Impact of Vehicle Automation on Electric Vehicle Charging Infrastructure Siting and Energy Demand

Avi Chaim Mersky

(Amersky@alumni.cmu.edu)

Constantine Samaras

Carnegie Mellon University

Department of Civil and Environmental Engineering

Economics of Autonomous and Electric Vehicles

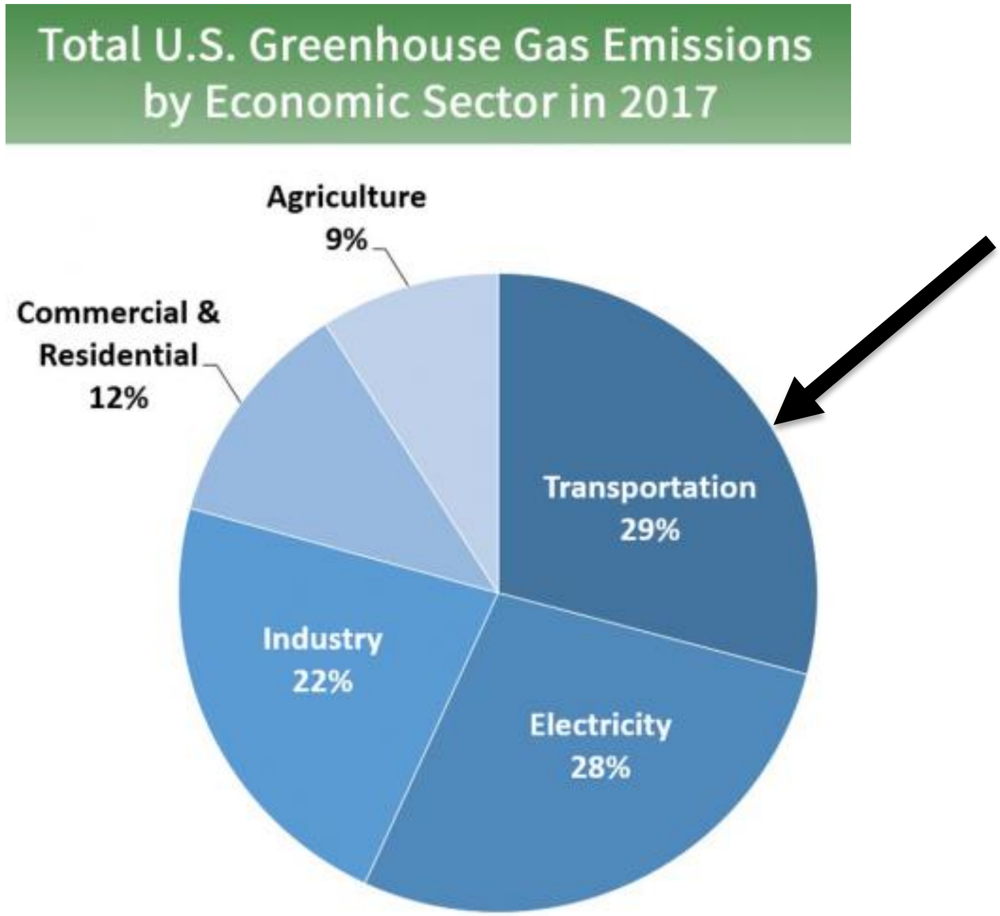
The National Bureau of Economic Research

