Assessment of Electric Cars' Range Requirements and Usage Patterns based on Driving Behavior recorded in the National Household Travel Survey of 2009

A Study conducted as part of:

solar journey usa

"3,200 Miles, Powered by the Sun"

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Foreword

This study was conducted as part of the *Solar Journey USA* project, an initiative to educate the American people about Electric Vehicles, Solar Energy and the synergy of 'Sustainable Driving' that arises from the two. In the summer of 2012, Garrett Fitzgerald and I aim to make a cross-country trip powered strictly by solar energy, generated by the PV-array that we tow with us. Each day, we will recharge the batteries in our electric car for the next leg of the trip, while giving presentations and workshops about these world-changing technologies. Please consider a contribution to our project, as we need all the support we can get. For more information, visit our website: www.solarjourneyusa.com.

Kind Regards,

Rob van Haaren

Abstract

The main barrier to electrification of the car industry is the electric car's limited range. The fear of getting stranded on the side of the road with an empty battery, first observed in General Motor's EV1 project is named: 'Range Anxiety'. The purpose of this study is to characterize driving behavior of the United States population (on a National and State level) and to give an overview of what percentage of trips can be covered with a fully charged electric car. Also, this study has successfully identified factors that influence driven distances, such as the effect of urbanity and household ethnicity. The second research goal is to provide future research on grid integration of electric cars with a temporal outline of when electric cars will be connected to the electricity grid. Data for this can be downloaded for free from the website[1].

1. Introduction

Over the last century, the car has become the primary means of transportation for the developed world, as well as an icon of wealth and culture. Trillions of dollars were invested in the refueling infrastructure for cars, which now supplies about nine million barrels of gasoline per day to the U.S. alone[2]. Today however, the auto industry is at the toe-tip of the greatest transition it has ever experienced.

The automotive and oil industry are experiencing two growing forces that limit their business: 1) air pollution prevention and 2) depletion of fuel resources. The first has evolved from a discussion about the harmful NO_x, CO and hydrocarbon emissions in the 70's, to a more global issue relating to the inevitable emissions of CO_2 in the combustion of hydrocarbon fuels. The emissions that impacted health were mostly mitigated by the invention of the Three-Way-Catalyst (TWC), which successfully converts the harmful flue gas pollutants to less harmful ones. The second limiting force has been tried to overcome by using alternative fuels, like biomass-based (methanol/ethanol) or other fossil fuels (like the liquefaction of coal) as a feedstock. These however have a limited capacity due to cost constraints, a high investment risk due to the fluctuating oil price and some face ethical issues when edible food is used to make fuel.
With these limiting forces and no tangible solutions on the horizon for combustion-powered vehicles, engineers started (re)implementing a variety of propulsion systems that require other energy sources than oil. Virtually all of them depend on electric motors as the apparatus to drive the wheels. Believed to be the most promising configuration is the Battery Electric Vehicle (BEV), a configuration that has been around since the invention and implementation of the internal combustion engine (ICE) into cars. At the end of the 19th century, the electric car was actually more popular than the gasoline powered car. However, because of their limited range and the availability of cheap gasoline, the electric car lost the head-to-head competition with its gasoline counterpart. Now, the electric car is on its way back, with many car manufacturers adopting this 'retro' propulsion system.

Still, the main barrier to electrification of the car industry is the electric car's limited range. The fear of getting stranded on the side of the road with an empty battery, first observed in General Motor's EV1-project is named: 'Range Anxiety'[3]. Besides this barrier on the consumer's side, electricity grid operators and independent researchers have expressed their concerns with the additional load from electric cars on the grid, especially during peak hours on hot summer days[4,5,6]. This study aims to provide insights into

[1] http://www.solarjourneyusa.com/EVdistanceAnalysis.php

[2] U.S. Energy Information Administration. (2010). Annual Petroleum & Other Liquids. *July 28th, 2011*. Retrieved from http://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbblpd_a.htm

[3] Acello, R. (1997, September 1). Getting into Gear with the Vehicle of the Future. *San Diego Business Journal*. San Diego.

[4] IRC ISO/RTO Council, & KEMA. (2010). *Assessment of Plug-in Electric Vehicle Integration with ISO / RTO Systems*. Retrieved from http://www.isorto.org/atf/cf/%7B5B4E85C6-7EAC-40A0-8DC3-

these issues by characterizing driving behavior in the United States using a dataset published by the Federal Highway Administration of the U.S. Department of Transportation. The hypothesis is that people overestimate the EV-range that they find necessary for their daily driven needs. All data and results are available from the website[1] and can be used as a backbone for further research on range requirements and grid integration of electric vehicles.

In the first part of this study, a statistical analysis is conducted on the distances driven by the U.S. population. The results are projected on typical range bins seen in the portfolio of electric cars that are available as of 2011. The second part covers car usage patterns on an hourly basis for weekdays and weekends, which are in turn used to assess when cars are connected to the grid and available for charging. This may benefit Vehicle-to-Grid (V2G) studies and other Smart-Grid initiatives.

Research Questions

Part 1: Driving Range Requirements (on both National and State level)

A. *What is the distribution of distance driven for individual car trips?*
B. *What is the distribution of daily driven distance for a single vehicle if it is used on that day?*
C. *How far do people commute to work by car?*
D. *What household characteristics affect the answers to the above questions (urban/rural)?*

Part 2: Usage Patterns for grid integration

A. *From all cars surveyed, at what time during the weekday/weekend are they being driven?*
B. *For how many trips are cars used during the weekday/weekend?*
C. *When are cars used for commuting during the weekdays?*

Before the methodology and results are covered, some background around EV implementation phases is given, which will introduce the range bins used in the results. Then, a more detailed description is given on 'Range Anxiety', experienced by current and future EV-owners.

2. The Implementation of Electric Vehicles

The electrification of cars is happening in phases, with gradually increasing electric/combustion power capacity ratios. This benefits the adoption of the electric car, as consumers can get used to the technology and adapt in small steps.

In the first phase, hybrid electric vehicles (HEV) came into the picture, allowing people to get the feel of small bits of electric driving. The Toyota Prius (1997) was the first widely available HEV, with a revolutionary mileage of ~50 mpg. The ICE is turned off when waiting for a traffic light and initial acceleration is done using the electric motor. The batteries are primarily charged by 'regenerative braking', which uses the electric motor as a generator (or: 'dynamo') while braking. Naturally, these applications boost mileage more for city driving than highway driving. Then, engine size decreased while battery size and electric motor power increased, again enhancing mileage. Some models even allow short

003829518EBD%7D/IRC_Report_Assessment_of_Plug-in_Electric_Vehicle_Integration_with_ISO-RTO_Systems_03232010.pdf

[5] Pacific Gas and Electric Company. (2009). "The Perfect Storm for Electric Vehicle Market Growth in California" Smart Grid Workshop. *California Public Utilities Commission Smart Grid Rulemaking*. San Francisco.

[6] Papavasiliou, A., Lee, A., Kaminsky, P., Sidhu, I., Tenderich, B., & Oren, S. (2008). *Electric Power Supply and Distribution for Electric Vehicle Operations*. Retrieved from http://cet.berkeley.edu/dl/EV2Grid_FinalREVISED.pdf

distances of Full-Electric drive under low-load conditions like for driving in residential areas (EV-mode for Toyota Prius, 2010).

The second phase is currently in its take off phase: Plug-in Hybrid Electric Vehicles (PHEV), which for the first time allows the driver to use another energy source besides gas, namely electricity from the grid. The all-electric range is sufficient for most trips, and for extended trips the engine automatically turns on to power the electric motor when the battery is depleted. The one major drawback of a full EV's (range) is therefore taken out of the equation, while retaining emissions- and cost benefits of full-electric driving.

Some car manufacturers have decided to leapfrog this step (Nissan and likely BMW) and started building BEVs right away. The Nissan LEAF is the first commercially available BEV after General Motors' EV1 was terminated in 2002. The BEV can be considered the final stage of the electrification of the automotive industry. From that point on, the further environmental improvements that can be made are cleaning the electricity source (less coal, more renewables) and improving the range of the vehicles.
The range is the BEV's major apparent drawback at this time, with its effect on the driver termed as 'Range Anxiety'. One interesting idea to overcome that is put in practice by the company Better Place, where BEVs can swap batteries instead of charging them. This allows the driver to 'refuel' his EV in about a minute, virtually eliminating the whole range issue of EVs, given enough of these swapping stations exist.

The use and benefits of the second and third stage configurations is subject to the user's driving behavior and it is therefore important to investigate what users' range requirements are for an electric vehicle of some sort.

3. On 'Range Anxiety'

The fear of getting stranded on the side of the road with an electric car from running out of battery charge has been termed 'Range Anxiety'. Range anxiety was first introduced when drivers of the General Motors' EV1 experienced fear to drive distances near the rated EV range of their vehicle (First gen. EV1: 100 miles, Second gen.: 140 miles). Now it is the major concern for people when considering an EV. With range of EVs so important to drivers, it has been added to the list of car specifications like Horsepower, 0-60 in …, etc. In the following, the technological cause of range anxiety will be explained, namely battery energy density and their recharge times. After that, some surveys about EV range requirements will be discussed.

3.1 Battery development is key

The low specific energy of the battery pack compared to gasoline (~0.25 kWh/kg vs ~13 kWh/kg) is the most important factor in range limitations. Numerous battery chemistries have been explored for use in EVs, each with their own advantages and disadvantages in cycle life, energy density, specific power and safety. The battery chemistries currently used in electric cars are mostly from the Li-ion family: LiCoO2, LiFePO4, LiMn2O4, Li(NiCo)O2 as well as Nickel-Metal Hydride (NiMH).

To achieve a 200+ miles range, the Tesla Roadster carries 992 lbs of Li-ion batteries (this includes other electrical components), which is more than a third of the total vehicle weight. That same range would take around 58 lbs of gasoline for a 30 mpg ICE car. Battery technology is in great development though, with a 'technology pull' force from the consumer electronics industry, demanding longer battery life from lighter and smaller cells. Consequently, the Li-ion energy density for batteries has increased from 88

Wh/kg (1991) to 280 Wh/kg (2011). There is a theoretical limit to the specific energy of all Li-ion battery types (ranges from 1-3 kWh/kg for the common types), but we are still far from that number.

In a recent poll by Deloitte[7], 80% of the U.S. participants of the survey want a range of 100 miles or more from an electric car. Around 60% of them want to be able to drive at least 200 miles before a recharge and 37% expects a range of 300 miles or more… In the results presented later, we will show how often people actually drive that far on a single day.

But do people know the range of the gasoline car they are driving today?[8] Of course, it only takes 10 minutes to fill up a gas tank, but it would be interesting to compare it to what people expect from electric cars. Table 1 shows the range of the top-10 best-selling cars in the United States (in 2010). Four out of ten vehicles have a range lower than 300 miles, with the Ford Fusion AWD FFV having the lowest range: 223 miles.

Table 1: Driving range of the 10 best-selling cars in the United States, for the year 2010. In case of multiple models, the version with the shortest range is picked. Source: www.fueleconomy.gov

Ranking	2010 Model	Range (miles)
1	Ford F150 Pickup 4WD	374
2	Chevrolet Silverado 4WD	491
3	Toyota Camry	383
4	Honda Accord	383
5	Toyota Corolla	297
6	Honda Civic	285
7	Nissan Altima	378
8	Ford Fusion AWD FFV	223
9	Honda CR-V	317
10	Dodge Ram 1500 Pickup	234

Many people are not affected by the range they get with their gasoline car. After all, refueling is quick, simple and possible virtually anywhere. Electric vehicles however, take longer to recharge: depending on the method, full recharge times range from typically 30 minutes (80% quick-charge[9]) to 48 hours (slowest wall-outlet charge for Tesla Roadster[10]).

To illustrate the difference between 'recharging' a gasoline car and an electric car, we can make an interesting comparison by deriving the rate at which energy is transferred into the vehicle during refueling/recharging:

A full 13.5 gallon tank of a 2009 Ford Focus holds about 1.7 GJ of calorific energy in the form of gasoline. Assuming you fill it up in 2 minutes, that's a rate of 14,000 kW. Believe it or not, that is the peak electricity consumption of almost 2,500 households. Electric cars are different: the several charging methods provide power ratings anywhere between 1.92 kW (standard US household outlet) and 62.5 kW

[7] Deloitte. (2011). *"Gaining traction: Will consumers ride the electric vehicle wave?"* . Retrieved from http://www.deloitte.com/assets/Dcom-Global/Local Assets/Documents/Manufacturing/Deloitte EV Survey Summary Findings China US Europe Japan April 2011 _ Final.pdf

[8] 'What's your gasoline car's range?' – www.solarchargeddriving.com

[9] http://www.wired.com/autopia/2009/08/nissan-electric-leaf/

[10] http://www.teslamotors.com/goelectric/charging

(DC fast-charging) for the Nissan LEAF. An innovative charging method procured by the company 'Better Place', swaps batteries instead of recharging them. According to the firm, the batteries are swapped in little over a minute[11]. Assuming 25 kWh batteries, that is a recharge rate of 1,500 kW (see Figure 1).

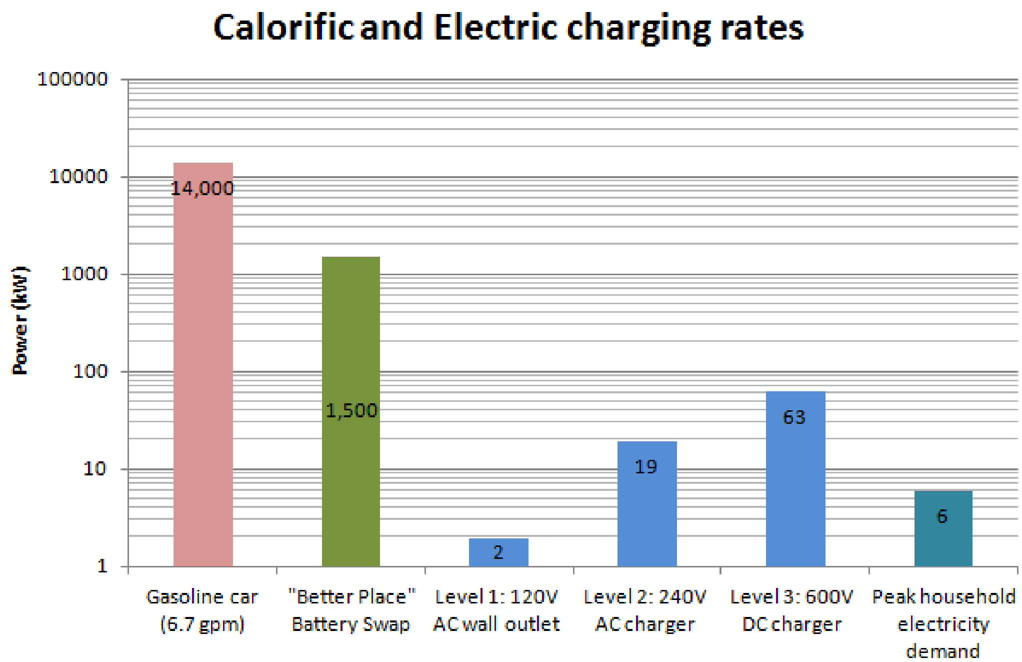


Figure 1: Energy transfer during refueling/recharging in kW. For fuel, the calorific energy transfer of a 2-minute, 13.5 gallon fill-up was assumed. Note that the y-axis is on a logarithmic scale.

Because gasoline cars waste a much higher proportion of the energy that was transferred to them, it would be more interesting to see how many miles are 'recharged' per unit of time. Figure 2 shows the 'effective charging rate' in miles per minute for different charging methods. Of course, the number of miles driven from 1 kWh or 1 gallon of gasoline depends on where those miles are driven (highway or city) as will be shown later, but for now we can assume the single EPA rating for the EV range.

[11] http://www.betterplace.com/the-solution-switch-stations

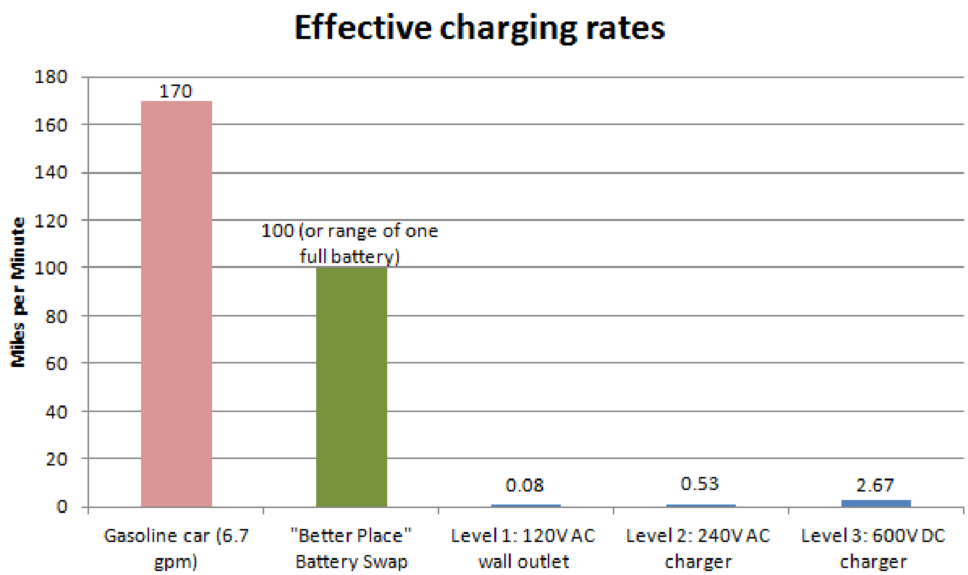


Figure 2: Effective charging rates in miles per minute for the different methods.

