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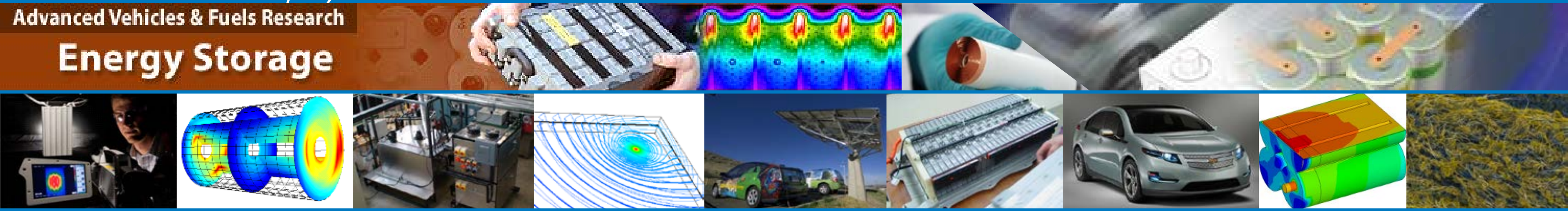
Project Milestone: Analysis of Range Extension Techniques for Battery Electric Vehicles



Jeremy Neubauer, Eric Wood, Ahmad Pesaran
Center for Transportation Technologies and Systems
National Renewable Energy Laboratory

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Foreword

This report documents completion of the July 2013 milestone as part of NREL's Vehicle Technologies Annual Operating Plan with the U.S. Department of Energy. The objective was to perform analysis on range extension techniques for battery electric vehicles (BEVs).

This work represents a significant advancement over previous thru-life BEV analyses using NREL's Battery Ownership Model, FastSim,* and DRIVE.* Herein, the ability of different charging infrastructure to increase achievable travel of BEVs in response to real-world, year-long travel histories is assessed. Effects of battery and cabin thermal response to local climate, battery degradation, and vehicle auxiliary loads are captured. The results reveal the conditions under which different public infrastructure options are most effective, and encourage continued study of fast charging and electric roadway scenarios.

The Energy Storage Program of the DOE Vehicle Technologies Office funded this work. We wish to thank our sponsors David Howell and Brian Cunningham in the DOE Office of Vehicle Technologies.

Ahmad Pesaran
Energy Storage Group Manager, NREL
(303) 275-4441
ahmad.pesaran@nrel.gov

** Developed by NREL's Vehicle Systems Analysis team*

Executive Summary

- Battery Ownership Model (BOM) development was initiated in FY10 and completed in FY11 to evaluate the techno-economic analysis of different battery ownership strategies for battery electric vehicles (BEVs).

- In FY13, we performed extensive model upgrades of BOM to enable higher resolution analyses via:
  - Addition of vehicle cabin and battery thermal models
  - Climate data for 100 cities
  - Additional real-world driver data to capture the effects of aggression and seasonality in trip taking
  - An upgraded equivalent-circuit battery model.

- We have applied this model to study the effects of different range extending infrastructure options on BEV utility herein.

- Our findings show that:
  - At-home level 1 charging is nearly as good as at-home level 2 charging on average, and sometimes better due to increased battery degradation with level 2 charging.
  - Adding at-work charging yields big gains for select commuters, but few to no gains for most commuters. Changing our driver profile toward more "range anxiety" may significantly change this conclusion, however.
  - Ubiquitous level 2 charging can increase average year-10 BEV utility from 83% to 90% for likely drivers without behavior change when compared to home-only charging.
  - When infrastructure access is universally accessible, the advantage of 50 kW fast charging over level 2 charging is marginalized.
  - Fast charging has the potential to enable 100% utility factors for many drivers when behavior is responsive to infrastructure availability, though further analysis is necessary to accurately quantify this potential.
  - Additional analysis of roadway electrification is merited.

Motivation, Objective, and Outline

Motivation

Our FY12 work has shown that the limited range of a BEV can result in a high amount of unachievable travel for some drivers. Not only does this incur high financial cost to the driver, but it also results in significant consumption of gasoline when alternative transport is employed. Several technologies have the capability to increase the utility of BEVs, reducing gasoline consumption and potentially total cost as well.

Objective: Quantify the ability of varied charging infrastructure (home, work, public (including fast charging), and roadway electrification) to increase achievable travel of BEVs under real-world conditions.

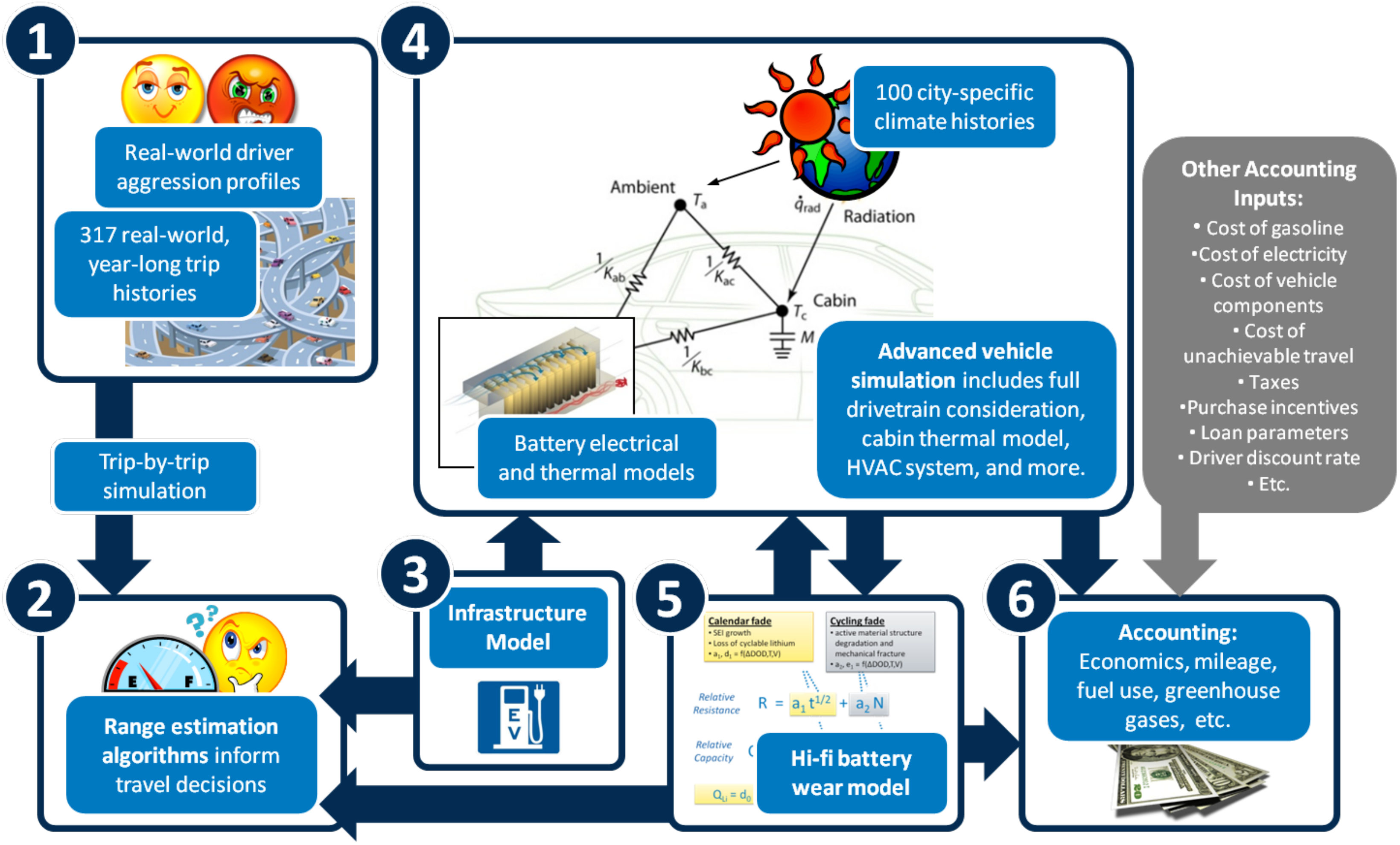
Outline

- Part 1: Simulation and assumptions
- Part 2: Results
- Part 3: Comparisons with previous studies
- Part 4: Conclusions and future work.

Part 1: Simulation and Assumptions

Battery Ownership Model (BOM) V3

Major FY13 upgrades: New language (Matlab), higher driving pattern resolution, battery and cabin thermal models, inclusion of cabin HVAC and battery Thermal Management System (TMS), improved battery electrical model, and more.



Real-world driver aggression profiles

317 real-world, year-long trip histories

Trip-by-trip simulation

Range estimation algorithms inform travel decisions

Infrastructure Model

100 city-specific climate histories

Battery electrical and thermal models

Advanced vehicle simulation includes full drivetrain consideration, cabin thermal model, HVAC system, and more.

Hi-fi battery wear model

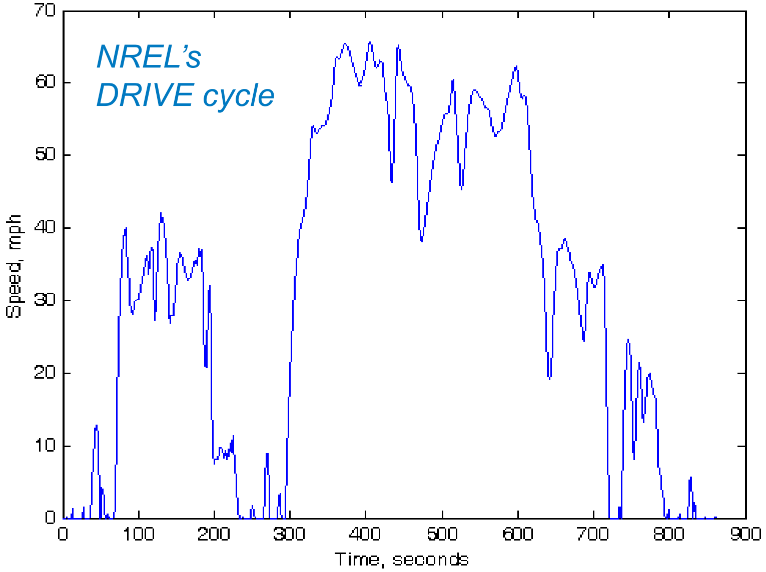
Other Accounting Inputs:

- Cost of gasoline
- Cost of electricity
- Cost of vehicle components
- Cost of unachievable travel
- Taxes
- Purchase incentives
- Loan parameters
- Driver discount rate
- Etc.

Accounting: Economics, mileage, fuel use, greenhouse gases, etc.

Vehicle Design and Efficiency

- **Employed NREL's DRIVE cycle for real-world efficiency prediction**
  - The DRIVE cycle was created by applying NREL's DRIVE tool (developed by the NREL Vehicle Systems Analysis team) to a set of 2,000+ real-world day-long vehicle records to create a speed vs. time history representative of actual driver behavior.
  - For more information, see: Neubauer, J.; Wood, E. (2013). "Accounting for the Variation of Driver Aggression in the Simulation of Conventional and Advanced Vehicles." Presented at SAE 2013 World Congress & Exhibition, April 16: http://papers.sae.org/2013-01-1453/.
  - Note: does not account for grade.



- **Assumed a year 2020 mid-size sedan for the vehicle platform**

- **Applied FastSim to design specific drivetrains**
  - FastSim is a vehicle simulation tool developed by NREL's Vehicle Systems Analysis team
  - Note: We applied a 300 W aux load for EPA-based sizing, but removed the aux load for DRIVE efficiency calculation. Aux loads were then added as appropriate within the BOM simulations.

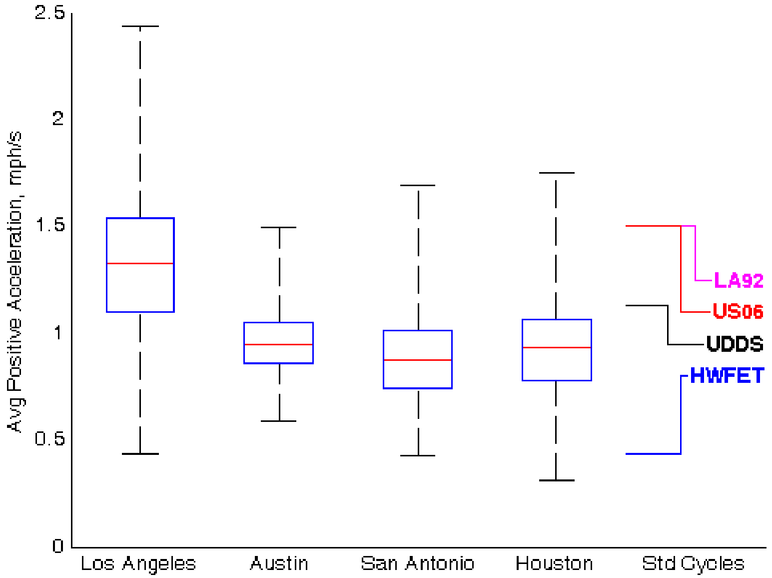
Vehicle 1:
9 sec 0-60 mph
75 mile EPA range
22.1 kWh battery
106 kW motor
1576 kg curb weight
220 Wh/mi on DRIVE cycle w/o aux.

