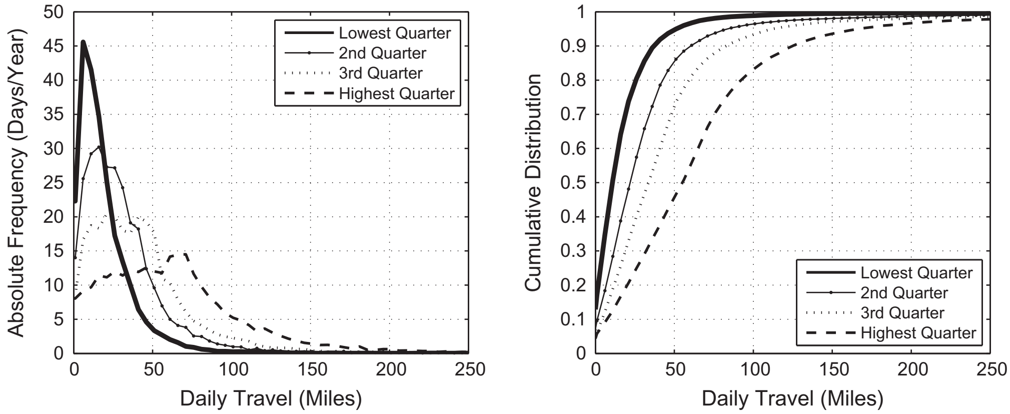

Fig. 7. Trip length distribution by sub-group. The absolute (left graph) and cumulative (right graph) frequencies of daily distance travelled, for four sub-groups, selected by their average daily distance driven.

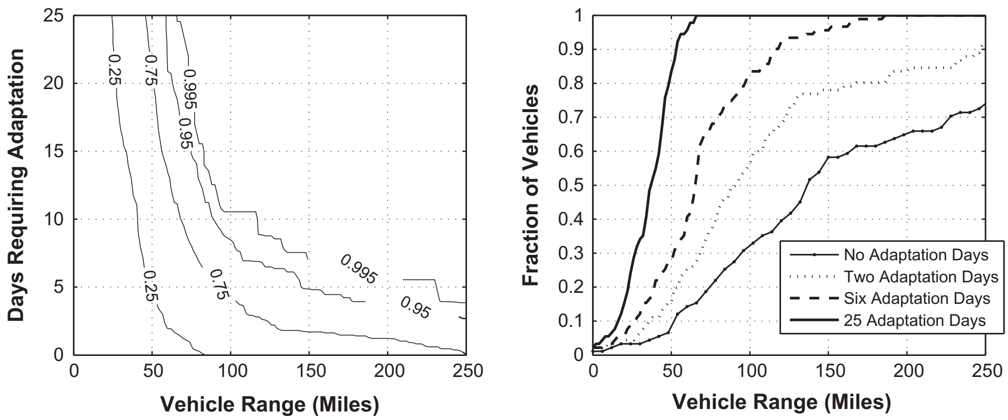

Fig. 8. Driving success surface for the 91 vehicles with the lowest average daily travel. The fraction of the fleet surface (left plot), and travel adaptations needed (right plot) are shown as a function of vehicle range. See captions for Figs. 5 and 6.

driving distance.[6] Daily driving distance is again defined by summing the mileage of all trips started on each day, and taking the average mileage of those days, excluding from the calculation days when no trips were made. This method provides simple market segmentation by driving distance, where people who drive the shortest daily distances may be the most suitable buyers of limited-range EVs. This group, if they are aware of their own range needs, may be more likely to seek to buy an EV. (Other attributes of buyers, such as willingness to pay the cost of the vehicle and cost per mile, would be included in a more complete market segmentation, but those would require very different data and analysis, and are not included in the present analysis of driving range needs.)

In Fig. 7, the distribution of daily miles traveled is shown for each of the four groups. The one-quarter of drivers with the lowest daily mileage is shown by the darkest line. Note that each group is one-fourth of the vehicle fleet, thus the number of vehicles is reduced from the total of $N = 363$ to this group's of $N = 91$.

Fig. 7 (left graph) shows that an EV designed with 150 mile range would satisfy nearly all driving requirements of three-quarters, that is, all but the highest-mileage quarter of the vehicles (dashed line). Or, referring to the right graph in Fig. 7, to satisfy 95% of the days of driving requires only a 56-mile range for the lowest-traveling quarter, a 86 mile range for the second group, a 116-mile range for the third group, and a 171-mile range for the highest-mileage quarter.