3.2 Surveys on Range Anxiety

Surveys have been conducted around 'range anxiety' and the implementation of (PH)EVs. The statistical correctness of this type of studies should be carefully reviewed, as same-topic questions from multiple studies show very different answers. Causes of this could be a selection bias (people who do not care about EVs are less likely to take the survey), the use of cluster sampling (surveys spread through networks like Facebook are likely to cover younger age-groups) or simply the way questions and perhaps multiple choice answers are formulated. From a pool of seven surveys, the two below were selected as the best-described and reported. Their results are briefly summarized below.

Accenture (PH)EV survey 2011
Accenture conducted a survey on consumer preferences regarding electrified vehicles in 13 countries, during December 2010 and January 2011[12]. Random participants were chosen, representing gender, age and income groups according to the general populations' distributions (n = 7003). Very interesting from this particular study was the observed difference in opinions on the subject between countries.

For example, the question: *'Are you in favor of electric vehicles (plug-in hybrid electric vehicles and full electric vehicles) replacing conventional cars over time?'* was answered with: *'Yes, I am very much in favor of this'* by 86% of Chinese participants (highest of all) and only 41% of the Dutch (lowest of all). Average over all countries was 60%.

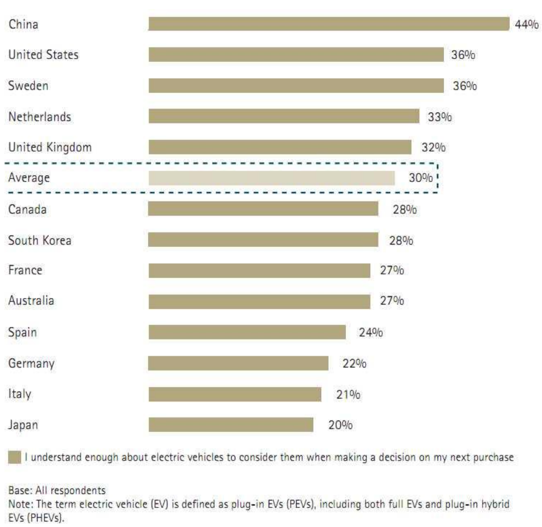
The question: '*Would you consider electric vehicles (plug-in hybrid electric vehicles or full electric vehicles) as an option for your next car purchase?'* was answered with '*Certainly'* or '*Probably'* by 95% of Chinese and 41% of Dutch respondents, again the two extreme countries (average: 58%).

When asking about the favored range of an EV: *'How many kilometers would you like to be able to drive with a fully charged battery in order to consider an electric vehicle for your next purchase?'*, people

[12] http://www.accenture.com/SiteCollectionDocuments/PDF/Resources/Accenture_Plug-in_Electric_Vehicle_Consumer_Perceptions.pdf

responded that they require at least 272 miles (437 km) of range on average. This is a very interesting figure, compared to their self-estimated average driven distance of 32 miles. As will be shown later, the 272 miles is even beyond the full-tank range of some of the top-10 sold conventional cars.

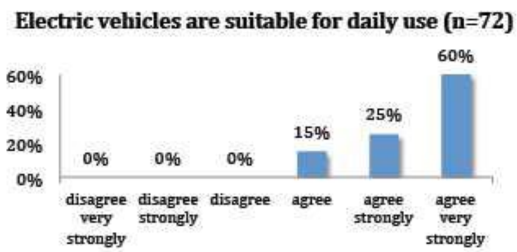
Another interesting finding is that only 30% of the participants regard their understanding of (PH)EVs as 'enough' to consider electric cars when making a decision on their next car purchase. This figure ranges from 20% to 44% over all countries.

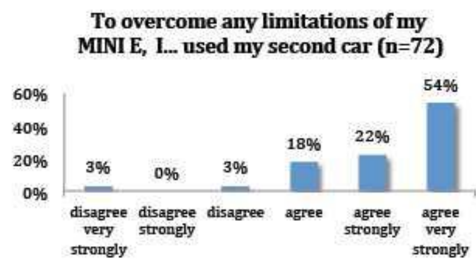


This shows that there is a lot to be done in terms of public education on the topic of electric cars. Accenture even states that their interpretation is that some people in this category overstate their level of knowledge.

Mini-E consumer study (UC-Davis)
The Mini E Consumer Study led by UC Davis, investigated consumers' opinions after a year-long trial of driving BMW's Mini E in Los Angeles and New York City[13]. As can be expected, the survey sample is by no means representative for the general U.S. population, as the only eligible people were the ones that signed up for the EV trial (a total of 235). The data was collected using online surveys, driving diaries and maps, and by interviews (by phone and in person). Some of the survey questions covered specific aspects about the driven vehicle, like the regenerative braking system. Other questions, more applicable for this study, covered range issues and daily driven miles with the vehicle.

In interesting finding is that all 72 participants of the BMW-survey agreed that electric vehicles are suitable for daily use, of which 60% agreed very strongly. In the End-of-Lease survey (n = 102) however, when asked: *'Are there any locations you would like to be able to access in your Mini E but can't or prefer not to because of range issues?'*, 81% answered *'Yes'*. And it appears that almost all (94%) participants relied on their second car, when (likely range or person-seating) limitations had to be overcome. This is an important conclusion: Even though users are content with their EV for daily use, a second car is almost a must-have in order to deal with range limitations (the seating-limitations is specific to the Mini E as it only has two seats; the rear seats are taken up by the battery). In order to get a better picture on this, the number of cars in households is taken into account in the analysis of the NHTS datasets.





4. The Range of Electric Car Ranges

Commercially available electric cars are labeled with an EPA Fuel Economy window sticker, displaying the vehicle's range as a single number of miles. As can be seen in

Table 2, the range of typical BEVs is up to 100 miles, with the Tesla models being big exceptions with driving ranges up to 300 miles.

Table 2: Overview of 2011-2012 Electric Vehicle models. Marked with an asterisk are manufacturer-estimated ranges, not rated by the EPA.

Brand	Model	EPA electric Range (miles)	EPA consumption (Wh/mile)	Type
Tesla	Roadster	245	300	BEV
Nissan	LEAF	73 (100*)	340	BEV
Mitsubishi	i-MiEV	62	300	BEV

[13] Turrentine, Thomas S., Dahlia Garas, Andy Lentz, Justin Woodjack (2011) The UC Davis MINI E Consumer Study. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-11-05. Retrieved from: http://pubs.its.ucdavis.edu/publication_detail.php?id=1470

Chevrolet	Volt	35 (electric)	360	PHEV
Fisker	Karma	32 (electric)	650	PHEV
Ford	Focus	100*	-	BEV
Tesla	Model S	160/230/300*	-	BEV
Coda	Sedan	120*	-	BEV
Smart	ED	70-80*	-	BEV

Because of various factors influencing the range of electric vehicles, it would have been much more appropriate to display a range or ranges instead of giving that single number. This paragraph aims to provide more insight into how actual range might differ from labeled range and it shows how significantly they may differ. Before we go into that, we will describe the method which is used by the EPA to determine EV ranges.

4.1 The SAE-J1634 test procedure

The range of electric vehicles is determined by the Environmental Protection Agency (EPA), following a test procedure by the Society of Automotive Engineers called 'Electric Vehicle Energy Consumption and Range Test Procedure', or: SAE-J1634. The procedure is similar to that used for determining gasoline cars' mileage, except it includes some additional practices specific to BEVs and PHEVs, regarding the battery charge, operating temperature and calculations for the range and mileage (mpg_e, explained below).

The testing is conducted as follows: the electric vehicle is fully charged, parked overnight, and then the following day driven over successive drive cycles until the battery becomes discharged and can no longer follow the driving cycle. Some vehicles enter 'limp-home' mode when the battery is almost empty (limited velocity to maximize the leftover range to reach a recharge point) and this rule implies that the EPA does not add this reserve to the vehicle's range label. After, the vehicle is recharged with a normal AC source and the energy consumption determined by dividing the kWh AC consumption by the miles driven.

The EPA currently applies the '5-cycle' method, which includes five city and highway driving cycles (FTP, HFET, US06, SC03, Cold FTP; the same cycles used for establishing mpg-ratings for conventional cars). In order to calculate mileage and range estimates, weighting factors are applied to the results of each of the driving cycles[14]. The same document states that the estimate also incorporates an additional 30% adjustment factor 'to more accurately reflect the energy consumption and driving range that customers can expect to achieve in the real world'. In other words, the range found in the tests is adjusted with a factor of 0.7.

[14] Environmental Protection Agency. (2011). *EPA Test Procedures for Electric Vehicles and Plug-in Hybrids (draft summary)*. *Fuel*. Washington, DC. Retrieved from http://www.smidgeindustriesltd.com/leaf/EPA/EPA_test_procedure_for_EVs-PHEVs-1-13-2011.pdf

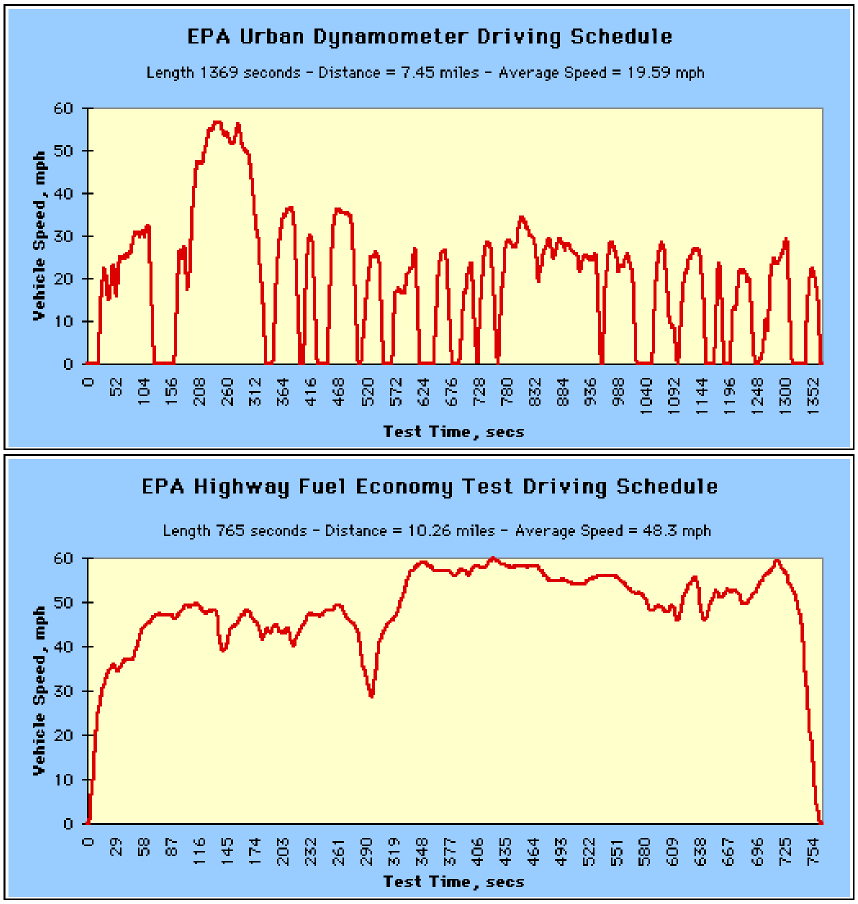


Figure 3: Two typical driving cycles used in determining fuel economy and EV range: EPA's Urban Driving Schedule, often called 'LA4 test cycle' (top) and the Highway Fuel Economy Test (bottom).

In order to compare conventional gasoline cars to alternative fuel vehicles, the EPA has introduced a metric mpg_e, miles per gallon equivalent, based on the energy content of different types of fuels. We can describe the energy content of a gallon of gasoline as 115,000 BTUs, but also in other units: 121 MJ, or 33.7 kWh. The latter comes in handy when we compare electric vehicles to gasoline cars: miles per kWh and miles per gallon.

As an example, observe the FE-label of the 2011 Nissan LEAF in Figure 4. As a result of the SAE J1634 test procedure, the LEAF was labeled 99 mpg_e. This was calculated using the following formula:

$$mpg_e = \frac{33.7\ kWh/gallon}{x\ kWh/mile}$$

Where x is the 'adjusted' AC electricity consumption divided by the miles travelled until the electric car was not able to follow the cycle any longer. x (or rather 100x) can be found on the sticker as well: 34 kWh per 100 miles.

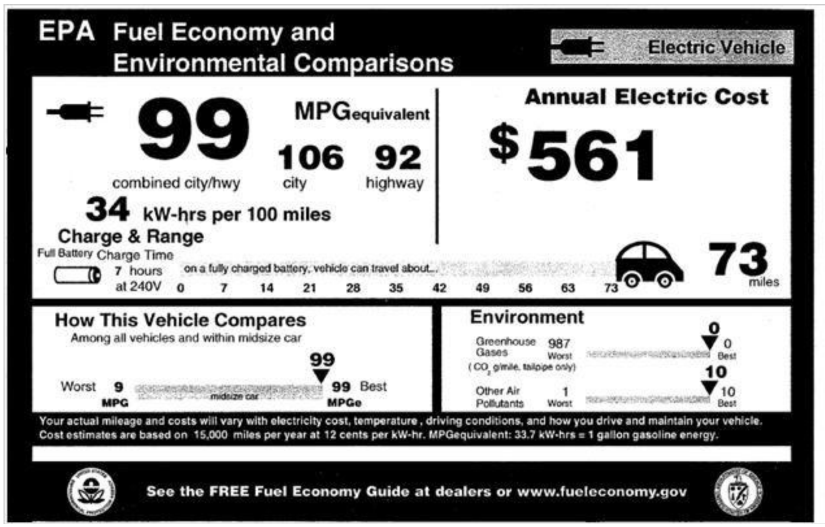


Figure 4: EPA Fuel Economy sticker for the Nissan LEAF.

Based on the displayed mpg$_e$ values of city and highway, the range would be between 78 and 68 miles, respectively. However, LEAF drivers have achieved ranges of up to 132 miles on a single charge[15]. The difference is probably a result of the 30% adjustment the EPA factors in. Nissan states a range for their LEAF between 62 and 138 miles, giving scenarios with some more insight into the driving conditions:

- Ideal driving conditions (138 miles): Constant 38 mph, climate control off.
- Suburban on a nice day (105 miles): average 24 mph, climate control off.
- EPA LA4 test cycle (100 miles): Top speed 56.7 mph, average 19.59 mph, climate control off.
- Highway in the summer (70 miles): average 55 mph, 95 degrees outside.
- Cross-town commute on a hot day (68 miles): average 49 mph, 110 degrees outside.
- Winter, urban stop-and-go (62 miles): average 15 mph, cockpit heating high.

In Figure 5, the range scenarios are plotted together with the labeled EPA Fuel Economy range. It shows that the worst-case scenario range (winter, urban stop-and-go) is 15% below the EPA labeled sticker value.

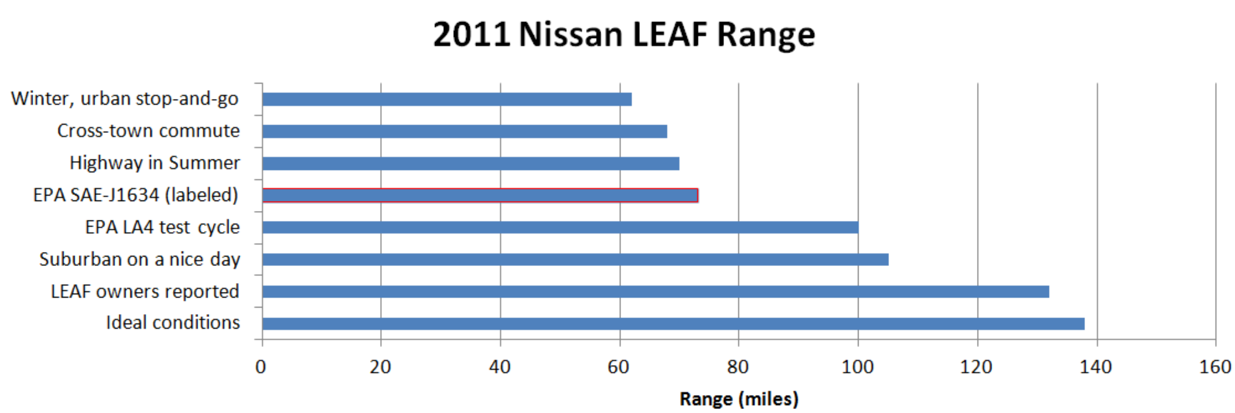


Figure 5: Range scenarios of the 2011 Nissan LEAF and the vehicle's EPA Fuel Economy sticker value (highlighted).

Given the LEAF's battery capacity of 25 kWh, the DC electricity consumption varies from 180 to 400 Wh/mile in these scenarios, over a factor of two different. With such a variety in possible ranges, it hardly

[15] http://blogs.insideline.com/roadtests/2011/05/2011-nissan-leaf-driving-it-to-the-bitter-end.html

makes sense to put a single number on an EV. Especially considering that the above scenarios are based on brand new batteries and thus do not take into account battery degradation. For future drivers, this uncertainty in expected range may be addressed by estimating EV consumption based on temperature and GPS readings from trips made in conventional gasoline cars (like an EV simulator; see 'Discussion & Future Research').

Figure 6 shows the EPA fuel economy sticker for the 2011 Tesla Roadster, displaying a 245 miles range on a single charge. The range is so much higher than the LEAF's 73 miles due to a bigger battery (56 kWh vs. 24 kWh) and better energy efficiency (300 Wh/mile vs. 340 Wh/mile). The record range driven in a Tesla Roadster (347.2 miles[16]) is 42% higher than the EPA range, compared to the LEAF's record range 132 miles, an 81% increase of the EPA label value. The interesting thing is that the LEAF record was set at a higher constant velocity than the Roadster (35 mph vs. 25 mph). Perhaps the LEAF has higher ancillary loads compared to the Roadster.