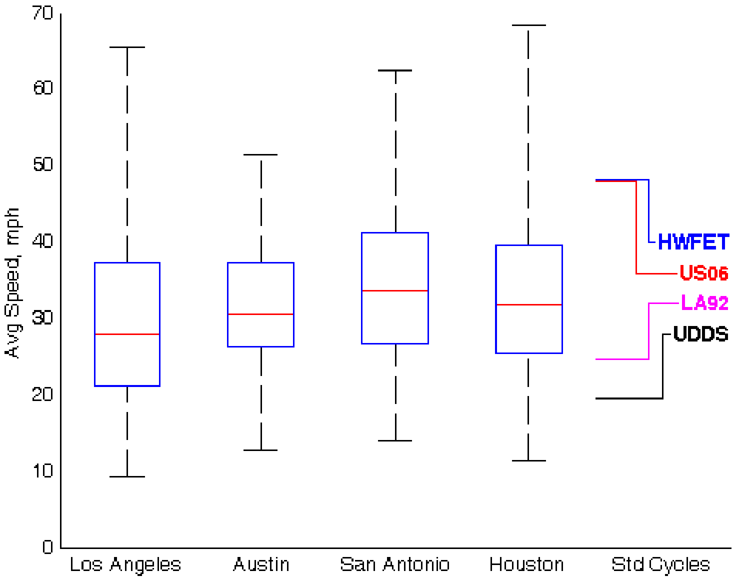
Real-World Driving Data: Aggression

- Real-world, high-accuracy, and high-resolution vehicular velocity histories are needed to predict the actual on-road variation in vehicle efficiencies of different driver and powertrain combinations

- 2,154 unique vehicle records (spanning 1-2 days each) were sourced from the NREL Transportation Secure Data Center—a composite of data from Los Angeles, CA; Austin, TX; San Antonio, TX; and Houston, TX travel studies

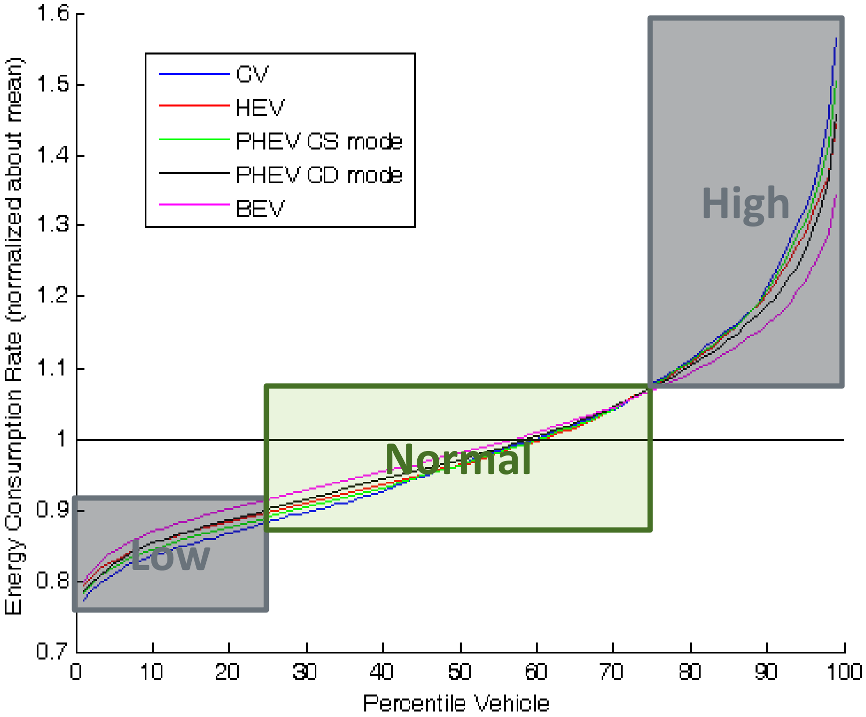
- The data were recorded using on-board global positioning system data acquisition systems filtered down to second-by-second acceleration and velocity histories.





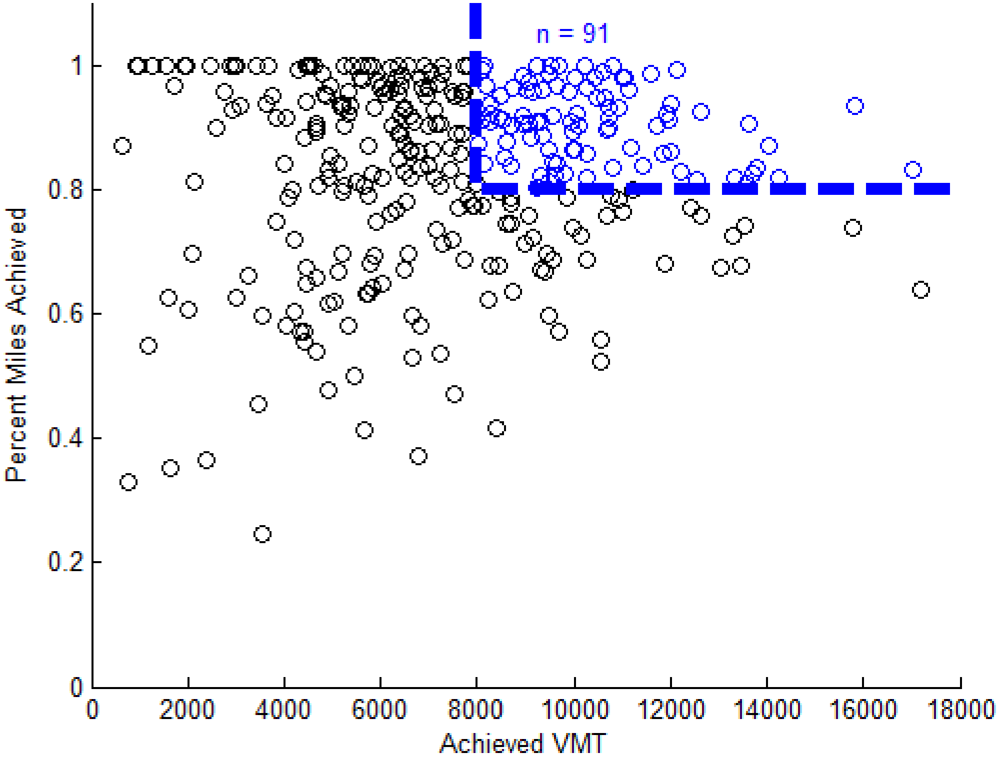
Segmenting Driver Aggression Levels

- Normalized energy consumption rates show the variation in consumption (y-axis) as a function of the level of aggression within our data sample (x-axis)
- We segmented the data into three groups: low aggression (0-25th percentile), normal aggression (25th-75th percentile), and high aggression (75th to 100th percentile)
- Average value from **normal** segment used to weight result of consumption predicted by DRIVE cycle for this study
- Similar process employed for weighting battery RMS power, used to predict battery thermal response.



Real-World Driving Data: Trip Distribution Set A

- **317 vehicle-specific, year-long data records were pulled from the Puget Sound Regional Councils Traffic Choices Study**
  - Records selected based on availability of 365 consecutive days of data without significant error
- **Not all drivers are likely to purchase BEVs; total mileage and percent-achievable mileage may be good indicators of likely BEV drivers**
- **We chose to analyze drive patterns that meet the following criteria:**
  - 80% of their year-one driving is achievable with the BEV *without infrastructure support*
  - More than 8,000 miles are achieved with the BEV in year one
- **With these criteria, 91 of 317 (29%) drivers were selected as stand-alone BEV drivers (shown in blue).**

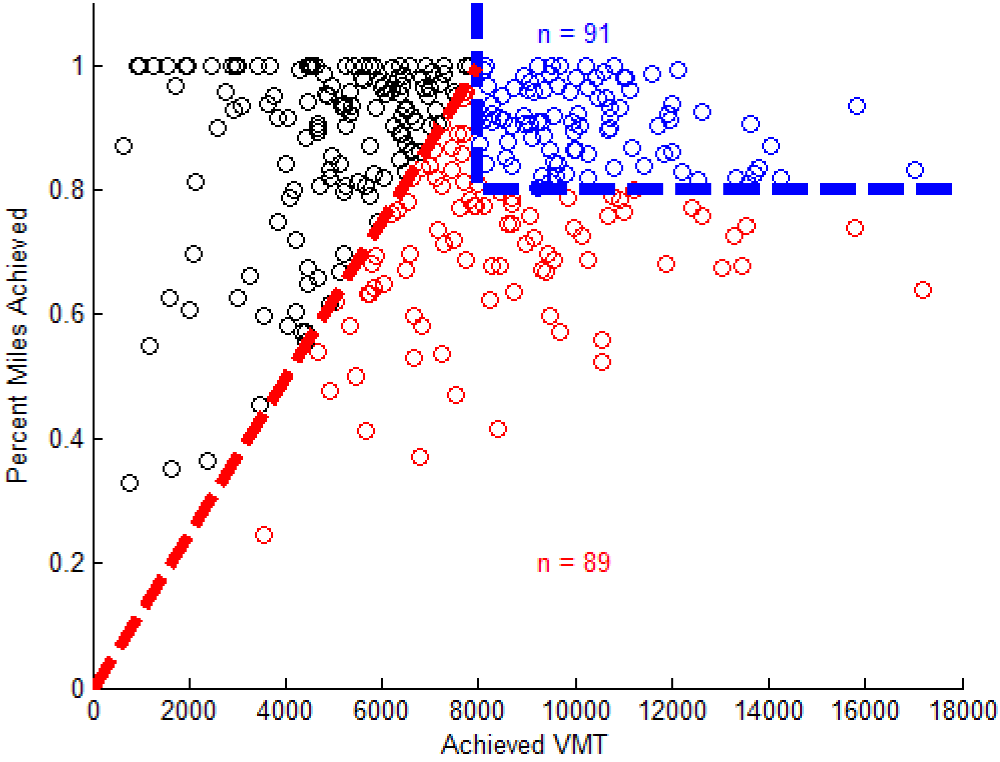


Real-World Driving Data: Trip Distribution Set B

- **The previous 80% utility factor counts out some high mileage drivers that could benefit from infrastructure**

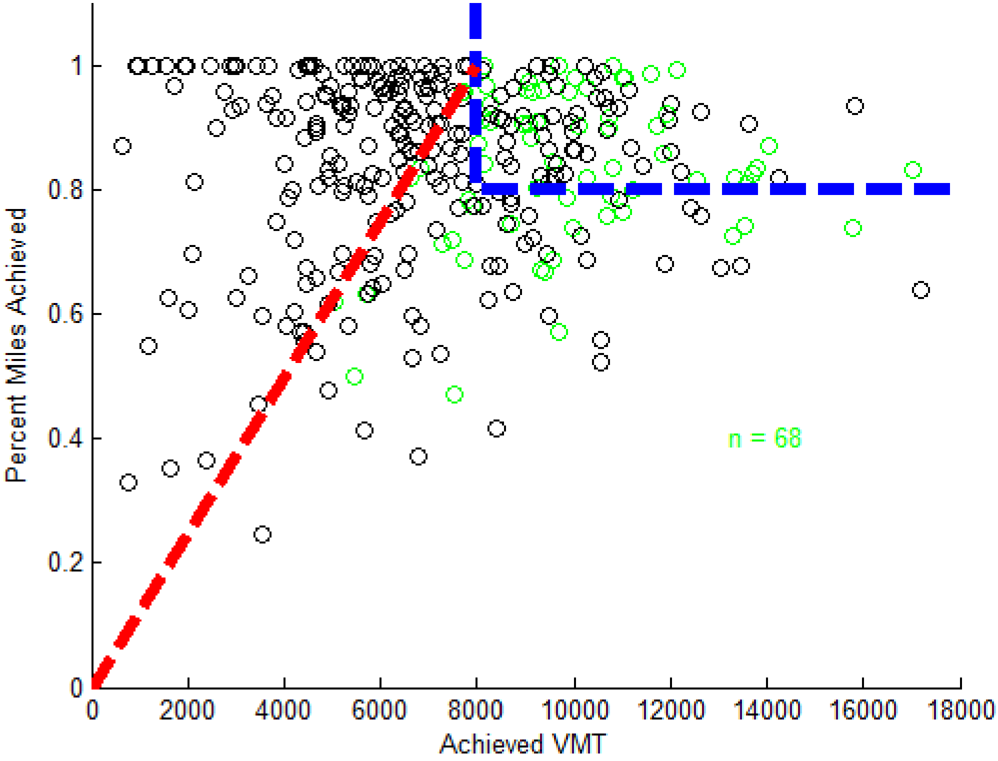
- **We therefore created and added a second set of drive patterns that met the following criteria:**
    - Not included in Set A
    - More than 8,000 miles per year are driven with a CV

- **With these criteria, an additional 89 of 317 (28%) drivers were selected (shown in red).**



Real-World Driving Data: Trip Distribution Set C

- **"C" is for "Commuter"**
- **We segmented a third set of drive patterns that met the following criteria:**
    - More than 8,000 miles per year are driven with a CV
    - More than 200 days per year with a trip to work
- **With these criteria, a total of 68 of 317 (21%) drivers were selected as commuters (shown in green).**



Tour Decisions

- **Tour = a sequence of trips that begins and ends at home**
- **Before each tour was taken, we calculated the expected vehicle range remaining at the end of the upcoming tour**
  - Calculated average vehicle efficiency (Wh/mi) observed over the past 100 trips
  - Assumed perfect knowledge of tour distance to compute required tour energy
  - Assumed perfect knowledge of battery health to calculate remaining range after tour
- **If the predicted remaining vehicle range was > 5 miles, the tour was taken; if not, the entire tour was counted as unachieved VMT**
- **Note:** The small (5 mile) range buffer, perfect tour knowledge, and perfect battery health knowledge made this process representative of a best-case **"bold-informed"** BEV driver.

Small range buffer

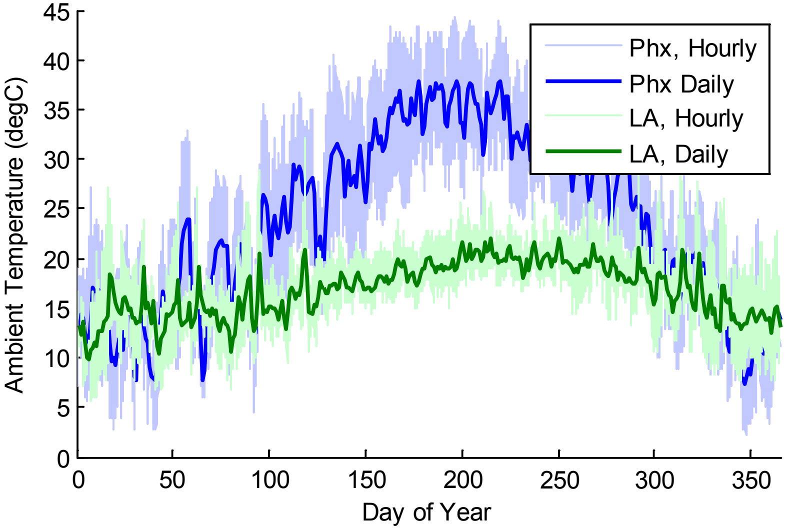
Good knowledge of vehicle efficiency, tour distance, and battery health

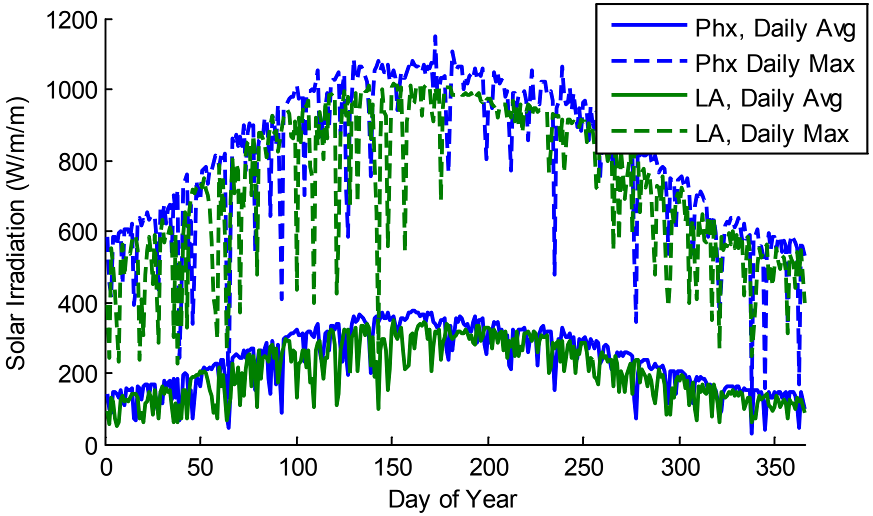
Other combinations of **"anxious"** and **"uninformed"** drivers would not perform as well.