Friday, June 7, 2019

Agenda

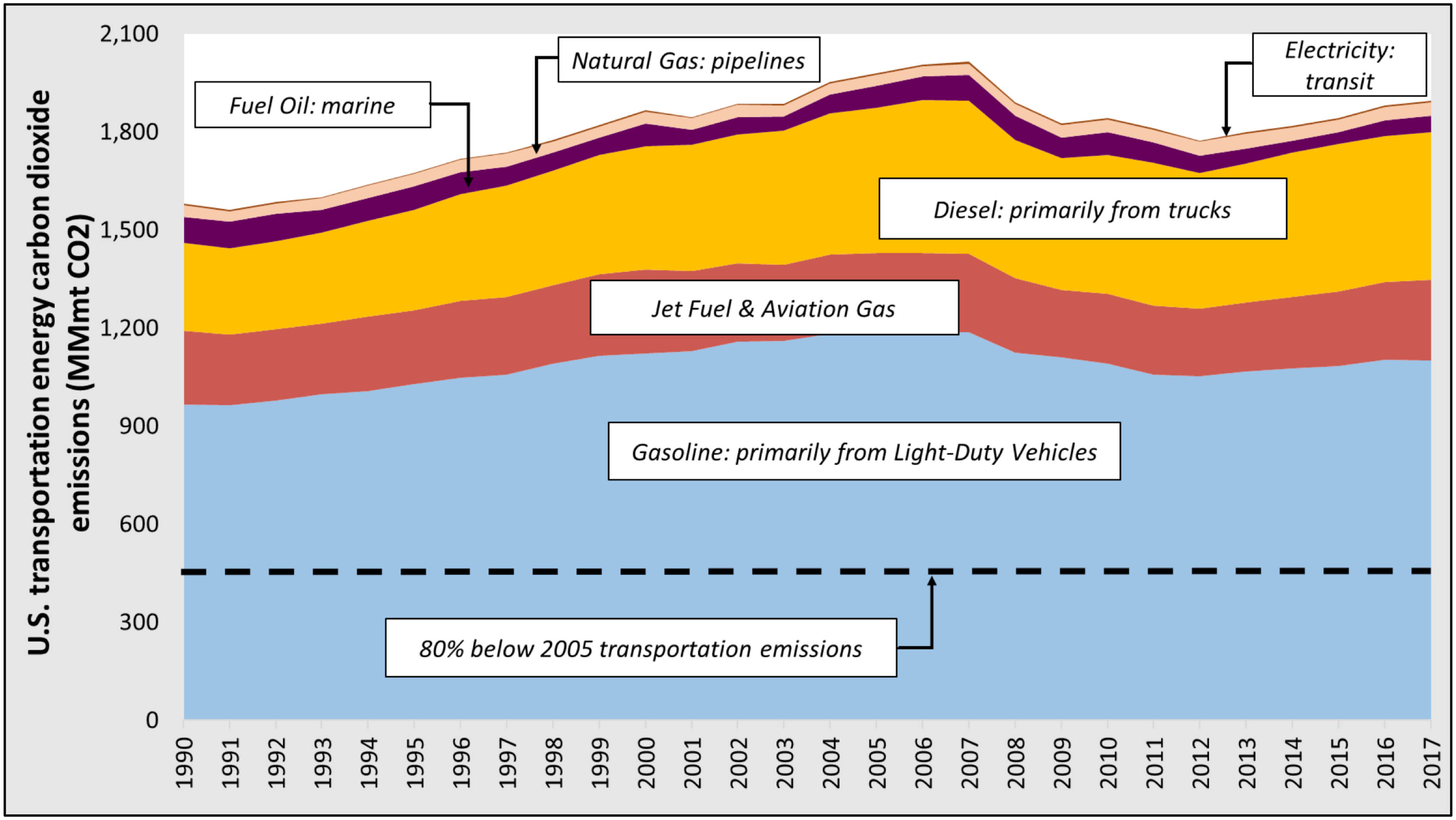
- Why this Matters
- How Vehicle Automation May Affect EV Charging
- Trip Characteristics and Charger Selection
- Optimization Methods
- Results
- Implications
- Limitations and Future Work