The new Model S, which will be released mid-2012, has three battery options (40, 60 and 85 kWh) and has estimated ranges of 160, 230 and 300 miles at 55 mph (note the relative difference between the battery capacities and range). Assuming the Model S EPA range resembles the manufacturer's estimates, the 15%-rule would yield a range of at least 136, 196 and 255 miles, respectively. Applying the same 1.42:1 record-to-EPA ratio from the Roadster, maximum ranges lie at approximately 227, 327 and 426 miles.

Figure 6: Fuel Economy window sticker of the Tesla Roadster.

4.2 Energy losses for EVs at constant driving velocity

It is useful to look more closely into where the battery electricity is going and what factors play a major role in the vehicle's energy consumption. A good backbone for this is a blog post of Tesla Motor's CTO, JB Straubel. He broke down the different end uses of the battery capacity consumed at different constant driving velocities for the Tesla Roadster[17].

[16] http://thephoenixsun.com/archives/11976
[17] http://www.teslamotors.com/blog/roadster-efficiency-and-range

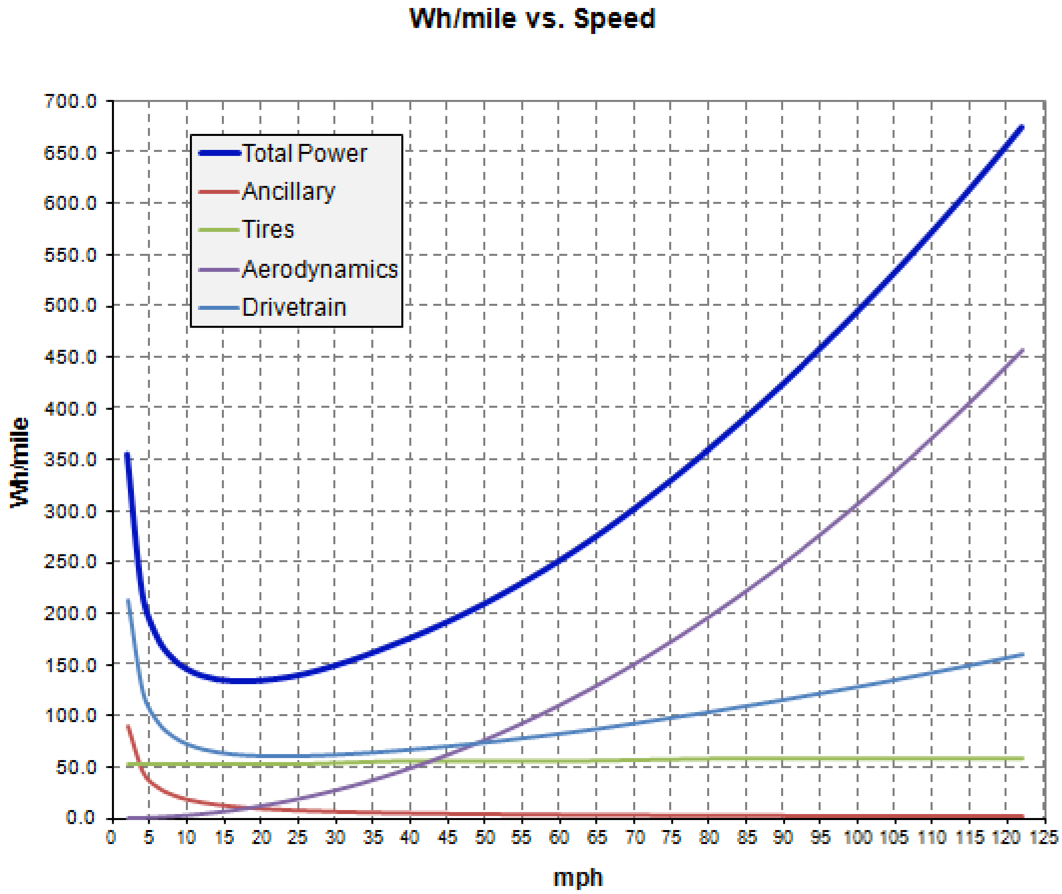


Figure 7: Tesla Roadster energy losses in Wh/mile taken from the battery. Source: Straubel, JB; "Roadster Efficiency and Range" [2].

As shown in Figure 7, Straubel reported Wh/mile losses for Aerodynamics, Drivetrain, Tires and Ancillary systems at different constant velocities for the Roadster. Aerodynamic losses are the major factor in the high velocity regime (>50 mph), as air friction is proportional to V^2. Every doubling of velocity quadruples the amount of Wh/mile in aerodynamic losses. At lower velocities the drivetrain is responsible for the majority of losses. To investigate power usage, we can convert these Wh/mile values to power (W) by multiplying each value with its respective velocity (in mi/h).

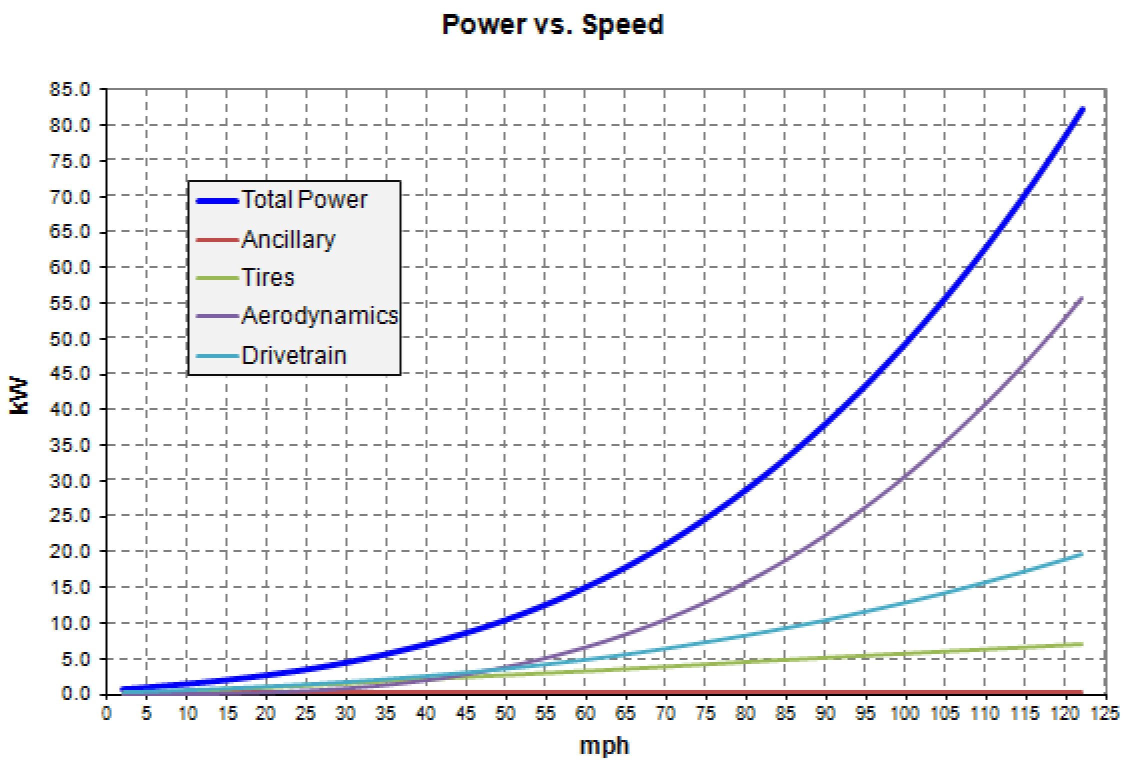


Figure 8: Power usage versus speed for the Tesla Roadster. Data source: Straubel, JB; "Roadster Efficiency and Range" [2]

Power loss groups can have a fixed and speed-dependent component. Ancillary systems only have a fixed component, as for example power usage of the A/C or audio system is independent of speed. All other losses are reportedly speed-dependent, and all except the aerodynamic losses have some fixed component to it (notice the steep slopes in Figure 7 at $V < 5$ mph). In the following, the loss groups, ordered by importance, are briefly described and their dependency on velocity is discussed:

Aerodynamics
Aerodynamic losses are important especially at high velocities. The force of air friction on an object is a vector pointing in the opposite direction of movement and it has a magnitude of F_D:

$$F_D = \frac{1}{2}\rho\, V^2 A\, C_d$$

In applying this equation to a car, ρ is the air density, V is the velocity of the car (relative to the air), A is its frontal area and C_d is the drag coefficient depending on the shape of the vehicle (the Roadster is reported to have a C_D of 0.35[18]). We can aggregate all of the constants into α_{Aer}, and multiply with V to find power losses from aerodynamics:

$$P_{Aer} = \alpha_{Aer} V^3$$

Fitting this curve to Straubel's data, we get $\alpha_{Aer} = 3.45 \times 10^{-4}$ (for power in kW). As is evident from this equation, the estimated range on a vehicle is highly dependent on the velocity at which it is driven.

[18] http://green.autoblog.com/2009/03/26/tesla-model-s-50-000-ev-sedan-seats-seven-300-mile-range-0-6/

Drivetrain

Drivetrain losses are any losses resulting from the process of converting energy in the battery into torque at the wheels of the car. These include losses in the inverter, the three-phase AC induction motor, gears, etc. Compared to the aerodynamics, drivetrain losses are more difficult to derive from simple physics equations, as the performance of the various subsystems of the vehicle need to be individually modeled. However, we can consider this as a black box and fit polynomial to the data published by Mr. Straubel:

$$P_{Dr} = \alpha_{Dr}V^3 + \beta_{Dr}V^2 + \gamma_{Dr}V + C_{Dr}$$

Constant C_{Dr} represents the power usage of the complete drivetrain system when the car is not moving, which becomes 0.375 kW. Coefficients α_{Dr}, β_{Dr}, and γ_{Dr} become $4*10^{-6}$, $5*10^{-4}$ and 0.0293, respectively.

Tires

The primary cause of rolling resistance is the effect of 'hysteresis': the energy required for deforming the tire's shape is bigger than the energy of recovery. For this reason, it is advised to regularly check the tire pressure of your car, as soft tires exhibit more hysteresis than hard tires. The power required to overcome the rolling resistance is a function of the normal force N (weight carried by the tire) and the coefficient of rolling resistance (C_{rr}), and is proportional to velocity V:

$$P_{Tire} = C_{rr}NV$$

Low rolling-resistance tires have $C_{rr} < 0.0075$, and the normal force is the curbed weight gravitational forces of the vehicle that the specific tire is carrying. With a 35/65 front/rear weight distribution for the Roadster, a C_{rr} of 0.0075 and a curbed weight of 1,235 kg, one rear wheel carries approx. 4 kN, and P_{Tires} for that single wheel becomes ~650 Watts at 50 mph. All wheels together would result in a power loss of about 2 kW, which is slightly lower than the 2.8 kW according to Straubel.

Ancillary systems

Ancillary losses are considered 'all other' electrical loads in the vehicle. Examples are user-related systems like climate control, external lights, and audio, as well as systems necessary to regulate battery temperature. In equation form for ancillary load on the battery:

$$P_{Anc} = P_{Clim.Contr.} + P_{Bat.Mngmnt} + P_{Lights} + P_{Audio}$$

All of the above are independent of velocity and therefore show up as a constant power usage in Figure 8. The P_{Anc} shown there was reported to be 0.18 kW by Straubel. However, it is important to note that the Air Condition (AC) system was assumed off. According to a report by NREL, an electric car's AC system can result in a significant range reduction[19]. With a peak AC electrical load of 3 kW, the study found a 18-38% range reduction on four different driving cycles, with the highest reduction at low velocity driving. Here, we assume that the EV has a mid-size 2 kW peak electrical load AC installed.

Also, the Tesla features a 300 Watt (peak) sound system, which could appreciably contribute to power consumption, especially if the driver is a fan of any hard-rock or metal band.

Lights are not expected to be a big contributor to power consumption, as efficient LED lights are used in new vehicles. Here it is assumed that the maximum power consumption of internal & external lights is equal to 80 Watts.

It is concluded that P_{Anc} may vary between 0.2-2.2 kW, mostly depending on the size and use of climate control. This may not seem a significant load in Figure 8, but it is when considering low driving speeds:

[19] Farrington, R. and Rugh, J., (2000). Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range. Retrieved from http://www.nrel.gov/docs/fy00osti/28960.pdf

energy consumption per mile at 20 mph would almost double, therefore cutting range in little over half compared to the AC turned off (see Figure 9). Owners of EVs should therefore be wary of stop-and-go traffic on hot summer days. Better turn on a small fan or set the AC to a moderate temperature (e.g. 85 F when ambient temperature is 110 F). Manufacturers of EVs can minimize the load on air conditioning by taking measure to decrease the heat gain from the sun. Examples are: using light colors in the vehicle's interior to increase the overall cabin albedo, special IR-reflective glazing and high R-value insulation around the compartment.

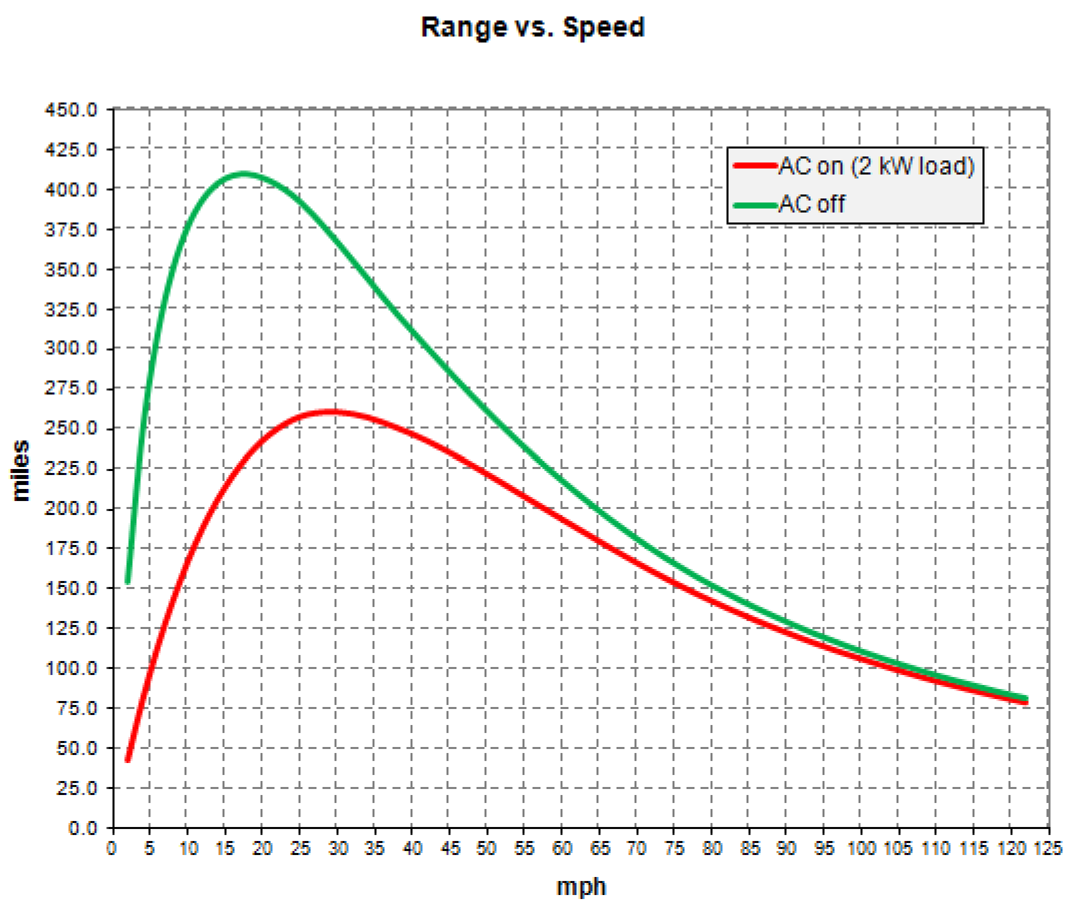


Figure 9: Effect of air-conditioning load on driving range of the Tesla Roadster. The red line represents a constant 2 kW load, as simulated by NREL[4]. Total battery capacity is 55 kWh. Data source: Straubel, JB; "Roadster Efficiency and Range" [2].

4.3 Energy losses at varying velocities

The above factors were only quantified at constant driving velocities. However, real driving conditions include acceleration and braking, respectively increasing and decreasing kinetic energy of the vehicle. In the following, it will be briefly shown how aggressive driving affects energy consumption and range.

Kinetic energy in the vehicle is stored as linear and rotational kinetic energy, where linear kinetic energy is the movement of the total car in its direction and rotational energy is stored in the rotating parts of the vehicle (primarily the wheels). The equations for these are as follows:

$$E_{kin.\ lin} = \frac{1}{2}mV^2$$

where m is the total mass of the vehicle (in kg) and V is the velocity (in m/s). Rotational kinetic energy for any rotating object is of a similar form:

$$E_{kin.\ rot} = \frac{1}{2}I\omega^2$$

with I the inertia of the rotating object (gears, wheels) and ω the radial velocity (in radians/s), which is proportional to V with one gear. Typically, rotational kinetic energy is only 5-10% of the total kinetic energy stored in a car. Because it is easier to find the total mass of the car than the inertia of its wheels and interior rotating gears, it is assumed that the total $E_{kin.} = 1.05 \cdot E_{kin.\ lin}$.