Next we pick only the lowest-mileage group of 91 vehicles to examine more closely. The rationale for looking at this group more carefully is that they are the ¼ of the population most likely to find that EVs with limited range have little impact on their driving needs. This group corresponds to the solid black lines in Fig. 7. In Fig. 8, the graphs from Figs. 5 and 6 are repeated for only these low daily mileage vehicles. Note that the maximum displayed mileage (x-axis) was 600 miles in Figs. 5 and 6, but has been reduced to 250 miles in Fig. 8, for higher resolution.

[6] The use of four groups was guided by the desire to keep the group size large (suggesting fewer divisions), yet focus on the group with smallest range needs (suggesting a small first group).

Please cite this article in press as: Pearre, N.S., et al. Electric vehicles: How much range is required for a day's driving? Transport. Res. Part C (2011), doi:10.1016/j.trc.2010.12.010

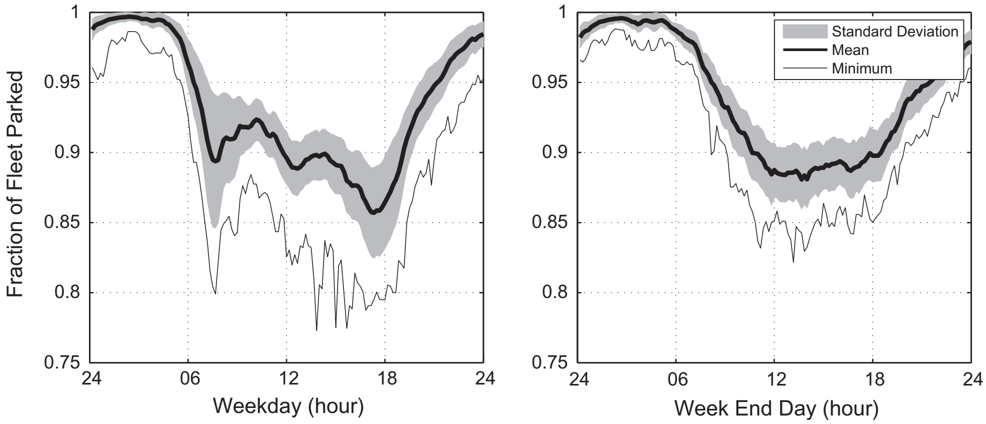

Fig. 9. Parked fraction. Fraction of vehicles parked in each 10 min interval on weekdays (left graph) and on weekends (right graph). The average of 484 vehicles over all days is indicated by the thick black line, while 1 standard deviation of the distribution is outlined in grey. The minimum fraction during the year is indicated by the thin black line; note that the *y*-axis scale is truncated at .75, not zero.

For the lowest travel distance quarter of vehicles, an EV with a 100-mile range would be sufficient for 32% of drivers, without requiring any adaptation (up from 9% of the whole fleet). If two days per year of adaptations are tolerable, the 100-mile EV could satisfy 56% of these drivers. And if these drivers were willing to adapt their behavior six days per year (the dashed line), 83% of those lower mileage vehicles could be replaced with 100-mile range EVs.

3.6. Time-of-day driving patterns

As noted in Section 1, as utilities and automakers plan for large number of electric vehicles, two statements about electrical load have been made without definitive empirical support. The first is that there will be a large load on the power grid when drivers return home and plug in after work, said to be between 5 and 6 pm. The second, countervailing statement is that vehicles will complement electric load, even in the absence of time- or price-based charging signals, because they are parked overnight and are either driving or parked away from home during the day when loads are high. These expectations may be tested against our driving data.

The same vehicle trip data can be used to examine the rate at which these vehicles enter the parked state, at high time resolution. Because we have processed the database into trips, a calculation of the "simple parked vehicle count" is, for any one minute, the number of vehicles in the study at that time minus the number traveling at that time.

To account for vehicles that did not participate in the study for the full year, the parked vehicle count on each day of the year was divided by the total number of vehicles in the fleet on that day, to produce the parked fraction. Parked fraction analysis was done on a 10-min time increment throughout the year. Thus, the results are based on the 484 vehicles, each with up to 52,704 data points (366 days × 24 h × 6 ten-min intervals per hour).

In Fig. 9, the resulting curves have been aggregated to show the distribution for weekdays (left plot) and weekend days (right plot).