Transportation is Now The Largest Source of U.S. GHG Emissions



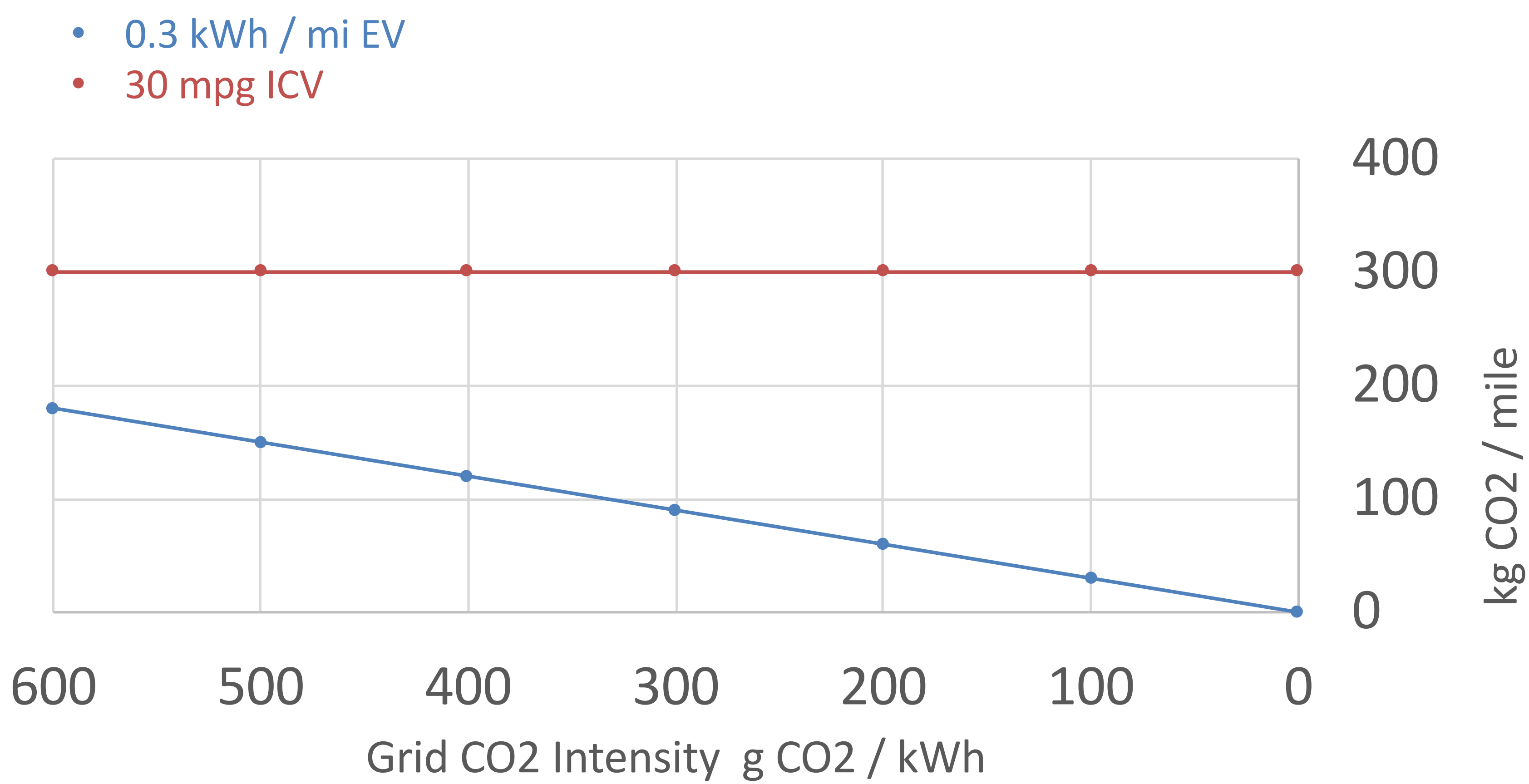
Source: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Transportation is Hard to Decarbonize