Large range buffer

Poor knowledge of vehicle efficiency, tour distance, and battery health

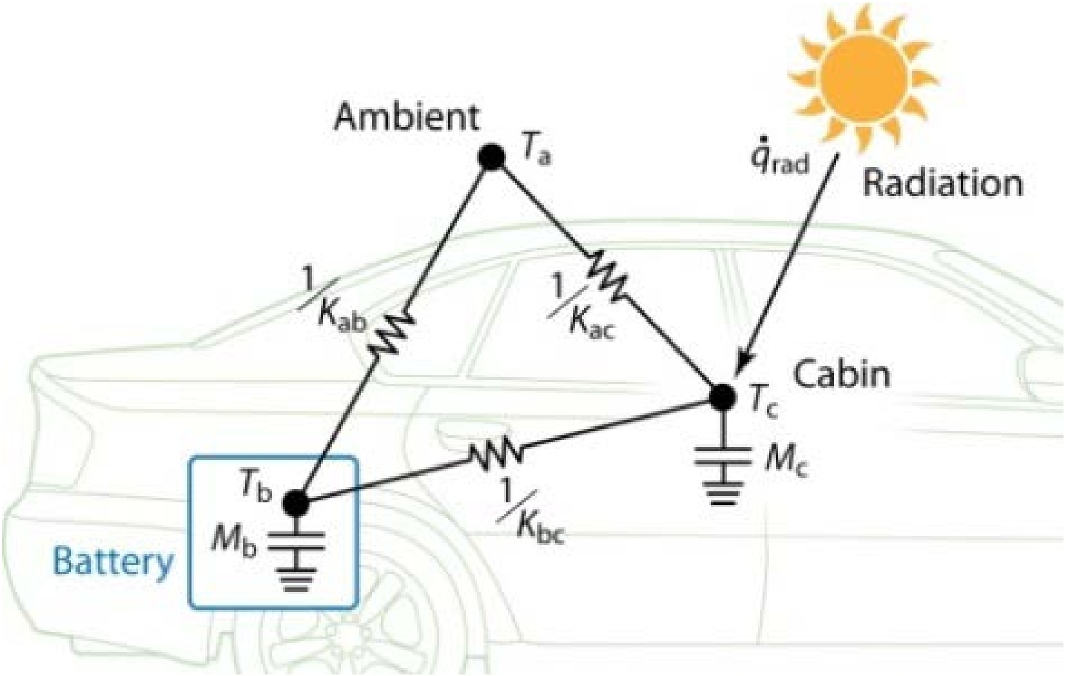
Climate Data





- **Annual ambient temperature and solar irradiance histories resolved at the hourly level were employed**
- **Data readily available for a selection of 100 cities**
    - Los Angeles, CA, selected as (1) a likely location for BEV adoption and (2) a climate representative of U.S. average conditions
    - Phoenix, AZ, selected for high ambient temperature and solar irradiance
    - Minneapolis, MN, selected for cold average temperature.

Cabin Thermal Model



- **Passive System:**
  - Lumped-capacitance network model driven by battery heat generation, ambient temperature, and solar loading

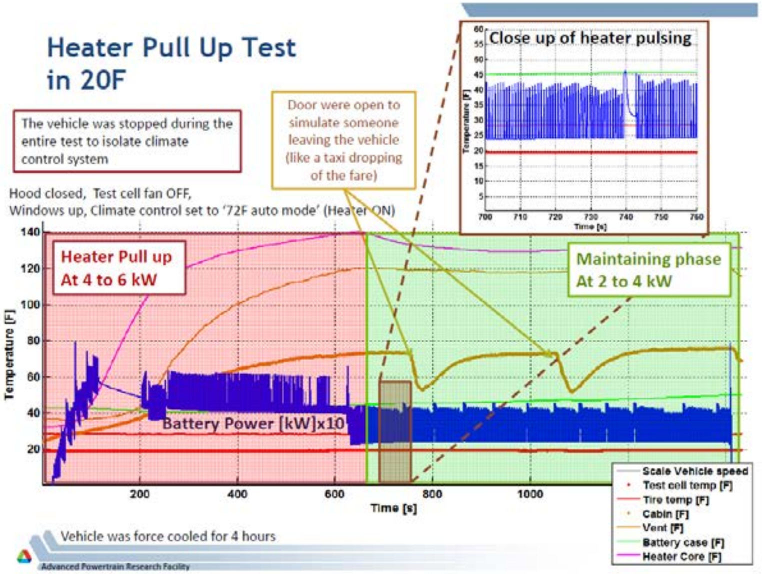
- **Parameter Fitting:**
  - Thermal masses and heat transfer coefficients fit from test data.

Cabin Heating

- **DOE Advanced Vehicle Testing Activity (AVTA) results show cabin heats from 25°F to 72°F in ~600 sec.**
    - Henning Lohse-Busch, et. al., “Advanced Powertrain Research Facility AVTA Nissan Leaf Testing and Analysis,” http://www.transportation.anl.gov/D3/data/2012_nissan_leaf/AVTALeaftestinganalysis_Major%20summary101212.pdf [accessed 16 July 2013]

- **BOM results show similar performance with cabin heat power at 4,000 W and on/off control**
    - Note: a 300 W battery heater is included in this simulation, but has minimal effect on cabin response

- **We set cabin power = battery power, assuming a perfectly efficient heater.**



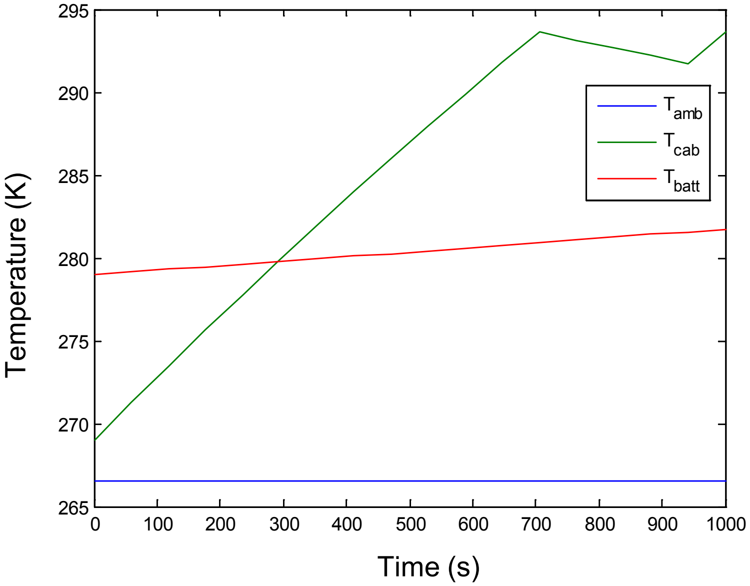
Heater Pull Up Test in 20F

The vehicle was stopped during the entire test to isolate climate control system

Door were open to simulate someone leaving the vehicle (like a taxi dropping of the fare)

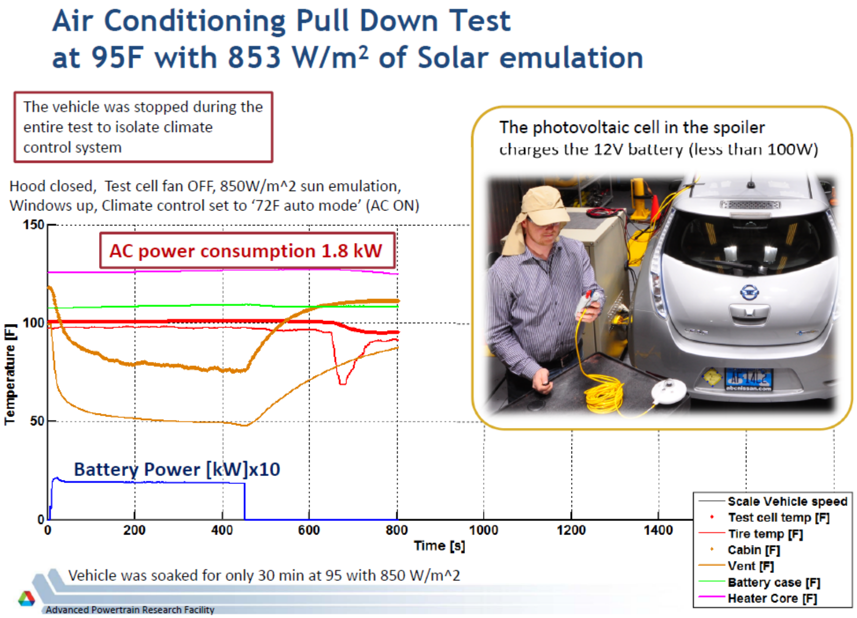
Hood closed, Test cell fan OFF, Windows up, Climate control set to ‘72F auto mode’ (Heater ON)

Vehicle was force cooled for 4 hours



Cabin Cooling

- **AVTA results show cabin cools from ~120°F to ~72°F in ~200 sec with a power consumption of 1,800 W**
  - Henning Lohse-Busch, et. al., “Advanced Powertrain Research Facility AVTA Nissan Leaf Testing and Analysis,” http://www.transportation.anl.gov/D3/data/2012_nissan_leaf/AVTALeaftestinganalysis_Major%20summary101212.pdf [accessed 16 July 2013]
- **BOM model does not account for cabin air mass transfer (Note: AVTA vent temp starts at ambient)**
- **We modified K_{ac} to represent this mass transfer as follows:**
  - If $T_a > T_c$, $K_{ac} = K_{ac} + 1500$ W/K
- **We modeled air conditioning as a constant heat removal from cabin of 4,500 W; load on system was 1,800 W (coefficient of performance = 2.5)**
- **Then our cabin response agreed reasonably well with AVTA data.**



Air Conditioning Pull Down Test
at 95F with 853 W/m² of Solar emulation

The vehicle was stopped during the entire test to isolate climate control system

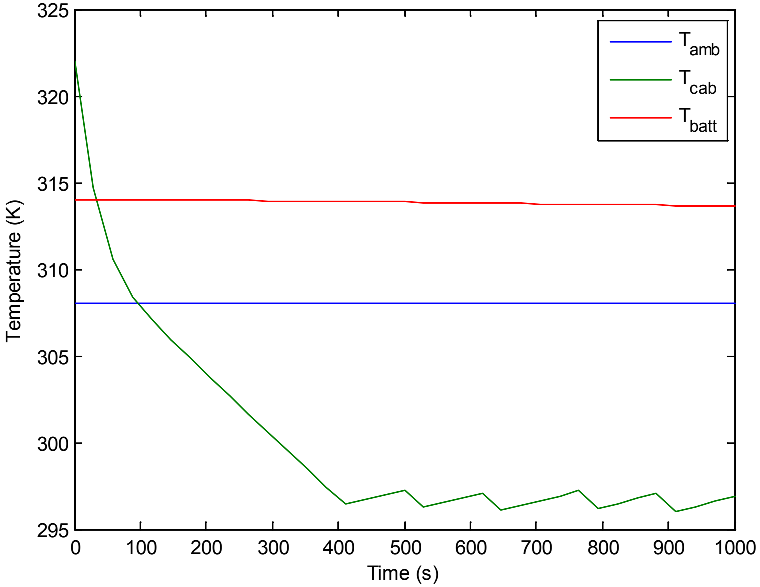
Hood closed, Test cell fan OFF, 850W/m^2 sun emulation, Windows up, Climate control set to ‘72F auto mode’ (AC ON)

AC power consumption 1.8 kW

The photovoltaic cell in the spoiler charges the 12V battery (less than 100W)

Vehicle was soaked for only 30 min at 95 with 850 W/m^2

Advanced Powertrain Research Facility



Battery Thermal Management System

- Previous studies showed that active thermal management offers minimal benefit for BEVs

- With range extension technologies – particularly fast charging – BEVs may benefit from active thermal management systems.

- Only passive battery thermal management was simulated herein, however, to reduce the size of the design space.

Life Model Approach

Battery aging datasets fit with empirical, yet physically justifiable, formulas.

Calendar fade

- SEI growth
- Loss of cyclable lithium
- a_1, d_1 = f(ΔDOD,T,V).

Cycling fade

- Active material structure degradation and mechanical fracture
- a_2, e_1 = f(ΔDOD,T,V).

Relative Resistance

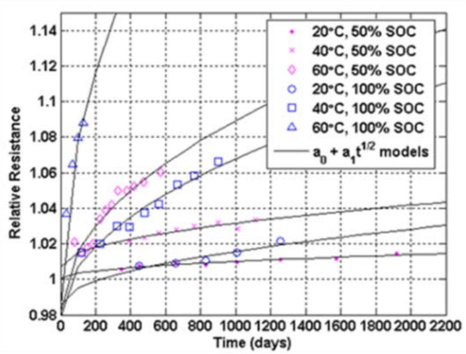
$$R = a_1 t^{1/2} + a_2 N$$

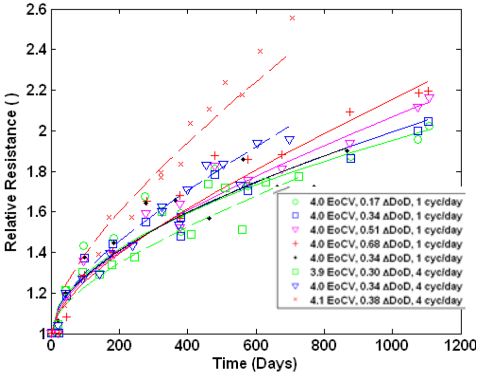
Relative Capacity

$$Q = \min(Q_{Li}, Q_{active})$$

$$Q_{Li} = d_0 + d_1 t^{1/2}$$

$$Q_{active} = e_0 + e_1 N$$

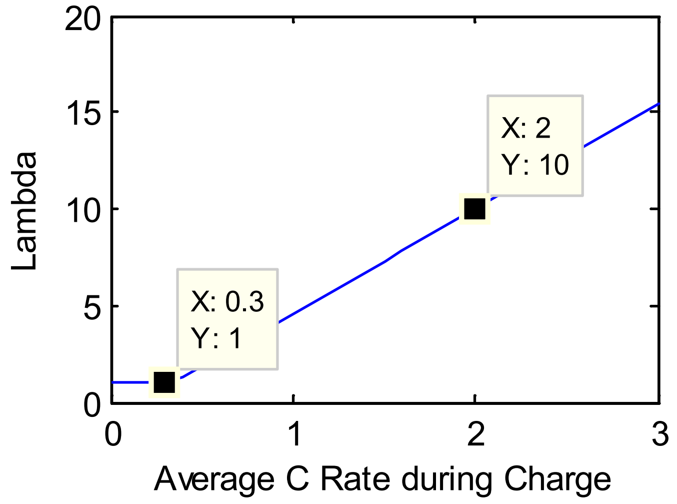




The life model approach enables life predictions for untested real-world scenarios.