Based on the above calculations, the black line in Fig. 9 shows the fraction of vehicles parked throughout average weekdays (left plot) and weekend days (right plot). One standard deviation (1σ) of the distribution about that average is displayed as a grey band about the mean. The yearly minimum, that is, the minimum fraction of vehicles parked during that 10-min segment on any day during the year is plotted as a thin black line.

We find that at the 5 pm weekday rush hour, on average, about 85% of vehicles are parked. This may be surprising, but it is consistent with prior work using different methods (Kempton et al., 2001; Gondor et al., 2007; Axsen and Kurani, 2008). The number parked increases steadily up to midnight, when on average 98.5% of the fleet is parked. Gondor et al. (2007) found slightly higher parked fractions, but very similar temporal weekday driving distribution. Even on the day of the year with most vehicles on the road (thin black line), over 75% of cars are already parked at 5 pm.[7]

In the early morning, on both weekdays and weekends, on average more than 99% of the fleet is parked during the hours of 12:10–5:50 am. This result corroborates National Household Travel Survey data, which find that only 0.2% of trips are taken in any hour between 1 and 3 am, and only 0.1% of trips are taken 3–4 am (USDOT, 2003a; Table A-12 "Distribution of Trips by Time of Day, in Percent").

The next analysis is to determine how quickly the fraction of the vehicle fleet that is parked increases, which is relevant to whether a sudden load might be imposed on the electrical grid. The concern about rapid load increase is based on the

[7] This is relevant to deferred charging and provision of grid services from plug-in vehicles (Kempton and Tomic, 2005), as it means that vehicles are parked and connected to the electric grid throughout the day. There is no 'rush hour gap' during which few vehicles would be available to the grid.

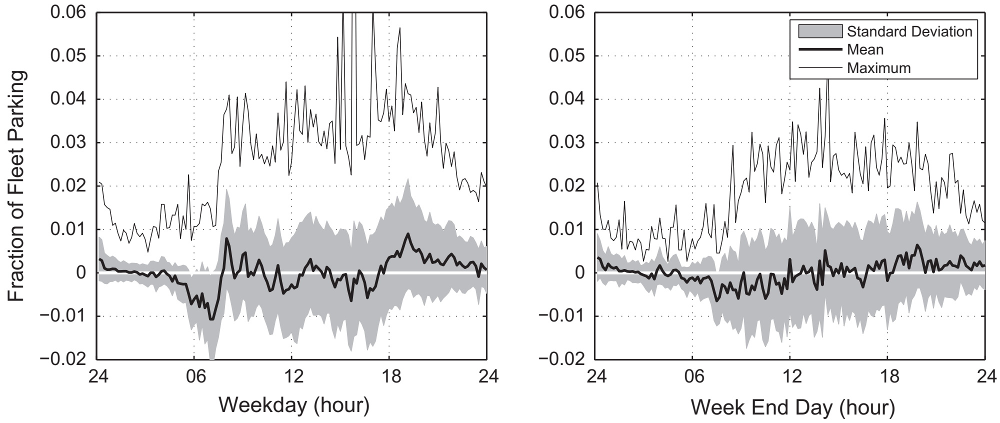

Fig. 10. Net parking rate. Rate of change of the fraction of vehicles parked in each 10 min interval on weekdays (left graph) and on weekend days (right graph). The annual average is indicated by the thick black line; one standard deviation of the distribution is outlined in grey. The maximum for the year is indicated by the thin black line.

assumption of electric vehicles reaching their trip end, parking and beginning to charge in the absence of intelligence in the charging equipment. The rate of change in vehicles parked at each time interval compared to the preceding time interval, using 10-min intervals, is presented Fig. 10.

In Fig. 10, the net fraction of cars parking in each 10-min interval is plotted in a heavy black line. That is, an increase in the number of parked cars is indicated by positive numbers (increasing load) and a decrease is indicated by negative numbers (reducing load). Fig. 10 shows a weekday pattern of vehicles leaving for work (negative numbers) between 5:00 and 7:45 am and arriving at work (positive numbers) between 7:45 and 9:00 am. The corresponding departure from work from 4:30 to 5:30 pm and net arrival at home (arrivals > departures) from 6:00 pm to 12:00 am can also be seen. Although the patterns are clear, the magnitude of the effect is very small, exceeding 0.5% of the fleet per 10-min increment only between 6:30 and 7:40. The sharpest increase in parked vehicles, at about 7:00 pm, is less than 1% of the study vehicle fleet in 10 min, and less than 4% in the worst 60-min span. Again, the standard deviation is indicated by the grey band around the mean, and the maximum value throughout the year is indicated as a thin black line.[8]