Using this relation, we can get an idea of the energy required to accelerate to a certain velocity (and the energy that needs to be dissipated to bring the car to a halt), without taking into account the other losses that were described above. Like with aerodynamic losses, we will explain that it makes sense to keep your velocity as constant as possible. Figure 10 shows the kinetic energy stored in a 1,235 kg car like the Tesla Roadster, at different velocities. The kinetic energy stored in the car at 90 mph is about 0.3 kWh, or about 0.5% of the total battery capacity on board.

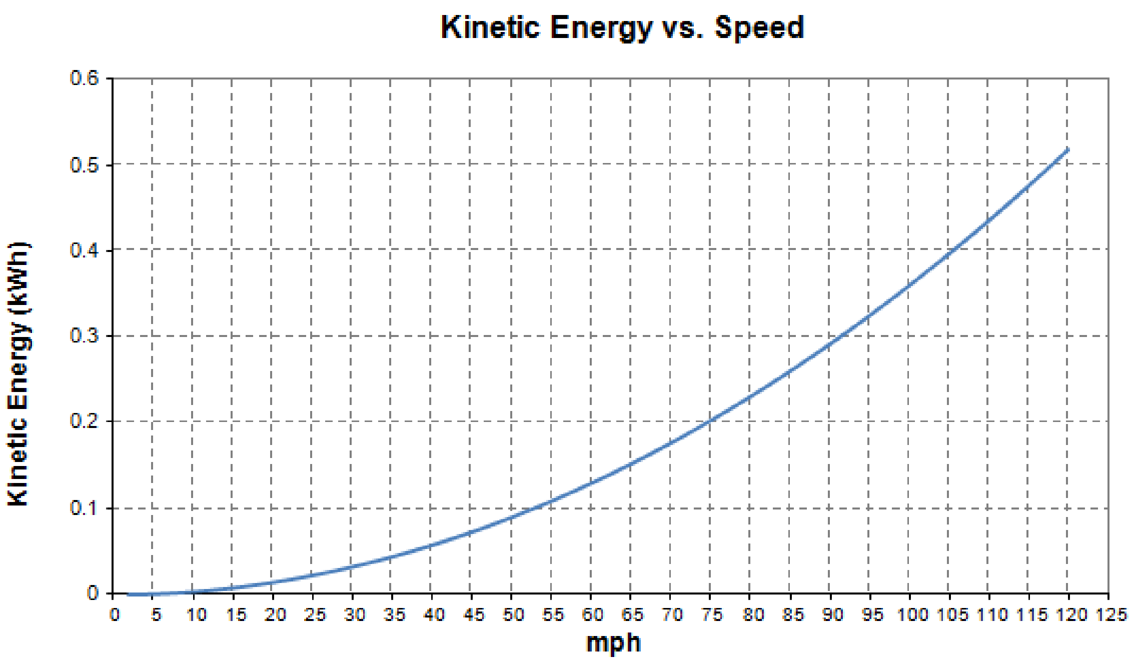


Figure 10: The kinetic energy stored in a car with curb weight of 1,235 kg as a function of driving speed. To account for rotational kinetic energy, the total kinetic energy is assumed 1.05 times the linear kinetic energy.

Even though an electric car is capable of regenerative braking (recover some of the kinetic energy and store it in the battery), most of the energy is lost as heat in the disc brakes when you stomp down hard on the brake pedal. To illustrate the difference in energy consumption for aggressive versus calm driving, consider the following example:

A Tesla Roadster (1,235 kg) is driving 1 mile behind a truck, both travelling at 50 mph on a long, single-lane road. The aggressive Tesla driver accelerates to 80 mph and 2 minutes later decelerates back to 50 when he reaches the truck, because he can't pass the vehicle. A smart driver would accelerate to 54 mph and go back to 50 when he reaches the truck (~15 minutes later). Earlier, we learned that the aggressive

driver will have a higher energy consumption per mile because of his high velocity, but now we focus on the acceleration and braking.
The battery capacity the aggressive driver consumes from accelerating is 140/0.8 = 180 Wh (80% battery-to-wheel efficiency and $E_{kin.}$= 140 Wh to accelerate from 50 to 80 mph), of which he gets 40 Wh back (assuming a 30% regenerative braking recovery efficiency for braking hard). Besides the additional losses from driving at a higher velocity, he will use an additional 100 Wh for his acceleration and braking. The smart driver will only use 18 Wh on his 50-54 mph acceleration and gets about 7 Wh back during braking (now assuming 50% efficiency), yielding a total energy use of 11 Wh, or about a tenth of what the aggressive driver is using. Again, this does not take into account the savings from driving at a lower velocity.

The above example shows how careful and anticipative driving can help increase efficiency and driving range. To maximize your range with your driving behavior:

- aim to keep your speed between 15-25 mph (but within safety limits);
- hold your velocity constant. Use cruise-control if you have it;
- prevent unnecessary hard braking and quick acceleration (anticipate!).

4.4 Other range influencing factors

In the last two paragraphs, we looked at how driving behavior influences energy consumption and possible range. Energy consumption in Wh/mile was shown to increase with driving velocity above 25 mph and aggressive braking and accelerating. Also, the use of climate control affects range significantly, especially at low traveling speeds. There are some other factors that the user often cannot control, but that will affect driving range:

- Driving route: hills may reduce range significantly;
- Battery State-of-Charge: a 'full charge' does not always mean that the batteries are 100% charged;
- Battery age: batteries degrade over time as a function of Depth-of-Discharge (DoD) and the number of cycles. Exposure to extreme temperatures is also known to accelerate degradation;
- Temperature: low ambient temperatures reduce the full charge capacity of the battery.

These factors are beyond the scope of this study and further research is needed to address them in more detail. Perhaps an equation can be developed that estimates range by incorporating all factors that influence range (planned GPS driving route, ambient temperature, use of A/C, battery age, and vehicle characteristics like curb weight, aerodynamic properties, tire pressure).

5. Methodology

To characterize driving behavior of the U.S. population, a dataset of the National Household Travel Survey 2009 was used (released Jan. 2010). The National Household Travel Survey (NHTS) provides information to assist transportation planners and others who need comprehensive data on travel and transportation patterns in the United States[20]. 150,147 households completed the NHTS between March 2008 and May 2009 and contributed data on four levels: household, person, vehicle and travel day. The data is organized in these four tables, although key variables occur in multiple tables to simplify analysis. Especially important to this study are the travel day and person tables, which include information about the covered distance on trips and the distance people commute to work.

[20] U.S. Department of Transportation. (2010). National Household Travel Survey of 2009. *2009 NHTS*. Retrieved August 2011, from http://nhts.ornl.gov/index.shtml

The NHTS data was collected with Computer Assisted Telephone Interviewing (CATI) technology that randomly dialed telephone numbers from a list of registered landline phone numbers. Besides that, the computer assigned the responding households a specific date as their 'Travel Day' on which the household members had to report all trips made using any type of transportation mode. Participants were asked to record trips in a Travel Diary that was sent to the household prior to their Travel Day. Each household received a reminder call the day before the assigned Travel Day. More information about the survey process can be found in the 2009 NHTS User's Guide[21].

The dataset was downloaded from the NHTS website and imported into SPSS 18[22]. Before the analyses were run, the data tables were preprocessed as described in the following paragraph.

5.1 Data description & preprocessing

The two primary NHTS tables used in this study are the Travel Day Dataset and the Person Dataset. A schematic overview of pre-processing steps is shown in Figure 11:

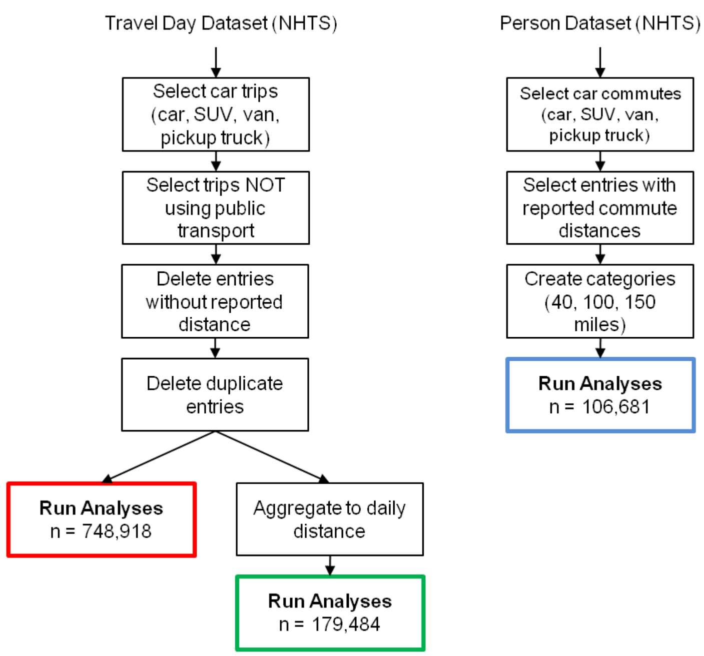


Figure 11: Schematic overview of data selection and preparation before analyses were run on distances driven.

150,147 households participated in the survey, counting 308,901 people and they owned altogether 294,409 cars. That is 1.96 cars per household. 179,484 cars (61%) were actually used on the 'Travel Day', making a total of 748,918 individual trips.

The Travel Day and Person datasets contain 103 and 111 variables respectively, of which 19 and 6 were used for analyses. The selected variable names and description are shown in the table below, with bold variables representing identifiers for either households, persons, vehicles and trips.

[21] U.S. Department of Transportation. (2011). *National Household Travel Survey User's Guide*. *Transportation* (Vol. 2011). Retrieved from http://nhts.ornl.gov/2009/pub/UsersGuideV1.pdf

[22] IBM Analytics - SPSS. (2010). SPSS. Website: http://www-01.ibm.com/software/analytics/spss/

Travel Day Dataset

Variable	**Description**
TDCASEID	Trip Number
HOUSEID	HH eight-digit ID number
HHVEHCNT	Count of HH vehicles
HHSTATE*	State HH location
MSACAT*	MSA category for the HH home address
URBRUR*	Household in urban/rural area
URBANSIZE*	Size of urban area in which home address is located
URBAN*	Home address in urbanized area
PERSONID	Person ID number
VEHID	Vehicle ID number
TRIPPURP*	General Trip Purpose
TRAVDAY*	Travel day - day of week
TRPTRANS	Transportation mode used on trip
WHYFROM*	Trip purpose for previous trip
WHYTO*	Travel day purpose of trip
WHYTRP1S*	Trip purpose summary
PUBTRANS	Respondent Used Public Transportation on trip
STRTTIME	Trip START time in military
ENDTIME	Trip END time in military
TRPMILES	Calculated Trip distance converted into miles
WTTRDFIN	Final travel day weight

Person Dataset

Variable	**Description**
HOUSEID	HH eight-digit ID number
PERSONID	Person ID number
TIMETOWK	Minutes to go from home to work last week
WRKTRANS	Transportation mode to work last week
HH_RACE*	Race of HH respondent
WTPERFIN	Final person weight

Independent control variables

Some control variables were identified and their effect on dependent variables was quantified. For example, there is a significant difference between the average trip distances for households in either an urban or rural area. Similarly, car usage patterns greatly depend on whether the travel day is a weekday or in the weekend.

Weighting factors

The weighting factors WTTRDFIN, WTHHFIN and WTPERFIN are used to account for sample representativeness in each of the three datasets: Travel Day, Household and Person. Cases that are rare in the dataset compared to their occurrence in the Census are weighted heavier than abundant cases that are relatively rare in the population. For example, wealthier families may be less likely to take part in the NHTS and could therefore be underrepresented. To compensate for this, wealthy families participating are given a higher WTHHFIN than others. Similarly, WTPERFIN in the Person dataset may compensate for a certain age-group that is underrepresented. For all weighting factors, Census data is used as a baseline.

5.2 Analyses

5.2.1 Cars per household

As was shown in Paragraph 3.2, the large majority of Mini-E drivers (94%) used their gasoline car when 'EV limitations' had to be overcome. With 100% of the participants agreeing that "EVs are suitable for daily use", it seems that they learned how to deal with the vehicle's range limitations by simply taking their gasoline car for longer trips. Thus, an important factor in the integration of EVs is the presence of an alternative conventional car in households, so that they can be used for long range trips. It is hypothesized that the implementation of sub-100-mile range EVs is more difficult in households that do not own one or more gasoline cars on the side. So how many cars do U.S. households typically own? Fortunately, this was part of the NHTS 2009. From the Vehicles dataset, cars, SUVs, vans and pickup trucks were counted per household ID and weighted with 'WTHHFIN'. The number of households without cars was calculated as: the total number of households included in the NHTS minus the unique household IDs found in the Vehicles dataset (which owned at least one car). The results were plotted in a pie-diagram.

5.2.2 Driven distance per vehicle

In order to find the driven distance per vehicle, some data entries in the travel day table had to be refined. Since every person-trip is listed in that table, duplicate entries occur when two or more household members were on a trip in the same vehicle. One of the duplicates remained in the dataset, while the other(s) were deleted.
Then, the entries with the same vehicle ID's were aggregated (summed) on trip distance to find the daily driven distance per car. This is important because it is very likely that cars will only be charged at home, at least until the EV charging infrastructure is more established at destinations like workplaces and grocery stores. Because a significant difference was found in driven distance between urban and rural households, results are displayed for both groups separately.

5.2.3 Commuting distance

Because of the fixed distance of daily commutes, and the high likelihood of charging stations being installed at parking places for employees, it is useful to find out the distribution of commuting distances. From all people surveyed, 106,681 commute to work by car. The commuting distance distribution is derived from the variable DISTTOWK from the Person dataset.

5.2.4 Car usage patterns

The variables STRTTIME, ENDTIME and TRAVDAY were used to create a car usage distribution from the Travel Day dataset. For each minute of the day, binary variables were created (bin0001 to bin1440) which were coded '1' if the vehicle was used during that minute and '0' if not. The resulting usage patterns can be of value to electric grid planners for the expected rise in system load by Electric Vehicles. Because daily usage patterns are different for weekdays and weekends, multiple characterizations were performed. The car usage pattern analysis is done for 1) weekdays and 2) weekends. It is important to make this categorization because of obvious differences in usage patterns for weekdays and weekends. Before the results could be presented, some data preparation had to be done:

- The total number of cars is defined as: the sum of all cars, SUVs, vans and pick-up trucks recorded in the NHTS 'Vehicle' dataset for households that had their travel day in one of the above categories (total: 294,409 cars). This number includes cars of households that did not use their car on the travel day.

- 1440 variables were created for every minute of the day, coded as 'bin0001' to 'bin1440'. The bins were applied to the Travel Day-dataset where only trips with cars were selected (N=748,918). Each trip will have values of '1' in the bins that lie between the start- and end-time of a trip. For example, if a car trip has STRTTIME = 7:10 and ENDTIME = 7:45, bin0431 through bin0465 are assigned value '1'.
- Finally, a 'Frequencies' syntax was run to count car usage over all minutes of the day, and the results were inverted to display cars 'parked' (thus: possibly connected to a charging station) instead of cars being driven.

6. Results

6.1 Cars per Household

As was discussed before, it is important to take into account how many vehicles a household owns when studying the implementation of EV's. An electric car is more easily integrated when the household has a conventional car available for trips that go beyond the range of the EV. Households without this luxury are more likely to consider a vehicle equipped with a range-extender (like a PHEV).

In Figure 12, a pie-diagram is shown of the breakdown of 'cars per household' from the Vehicles dataset, weighted by 'WTHHFIN'. Again, only cars, vans, SUVs and pickup trucks were selected from the dataset (294,409 out of 307,956 vehicles).

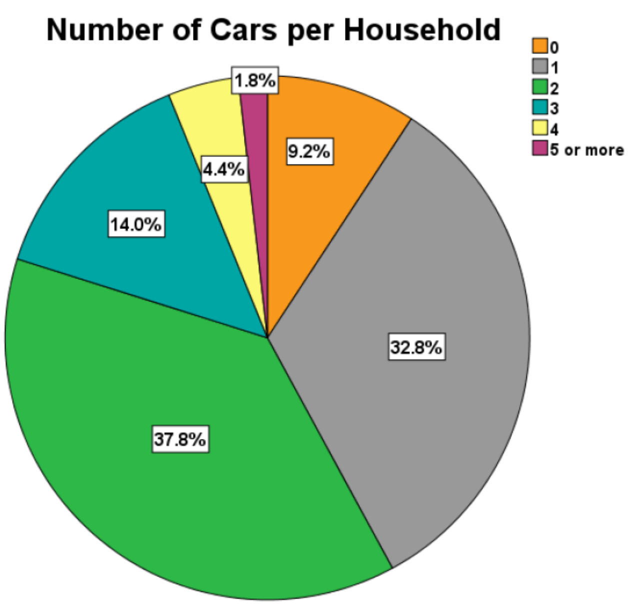


Figure 12: Number of total cars, vans, SUVs and pickup trucks per household based on 150,147 household surveyed in the NHTS 2009.

From the households that own at least one car, 64% own two or more cars. Members of these households could possibly plan for limited range of an electric car by simply assigning the gasoline car (or PHEV) to people with the need for extended range that day. The question arises whether both cars drive more than the EV's range, but this is something for future research.

6.2 Driven distance per vehicle

Now that we found out how many cars households have available, we can assess the travelled distance per vehicle from the Travel Day dataset. The length of individual trips, as well as the total travelled distance per vehicle-day was investigated. The latter is important because electric cars are likely to be charged at least once during the day (over night, at home). Because a significant difference is found between driving patterns of urban and rural households, results were also displayed for both groups separately.