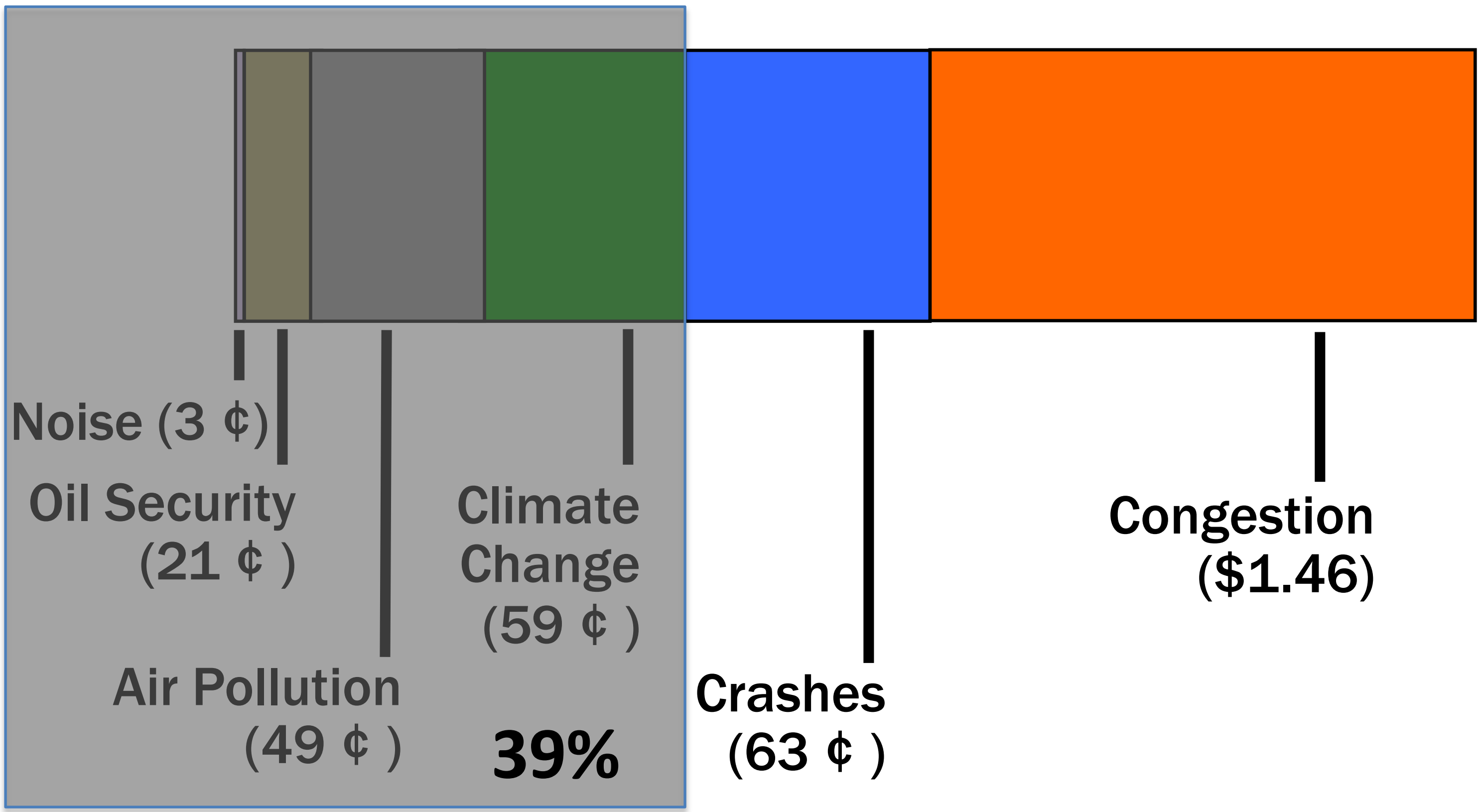


Data: DOE, Image by Abdullah Alarfaj, CMU

Low-Carbon Electricity Can Enable Deep GHG Reductions with EVs



Oil Use Accounts for 39% of Transportation Externalities



Source: Updated from Anderson et al., 2014, Uses NHTSA 2017-2025 Estimates, updated SCC Costs, GREET WTW emissions, assumes 25 mpg, $2013

However, Public Charging Stations can be Expensive

- Cost for a single vehicle 240 volt charger installed can vary between $4,000 and $20,000
- DC Fast charging can cost between $40,000 and $90,000

Source: Smith, M., and Castellano, J. (2015).