It should be noted that Fig. 10 plots net vehicles parked. Hence if one vehicle departs and two park, there is a net increase of one parked. Recalling the earlier methodological assumption that vehicles will not plug in unless parked at least ½ h, short stops such as errands on the way home are not counted as parking. In short, to extrapolate this analysis to electrical load, these imprecisions should be minor and the rates of 0.5% parking per 10-min, and 4% parking during the worst hour, seem likely to be reasonable estimates.

A full electrical analysis of these rates is beyond the scope of this article, but we note briefly that 10% of the plug-in fleet arriving over a three hour period seems very manageable. At the transmission level, this is unlikely to even be noticeable. At local distribution levels, some early EV adopters may cluster in adjacent houses. Local clustering, if combined with similar driving schedules, could cause local peak loading effects on the electrical distribution system. On the other hand, local effects, if found, are fairly easily accommodated by local distribution system upgrades (Kempton et al., 2008).

From the above analyses, it seems that both pre-suppositions, often repeated but without empirical support, are likely to be incorrect. Regarding the first, a large jump in vehicles parked after work on weekdays is not found in the data sample. Rather, there is a gradual increase in fraction of parked vehicles all evening, but in total, less than 10% of fleet parks and plug into recharge between 5 and 9 pm. In the worst evening peak hour, less than 4% of the vehicles park within that hour. Furthermore, the fraction of parked vehicles increases more after 9:00 pm than it does between 5 and 7 pm. The lack of a large 5–7 pm peak is consistent with the NHTS data cited earlier, in that only 18% of trips are work-related. Regarding the second supposition, one cannot assume that driving patterns will by themselves dictate that home charging will occur primarily at night; over 85% of cars are parked at any given hour of the average day, and never in a year are less than 75% parked. Thus, if daytime charging is undesirable due to peak load problems, time of day of charging will need to be managed by intelligent charging controls capable of responding to time of day rates, a real-time price, or other signals; the industry cannot count on charging to occur at night simply as a result of driving patterns.

4. Discussion

This empirical investigation of daily range needs, based on actual driving behavior of almost 500 vehicles over a full year, makes clear that limited-range EVs can meet the needs of a large proportion of drivers. Nine percent of vehicles do not

[8] Caution must be used in attempting to interpret the maximum net parking rate, as the maxima of any two 10-min assessment periods are unlikely to come from the same day.

exceeded 100 miles in any one day in the study year. For drivers who are willing and able to make adaptations on a few days a year, the suitable population is larger: If they are willing to make adaptations on 2 days a year, the same 100 mile range EV would meet the needs of 17% of drivers, and if they are willing to do so six times a year, limited-range vehicles would work for 32% of drivers.

The suggested adaptations in driving behavior are reasonable for a large percentage of the population. In the United States, for example, the average household owns 1.9 vehicles, and 66.4% of households own two or more vehicles (NHTS, 2001). In these multi-car households, when trips outside the range of the EV are to be taken, "adaptation" as discussed in our analysis, would be a simple matter of taking a different vehicle. On trips, the most common cause of extreme daily mileage, the family is likely already choosing a longer-range vehicle from the household.

We have analyzed the distance driven daily, but actual vehicle design would need to leave some margin of surplus range over the needed driving. This is to prevent an error or an unplanned side trip from stranding the driver, and to avoid driving with little energy remaining in the battery, sometimes dubbed "Range Anxiety". Turrentine (1994) interviewed drivers about the amount of additional range they would like, above expected trips. They call this additional capacity the "range buffer" and find that 20 miles is sufficient for most. Thus, in design of EV range capacity, we would suggest that an automobile designer might add 20 miles to the driving range figures from our analysis.