6.2.1 Individual trip distance

The relative occurrence of individual car trips (one way) was found to rapidly decrease with trip distance beyond 3 miles. In fact, almost 10% of all 748,918 recorded individual car trips were shorter than a mile. Figure 13 shows a histogram with 1-mile bins for distance. There is some inaccuracy in the graph, since it appears that participants tend to round up their reported distance to 5 mile increments.

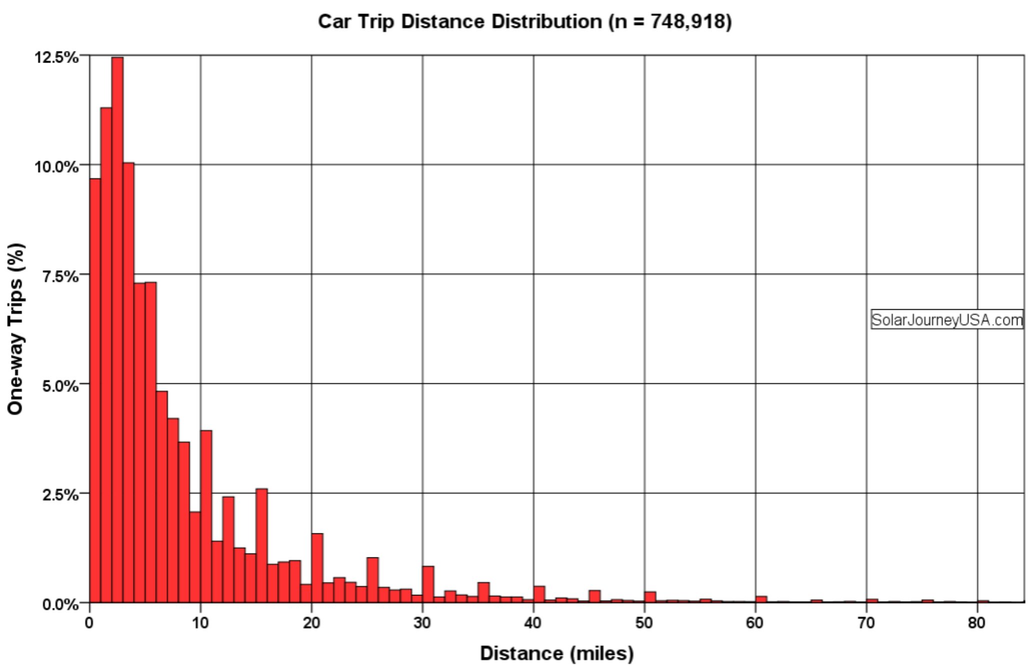


Figure 13: Individual trip distance distribution from 748,918 car trips recorded in the 2009 NHTS. Each trip is weighted with variable 'WTTRDFIN'.

Plotting the distribution of trips over a Cumulative Distribution Function (Figure 14) gives an indication of the percentage of one-way trips that can be covered by electric vehicles with a range equal to the number on the x-axis. However, underlying trip characteristics like driving speed and the use of climate control can significantly affect electricity consumption (paragraph 4). These factors are not recorded in the dataset and the use of the graph is therefore limited.

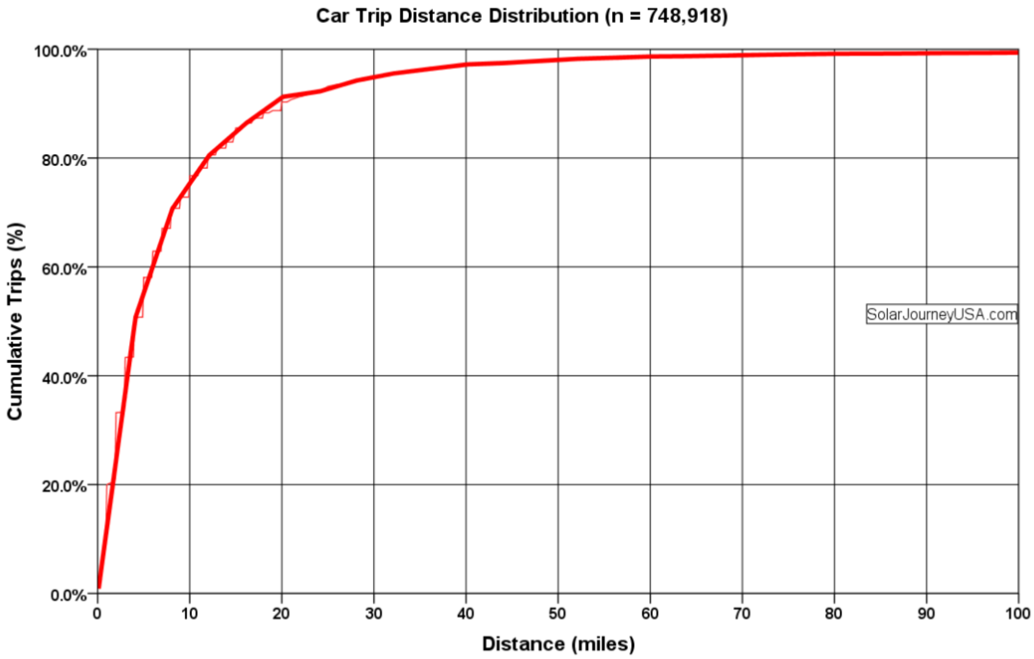


Figure 14: Cumulative distribution of driven miles per trip from 748,918 car trips recorded in the 2009 NHTS. A thick red interpolation line is drawn to hide participants' rounding evident in Figure 13.

The graph shows that 95% of trips are shorter than 30 miles, and 99% is below 70 miles. The weighted average trip distance is 9.4 miles. Vehicles owned by urban households averaged 8.5 miles and rural vehicles averaged 12.1 miles.

Overall, trips for errands, meals and school are shortest (See Table 3). Trips for recreation and work are on average the longest, with means of 15.4 and 12.1 miles, respectively. As expected, differences are found between urban and rural households: Car trips to work were found to be (weighted) 3.5 miles longer for rural households (14.8 miles) compared to urban (11.2 miles). Another interesting difference is trips to not so widely distributed services like doctors/dentists, which accounted for 2% of all recorded trips: urban cars used for this purpose travel only 8.9 miles on average, while people from rural households tend to travel almost twice as far (16.7 miles) for these services.

Table 3: Overview of purposes of car trips recorded in the NHTS 2009. Means and 95th percentile distances are given for urban, rural and all trips weighted.

Trip Purpose	All trips			Urban HH (weighted)		Rural HH (weighted)	
	Unweighted count (%)	Mean (mi)	Percentile 95 (mi)	Mean (mi)	Percentile 95 (mi)	Mean (mi)	Percentile 95 (mi)
Home	34%	9.3	30	8.2	28	12.7	39
Work	13%	12.1	36	11.2	35	14.8	41
School	4%	7	24	6.3	20	9.4	30
Medical	2%	10.7	34	8.9	27	16.7	50
Errands	22%	6.1	20	5.3	17	8.7	30
Social/Recreational	9%	15.4	50	15.2	50	15.8	55

Family/Obligations	3%	11	35	10	31	13.8	43
Transport someone	5%	7.8	26	7.1	23	10.6	34
Meals	7%	7	22	6.7	20	8.2	30
Other	0%	15.3	47	16	48	13.2	45

As was mentioned before, significant differences between States can be found for driven distances. It is hypothesized that driving distances are influenced by the:

- State being bound by regions where cars cannot go (e.g. water);
- State's size (e.g. DC);
- number of single dwellings (typically agricultural States);
- ratio of urban/rural households, or population density in general.

Studying the impact of these different factors is beyond the scope of this study and perhaps material for further research, but several interesting States can be identified where driven car distances differ significantly from the U.S. mean. One good example is Hawaii, where the State's biggest island Hawai'i measures 90 miles from tip to tip. The highly populated islands are O'ahu and Maui, both measure around 45 miles from tip to tip. The longest highway on the Island of Maui is about 60 miles long, looping around the island. From the 1,226 car trips recorded in the NHTS, 99% was shorter than 30 miles and the mean distance was 5.95 miles. Besides the favorable distances in Hawaii for the integration of EV's, the economics also make sense, as gas prices are the highest found in all of the United States.

The District of Columbia also shows low trip distances, averaging 6.5 miles, as the whole DC area is 'urban' and counts only 61 square miles. The only contributor to long car trips would be those that have destinations in neighboring States, for instance commutes to Baltimore, Maryland or perhaps trips to Philadelphia.

6.2.2 Daily driven distance

The one-way trip distance distribution may not be a good indicator of the necessary range for an electric car. This is especially true for the first years of implementation, as the charging infrastructure for EVs is limited to Level 1 and Level 2 chargers at the owners' homes. For this reason, daily driven distances for vehicles were calculated, assuming the EVs will be charged overnight. Trip distances were summed for unique Vehicle IDs and plotted in the same histogram (Figure 15) and cumulative distribution graphs (Figure 16). Note that the graphs do not include cars that were not used on the Travel Day.

Cars that were used on their Travel Day in the NHTS made an average of 4.2 trips, yielding a weighted average daily distance of 39.5 miles. The distribution of the total driven distance on the Travel Day is depicted in Figure 15.

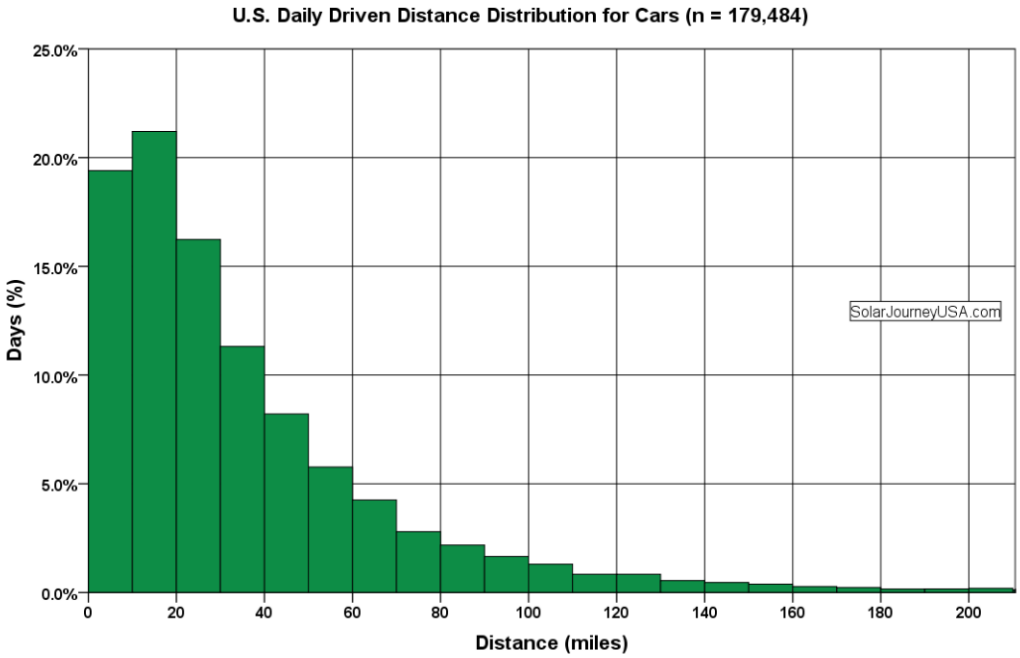


Figure 15: Distribution of daily driven distance for U.S. household cars if the car is used that day. Data source: NHTS 2009

With car trips aggregated for the Travel Day, 93% of all vehicle-days show a total distance below 100 miles and only 1.5% is above 200 miles. It is important to note that only vehicle-days are included where the cars were used that day. As was mentioned before, 39% of cars owned by the participating households were not used on the Travel Day.

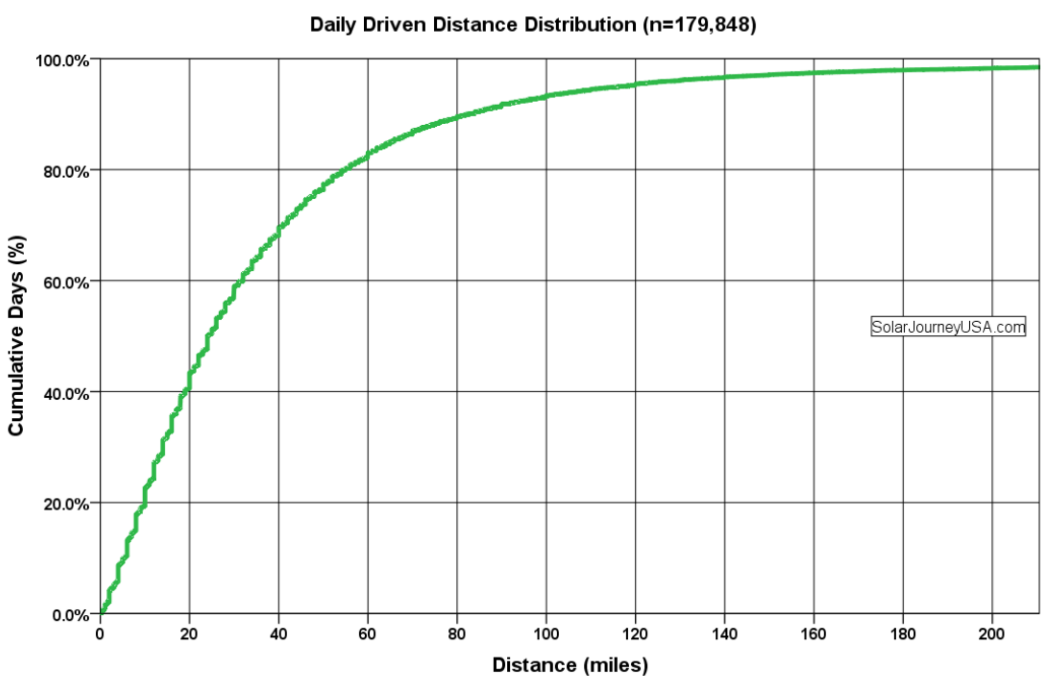


Figure 16: Cumulative distribution curve for daily driven distance by cars that were used on the Travel Day (representing 61% of all cars owned by the participating households). Data source: NHTS 2009.

Again, a significant difference was found between daily driven distance of urban and rural household owned vehicles. Urban vehicles used on the Travel Day averaged 36.5 miles and rural vehicles averaged 48.6 miles.

Vehicles from Hawaii and District of Columbia showed 99.0% and 98.1% of daily driven distances below 100 miles, with averages of 24.5 and 24.3 miles per vehicle-day. Alabama, Kansas, Missouri and Montana showed the highest driven distances per vehicle-day, with averages between 48 and 49 miles. New York, California and Texas averaged 34.8, 36.2 and 41.0 miles, respectively.

6.2.3 Commuting distances

The use of electric cars for commuting makes sense, as the daily commute is typically of fixed length and employees' parking space is likely to be one of the first places where charging stations will be installed. With the NHTS 2009 data, a distribution of commuting distances was made based on the variable DISTTOWK from the Person dataset. Again, only people are selected that commute to work by car, SUV, van or pickup truck.

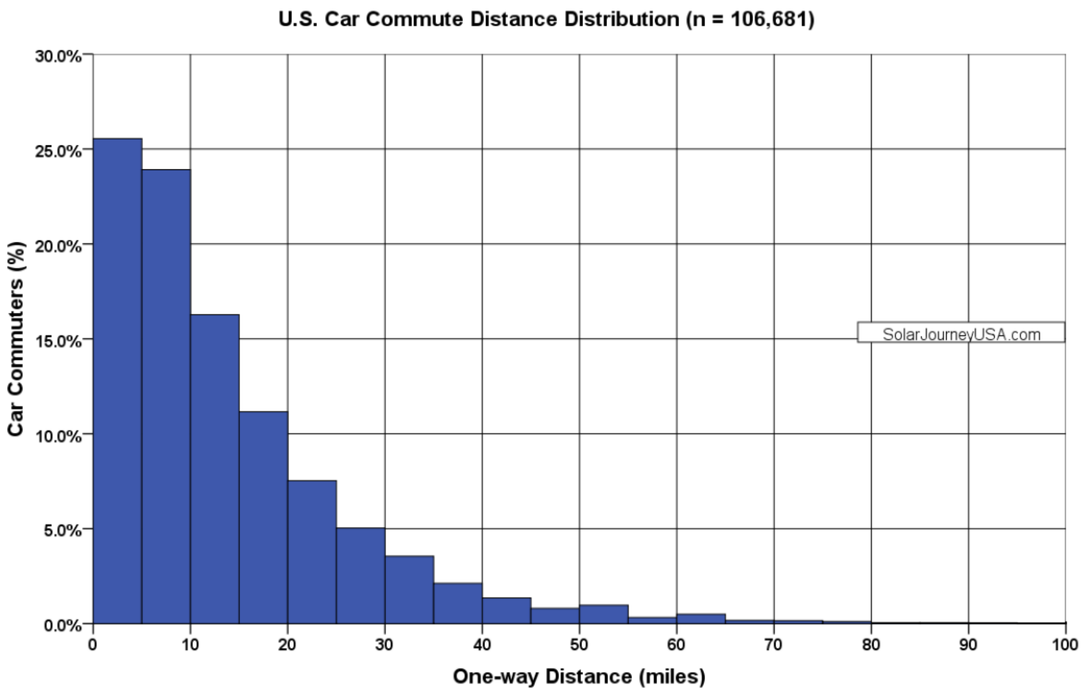


Figure 17: One-way distance distribution for commutes made by car. Data source: NHTS 2009.