It is Challenging to Reduce EV Charging Infrastructure Costs

- Vehicles take up the chargers physical space and ports until someone moves/disconnects them
- Vehicles need to either charge near the driver's destination or must charge in comparable times to gasoline pumps
- Level 4 & 5 automation could allow for a reduction in the number of necessary chargers

What We Mean When We Say Level "X" AV

Level	Name	Who is Driving?	Who is Monitoring?	Who Intervenes?
0	No Automation	😀	😀	😀
1	Driver Assist	😀🤖	😀	😀
2	Partial Automation	🤖😀	😀	😀
3	Conditional Automation	🤖	🤖	😀
4	High Automation	🤖	🤖	🤖😀
5	Full Automation	🤖	🤖	🤖

Source: Adapted from NHTSA and SAE J3016

Research Question

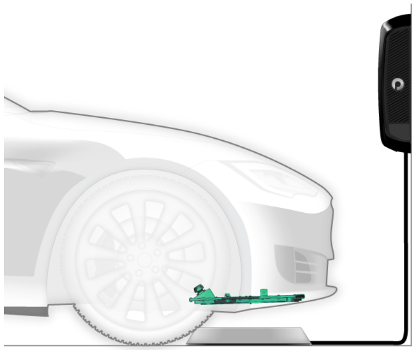
How can the various levels of vehicle automation affect the economics and energy use of charging EVs?

How Vehicle Automation may Affect EV Charging

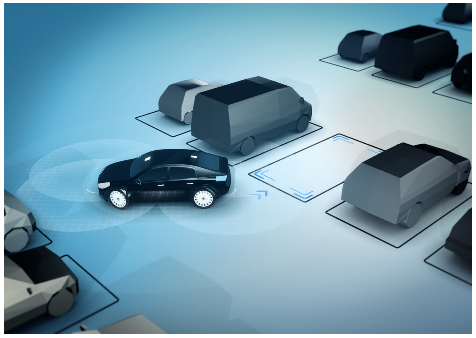
- Level 0-3 Automation
  - The charger is occupied until the commuter moves it.
  - The commuter must walk from the parking spot to their destination and back

How Vehicle Automation may Affect EV Charging

- Level 4 Automation
  - The vehicle can move itself on and off the charger
  - The commuter must still walk after parking
- Level 5 Automation
  - The vehicle can move itself on and off the charger
  - The vehicle and drop off and pick up the commuter



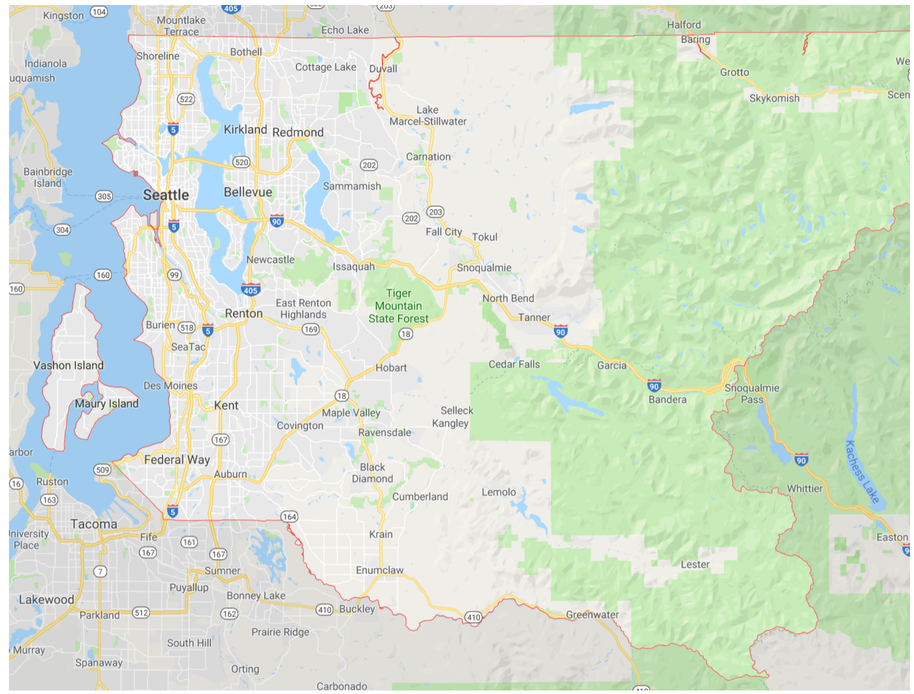
https://www.pluglesspower.com/learn-about-plugless/



https://www.media.volvocars.com/global/en-gb/media/pressreleases/49569/photos

Data and Methods

- We investigated King County, Washington
- We used the 2014 Puget Sound Household travel survey data directly