Two significant observations can be drawn from the data on time of day of driving and parking: (1) at the time of maximum vehicle utilization during weekday evening rush hours, over 80% of the vehicle fleet is inactive and (2) the weekday evenings return of vehicles is more gradual than seems generally to be believed and lasts from before 5 pm to after midnight. Even during the peak of most evening rush hours, fewer than 20% of vehicles are on the road, and between that peak and midnight those 20% of vehicles cease their travels as a reasonably even stream, with a maximum rate of less than 1% of the vehicle fleet parking in a 10-min interval, and less than 4% in the worst hour. The slow rate of return home and large fraction of vehicles already parked during the day together mean that vehicle return will not impose a rapid increase in load right after working hours. That finding does not preclude the possibility of an accumulating electric load effect if the charging rate is slow enough to span a large fraction of the 7 h return interval (5 pm–12 m). Nor do our findings preclude local electric distribution overloads, if return time happens to be synchronized within local neighborhoods. Local electric loads are less problematic because they are handled by routine distribution system upgrades and paid for via rate recovery (Kempton et al., 2008). These questions will be the subject of further investigation.

On the other hand, the large number of vehicles parked during the afternoon peak hours means that active, intelligent charging may be needed to prevent large daytime charging loads (a more precise analysis would examine how many of those mid-day parked vehicles were driven earlier in the day).

Battery science and technology are moving quickly, and we do not consider the range limitations of current EVs to be an enduring feature. One current (but high priced) model, the Tesla Roadster, already can drive almost 250 miles (400 km) on a single charge. Advanced materials and electrochemistries (e.g. silicon nanowires rather than graphite sheet for the anode) already have shown the possibility of batteries with seven times the specific energy of today's Li-ion designs (Chan et al., 2007). If industrialized, such a magnitude of improvement would hold the promise of a practical vehicle with 1000 miles of range on a single charge. Whether or not 7× improvements are reached, if one expects continuing improvement in battery capacity and lifetime, then the question is not whether today's limited-range vehicles will work for everyone. Rather, the question is whether there is there a sufficiently large market to support a limited-range EV industry for a decade or two as battery performance improves. Our data suggest that the answer to this question is, yes, there is such a market.

5. Conclusions

Comparing our results with prior literature and with many discussions with OEMs, we find sparse quantitative understanding among vehicle designers as to how US drivers use their gasoline vehicles, in terms of EV-relevant criteria such as daily range needs, their range maxima, and the distribution of range needs. This paper has documented these parameters.

In general, our analysis shows that even with limited range, electric vehicles could provide a large fraction of transportation needs. When a driver has the ability to adjust on a few days per year, by substituting alternative transportation or charging during the day, even short-range electric vehicles can be satisfactory for a significant fraction of the population. Thus, understanding the customer's needs, and correctly segmenting vehicle buyers by range needs, appears to be a more cost-effective way to introduce electric vehicles than assuming that all buyers, and all drivers, need currently-expensive large batteries or liquid-fuel range extenders.

6. Future research

In this paper, we analyze daily driving distances for all purposes combined, for all days in a year, using primary instrumented data. In subsequent articles, we will analyze each trip rather than each day, and the frequency with which vehicles park at locations likely to be effective vehicle charging sites. We anticipate that this trip-based analysis will provide more refined results of value in designing and marketing both electric vehicle capacities and public charging infrastructure.

Correspondingly, a form of driver travel adaptation not quantitatively assessed in this paper is charging during the day. We will examine this issue by breaking travel into discrete trips, rather than total daily range. This will allow us to analyze

Please cite this article in press as: Pearre, N.S., et al. Electric vehicles: How much range is required for a day's driving? Transport. Res. Part C (2011), doi:10.1016/j.trc.2010.12.010

when recharging during the day would be possible to extend range and vehicle utility. In some cases, such as recharging at work, or recharging during a trip stopover for a meal, stopping to charge would be an adaptation incurring minimal user inconvenience.

Subsequent analysis will also model various charging algorithms, which will provide a more refined understanding of the potential interactions between vehicles and the electric grid. This will extend beyond load assessment, to an evaluation of surplus energy and power capacity that could be utilized for grid stabilization services through Grid-Interactive Vehicles with Vehicle to Grid power (Kempton and Tomic, 2005).

Acknowledgements

We are grateful for extensive comments by the reviewers for Transportation Research. This research was supported by funding from the US Department of Energy, Office of Electricity (Grant Number DE-FC26-08NT01905), and from AC Propulsion, Inc. (Willett Kempton, PI). The driving data was collected by the Georgia Institute of Technology (Randall Guensler, PI) with support from the Federal Highway Administration and the Georgia Department of Transportation.

References

Axsen, J., Kurani, K., 2008. The Early US Market for PHEVs: Anticipating Consumer Awareness, Recharve Potential, Design Priorities and Energy Impacts. Institute of Transportation Studies, University of California at Davis. UCD-ITS-RR-08-22.