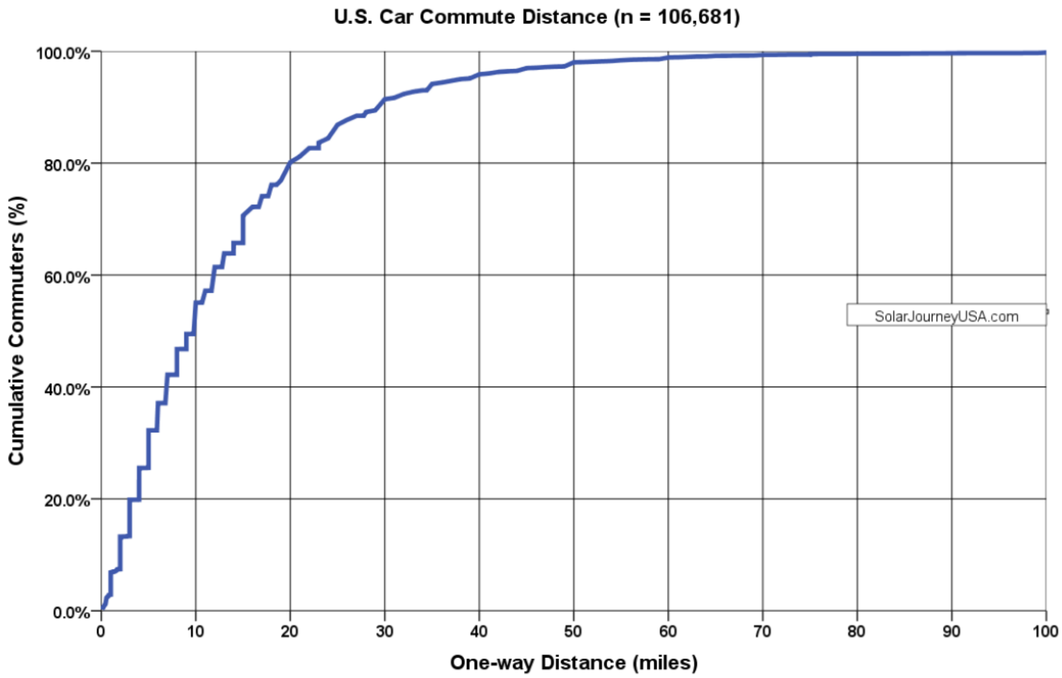


Figure 18: Cumulative distance distribution for commutes made by car. Data source: NHTS 2009.

As can be seen from Figure 18, approximately 95% of car commuters in the U.S. travel less than 40 miles to work (the weighted average is 13.6 miles). Weighted averages for States vary from 7 miles (Alaska, North & South Dakota) to 22 miles (Mississippi), although the sample sizes of these States (around 200) yields a ~10% error on a 95% confidence interval.

6.3 Car Usage Patterns

Electric cars are expected to have a significant impact on the electricity grid when they reach high penetration levels. An electric car that drives an average 40 miles per day will take approximately 14 kWh to recharge[23]. This additional load would increase average U.S. household electricity consumption (11,496 kWh/year[24]) by ~50%. The time at which this additional load is required from the grid is of great importance, as generators and transmission lines are limited to a certain capacity. With the results presented below, follow up studies can be done on EV grid integration and necessary capacity upgrades to maintain reliability of electricity supply (data can be downloaded from the website[25]).

In Figure 19, car usage patterns are displayed for each day of the week. The results are based on the car trips recorded in the NHTS Travel Day dataset, and the total number of cars owned by the surveyed households (294,409 cars, of which 61% were used on the Travel Day). For each day, around 42,000 cars are included. For each minute of the day, the number of cars in use is evaluated. Car usage ramps up on weekdays at around 4am, increasing to ~6% at 7:30am. After the morning commute, it dips back down to 4.5% at 9:30am. During the day, usage gradually increases to its daily peak (7%) at 5pm. In the evening, usage falls down steadily to 3.5% at 8pm and 1% at 10pm.

[23] Based on Nissan LEAF consumption figure: 340 Wh/mile
[24] http://205.254.135.7/tools/faqs/faq.cfm?id=97&t=3

Weekends show a different pattern, naturally without a commuting peak in the morning, but car usage peaking around lunchtime (11-12am). Throughout the daytime, car usage on Saturdays is around 1% higher than on Sundays.

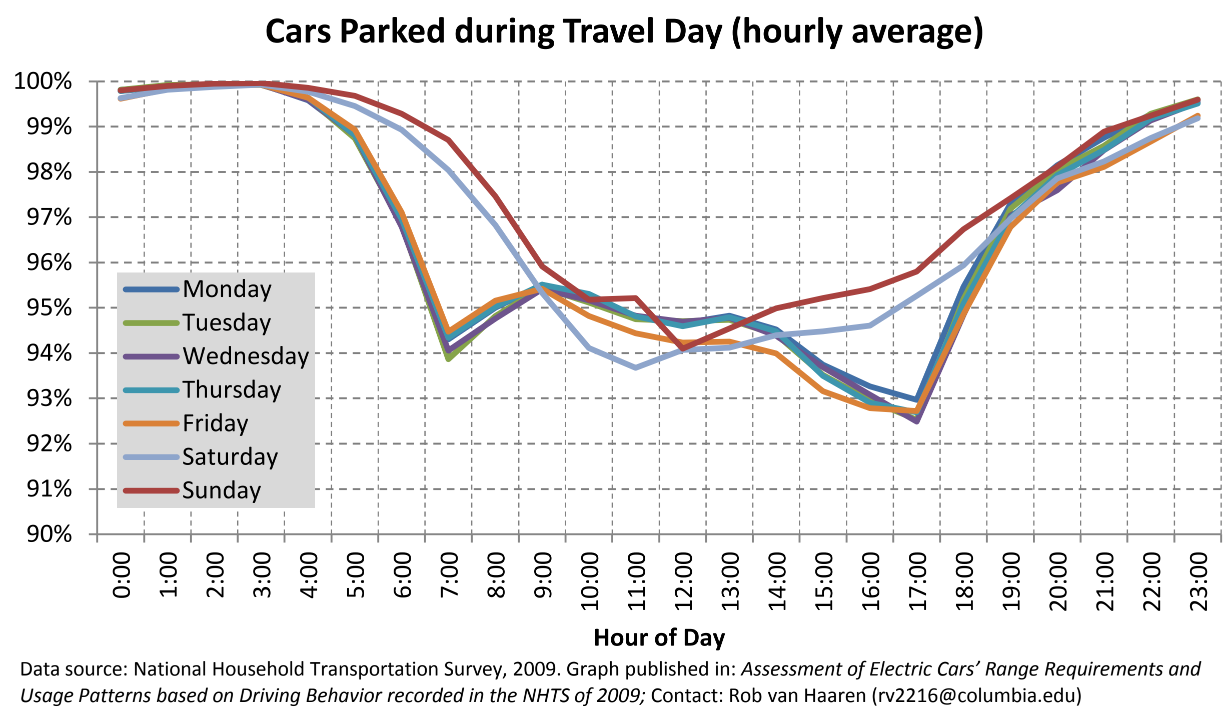


Figure 19: Car usage (parking) pattern plotted for each day of the week. Data source: NHTS 2009. For further research, data tables can be downloaded from the website[25].

Peak load for most electric operating regions happens on hot summer afternoons between 3-5pm, due to high air-conditioning loads. Due to increased EV recharging loads from commuters arriving back home, the peak is expected to shift to 5-7pm. Smart meters for recharging electric cars may assist in smoothing out this peak over the night, depending on the car requirements for the evening (errands, recreational). The raw minute-by-minute data shows bi-hourly peaks, which are likely the result of participants rounding their answers to half hour increments. Taking hourly averages of the data yielded Figure 19.

Raw data for these graphs is available from the website[25], so that research on grid integration can be performed without having to dig into the NHTS survey.

7. Conclusions

The electric car adds a new feature to the list of car specifications: 'Driving Range'. The fear of getting stranded on the side of the road with an empty battery (Range Anxiety) presents a roadblock for future buyers, and several surveys have shown that the large majority of people want a driving range far beyond what most electric cars are capable of, but also far beyond the average distance they drive. People demand freedom and comfort from their cars, so that they can go wherever they want, whenever they want.

The cause of the BEV's limitations is the relatively low energy density and high price of batteries, which limit car manufacturers to build affordable electric cars with a high range. Until battery prices come

[25] www.solarjourneyusa.com/EVdistanceAnalysis.php

down, range anxiety remains a major hurdle for buyers. Plug-in Hybrid Electric Vehicles (PHEV) do not have this problem, as they allow the driver to get more acquainted with the concept of electric driving, while having the comfort of 'unlimited range'.

Range anxiety is especially problematic because the range of an electric car is greatly affected by driving velocity, aggressive driving, as well as the use of climate control. Actual range may be ±40% of the displayed range by the manufacturer[26]. The use of different drive cycles allows for the derivation of multiple energy consumption figures and range estimates, but these are not communicated to the public; instead, a single number is used. The inclusion of a '±x miles' metric in the EV driving range specifications and more education on this topic are strongly recommended in the implementation process of Electric Vehicles.

This study attempted to give more insights into the distance people (or: vehicles) drive, using the National Household Travel Survey of 2009. From this resourceful dataset, it was found that 61% of all participating cars, SUVs, vans and pickup trucks were used on the Travel Day. For individual trips, 95% is below 30 miles and 99% is below 70 miles. When driven distance is aggregated over the whole day, it is found that ~95% is below 120 miles and 99% is below 250 miles. Car commuting distances were found to average 12.6 miles nationally, with 95% below 40 miles and 99% shorter than 60 miles. Assuming the electric car is charged overnight only, a Nissan LEAF with a 62-138 mile range would be able to satisfy 83-95% of all travel days, depending on driving conditions as described before. A 2011 Tesla Roadster would be able to satisfy >98.5% of travel days, assuming a minimum range of 0.85 times the EPA-labeled range.

Great variation was found over all States. Vehicles owned by households in districts constraint by area like Hawaii and District of Columbia were found to be driven shorter distances than others (~24 miles per day, compared to a National average of 39.5 miles per day). On the other hand, States with primarily rural areas and a large fraction of the population living in single dwellings or small towns (typically in the Midwest) averaged higher driven distances (up to 49 miles per day).

Perhaps the most important conclusion is that the majority of U.S. households have the luxury to simply pick their gasoline car in case they plan on a long trip. 64% of households that own one or more cars have the luxury of owning a gasoline car besides their future EV (assuming the EV replaces a gasoline car). Think of it as owning both a two-seater and a sedan: would you choose the two-seater if you're picking up three friends to go watch the football game? We've seen that 39% of all cars are not even used on the Travel Day. This gives rise to a new research question: 'From all cars owned by members of a household, how many vehicles drive beyond a distance of x miles on the Travel Day?'

Car usage patterns were also derived from the NHTS dataset. The percentage of cars parked during the day was found to differ between weekdays and weekends, with a minimum of 93% (5pm) and 94% (11am-12pm), respectively. The results presented in this paper can be useful to grid operators in assessing additional load from EVs connected to their system. Together with the distribution of driven distances, charging patterns can be derived and applied to models of future load scenarios in electric grid systems. Population density maps can be used to derive the locations of this additional demand in the grid. All data presented in this paper is available for download from the website[25]. Also, requests for State-specific data or other inquiries can be sent to rv2216@columbia.edu.

[26] According to Nissan, their LEAF has a range of 100 miles, but different scenarios yield a range of 62-138 miles (Paragraph 4.1).

8. Discussion & Future Research

Although the results presented in this paper are good indicators for driving behavior of a large population, they cannot be applied to individual people or households. Besides that, driving velocity, use of climate control and other range influencing factors were not captured by the survey and these were shown to greatly influence range.

Further research will focus on expanding the car usage patterns, by specifying parking spots (home, workplace) which are likely to adapt charging stations early on in the implementation process. This will increase accuracy of electricity load prediction.

In terms of range analysis, an average driving velocity may help in estimating consumption. Trips of longer distance are likely to take place on highways, therefore effectively increasing energy consumption per mile (as shown in section 4). Average velocity can be derived from the NHTS database as distance and duration are recorded for each trip. Also, additional analyses may be done on households with more than one car, as simple decisions may be made on: 'who takes the electric car today?', to assure that trips with a range beyond the EV's driving range are made by the gasoline car in the family.

Another useful expansion on Section 4 of this paper would be to build a personal 'EV range-assessment tool'. A Smartphone or GPS-device may be used to collect people's car coordinates during trips, of which the data can be used to estimate velocity and acceleration for each timestamp and consequently the EV battery consumption of the whole trip. Additional data that can be used in this model would be:

- Temperature (to estimate use of climate control);
- Elevation differences (to estimate potential energy necessary to climb hills);
- Wind velocity and direction (may add significantly to energy consumption).

This tool may help future car-buyers to assess whether an EV would fit their needs, and what range the vehicle needs to have. Also, it could estimate the payback time for the EV or PHEV and for the people who are interested, the reduction in their carbon footprint.

9. Acknowledgements

I want to thank Sander A. Mann for the discussions and brainstorm sessions we had during the start-up of this study. Ik hoop je snel weer in NYC te mogen begroeten!

10. Appendices

Below are the tables for the 'EV distance assessment' of the study. They are organized by a) Single Trip Distances, b) Daily Driven Distances and c) Car Commuting Distances.
Feel free to contact me (Rob van Haaren: rv2216@columbia.edu) if you want a specific assessment done for a State of your interest or any other request, question or comment.

Appendix A: Single Trip Distances

Tables and graphs:

Single trips: **Weighted** means and standard deviations for urban & rural:

Report

TRPMILES

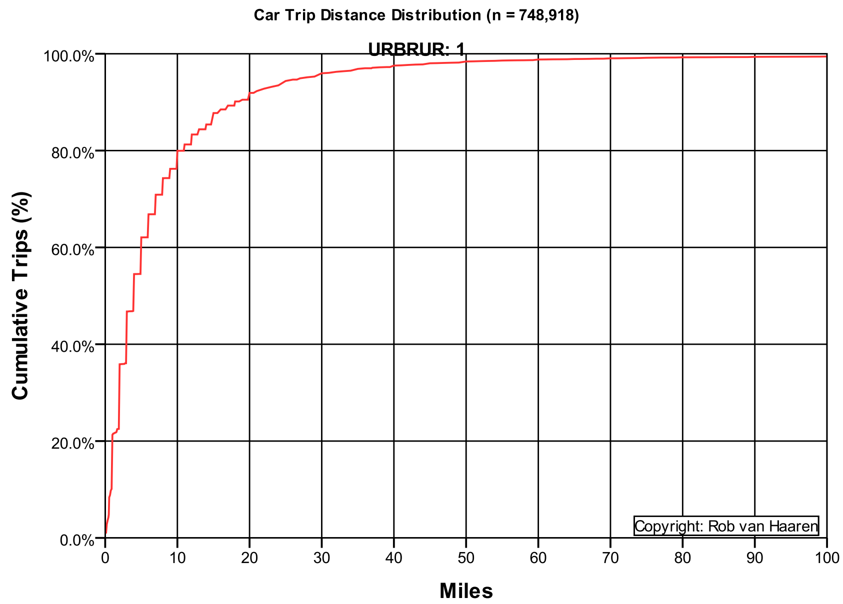
URBRUR	Mean	N	Std. Deviation
NA	11.00	313651	.00
Urban	8.55	2.E11	23.84
Rural	12.09	6.E10	23.85
Total	9.40	2.E11	23.90

Single trips: **Unweighted** means and standard deviations:

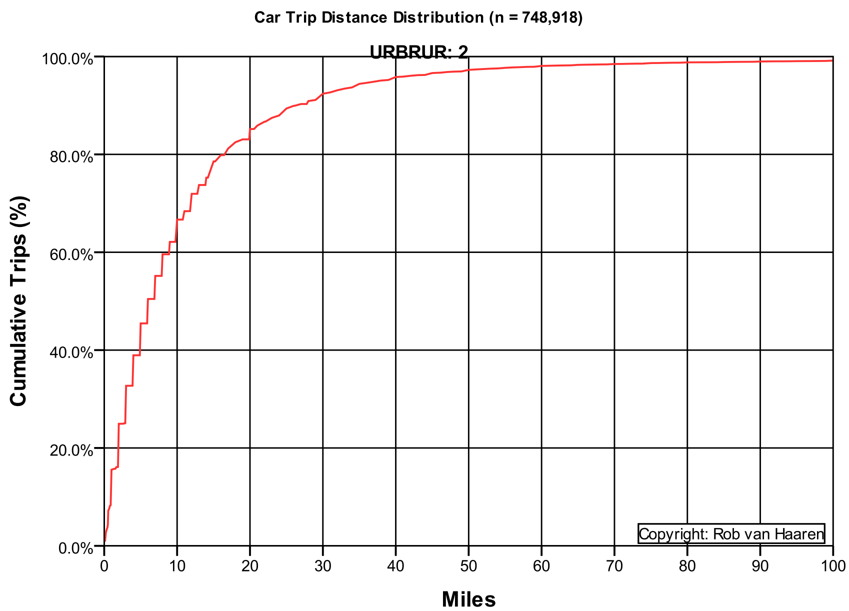
Report

TRPMILES

URBRUR	Mean	N	Std. Deviation
NA	11.00	2	.00
Urban	8.19	533065	23.15
Rural	11.48	215851	24.71
Total	9.14	748918	23.66