Life Model Augmentation

$$\lambda = f(\text{C rate})$$
$$\Delta Q' = \lambda * \Delta Q$$
$$\Delta R' = \lambda * \Delta R$$

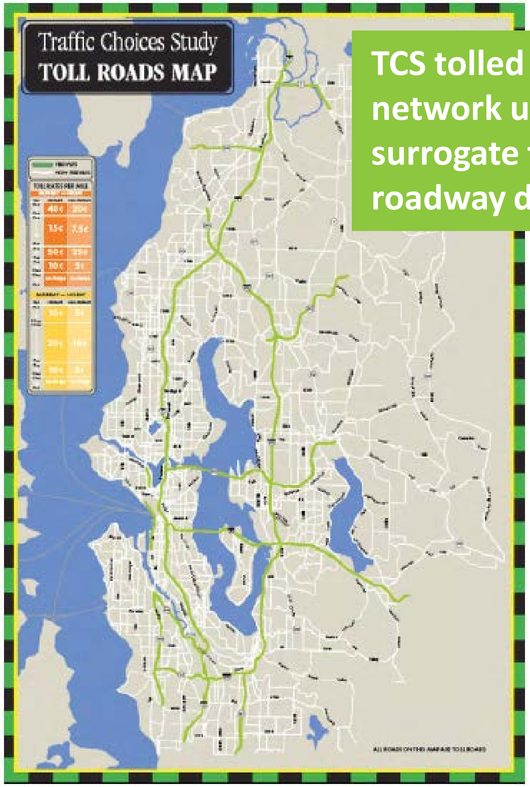


- Life model is mathematically manipulated to compute ΔR and ΔQ for each drive and park event
- ΔQ' & ΔR' are calculated from ΔQ & ΔR to adjust for the effects of high rate charging not directly accounted for in the model
- Wear from charge rates less than 0.3C (level 2) are unaffected; wear from 2C charges are increased by a factor of 10 when the "high wear" option is activated.

Range-Extending Infrastructure Options

- Parked at Home Charging
  - Level 1 (L1: 120V, 15 A AC circuit) opportunity
  - Level 2 (L2: 240V, 32 A AC circuit) timed (midnight to 1 pm)
  - L2 opportunity
- Parked at Work Charging
  - L1 opportunity
  - L2 opportunity
- Parked at Public Charging
  - L1 opportunity
  - L2 opportunity
  - Level 3 (L3: 50 kW DC to battery) opportunity
- Driving at Select Roadways
  - Road and cabin loads are powered (battery SOC is constant)
  - Active 8 am to 10 pm covers 57% of all TCS miles traveled.

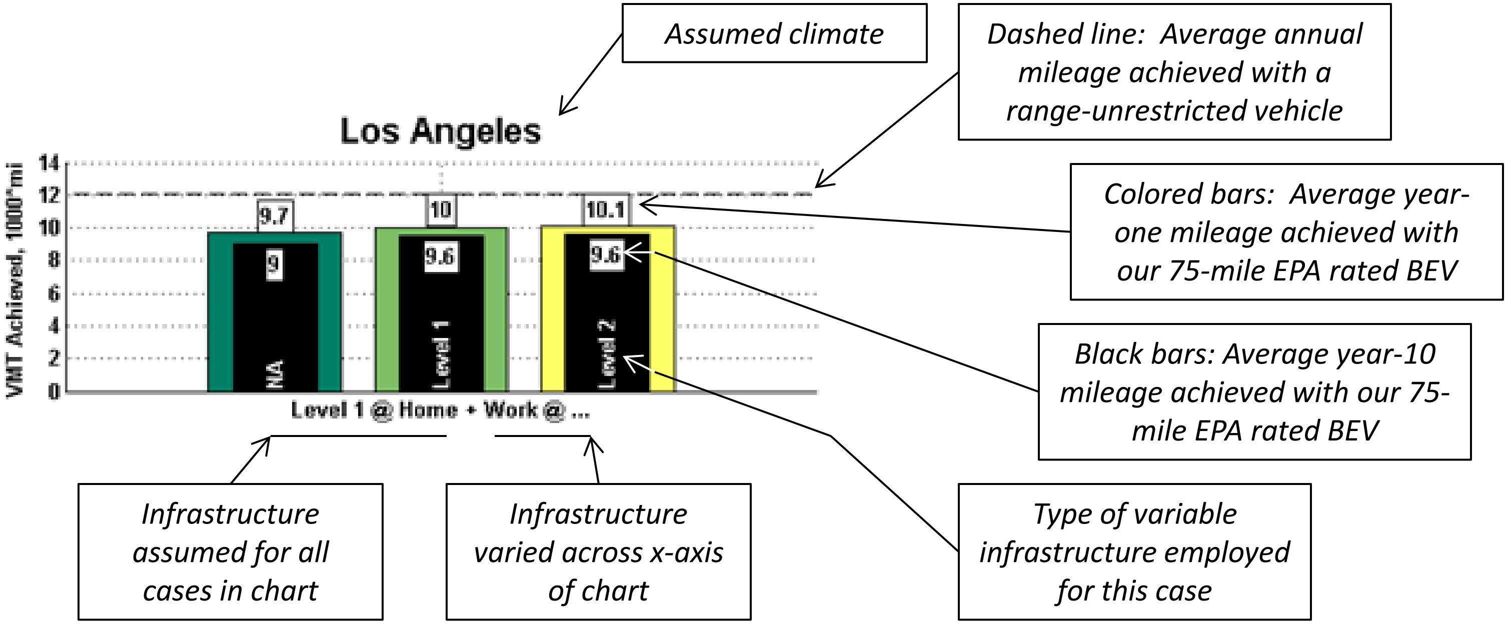
Traffic Choices Study – Summary Report, http://www.psrc.org/assets/37/summaryreport.pdf [accessed 16 July 2013]



TCS tolled road network used as surrogate for electric roadway deployment

Note: In this study, driver behavior is NOT changed in response to infrastructure availability (i.e., drivers do not make additional stops for fast chargers).

How To Read The Following Plots



Assumed climate

Dashed line: Average annual mileage achieved with a range-unrestricted vehicle

Colored bars: Average year-one mileage achieved with our 75-mile EPA rated BEV

Black bars: Average year-10 mileage achieved with our 75-mile EPA rated BEV

Infrastructure assumed for all cases in chart

Infrastructure varied across x-axis of chart

Type of variable infrastructure employed for this case

For this example....

- *9,700 miles were achieved on average across all drive patterns in year-one when L1 home charging and no work charging was employed*
- *9,600 miles were achieved on average across all drive patterns in year-10 when L1 home charging and L2 work charging was employed*

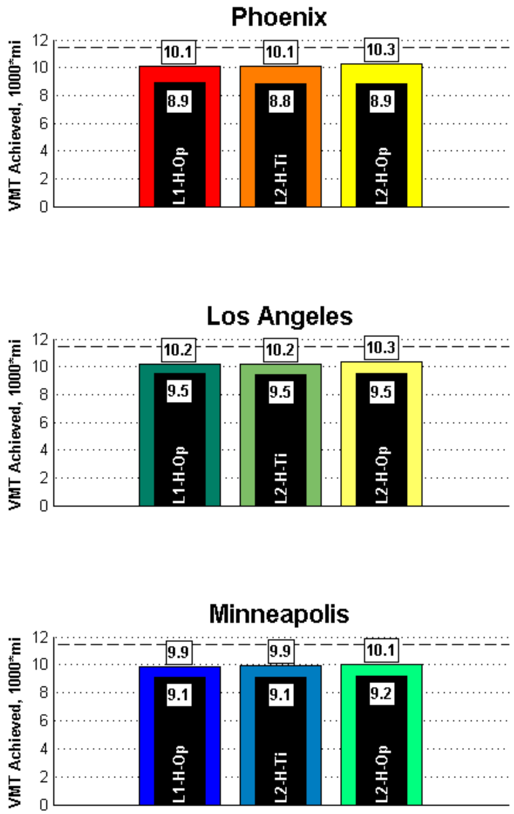
Note: We employed ***Achieved VMT*** as a high level metric of BEV utility. More Achieved VMT = more gasoline, emissions, and financial savings.

Part 2: Results

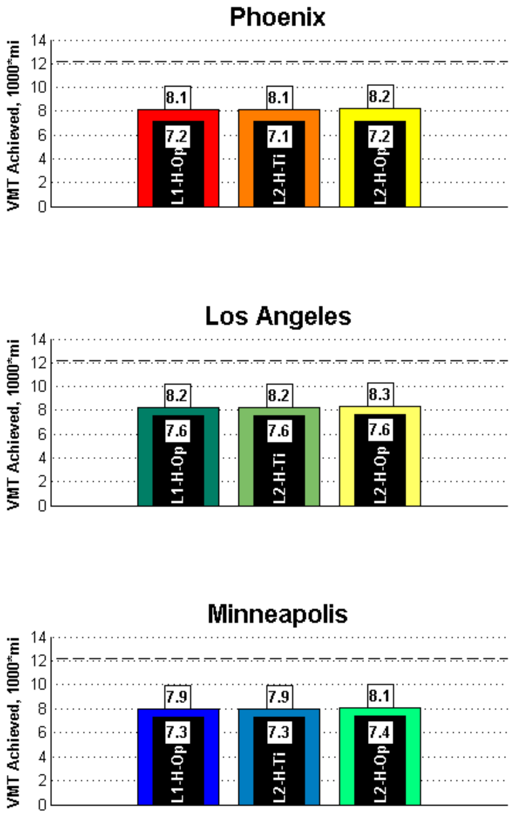
Home Charging

- Minimal penalty for downgrading from a L2 to L1 charger for Set A and B drivers
    - *Capacity for L2 charging at home may not be a prerequisite for BEV ownership*
- Set B drivers achieve an average ~71% utility factor when only home charging is available.

Drive Pattern Set A



Drive Pattern Set B

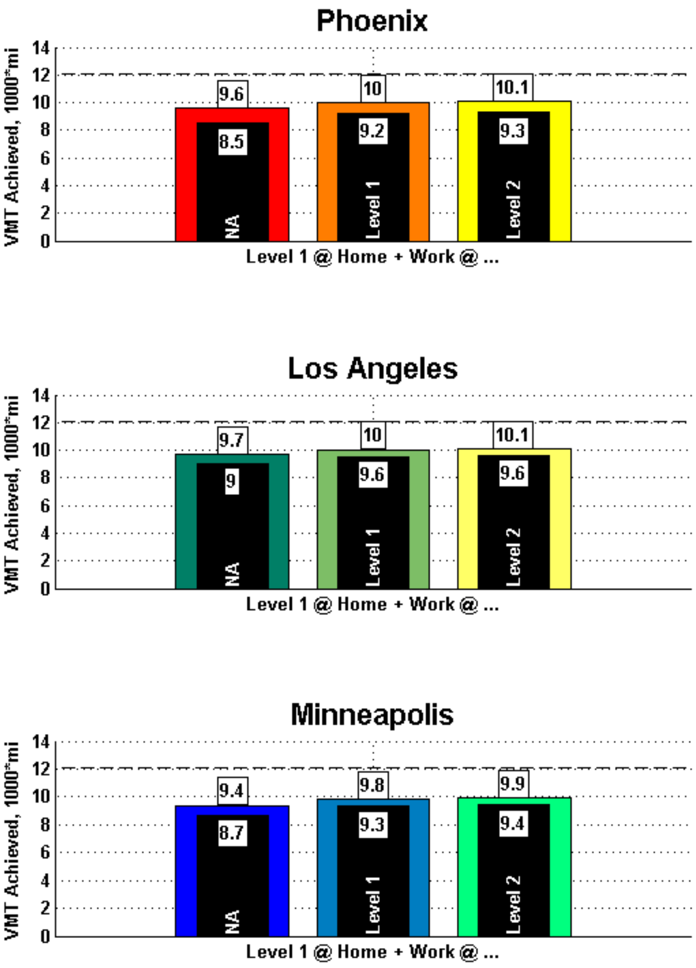


Work Charging

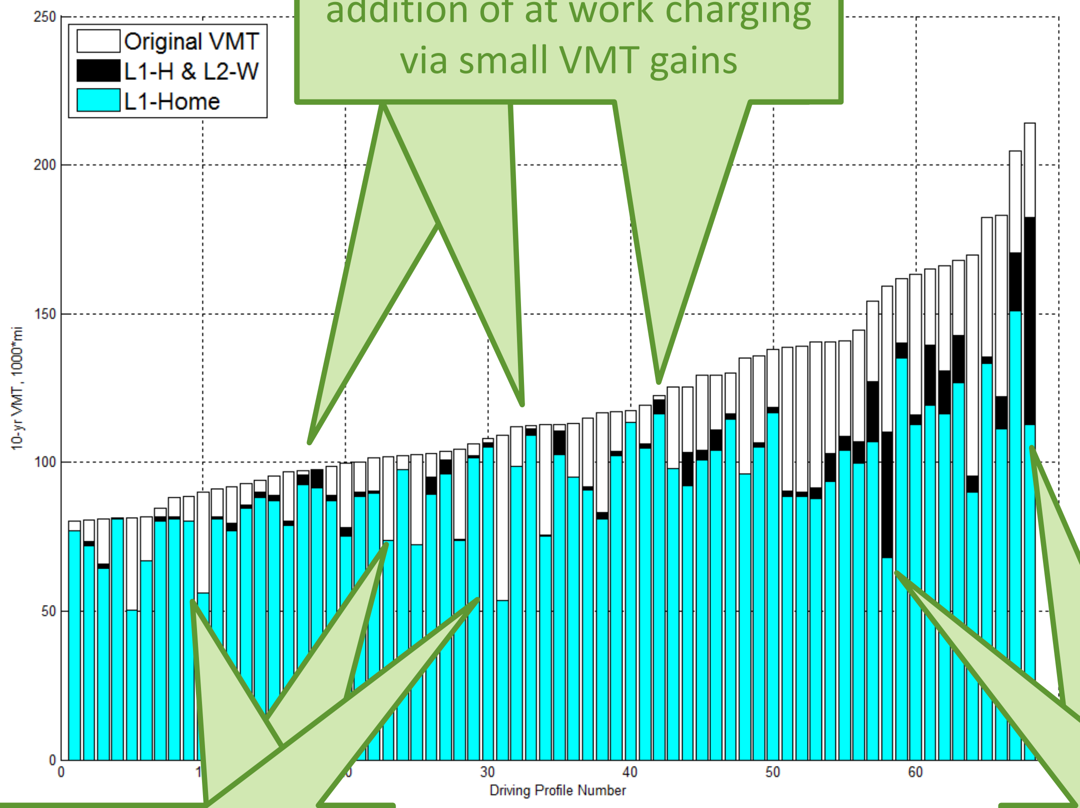
- Adding L1 charging at work adds ~600 miles / year on average at year-10
  - *But some commuters benefit much more than others*