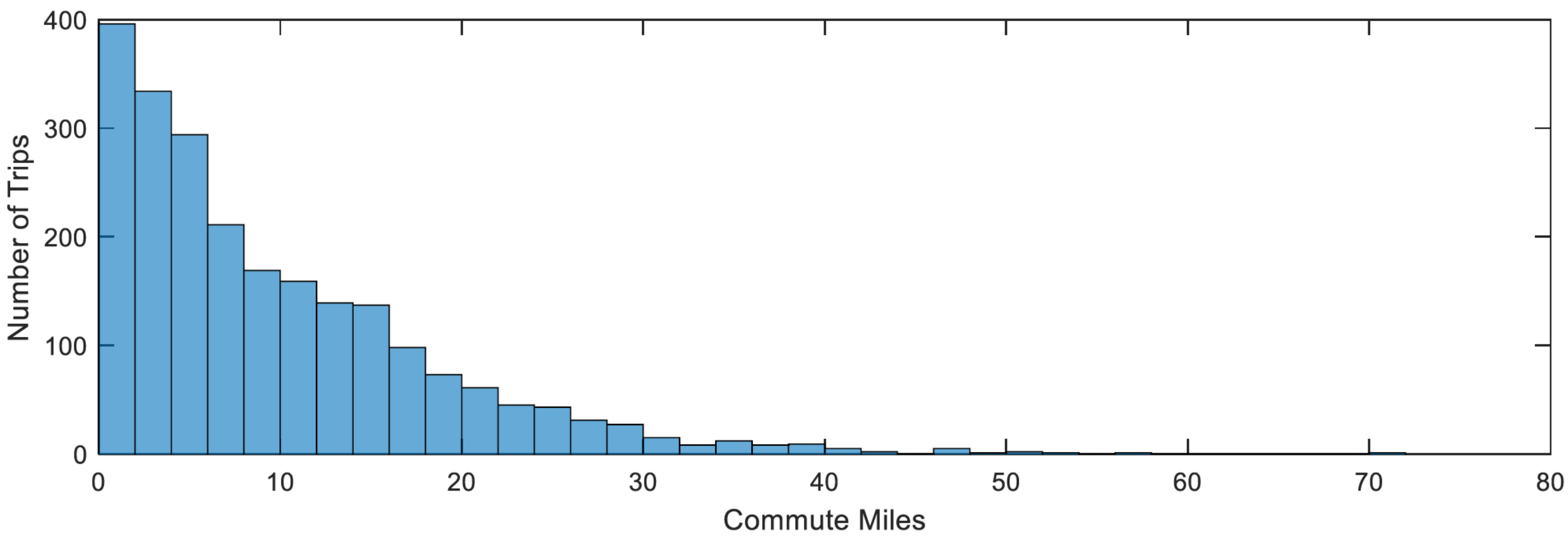


Source: Google Maps

Trip Characteristics

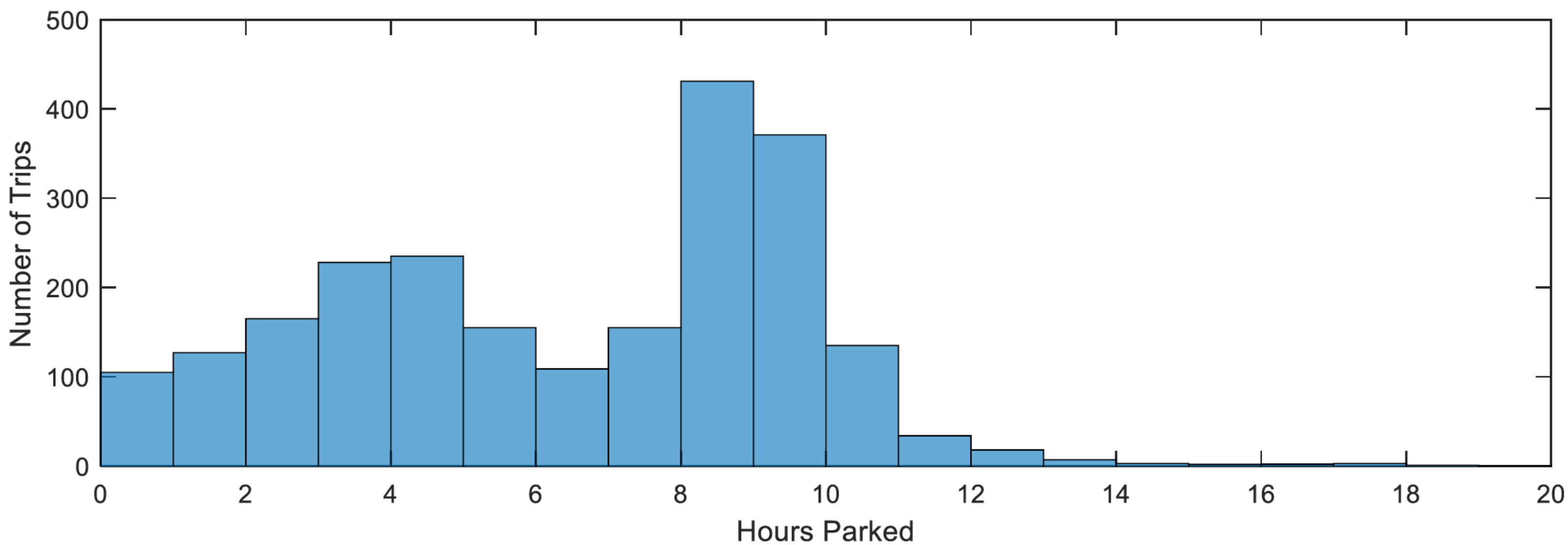
- 2,300 trips Total
- 1,900 parking spaces demanded during peak hour
- Max possible modeled charger utilization is 31%
  - Based on commuter distances and charge switching time