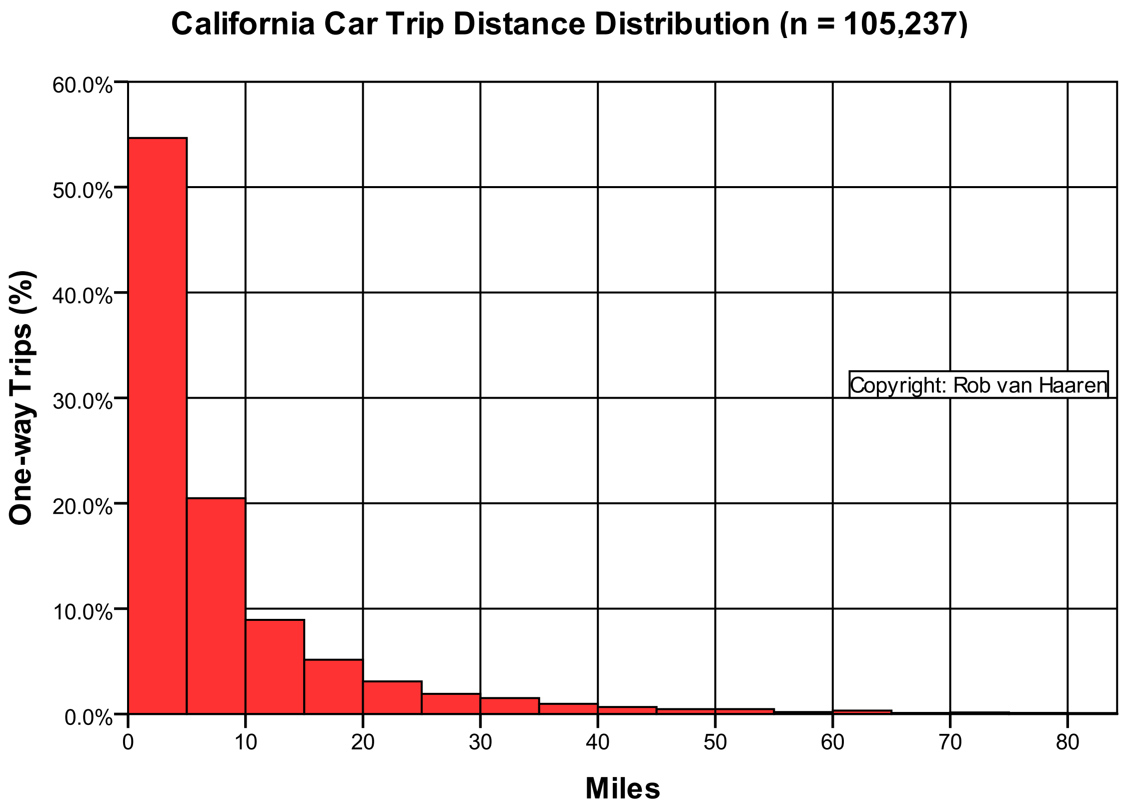

Car Trip Distance Distribution (n = 748,918)
URBRUR: 1
Cumulative Trips (%)
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
0
10
20
30
40
50
60
70
80
90
100
Miles
Copyright: Rob van Haaren

Urban:


Car Trip Distance Distribution (n = 748,918)
URBRUR: 2
Cumulative Trips (%)
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
0
10
20
30
40
50
60
70
80
90
100
Miles
Copyright: Rob van Haaren

Rural:

Example State: California Trip Distance Distribution:



Single State Range classification: What percentage of (weighted) trips are below x miles?

		Range Category (x miles)			
		40	100	150	>150
		Row N %	Row N %	Row N %	Row N %
HHSTATE	AK	98.2%	1.3%	.1%	.5%
	AL	95.1%	4.0%	.8%	.1%
	AR	96.5%	3.2%	.3%	.0%
	AZ	97.9%	1.6%	.4%	.2%
	CA	96.7%	2.7%	.3%	.2%
	CO	97.9%	1.5%	.3%	.3%
	CT	94.9%	4.6%	.5%	.1%
	DC	98.3%	1.5%	.1%	.0%

	DE	96.1%	3.2%	.6%	.0%
	FL	97.2%	2.3%	.2%	.2%
	GA	96.1%	3.1%	.4%	.4%
	HI	99.6%	.4%	.0%	.0%
	IA	97.0%	2.5%	.3%	.2%
	ID	97.5%	2.4%	.0%	.0%
	IL	97.6%	2.1%	.1%	.2%
	IN	96.9%	2.7%	.2%	.2%
	KS	95.2%	2.9%	1.1%	.8%
	KY	96.9%	2.3%	.3%	.5%
	LA	96.9%	2.3%	.0%	.8%
	MA	96.0%	3.1%	.5%	.5%
	MD	95.9%	3.1%	.3%	.7%
	ME	95.2%	3.7%	.3%	.7%
	MI	97.4%	2.2%	.1%	.3%
	MN	97.3%	1.9%	.4%	.3%
	MO	96.3%	2.9%	.2%	.6%
	MS	93.9%	5.4%	.5%	.2%
	MT	96.8%	2.2%	.2%	.8%
	NC	96.7%	2.5%	.3%	.4%
	ND	95.9%	2.6%	1.4%	.1%
	NE	96.3%	3.2%	.2%	.2%
	NH	95.7%	3.6%	.7%	.0%
	NJ	95.3%	3.7%	.4%	.6%
	NM	98.0%	1.3%	.2%	.5%
	NV	97.8%	1.1%	1.0%	.0%
	NY	97.3%	2.2%	.2%	.3%
	OH	97.0%	2.4%	.3%	.3%
	OK	95.9%	2.5%	1.0%	.7%
	OR	98.0%	1.3%	.4%	.3%
	PA	97.1%	2.0%	.3%	.5%
	RI	96.7%	2.5%	.2%	.5%
	SC	97.1%	2.4%	.3%	.2%
	SD	95.8%	3.3%	.3%	.7%
	TN	96.7%	2.5%	.3%	.5%

	TX	96.9%	2.5%	.3%	.4%
	UT	96.9%	2.8%	.1%	.2%
	VA	96.6%	2.8%	.3%	.3%
	VT	96.3%	3.2%	.3%	.3%
	WA	96.7%	2.8%	.4%	.1%
	WI	96.1%	3.0%	.5%	.5%
	WV	94.2%	4.9%	.4%	.5%
	WY	95.2%	3.6%	.8%	.3%

Single State (weighted) trip distance mean, unweighted count, 99th percentile and 95th percentile.

		Trip Miles			
		Mean	Unweighted Count	Percentile 99	Percentile 95
HHSTATE	AK	6.4565149278	1369	50.0000000000	18.0000000000
	AL	11.8892547986	2145	86.0000000000	38.0000000000
	AR	9.3967919583	1320	65.0000000000	34.0000000000
	AZ	9.5640557474	35669	77.0000000000	25.0000000000
	CA	8.6994105335	105237	70.0000000000	30.0000000000
	CO	8.7281454131	1711	60.0000000000	26.0000000000
	CT	10.3827435608	1451	90.0000000000	40.0000000000
	DC	6.5201425801	721	43.0000000000	30.0000000000
	DE	9.6832771877	1324	90.0000000000	35.0000000000
	FL	8.9707590552	73627	64.0000000000	30.0000000000
	GA	10.6676826044	36419	72.0000000000	34.0000000000
	HI	5.9527530485	1226	30.0000000000	18.0000000000
	IA	8.2608614473	20316	75.0000000000	30.0000000000
	ID	7.1562515914	1383	52.0000000000	25.0000000000
	IL	8.3818185429	4321	55.0000000000	30.0000000000
	IN	8.6939605110	18029	65.0000000000	30.0000000000
	KS	10.9361783060	1505	141.0000000000	36.0000000000
	KY	10.2643821032	1291	65.0000000000	34.0000000000
	LA	9.8715676782	1540	91.0000000000	25.0000000000

	MA	10.1471788316	2051	94.0000000000	34.0000000000
	MD	11.7393552688	1698	100.0000000000	37.0000000000
	ME	10.4736916959	1465	100.0000000000	38.0000000000
	MI	8.3403790998	3572	60.0000000000	27.0000000000
	MN	8.5227669188	1728	90.0000000000	28.0000000000
	MO	10.8324348468	2156	75.0000000000	30.0000000000
	MS	11.3549073953	1215	98.0000000000	43.0000000000
	MT	9.2435898582	1388	91.0000000000	25.0000000000
	NC	10.2209415717	56047	80.0000000000	30.0000000000
	ND	8.3260371285	1434	106.0000000000	35.0000000000
	NE	8.9174344788	7297	70.0000000000	32.0000000000
	NH	10.9550810593	1356	70.0000000000	37.0000000000
	NJ	10.5429493638	2983	102.0000000000	38.0000000000
	NM	8.0353398878	1227	70.0000000000	25.0000000000
	NV	8.4184852611	1298	115.0000000000	23.0000000000
	NY	8.5250174840	76875	67.0000000000	30.0000000000
	OH	9.3978280193	3819	70.0000000000	30.0000000000
	OK	10.2335734011	1294	146.0000000000	31.0000000000
	OR	7.6030322881	1396	65.0000000000	23.0000000000
	PA	9.4271316291	4081	80.0000000000	30.0000000000
	RI	8.6723347838	1286	62.0000000000	30.0000000000
	SC	9.8119415427	26696	70.0000000000	30.0000000000
	SD	9.4346690909	9796	87.0000000000	34.0000000000
	TN	10.3222398690	12419	76.0000000000	31.0000000000
	TX	9.7391467929	113506	75.0000000000	30.0000000000
	UT	7.6610730387	1507	50.0000000000	26.0000000000
	VA	9.9987824427	76870	71.0000000000	31.0000000000
	VT	9.6545908222	8408	69.0000000000	33.0000000000
	WA	8.5724345401	2053	59.0000000000	28.0000000000
	WI	9.7717472377	8865	95.0000000000	34.0000000000

	WV	11.2008267784	1075	75.0000000000	42.0000000000
	WY	8.5952480287	1453	110.000000000 0	38.0000000000

Single trip purpose and distance characteristics:

		Trip Miles			
		Mean	Unweighted Count	Percentile 95	Percentile 99
WHYTRP1S	Home	9.3	258097	30.0	66.0
	Work	12.1	95554	36.0	70.0
	School/Daycare/Religious	7.0	28364	24.0	50.0
	Medical/Dental Services	10.7	16503	34.0	90.0
	Shopping/Errands	6.1	163502	20.0	51.0
	Social/Recreational	15.4	67215	50.0	200.0
	Family personal business	11.0	24883	35.0	112.0
	Transport Someone	7.8	40833	26.0	64.0
	Meals	7.0	51152	22.0	65.0
	Other	15.3	2358	47.0	200.0

Appendix B: Daily Distances

Unweighted frequency of trips with one member of the household on board (= driver) and the number of household members on board of all these trips.

Indicator of each last matching case as Primary

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Passenger members	201311	20.2	20.2	20.2
	One member	796861	79.8	79.8	100.0
	Total	998172	100.0	100.0	

Unweighted means, counts and standard deviations of urban and rural vehicles for daily distance graphs:

Report

Daily Miles Driven

URBRUR	Mean	N	Std. Deviation
-9	22.00	156825	.00000
Urban	36.48	41493288622	60.86
Rural	48.58	14096513066	62.29
Total	39.55	55589958513	61.45

Weighted Daily Distance distribution by State: What percentage of days do cars drive below x miles?

		Range Category (x miles)			
		40	100	150	>150
		Row N %	Row N %	Row N %	Row N %
HHSTATE	AK	81.7%	12.9%	2.7%	2.7%
	AL	56.1%	32.2%	7.2%	4.5%
	AR	64.0%	25.5%	7.1%	3.5%
	AZ	70.4%	22.8%	3.7%	3.1%
	CA	70.4%	23.2%	3.9%	2.5%
	CO	74.4%	21.5%	1.6%	2.5%
	CT	63.1%	26.2%	6.4%	4.3%
	DC	76.5%	21.4%	2.0%	.1%
	DE	65.5%	23.7%	6.7%	4.1%
	FL	69.6%	24.8%	3.4%	2.3%
	GA	62.6%	29.8%	4.7%	2.9%

	HI	81.8%	17.2%	1.0%	.0%
	IA	70.6%	23.0%	3.7%	2.7%
	ID	74.9%	19.9%	2.9%	2.3%
	IL	68.4%	26.7%	3.1%	1.8%
	IN	70.8%	22.9%	3.6%	2.7%
	KS	65.8%	24.9%	3.9%	5.4%
	KY	62.0%	30.5%	4.0%	3.5%
	LA	73.3%	19.0%	3.5%	4.1%
	MA	67.0%	24.3%	5.0%	3.6%
	MD	60.6%	29.0%	5.0%	5.3%
	ME	62.2%	27.0%	6.6%	4.1%
	MI	67.3%	25.6%	4.8%	2.4%
	MN	75.1%	18.3%	3.6%	3.0%
	MO	70.7%	20.0%	5.7%	3.6%
	MS	55.4%	32.7%	7.8%	4.0%
	MT	75.0%	17.9%	4.1%	3.0%
	NC	66.5%	26.3%	3.5%	3.7%
	ND	72.3%	17.4%	7.0%	3.2%
	NE	71.3%	19.9%	3.8%	5.1%
	NH	59.2%	34.7%	4.6%	1.4%
	NJ	66.2%	26.4%	3.3%	4.1%
	NM	77.5%	12.4%	3.2%	6.8%
	NV	70.0%	22.6%	5.1%	2.3%
	NY	71.8%	22.7%	3.3%	2.3%
	OH	67.2%	25.9%	4.5%	2.4%
	OK	69.5%	20.0%	4.5%	6.0%
	OR	69.7%	25.9%	2.8%	1.6%
	PA	69.5%	24.2%	3.3%	3.0%
	RI	74.3%	19.0%	5.7%	.9%
	SC	63.2%	29.8%	4.5%	2.4%
	SD	73.5%	17.7%	3.9%	4.9%
	TN	62.9%	30.2%	3.9%	2.9%
	TX	66.4%	26.5%	4.0%	3.2%
	UT	70.4%	24.8%	2.8%	2.0%
	VA	65.5%	28.1%	3.7%	2.7%

VT	65.3%	27.4%	4.7%	2.6%
WA	71.3%	23.7%	3.5%	1.5%
WI	70.0%	22.6%	3.3%	4.1%
WV	64.7%	28.0%	3.1%	4.2%
WY	76.7%	13.8%	3.7%	5.8%

Weighted distribution of daily driven distances over all categories (all vehicles)

RANGECAT

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	40	37885667746	68.2	68.2	68.2
	100	13827890763	24.9	24.9	93.0
	150	2216368746	4.0	4.0	97.0
	>150	1660031259	3.0	3.0	100.0
	Total	55589958513	100.0	100.0	

		Daily Miles Driven			
		Mean	Percentile 95	Percentile 99	Count
HHSTATE	AK	28.82	102.00	235.22	123992050
	AL	48.13	134.00	285.00	918564707
	AR	40.82	123.00	181.00	476167337
	AZ	41.13	112.00	250.00	1205115585
	CA	36.22	109.00	217.00	6291615996
	CO	34.99	96.00	250.00	1053474405
	CT	44.09	148.56	246.00	703968086
	DC	24.27	65.67	146.00	55315499
	DE	42.56	139.06	214.00	172775602
	FL	36.77	104.56	213.00	3419087581
	GA	43.67	118.00	309.00	1775825743
	HI	24.53	56.00	107.00	238294312
	IA	35.06	119.22	233.00	601593530
	ID	32.10	100.56	183.22	279249839
	IL	35.89	98.00	186.00	2324711562
	IN	36.02	112.00	201.00	1248972869
	KS	48.40	150.00	647.50	563475259

	KY	40.69	131.00	235.00	867527977
	LA	43.99	124.00	267.00	826184984
	MA	39.44	121.00	214.00	1205148321
	MD	47.10	150.00	236.00	1013595214
	ME	46.97	138.00	330.00	265779633
	MI	39.27	120.00	205.00	1933126088
	MN	35.03	120.00	289.00	1007053406
	MO	48.91	122.11	575.00	1208244233
	MS	48.89	120.00	280.00	511076390
	MT	39.71	130.00	669.11	212660717
	NC	42.67	120.00	292.00	1761786667
	ND	35.94	112.33	217.00	123169964
	NE	38.86	164.00	245.11	358448247
	NH	43.66	104.00	253.00	274129695
	NJ	44.92	120.00	620.00	1631553530
	NM	39.26	197.00	273.00	342232681
	NV	36.69	126.56	236.00	426605130
	NY	34.76	105.00	220.00	2629552689
	OH	39.57	119.00	278.00	2222528759
	OK	46.88	190.00	472.00	640813392
	OR	36.91	93.00	193.44	687265765
	PA	38.67	105.00	282.00	2340685496
	RI	33.87	115.00	141.33	199929115
	SC	41.28	114.00	248.00	863018418
	SD	38.97	129.44	372.00	158612032
	TN	43.44	119.00	315.00	1205697472
	TX	41.00	118.00	264.00	4355822096
	UT	35.90	99.56	160.22	464458402
	VA	40.08	114.00	233.00	1505269940
	VT	39.40	120.00	238.67	124398620
	WA	34.44	96.00	192.61	1213066655
	WI	39.55	132.00	276.00	1105960831
	WV	43.89	117.89	261.00	342095678
	WY	37.66	152.89	334.00	110260313

		Daily Miles Driven			
		Mean	Percentile 95	Percentile 99	Count
HHSTATE	AK	29.72	87.00	180.00	306
	AL	39.68	116.00	240.00	521
	AR	37.84	123.00	175.89	321
	AZ	34.34	91.00	232.22	8495
	CA	36.07	108.00	220.00	25264
	CO	38.16	111.00	284.00	402
	CT	42.99	141.56	246.00	339
	DC	21.89	65.67	146.00	177
	DE	39.16	118.00	214.00	302
	FL	35.86	104.00	230.00	17956
	GA	42.65	126.00	298.11	8858
	HI	24.34	62.22	127.00	299
	IA	34.15	116.00	270.00	4733
	ID	33.15	112.00	186.56	314
	IL	35.83	111.00	239.00	996
	IN	35.95	108.56	211.00	4351
	KS	42.68	137.11	288.00	334
	KY	42.43	135.00	307.00	317
	LA	45.88	126.11	267.00	352
	MA	36.45	118.00	216.00	505
	MD	44.10	132.00	244.00	430
	ME	44.33	138.00	267.00	342
	MI	38.94	127.00	226.00	802
	MN	36.56	121.00	289.00	411
	MO	42.20	122.00	370.44	498
	MS	44.47	124.00	315.00	286
	MT	37.79	131.00	300.00	319
	NC	38.95	114.00	261.00	13401
	ND	37.52	147.33	255.00	331
	NE	33.55	96.00	300.00	1708
	NH	44.54	121.00	318.00	331
	NJ	39.01	110.00	237.00	712
	NM	34.53	153.22	273.00	281

	NV	35.43	126.56	210.00	317
	NY	37.62	116.00	235.22	18339
	OH	37.96	106.67	236.00	888
	OK	44.21	165.00	320.00	291
	OR	34.10	103.56	193.44	313
	PA	36.47	102.00	288.56	1000
	RI	36.08	115.00	180.00	307
	SC	38.69	110.00	278.00	6363
	SD	32.45	104.00	266.00	2277
	TN	42.41	123.00	300.00	3027
	TX	41.18	123.00	290.00	26711
	UT	37.09	108.00	351.00	334
	VA	39.26	120.00	255.00	18985
	VT	40.50	122.00	259.00	2072
	WA	35.87	107.67	224.00	488
	WI	40.12	140.00	293.00	2161
	WV	45.78	165.00	290.00	286
	WY	40.29	165.00	400.00	331

Appendix C: Car Commuting Distances

Note: Only commuting distances are included where people drive with their car to work.