- Minimal penalty for downgrading from an L2 to L1 charger at work
  - *L1 charging might be good enough at work, but the difference in L1 and L2 work charger installation costs may be marginal.*

Drive Pattern Set C



Work Charging



Some commuters approach 100% utility with the addition of at work charging via small VMT gains

Many commuters see little to no benefit from work charging

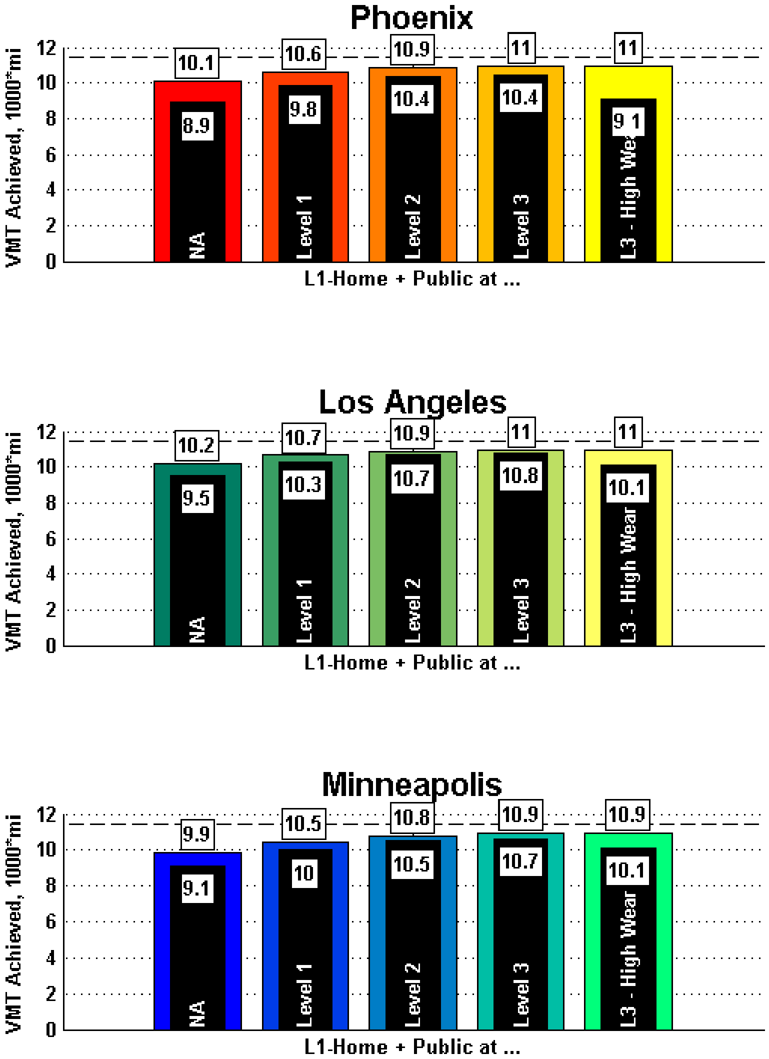
Select commuters benefit significantly from at work charging

Work Charging

- **Why not larger gains?**
  - Recall that we assumed a "bold-informed" tour decision algorithm with a small (5 mile) range buffer and near-perfect tour/vehicle/battery knowledge
  - A more "anxious" and/or "uninformed" tour decision algorithm would take fewer long (deep discharge) tours, resulting in less achieved VMT in the charge-at-home-only scenario **(i.e., our charge-at-home-only scenario overestimates achieved VMT for "anxious" drivers)**
  - However, charging at work enables long tours without deep-discharging the battery; in this situation it is therefore less likely that "anxious-uninformed" drivers would reduce tour-taking relative to "bold-informed" drivers **(i.e., our charge-at-home-and-work results may not vary much between "bold-informed" and "anxious" drivers)**
  - **Thus, "anxious" drivers should see a larger improvement in achieved VMT with the addition of work charging than the "bold-informed" drivers we have simulated;** additional investigation is necessary to confirm.

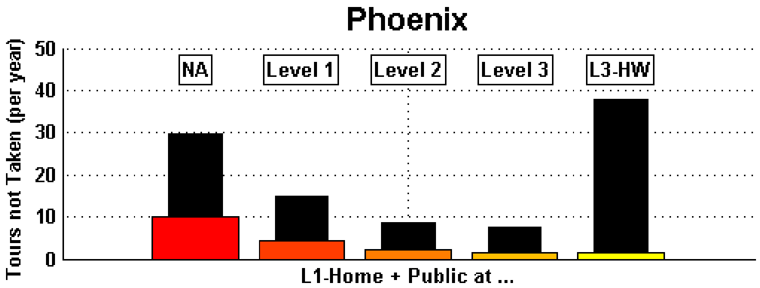
Public Charging: Drive Pattern Set A

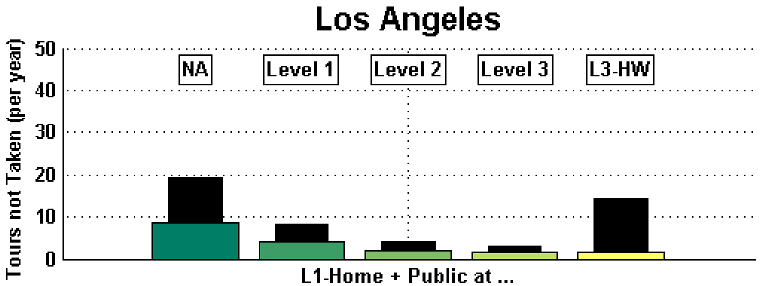
- Ubiquitous public charging adds up to 1,600 miles in year 10, **increasing the year-10 utility factor from 77% to 90%**
- We see diminishing returns as public charging power is increased (L3 adds little gain over L2)
    - *However, the benefit of lower power charging would be significantly reduced if stations were not universally available as is assumed herein*
- The high-wear L3 case significantly penalizes year-10 VMT, especially in hot climates.

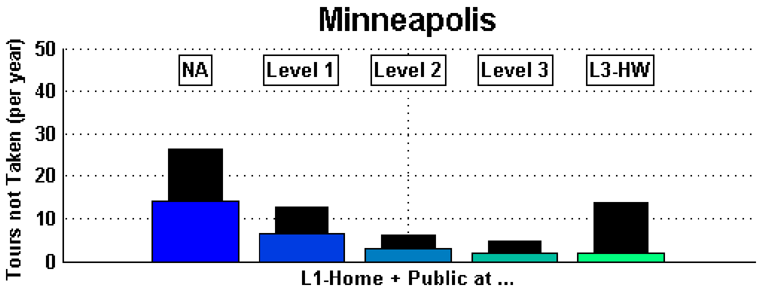


Public Charging: Drive Pattern Set A

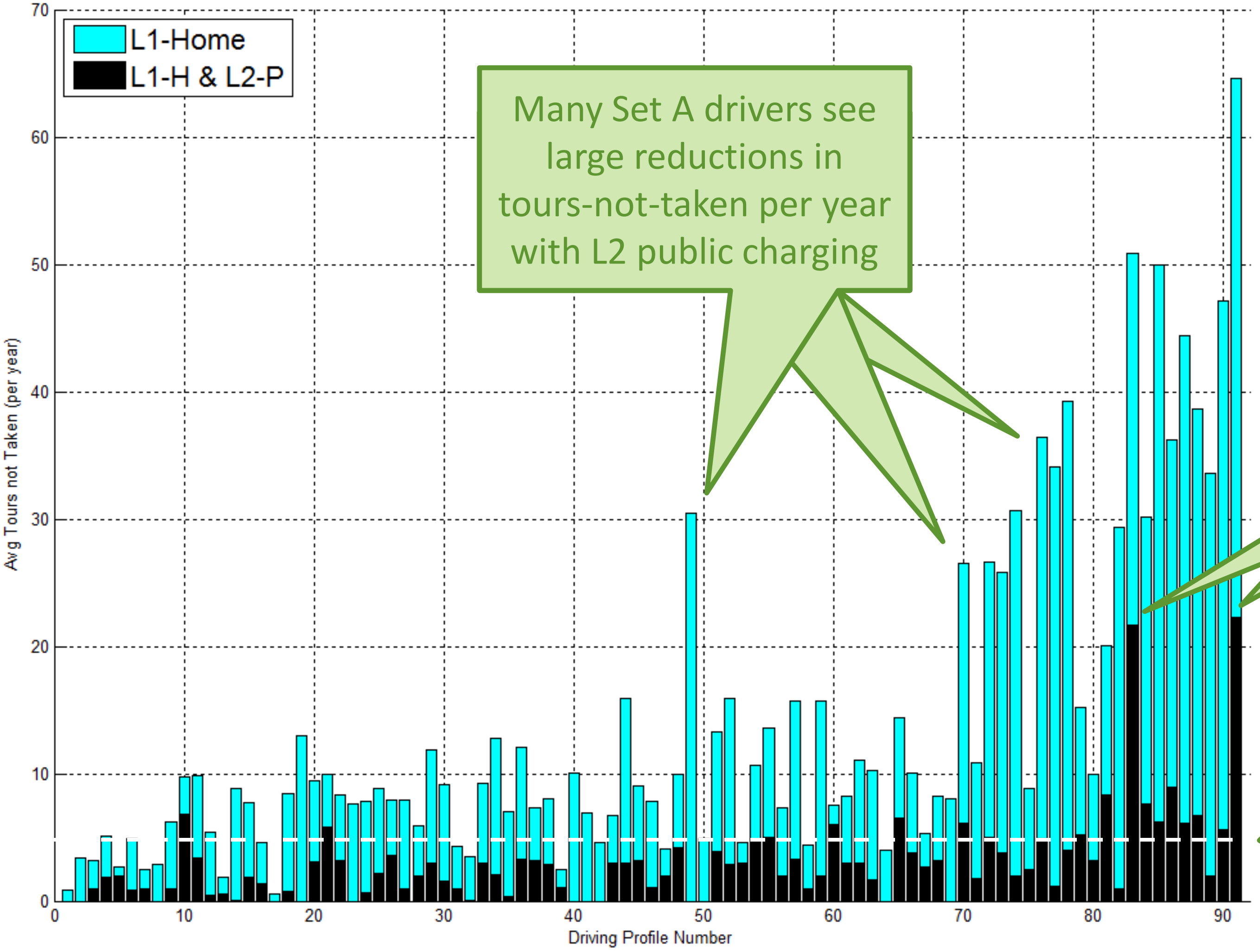
- **Tours-not-taken is indicative of the inconvenience of a BEV**
    - Indicative of the maximum number of times a borrowed or rental car must be acquired
- Without public charging, 10 to 30 tours are missed per year on average
- With ubiquitous L2 charging, **less than 10 tours per year are missed** on average across all three climates, even in year 10.







Public Charging: Drive Pattern Set A

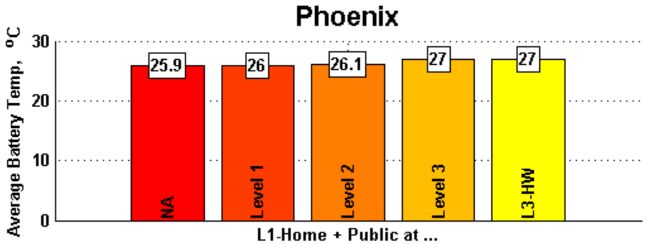


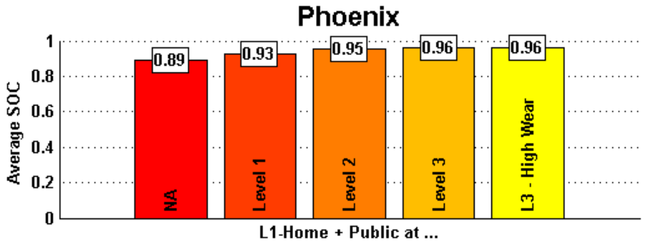
Many Set A drivers see large reductions in tours-not-taken per year with L2 public charging

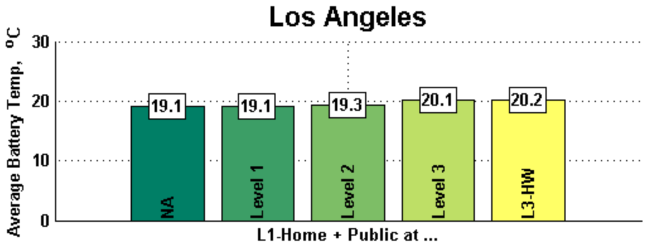
Only 2 Set A drivers average more than 10 tours-not-taken per year with L2 public charging

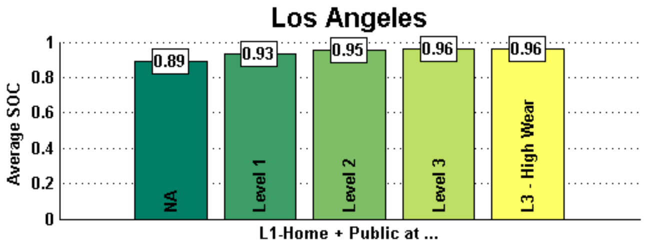
Most Set A drivers average less than 5 tours-not-taken per year with L2 public charging