Caramanis, M., Foster, J.M., 2009. Management of electric vehicle charging to mitigate renewable generation intermittency and distribution network congestion. Decision and control, 2009. In: Proceedings of the 48th IEEE Conference, Shanghai, pp. 4717–4722. doi:10.1109/CDC.2009.5399955.

Chan, C.K., Peng, H., Liu, G., McIlwrath, K., Zhang, X.F., Huggins, R.A., Cui, Y., 2007. High-performance lithium battery anodes using silicon nanowires. Nature Nanotechnology 3, 31–35.

Denholm, P., Short, W., 2006, An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-in Hybrid Electric Vehicles. Technical Report, NREL/TP-620-40293, October 2006. National Renewable Energy Laboratory.

Dennis, L., 2007. How did GM determine that 78% of commuters drive less than 40 miles per day? <GM-Volt.com> (accessed 18.01.10).

Ford, A., 1995. The impacts of large-scale use of electric vehicles in Southern California. Energy and Buildings 22 (3), 207–218.

Galus, M.D., Andersson, G., 2008. Demand management of grid connected plug-in hybrid electric vehicles (PHEV). In: Energy 2030 Conference, 2008. Energy 2008. IEEE. doi:10.1109/ENERGY.2008.4781014.

Gondor, J., Markel, T., Simpson, A., Thornton, M., 2007, Using GPS travel data to assess the real-world driving energy use of plug-in hybrid electric vehicles (PHEVs). Presented at the Transportation Research Board 86th Annual Meeting, Washington, DC, 21–25 January 2007. National Renewable Energy Laboratory.

Graham, R., 2001. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options. EPRI Report 1000349. Electric Power Research Institute, Palo Alto, CA.

Guensler, R., Williams, B., Ogle, J., 2002. The role of instrumented vehicle data in transportation decision making. In: Fourth International Conference on Decision Making in Urban and Civil Engineering, London, England.

Kamboj, S., Decker, K., Trnka, K., Pearre, N., Kern, C., Kempton, W., 2010, Exploring the formation of electric vehicle coalitions for vehicle-to-grid power regulation. In: 9th International Conference on Autonomous Agents and Multiagent Systems Workshop on Agent Technologies for Energy Systems. Toronto, Canada, 10–14 May 2010.

Kelly, J.Southern California Edison, 2009. Building a Plug-in Future, Plug-in 2009. University of California at Davis, Davis, CA.

Kempton, W., Tomic, J., 2005. Vehicle to grid fundamentals: calculating capacity and net revenue. Journal of Power Sources 144 (1), 268–279. doi:10.1016/j.jpowsour.2004.12.025.

Kempton, W, Tomic J., Letendre S., Brooks A., Lipman T., 2001. Vehicle-to-grid power: battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California. Institute of Transportation Studies Report #IUCD-ITS-RR 01-03, 77+xiv Davis, CA, 2001. <http://www.udel.edu/V2G> and <http://www.repositories.cdlib.org/itsdavis/UCD-ITS-RR-01-03-a>.

Kempton, W., Udo, V., Huber, K., Komara, K., Letendre, S., Baker, S., Brunner, D., Pearre, N., 2008, A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System. Report, Center for Carbon-free Power Integration. University of Delaware. <http://www.magicconsortium.org>.

Kintner-Meyer, M., Schneider, K., Pratt, R., 2009. Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional US Power Grids. Part 1: Technical Analysis. Pacific National Labs, 2009-04-30.

Kurani, K.S., Turrentine, T., Sperling, D., 1996. Testing electric vehicle demand in 'hybrid households' using a reflexive survey. Transportation Research Part D 1–2, 131–150.

Kurani, K.S., Heffner, R.R., Turrentine, T.S., 2007. Driving Plug-In Hybrid Electric Vehicles: Reports from US Drivers of HEVs Converted to PHEVs, circa 2006-07. Institute of Transportation Studies, University of California, Davis. Research Report UCD-ITS-RR-08-24.

Lemoine, D.M., Kammen, D.M., 2009. Addendum to 'an innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles'. Environmental Research Letters 4 (3), 039701. doi:10.1088/1748-9326/4/3/039701.

Lemoine, D.M., Kammen, D.M., Farrell, A.E., 2008. An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles. Environmental Research Letters 3 (1), 014003. doi:10.1088/1748-9326/3/1/014003.