Most Drivers in the Sample Commute Short Distances



Source: 2014 Puget Sound HHTS

Almost All Sampled Commuters Park Long Enough to Fully Charge



Source: 2014 Puget Sound HHTS

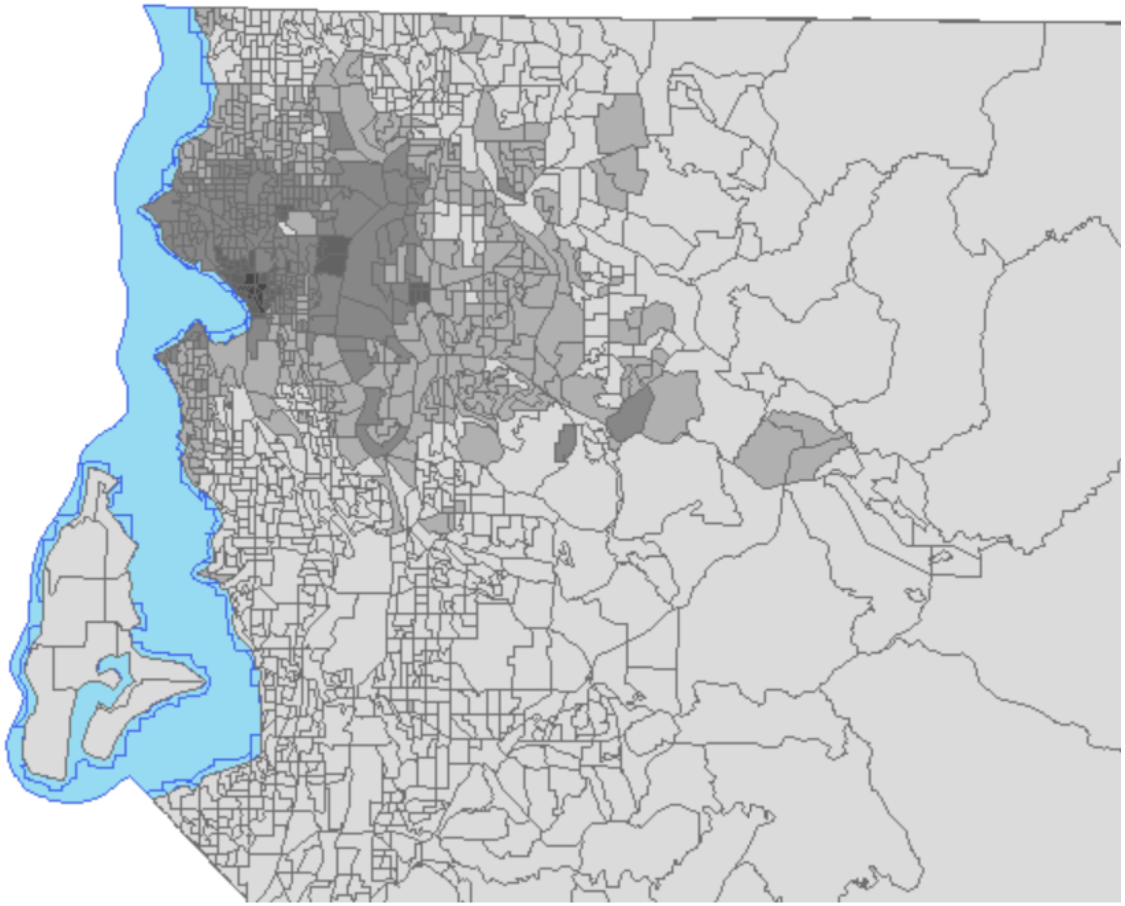
Charger Selection

- AC Level 1 / 120 V Charging
  – About 5 miles per hour
  – <$2,000 (significantly less for new construction)
- AC Level 2 / 240 V Charging
  – About 20 miles per hour
  – About $10,000 per charger
- DC Fast Charging
  – About 150 miles per hour
  – About $50,000 per charger

Costs are Evaluated for Charger Station Owners as well as Drivers

- Charger Owner Costs
  - Real Estate
  - Amortized Capital Equipment and Installation Costs
    - Number of Chargers
    - 15 years with a 4.1% discount rate
- Driver Costs
  - Walking
    - Derived from median income and time
  - Additional Vehicle Depreciation and Energy Costs

King County Assessed Real Estate Prices



Optimization Methods

- We know when each commuter arrives and leaves each Travel Analysis Zone (TAZ)
- We assume each commuter will drive an electric vehicle
- We want to minimize the total costs of Drivers and Charger Owners

Optimization Methods

- Level 0-3 Automation (No Self-Driving Vehicles)