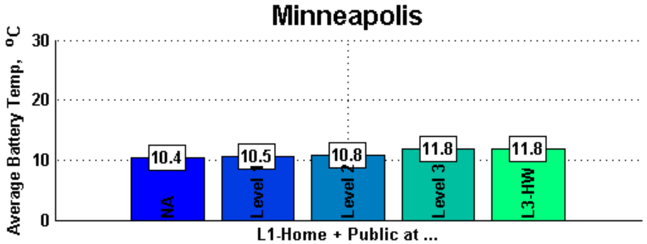
Public Charging: Drive Pattern Set A

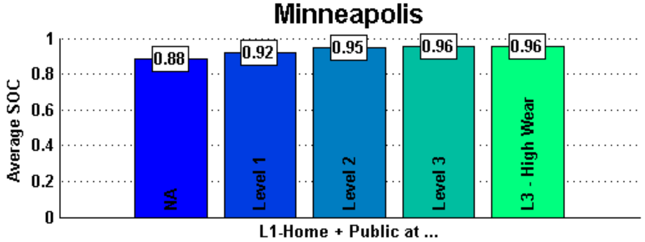






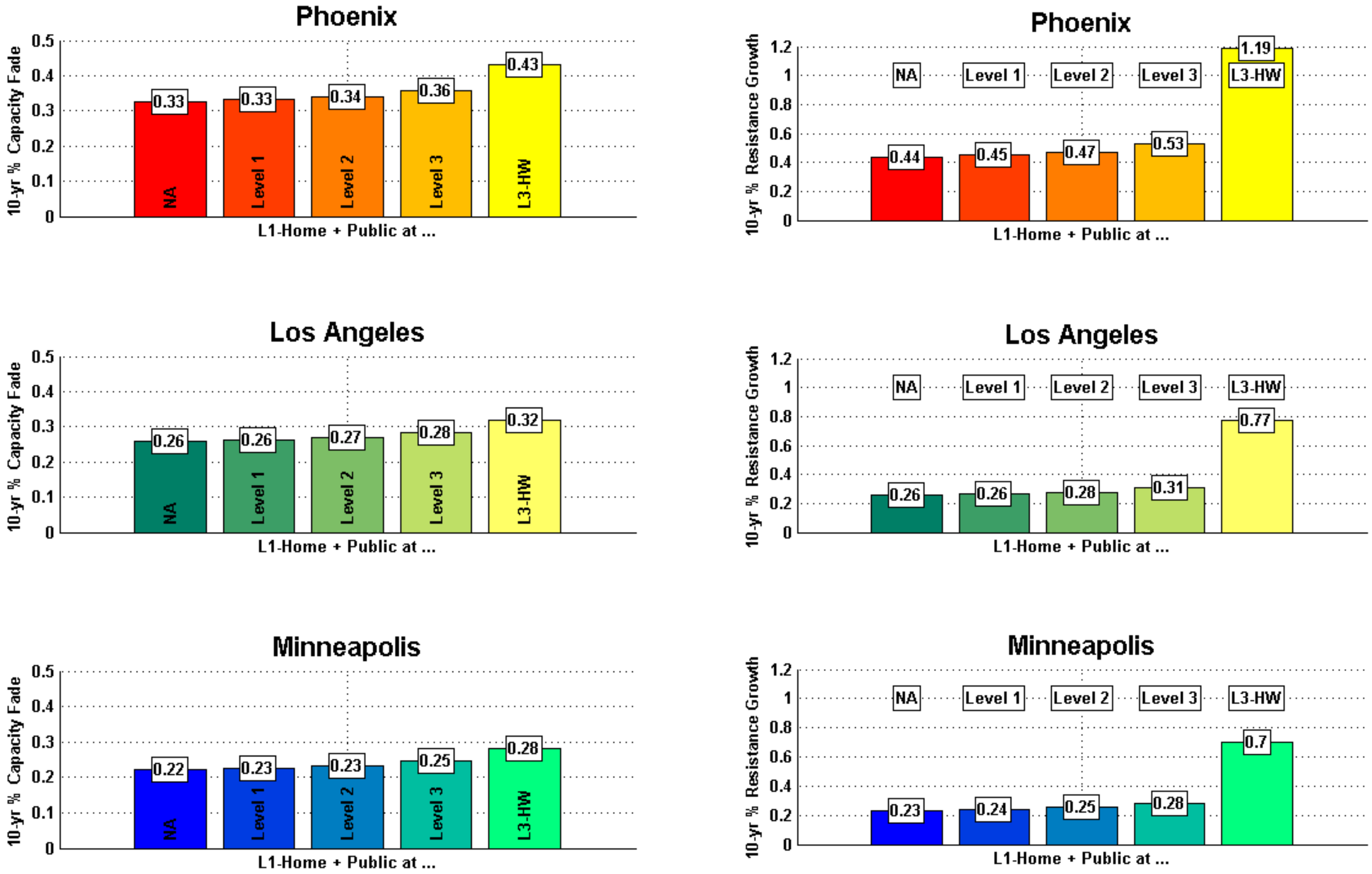






Increased driving and charging leads to slight **elevations in average battery temperature and SOC.**

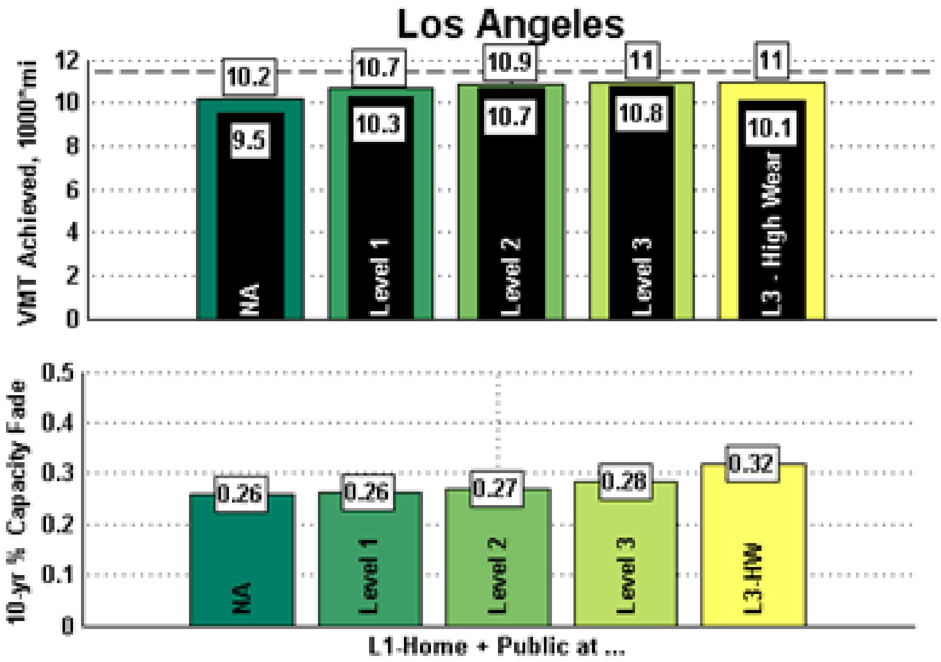
Public Charging: Drive Pattern Set A



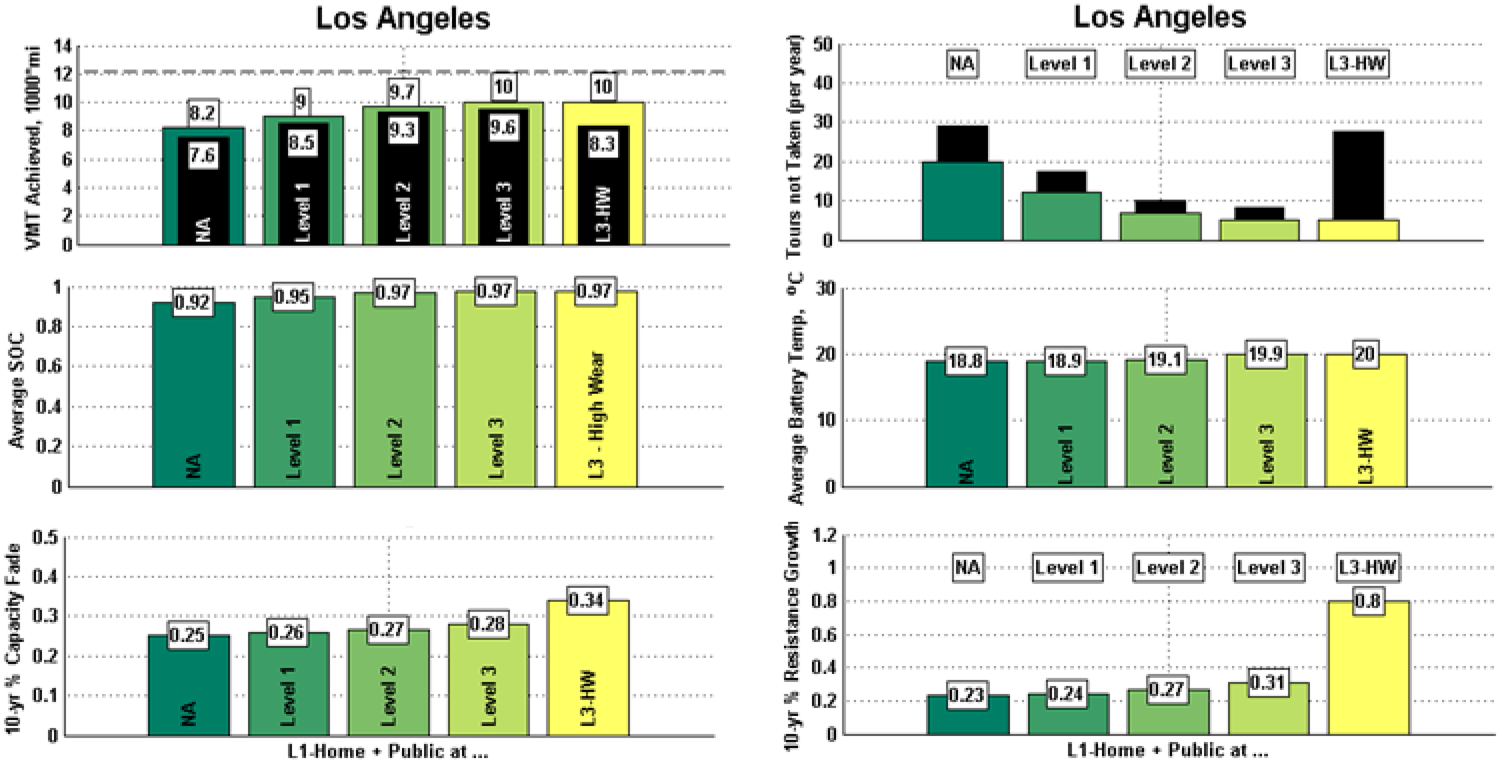
- Increased throughput, temperature, and SOC of public charging combine to **increase battery wear**, despite reductions in average cycle DOD
- Battery wear is **dominated by calendar effects** in all cases but the L3 high wear case, in which battery wear is dominated by cycle effects.

Public Charging: Drive Pattern Set A

Higher VMT at EOL with **more battery capacity fade** implies that high penetration public charging could **enable cheaper, smaller range vehicles** to offer the same utility.



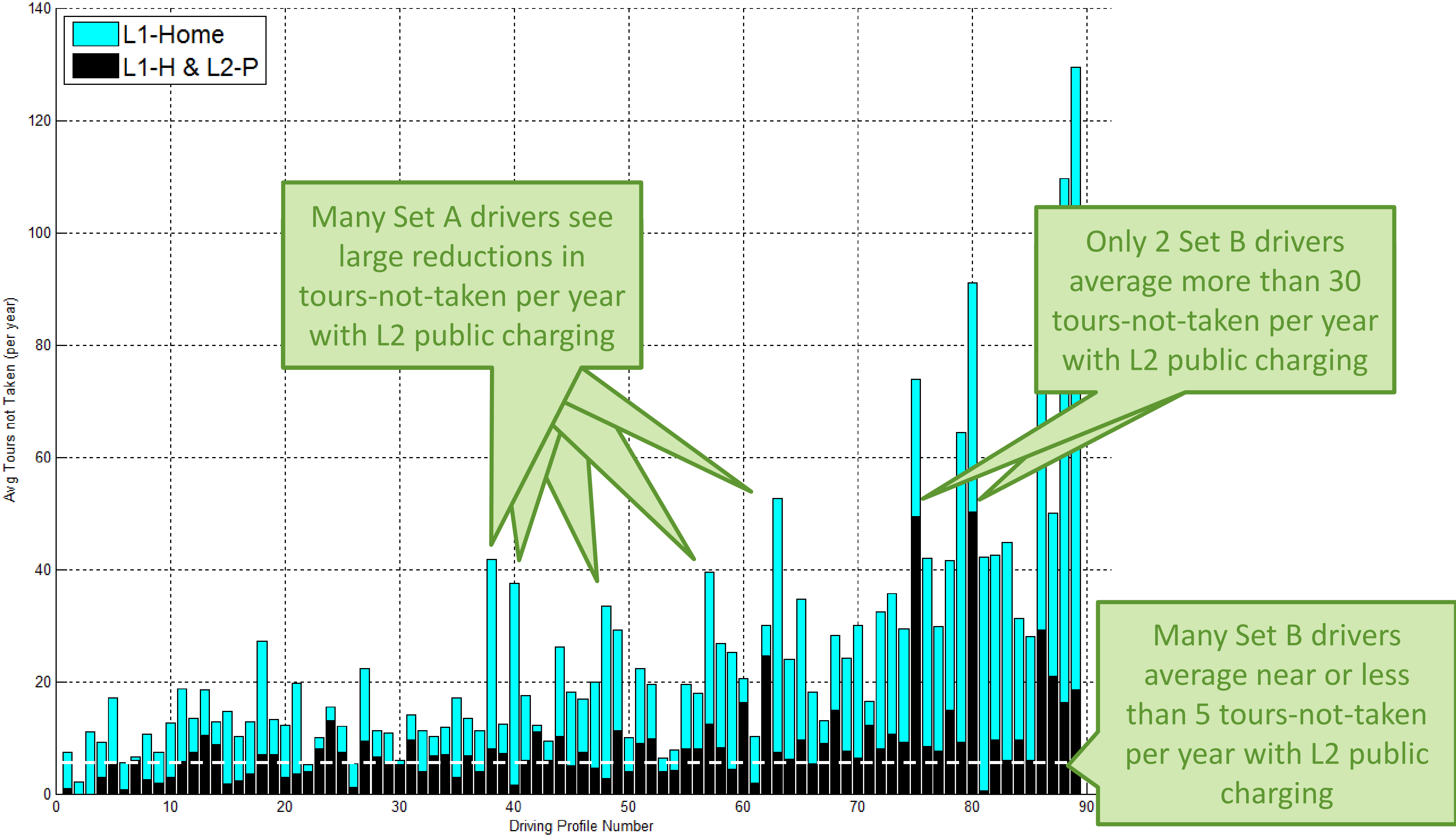
Public Charging: Drive Pattern Set B



- Bigger VMT gains (up to 2,000 miles at year-10) than Set A, but lower utility factor (80% in year-10 with level 3 public charging)

- Trends in SOC, temperature, capacity fade, and resistance growth are similar between driver Sets A and B.