Mets, K., Verschueren, T., Haerick, W., Develder, C., De Turck, F., 2010. Optimizing smart energy control strategies for plug-in hybrid electric vehicle charging. in: Network Operations and Management Symposium Workshops. IEEE/IFIP 10.1109/NOMSW.2010.5486561.

Nesbitt, K.A., Kurani, K.S., DeLuchi, M.A., 1992. Home recharging and the household electric vehicle market: a constraints analysis. Transportation Research Record 1366, 11–19.

NHTS, 2001. Table Designer, Based on NHTS 2001. Omnibus Household Survey, vol. 3(4). Household file, variable HHVEHCNT. <http://nhts.ornl.gov/tables/ae/TableDesigner.aspx> (accessed December 2009).

Nicolas, M.A., Handy, S.L., Sperling, D., 2007. Using geographic information systems to evaluate siting and networks of hydrogen stations. Transportation Research Record 1880, 126–134.

Ogle, J., Guensler, R., Elango, V., 2005. Commute Atlanta Value Pricing Program: Recruitment Methods and Travel Diary Response Rates, Transportation Research Record. National Academy of Sciences, Washington, DC. No. 1931, pp. 28–37.

Parks, K., Denholm, P., Markel, T., 2007. Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory. NREL Report No. TP-640-41410. 29pp.

PG&E, 2009. The Perfect Storm for Electric Vehicle Market Growth in California, Smart Grid Workshop. California Public Utilities Commission.

Pratt, R., Kintner-Meyer, M, Schneider, K., Scott, M., Elliott, D., Warwick, M., 2007. Potential impacts of high penetrations of plug-in hybrid vehicles on the us power grid. In: DOE/EERE PHEV Stakeholder Workshop, Washington DC, June 2007.

Schoenfelder, S., Li, H., Guensler, R., Ogle J., Axhausen, K.W., 2005. Analysis of Commute Atlanta Instrumented Vehicles GPS Data: Destination Choice Behavior and Activity Spaces. Arbeitsberichte Verkehrs- und Raumplanung, 303, IVT, ETH, Zürich.

Shao, S., Pipattanasomporn, M., Rahman, S., 2009. Challenges of PHEV Penetration to the Residential Distribution Network. IEEE/PES General Meeting.

Turrentine, T., 1994. Lifestyles and Life Politics: Towards a Green Car Market. Ph.D. dissertation. Reprinted as: University of California, Davis: Institute of Transportation Studies, UCD-ITS-RR-94-30, 1994.

USDOT, 2003a. NHTS 2001 Highlights Report. US Department of Transportation, Bureau of Transportation Statistics, BTS03-05, Washington, DC.

USDOT, 2003b. Omnibus Household Survey, vol. 3(4). Fig. 2. US Department of Transportation, Bureau of Transportation Statistics. <www.bts.gov/publications/omnistats/volume_03_issue_04/html/figure_02.html>.

USDOT, 2007. State Transportation Statistics 2007. Bureau of Transportation Statistics.

Williams, B.D., Kurani, K.S., 2006. Estimating the early household market for light-duty hydrogen-fuel-cell vehicles and other "Mobile Energy" innovations in California: a constraints analysis. Journal of Power Sources 160–1, 446–453.

Wolf, J, Guensler R., Washington, S., Sarasua, W., Grant, C., Hallmark, S., Oliveira M., Koutsak, M., Thittai, R., Funk, R., Hsu, J., 1999. Development of a Comprehensive Vehicle Instrumentation Package for Monitoring Individual Tripmaking Behavior. Georgia Institute of Technology. GTI-R-99005.

Xu, Y., Zuyeva, L., Kall, D., Elango, V., Guensler, R., 2009. mileage based value pricing: phase II case study implications of the commute Atlanta project (09-3458). In: 88th Annual Meeting of the Transportation Research Board, Washington, DC, January 2009.

Zuehlke, K., 2007. Impossibility of Transit in Atlanta: GPS-Enabled Revealed-drive Preferences and Modeled Transit Alternatives for Commute Atlanta Participants. MCRP Masters Thesis. Georgia Institute of Technology, Atlanta, GA.

Please cite this article in press as: Pearre, N.S., et al. Electric vehicles: How much range is required for a day's driving? Transport. Res. Part C (2011), doi:10.1016/j.trc.2010.12.010