Statistic metrics describing weighted car commute distribution (unweighted count= 106,681):

Statistics

DISTTOWK

N	Valid	113437855
	Missing	0
Mean		13.57
Median		10.00
Mode		5.00
Percentiles	95	38.00
	99	63.00

Frequency table of car commuting distance:

DISTTOWK

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.1111	221736	.2	.2	.2
	.2222	609795	.5	.5	.7
	.3333	229964	.2	.2	.9
	.4444	312079	.3	.3	1.2
	.5555	1291823	1.1	1.1	2.3
	.6666	134470	.1	.1	2.5
	.7777	376337	.3	.3	2.8
	.8888	55425	.0	.0	2.8
	.9999	43206	.0	.0	2.9
	1.0000	4516964	4.0	4.0	6.9
	1.1110	66589	.1	.1	6.9
	1.2221	6646	.0	.0	6.9
	1.3332	100080	.1	.1	7.0
	1.4443	10444	.0	.0	7.0
	1.5554	106663	.1	.1	7.1
	1.6665	318636	.3	.3	7.4
	1.7776	7141	.0	.0	7.4

1.8887	32179	.0	.0	7.4
1.9998	5078	.0	.0	7.4
2.0000	6579308	5.8	5.8	13.2
2.1109	2259	.0	.0	13.2
2.2220	18155	.0	.0	13.3
2.3331	139	.0	.0	13.3
2.4442	1825	.0	.0	13.3
2.5553	4762	.0	.0	13.3
2.6664	5355	.0	.0	13.3
2.7775	83413	.1	.1	13.3
2.8886	507	.0	.0	13.3
2.9997	4673	.0	.0	13.4
3.0000	7347634	6.5	6.5	19.8
3.1108	411	.0	.0	19.8
3.2219	207	.0	.0	19.8
3.3330	4227	.0	.0	19.8
3.4441	783	.0	.0	19.8
3.5552	890	.0	.0	19.8
3.6663	3866	.0	.0	19.8
3.7774	434	.0	.0	19.8
3.8885	33849	.0	.0	19.9
3.9996	104	.0	.0	19.9
4.0000	6409961	5.7	5.7	25.5
4.3329	49	.0	.0	25.5
4.4440	12181	.0	.0	25.5
4.5551	83	.0	.0	25.5
4.6662	1448	.0	.0	25.5
4.7773	206	.0	.0	25.5
4.9995	19080	.0	.0	25.5
5.0000	7590960	6.7	6.7	32.2
5.2217	591	.0	.0	32.2
5.3328	872	.0	.0	32.2
5.4439	83	.0	.0	32.2
5.5550	1205	.0	.0	32.2
5.6661	904	.0	.0	32.2
5.7772	4558	.0	.0	32.2

5.8883	294	.0	.0	32.2
6.0000	5514128	4.9	4.9	37.1
6.1105	4386	.0	.0	37.1
6.5549	247	.0	.0	37.1
6.6660	476	.0	.0	37.1
6.7771	617	.0	.0	37.1
7.0000	5747043	5.1	5.1	42.2
7.1104	285	.0	.0	42.2
7.2215	3150	.0	.0	42.2
7.3326	237	.0	.0	42.2
7.4437	696	.0	.0	42.2
7.7770	1511	.0	.0	42.2
7.8881	15	.0	.0	42.2
7.9992	918	.0	.0	42.2
8.0000	5192864	4.6	4.6	46.8
8.1103	180	.0	.0	46.8
8.3325	12414	.0	.0	46.8
8.5547	369	.0	.0	46.8
8.9991	365	.0	.0	46.8
9.0000	3047007	2.7	2.7	49.5
9.1102	1002	.0	.0	49.5
9.4435	457	.0	.0	49.5
9.6657	2212	.0	.0	49.5
9.7768	122	.0	.0	49.5
10.0000	6354909	5.6	5.6	55.1
10.5545	1201	.0	.0	55.1
10.6656	89	.0	.0	55.1
11.0000	2405656	2.1	2.1	57.2
11.2211	184	.0	.0	57.2
11.4433	476	.0	.0	57.2
11.6655	1114	.0	.0	57.2
12.0000	4806222	4.2	4.2	61.4
12.4432	819	.0	.0	61.4
12.5543	93	.0	.0	61.4
12.7765	145	.0	.0	61.4
13.0000	2753020	2.4	2.4	63.9

13.5542	49	.0	.0	63.9
13.7764	11850	.0	.0	63.9
13.8875	171	.0	.0	63.9
13.9986	1793	.0	.0	63.9
14.0000	2118578	1.9	1.9	65.7
14.9985	38	.0	.0	65.7
15.0000	5537242	4.9	4.9	70.6
16.0000	1772522	1.6	1.6	72.2
16.1095	631	.0	.0	72.2
16.6650	508	.0	.0	72.2
17.0000	2186710	1.9	1.9	74.1
17.6649	83	.0	.0	74.1
18.0000	2286792	2.0	2.0	76.1
18.5537	1577	.0	.0	76.1
19.0000	873066	.8	.8	76.9
20.0000	3692910	3.3	3.3	80.1
21.0000	1162725	1.0	1.0	81.2
22.0000	1717337	1.5	1.5	82.7
22.9977	87	.0	.0	82.7
23.0000	1098755	1.0	1.0	83.7
24.0000	869532	.8	.8	84.4
25.0000	2762210	2.4	2.4	86.9
26.0000	971183	.9	.9	87.7
27.0000	843056	.7	.7	88.5
27.7750	558	.0	.0	88.5
28.0000	746047	.7	.7	89.1
29.0000	385117	.3	.3	89.5
30.0000	2234496	2.0	2.0	91.4
31.0000	269144	.2	.2	91.7
32.0000	794393	.7	.7	92.4
33.0000	442378	.4	.4	92.8
34.0000	284295	.3	.3	93.0
34.4410	1368	.0	.0	93.0
35.0000	1306376	1.2	1.2	94.2
36.0000	275936	.2	.2	94.4
37.0000	335228	.3	.3	94.7

38.0000	351875	.3	.3	95.0
39.0000	138204	.1	.1	95.1
40.0000	840433	.7	.7	95.9
41.0000	174095	.2	.2	96.0
42.0000	302707	.3	.3	96.3
43.0000	127113	.1	.1	96.4
44.0000	88508	.1	.1	96.5
45.0000	564883	.5	.5	97.0
46.0000	71086	.1	.1	97.0
47.0000	126831	.1	.1	97.2
48.0000	95879	.1	.1	97.2
49.0000	50675	.0	.0	97.3
50.0000	842264	.7	.7	98.0
51.0000	43756	.0	.0	98.1
52.0000	72267	.1	.1	98.1
53.0000	73699	.1	.1	98.2
54.0000	65407	.1	.1	98.2
55.0000	161867	.1	.1	98.4
56.0000	100078	.1	.1	98.5
57.0000	42510	.0	.0	98.5
58.0000	44624	.0	.0	98.6
59.0000	19602	.0	.0	98.6
60.0000	357193	.3	.3	98.9
61.0000	35732	.0	.0	98.9
62.0000	75862	.1	.1	99.0
63.0000	79244	.1	.1	99.1
64.0000	12930	.0	.0	99.1
65.0000	122946	.1	.1	99.2
66.0000	12994	.0	.0	99.2
67.0000	30699	.0	.0	99.2
68.0000	22343	.0	.0	99.2
69.0000	9142	.0	.0	99.2
70.0000	117250	.1	.1	99.3
71.0000	10760	.0	.0	99.4
72.0000	22180	.0	.0	99.4
73.0000	20382	.0	.0	99.4

74.0000	8901	.0	.0	99.4
74.9925	75	.0	.0	99.4
75.0000	84468	.1	.1	99.5
76.0000	34398	.0	.0	99.5
77.0000	152	.0	.0	99.5
78.0000	6263	.0	.0	99.5
79.0000	1669	.0	.0	99.5
80.0000	39798	.0	.0	99.5
81.0000	5882	.0	.0	99.6
82.0000	8002	.0	.0	99.6
83.0000	2396	.0	.0	99.6
84.0000	902	.0	.0	99.6
85.0000	16532	.0	.0	99.6
86.0000	21882	.0	.0	99.6
87.0000	9684	.0	.0	99.6
88.0000	6569	.0	.0	99.6
89.0000	1695	.0	.0	99.6
90.0000	24640	.0	.0	99.6
91.0000	17546	.0	.0	99.6
92.0000	5311	.0	.0	99.7
93.0000	5364	.0	.0	99.7
94.0000	2171	.0	.0	99.7
95.0000	1569	.0	.0	99.7
96.0000	1025	.0	.0	99.7
97.0000	2326	.0	.0	99.7
98.0000	16519	.0	.0	99.7
99.0000	2738	.0	.0	99.7
100.0000	98544	.1	.1	99.8
101.0000	2048	.0	.0	99.8
102.0000	1615	.0	.0	99.8
103.0000	3392	.0	.0	99.8
104.0000	6435	.0	.0	99.8
105.0000	3497	.0	.0	99.8
106.0000	1841	.0	.0	99.8
107.0000	739	.0	.0	99.8
108.0000	791	.0	.0	99.8

109.0000	115	.0	.0	99.8
110.0000	10047	.0	.0	99.8
111.0000	4573	.0	.0	99.8
112.0000	445	.0	.0	99.8
113.0000	440	.0	.0	99.8
114.0000	2591	.0	.0	99.8
115.0000	3115	.0	.0	99.8
116.0000	246	.0	.0	99.8
117.0000	11145	.0	.0	99.8
118.0000	868	.0	.0	99.8
119.0000	430	.0	.0	99.8
120.0000	22521	.0	.0	99.8
121.0000	4430	.0	.0	99.8
122.0000	1788	.0	.0	99.8
124.0000	379	.0	.0	99.8
125.0000	11690	.0	.0	99.9
>125	Rest	.1	.1	100.0
Total	113437855	100.0	100.0	

Weighted Mean, 95th percentile and 99th percentile of distance to commute to work by State:

		DISTTOWK (miles)			
		Mean	Percentile 95	Percentile 99	Unweighted Count
HHSTATE	AK	7.4824	24.0000	45.0000	228
	AL	19.5608	50.0000	91.0000	294
	AR	15.1937	36.0000	104.0000	181
	AZ	12.6065	30.0000	65.0000	4854
	CA	13.6707	40.0000	70.0000	14796
	CO	12.9874	35.0000	60.0000	237
	CT	13.2196	35.0000	87.0000	217
	DC	9.6452	35.0000	40.0000	95
	DE	12.5252	35.0000	75.0000	172
	FL	12.9138	35.0000	60.0000	9267

	GA	16.2197	45.0000	70.0000	5103
	HI	8.6320	27.0000	36.0000	180
	IA	12.1108	38.0000	60.0000	3261
	ID	9.6558	29.0000	45.0000	165
	IL	12.8642	35.0000	50.0000	597
	IN	12.5838	39.0000	61.0000	2784
	KS	13.1190	35.0000	90.0000	209
	KY	15.2169	50.0000	150.0000	185
	LA	11.7221	41.0000	60.0000	212
	MA	14.5051	46.0000	60.0000	313
	MD	15.7638	42.0000	50.0000	292
	ME	12.6941	40.0000	61.0000	205
	MI	14.7553	50.0000	60.0000	463
	MN	14.1781	36.0000	63.0000	273
	MO	13.7313	35.0000	60.0000	288
	MS	22.0347	65.0000	100.0000	150
	MT	10.0599	34.0000	60.0000	199
	NC	14.0728	36.0000	70.0000	7669
	ND	7.3877	30.0000	47.0000	237
	NE	12.2022	30.0000	42.0000	1203
	NH	14.9794	37.0000	62.0000	223
	NJ	15.1583	42.0000	75.0000	436
	NM	10.5457	37.0000	40.0000	134
	NV	9.9717	25.0000	60.0000	193
	NY	12.9754	36.0000	62.0000	11393
	OH	12.9374	33.0000	56.0000	538
	OK	12.4100	35.0000	63.0000	189
	OR	10.0530	25.0000	50.0000	189
	PA	12.1452	32.0000	59.0000	632
	RI	14.0635	45.0000	60.0000	182
	SC	13.9825	36.0000	65.0000	3476
	SD	8.8979	30.0000	56.0000	1676
	TN	14.0456	37.0000	51.0000	1814
	TX	13.9517	37.0000	65.0000	15884
	UT	12.4468	47.0000	50.0000	205

	VA	15.0975	40.0000	65.0000	11683
	VT	14.5857	40.0000	90.0000	1381
	WA	10.6950	30.0000	54.0000	297
	WI	12.4670	35.0000	60.0000	1469
	WV	17.1131	47.0000	60.0000	149
	WY	9.8139	40.0000	100.0000	209

Overview of weighted range categories for commuting: What percentage of people drives to work over a distance shorter than x miles? (note the 'unweighted count' column in the table above for sample representativeness):

		Range Category (miles)			
		40	100	150	>150
		Row N %	Row N %	Row N %	Row N %
HHSTATE	AK	98.0%	2.0%	.0%	.0%
	AL	88.9%	10.8%	.3%	.0%
	AR	95.1%	3.9%	1.0%	.0%
	AZ	97.7%	2.1%	.1%	.0%
	CA	94.3%	5.3%	.3%	.1%
	CO	95.5%	4.5%	.0%	.0%
	CT	96.2%	3.1%	.7%	.0%
	DC	95.2%	4.8%	.0%	.0%
	DE	97.2%	2.8%	.1%	.0%
	FL	96.0%	3.9%	.1%	.0%
	GA	93.0%	6.3%	.5%	.2%
	HI	100.0%	.0%	.0%	.0%
	IA	95.9%	3.8%	.3%	.0%
	ID	98.3%	1.7%	.0%	.0%
	IL	95.9%	4.0%	.0%	.1%
	IN	95.2%	4.7%	.1%	.0%
	KS	97.0%	2.3%	.7%	.0%
	KY	92.1%	6.5%	.0%	1.4%
	LA	94.4%	5.4%	.0%	.1%
	MA	94.2%	5.6%	.1%	.0%
	MD	94.4%	5.6%	.0%	.0%
	ME	94.2%	5.8%	.0%	.0%

	MI	92.8%	7.0%	.2%	.0%
	MN	95.5%	4.1%	.0%	.4%
	MO	95.8%	4.2%	.0%	.0%
	MS	82.9%	15.3%	1.3%	.5%
	MT	96.0%	4.0%	.0%	.0%
	NC	95.9%	3.8%	.2%	.1%
	ND	97.9%	2.1%	.0%	.0%
	NE	97.8%	1.5%	.0%	.6%
	NH	95.3%	4.7%	.0%	.0%
	NJ	93.3%	5.8%	.8%	.1%
	NM	96.5%	3.5%	.0%	.0%
	NV	98.3%	1.7%	.0%	.0%
	NY	95.6%	4.1%	.1%	.1%
	OH	96.8%	3.2%	.0%	.0%
	OK	95.7%	3.6%	.7%	.0%
	OR	98.7%	1.1%	.0%	.2%
	PA	96.5%	3.0%	.6%	.0%
	RI	94.2%	5.3%	.0%	.5%
	SC	95.9%	3.8%	.2%	.2%
	SD	96.9%	2.9%	.0%	.2%
	TN	95.5%	4.4%	.0%	.1%
	TX	95.5%	4.1%	.2%	.2%
	UT	95.0%	5.0%	.0%	.0%
	VA	94.1%	5.6%	.1%	.2%
	VT	94.4%	5.1%	.0%	.5%
	WA	97.6%	2.4%	.0%	.0%
	WI	96.6%	3.0%	.3%	.0%
	WV	87.0%	12.7%	.0%	.4%
	WY	94.8%	4.2%	1.1%	.0%