Public Charging: Drive Pattern Set B



Many Set A drivers see large reductions in tours-not-taken per year with L2 public charging

Only 2 Set B drivers average more than 30 tours-not-taken per year with L2 public charging

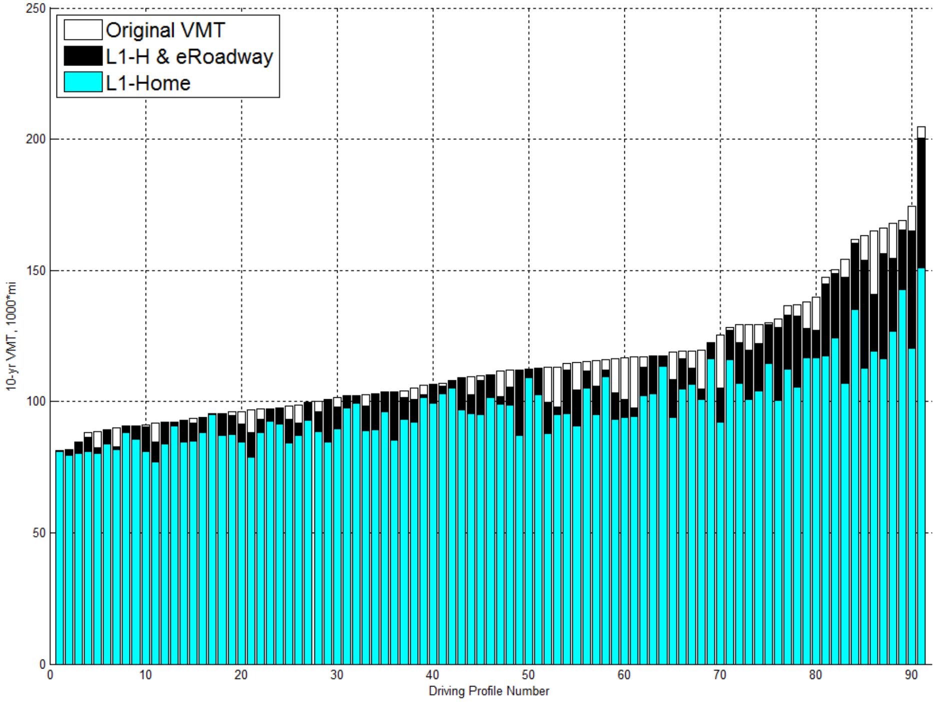
Many Set B drivers average near or less than 5 tours-not-taken per year with L2 public charging

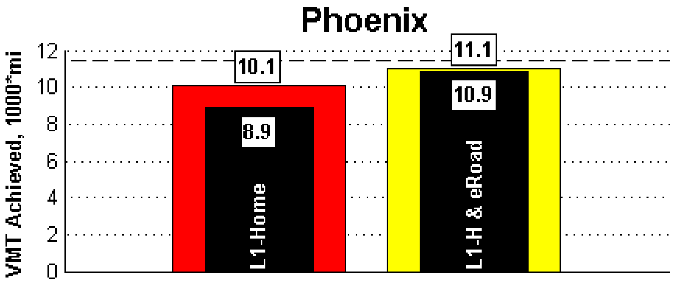
Public Charging: Drive Pattern Set B

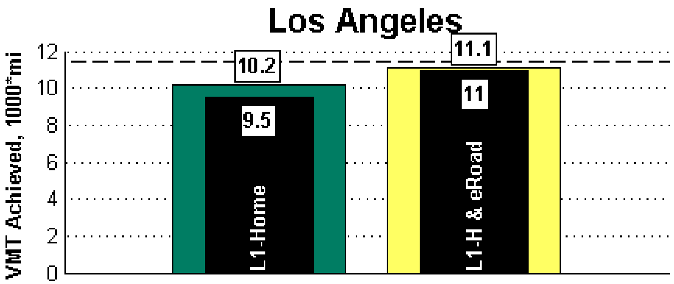
- Set B drivers achieve greater convenience and VMT with Level 2+ public charging than Set A drivers achieve without public charging
- With identical public charging access, however, Set A drivers achieve greater convenience and VMT than Set B drivers
- **Conclusion:** Even with ubiquitous public charging, Set A drivers are still better suited to BEVs than Set B drivers.

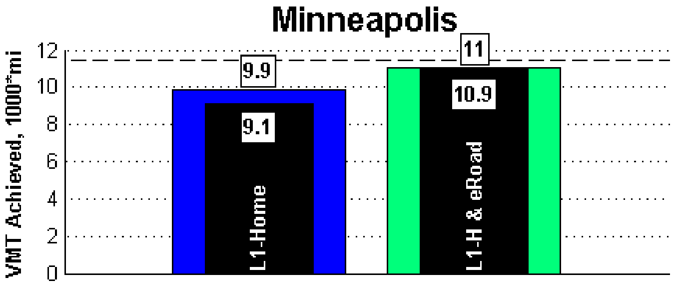
Electric Roadway: Drive Pattern Set A

- High utility factors (95%) in year-10
- Some drivers achieve 100% utility factor
- 800 to 1,800 mile average year-10 increase over ubiquitous level 3 public charging when the battery has a high wear rate.



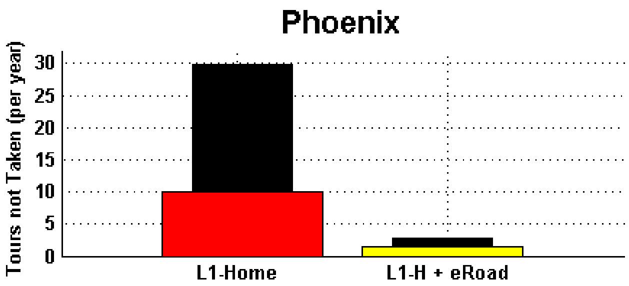


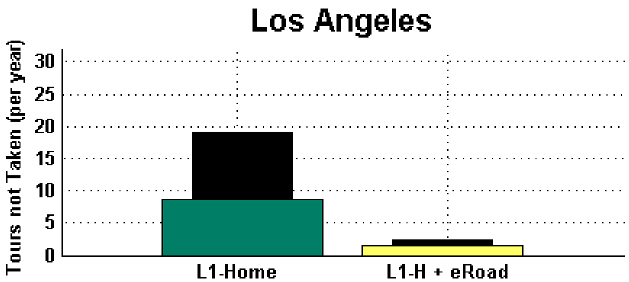


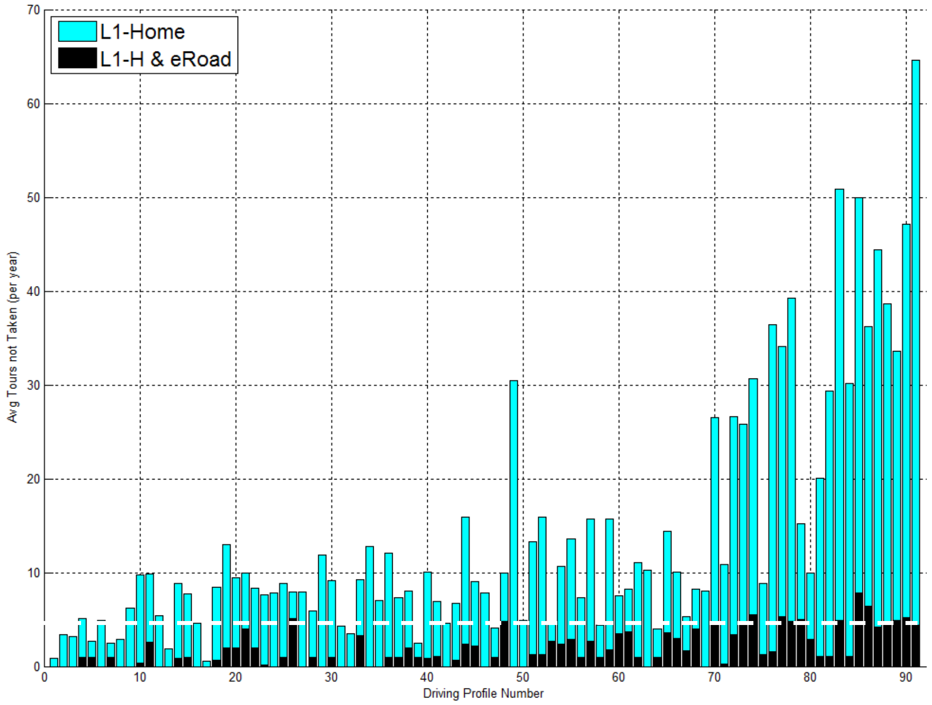


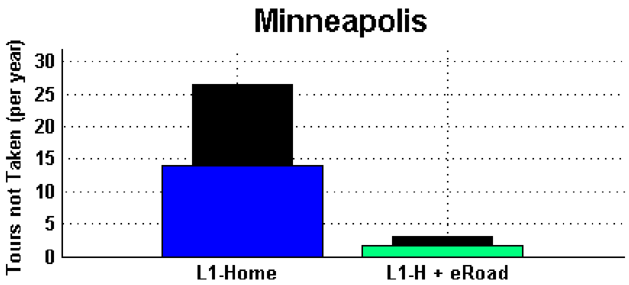
Electric Roadway: Drive Pattern Set A

- Some drivers have 0 tours-not-taken with the electric roadway
- Almost all have less than 5/yr.



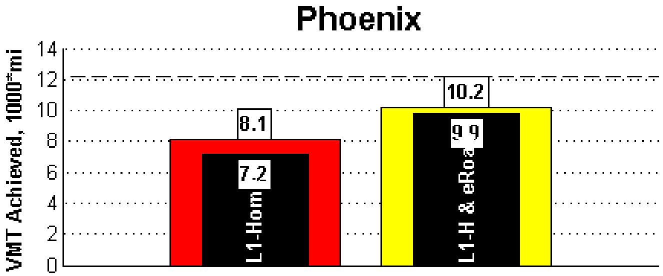


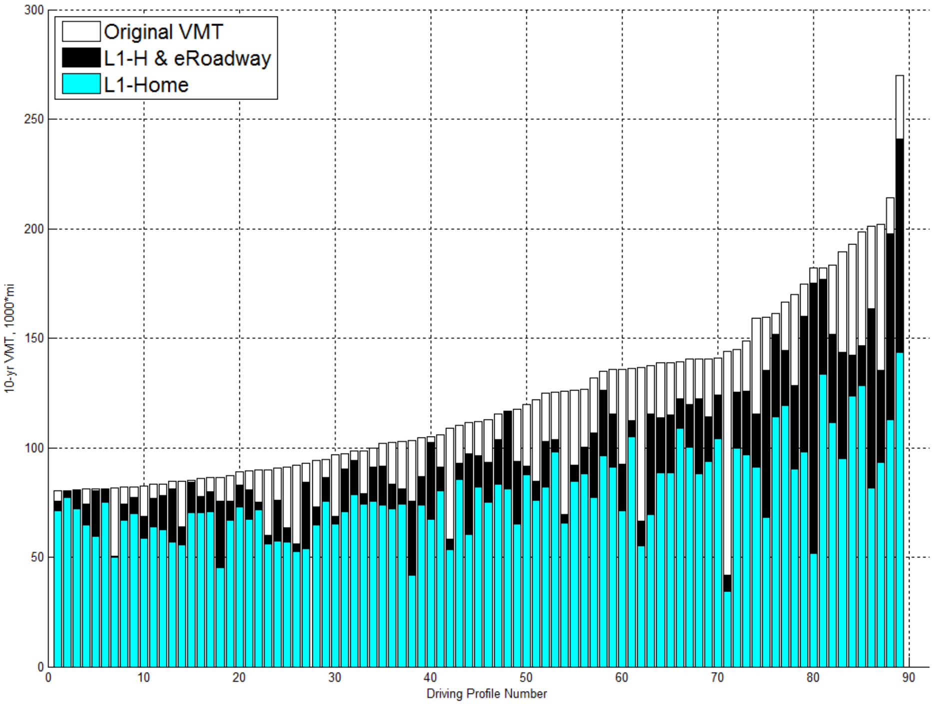


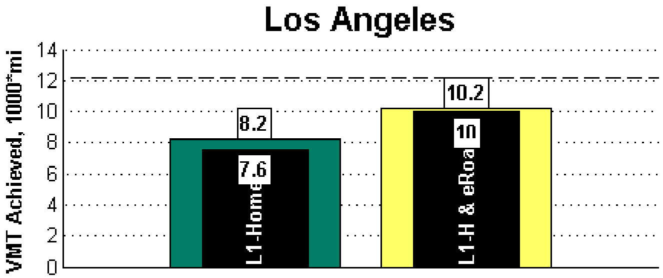


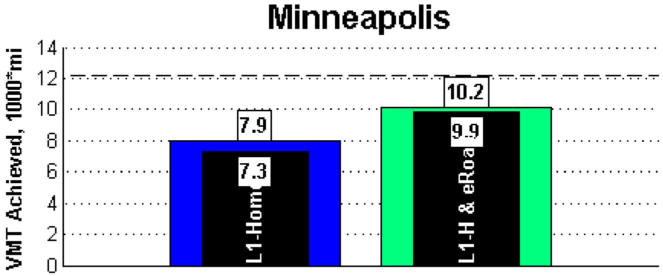
Electric Roadway: Drive Pattern Set B

- ~83% utility factor in year-10
- Few drivers achieve 100% utility factor
- 400 mile average year-10 increase over ubiquitous level 3 public charging.



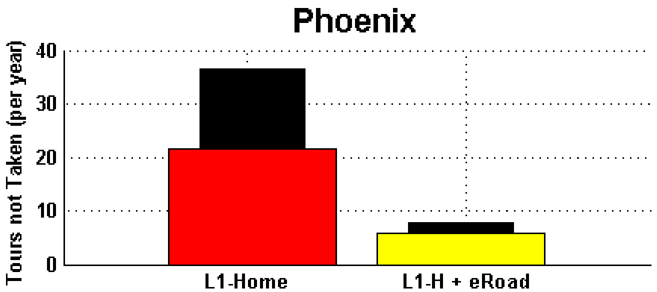


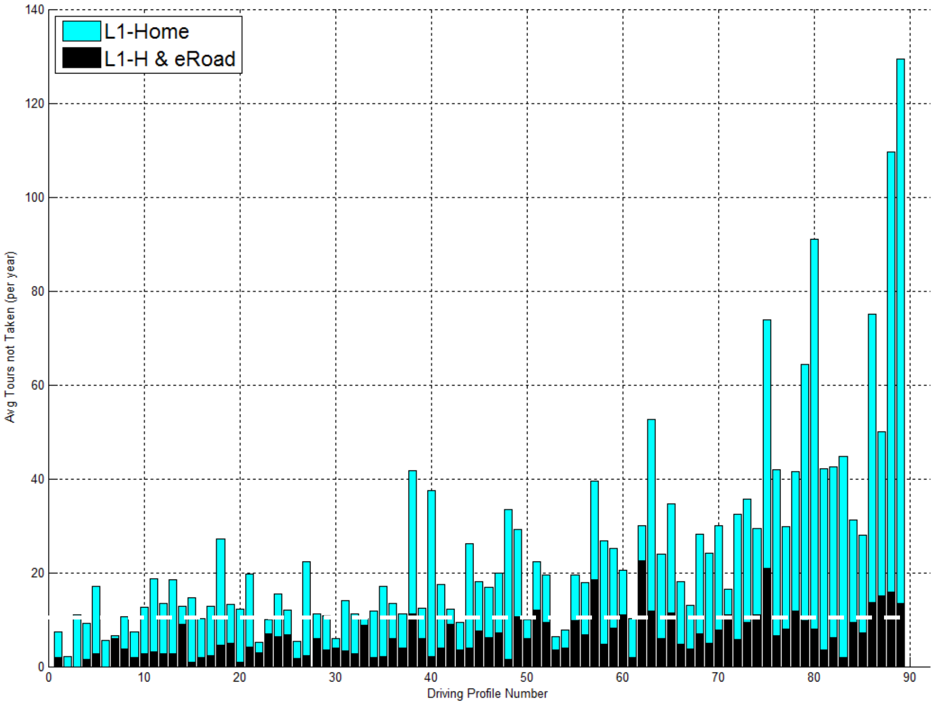


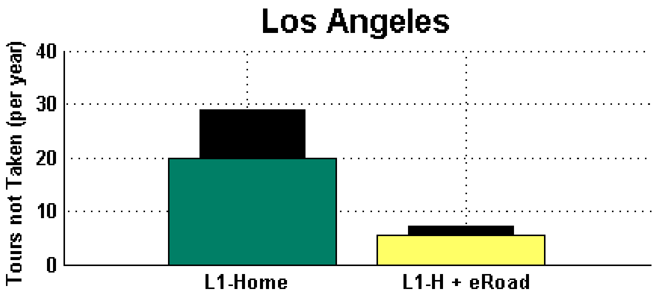


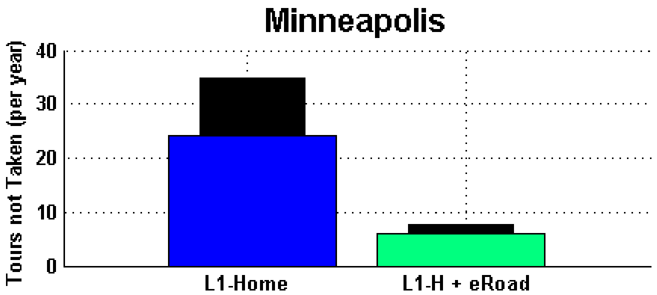
Electric Roadway: Drive Pattern Set B

- Only 2 drivers have 0 tours-not-taken with the electric roadway
- Most have less than 10/yr.









Electric Roadway

- Electric roadway offers only slightly better achievable VMT than ubiquitous level 3 charging, but **eliminates sensitivity to battery wear**
- Achieving 100% utility factor for a large fraction of drivers **may require out-of-network roadway electrification**
- Additional opportunities:
  - It is possible that a smaller deployment of electric roadway (class 1 and 2 roads only) could offer similar performance at lower cost
  - Allowing battery charging while on the electric roadway will improve utility, but by how much?
  - What's the impact of electric roadways on PHEVs and HEVs?
  - Significant battery down-sizing without sacrificing vehicle utility may be possible.

Part 3: Comparison with Previous Studies

Past Studies

- Neubauer, J.; Pesaran, A. (2013). **"A Techno-Economic Analysis of BEV Service Providers Offering Battery Swapping Services."** NREL/CP-5400-58608. Golden, CO: National Renewable Energy Laboratory. Presented at the SAE 2013 World Congress & Exhibition, April 16.

- Neubauer, J.; Pesaran, A. (forthcoming). **"A Techno-Economic Analysis of BEVs with Fast Charging Infrastructure."** Submitted to the EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, November 17-20.

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Presented at the SAE 2013 World Congress & Exhibition

SAE International

A Techno-Economic Analysis of BEV Service Providers Offering Battery Swapping Services

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04/08/2013

Jeremy S. Neubauer and Ahmad Pesaran
National Renewable Energy Laborator

ABSTRACT

Battery electric vehicles (BEVs) offer the po
both oil imports and greenhouse gas emi
upfront costs, battery-limited vehicle range, a
high battery replacement costs may disc
buyers. A subscription model in which a
owns the battery and supplies access to b
infrastructure could reduce upfront and bat
costs with a predictable monthly fee, while
range. Assessing the costs and benefits of su
complicated by many factors, including
patterns, the amount of required infrastruct
etc. The National Renewable Energy Labor
its Battery Ownership Model to compare th
utility of BEV battery swapping service plan
traditional direct ownership options. Our ev
followed four steps: (1) identifying drive pa
to battery swapping service plans, (2) modeli
statistics for the selected drive patterns, (3)
cost-of-service plan options, and (4)
economics of individual drivers under rea
service plans. A service plan option can
effective than direct ownership for driver
operate a BEV as their primary vehicle w
options for travel beyond the single-ch
expensive, and a full-coverage-yet-cost-ef
infrastructure network can be deployed. How
assumed cost of gasoline, tax structure,
purchase incentives, our calculations show
BEV is rarely more cost-effective than direc
conventional vehicle.

1. INTRODUCTION

Plug-in electric vehicles, which include bot
electric vehicles and battery electric vehicle
the potential to reduce both oil imports and g

EVS27
Barcelona, Spain, November 17-20, 2013

A Techno-Economic Analysis of BEVs with Fast Charging Infrastructure

Jeremy Neubauer[1], Ahmad Pesaran[2]

[1]*National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, jeremy.neubauer@nrel.gov*

[2]*National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, ahmad.pesaran@nrel.gov*

Abstract

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions, but high upfront costs, battery-limited vehicle range, and concern over high battery replacement costs may discourage many potential purchasers. One proposed solution is to employ a subscription model under which a service provider assumes ownership of the battery while providing access to fast charging infrastructure. Thus, high upfront and subsequent battery replacement costs are replaced by a predictable monthly fee, and battery-limited range is replaced by a larger infrastructure-limited range. Assessing the costs and benefits of such a proposal are complicated by many factors, including customer drive patterns, the amount of required infrastructure, battery life, etc. Herein the National Renewable Energy Laboratory applies its Battery Ownership Model to address these challenges and compare the economics and utility of a BEV fast charging service plan to a traditional direct ownership option. We find that operating a BEV under a fast charge service plan can be more cost-effective than direct ownership of a BEV for certain drivers, but it is rarely more cost-effective than direct ownership of a conventional vehicle.

Keywords: Battery Ownership Model, fast charge, electric vehicles, total cost of ownership, range extension

1 Introduction

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gases relative to conventional vehicles (CV). However, in practice, high upfront cost, concerns of battery life and high battery replacement costs, and battery-limited vehicle range of today's BEVs may discourage potential purchasers. One proposed solution is to employ a subscription model that insulates consumers from the risks of battery degradation and provides access to fast charge infrastructure.

Under such a scenario, drivers would purchase a BEV without a battery, while being provided with the use of service-provider-owned batteries and fast charge infrastructure access in exchange for a monthly subscription fee.

Comparing this option to a traditional one, though, is not straight forward. As discussed at length in [1], computing the total cost of ownership (TCO) of BEVs under a direct ownership (DO) scenario itself is challenging. Adding a service provider and fast charging to the equation increases complexity via the need to account for fast charge

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Past vs. Present Approach

- **In this study, driver behavior is NOT changed in response to infrastructure availability**
  - For example, drivers do not make additional stops for fast chargers

- **In previous NREL fast charging and battery swapping studies, behavior IS changed via explicit battery swapping and fast charge events**
  - Max of 2 fast charge events per driver per day
  - Max of 4 battery swap events per driver per day

- **Also, previous studies:**
  - Did not consider origin and destination of trips
  - Made travel decisions on daily VMT rather than tour distance and battery SOC
  - Utilized drive patterns based on 3 months of travel, not 12
  - Applied different driver pattern selection criteria.

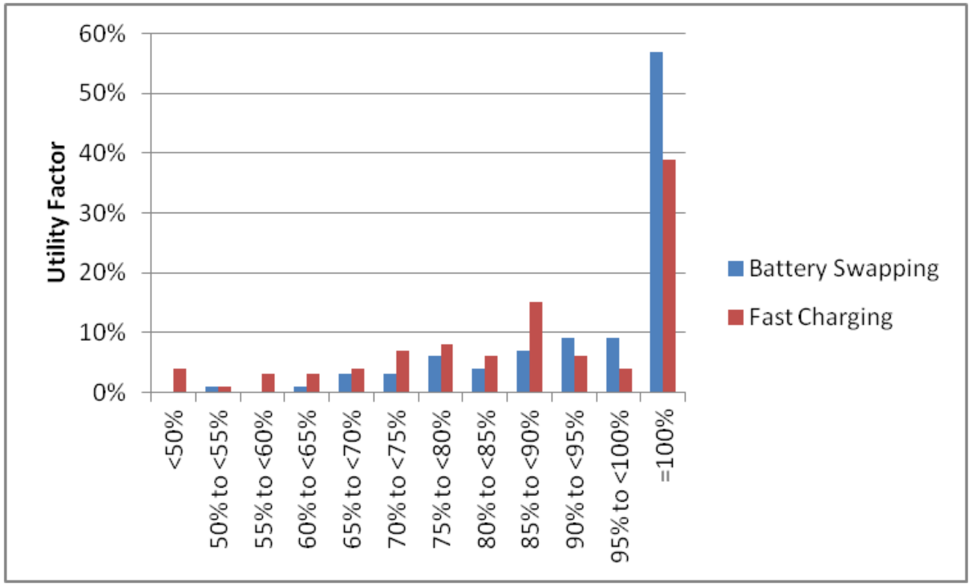
Past vs. Present Results

- **Previous studies:** nearly 40% of drive patterns achieved a ~100% utility factor when behavior changed in the presence of fast charge infrastructure

- **This study:** less than 20% of drive patterns achieved a ~100% utility factor when behavior was held constant in the presence of fast charge infrastructure
    - Set A: 15/91 (16%)
    - Set B: 3/89 (3%)

- **Conclusion:** accounting for changing driver behavior in response to infrastructure is important to quantify the value of fast charge strategies.

Previous Study Results



Part 4: Conclusions and Future Work

Home and Work Charging

- **Caveats**
    - We assumed “bold-informed” drivers (i.e., low range anxiety and accurate knowledge of vehicle, battery, and pending travel), which underestimated the relative value of work charging to less predictable, more conservative drivers (who would see less utility without work charging than our values indicate)

- **Conclusions**
    - *Home Charging:* L1 opportunity charging is nearly as good as L2 on average, and sometimes better due to increased battery degradation with L2 charging
    - *Work Charging:* Our analysis shows big gains for select drivers (+2,000 mi/yr), but biggest impact may be in reduction of range anxiety

- **Remaining Questions**
    - How capable is work charging when home charging is not available (i.e., for multi-dwelling urban homes)?
    - How is the value of work charging affected when drivers are more anxious and less informed?

Public Charging

- **Caveats**
  - We studied the effect of ubiquitous public charging infrastructure on “bold-informed” drivers (i.e., predictable travel and low range anxiety) without changing their behavior (i.e., altering trip patterns). As such, our results:

    - Marginalize differences between charge rates (if charging wasn’t available everywhere all the time, battery SOCs would fall lower and higher rate charging would be more valuable)

    - Underestimate the relative value of public charging to less predictable, more conservative drivers (who would see less utility without public charging than our values indicated)

    - Underestimate the absolute value of public charging to drivers willing to change behavior (e.g., make additional stops for fast charging)

    - BUT they accurately represent the maximum achievable vehicle utility without behavioral changes under high penetrations of public charging infrastructure.

Public Charging

- **Conclusions**
  - Drivers well suited (>80% utility and >8,000 mi/yr achieved) to 75-mile (EPA rated) BEVs without public infrastructure can increase their **utility factors from 77% to 90%** on average at EOL with L2 and L3 public charging, and can **reduce missed tours to less than 5/yr**
  - Remaining high mileage drivers increase their utility factor from 63% to **80% utility factor** with L3 public charging, and can **reduce missed tours to less than 10/yr**

- **Remaining Questions**
  - How capable is public charging when home charging is not available (i.e., for multi-dwelling urban homes)?
  - How is the value of public charging affected when drivers are more anxious and less informed?
  - How much more effective is fast charging when drivers change behavior in response to infrastructure availability?
  - How does reduced availability of fast charging affect utility?

Electric Roadway

- **Caveats**
    - We assumed a large number of in-network roads are electrified daily from 8 am to 10 pm and are capable of powering road and auxiliary loads, but not capable of charging the battery. This was selected for ease of implementation with the available data, and as such does not represent a best or worst case scenario.
- **Conclusions**
    - This electric roadway scenario offers only slightly better achievable VMT than ubiquitous level 3 charging, but eliminates sensitivity to battery wear
    - Achieving 100% utility factor for a large fraction of drivers may require out-of-network roadway electrification.
- **Remaining Questions**
    - Is it possible that a smaller deployment of electric roadway (class 1 and 2 roads only) could offer similar performance at lower cost?
    - Allowing battery charging while on the electric roadway will improve utility, but by how much?
    - What's the impact of electric roadways on PHEVs and HEVs?
    - Is significant battery down-sizing possible without sacrificing vehicle utility?

Acknowledgments

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  - David Howell
  - Brian Cunningham

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- **Technical questions regarding this work should be directed to Jeremy Neubauer at 303-275-3084 or jeremy.neubauer@nrel.gov.**