  - Minimize the total costs of walking and charger owners
    - $\min\left[\sum_{zonei}^{I}\left(\sum_{zonej}^{J}\{costWalk_{ij} * Trips_{ij}\}\right) + OwnerCost\right]$
  - One charger is required for every peak vehicle
  - Max walking distance of 0.25 miles

Optimization Methods

- Level 4 automation (Self Parking and Charging Vehicles)
  - Same as Level 0-3 but chargers can now serve multiple vehicles
    - $\min\left[\sum_i^I\left(\sum_j^J\{costWalk_{ij} * numTrips_{ij}\}\right) + OwnerCost\right]$
    - Vehicles can queue up to as charger with a one minute switching time after charging is finished
    - Max walking distance of 0.25 miles

Optimization Methods

- Level 5 Automation (Completely Self-Driving and Charging Vehicles)
  - Decouple commuter destination from parking location
  - Vehicles energy and depreciation costs are ~20 times less per mile than walking
  - $\min \left[\sum_i^I \left(\sum_j^J \{ costDrive_{ij} * numTrips_{ij} \} \right) + OwnerCost \right]$

Results: Level 0/No Automation

- $1.75 M Total Costs
  - Almost all is charger owner because of single charger per vehicle and max walking distance constraint
- 1,900 Chargers
  - 1.2 trips per charger
  - 4.4% Utilization
    - Time that the charger is actually used

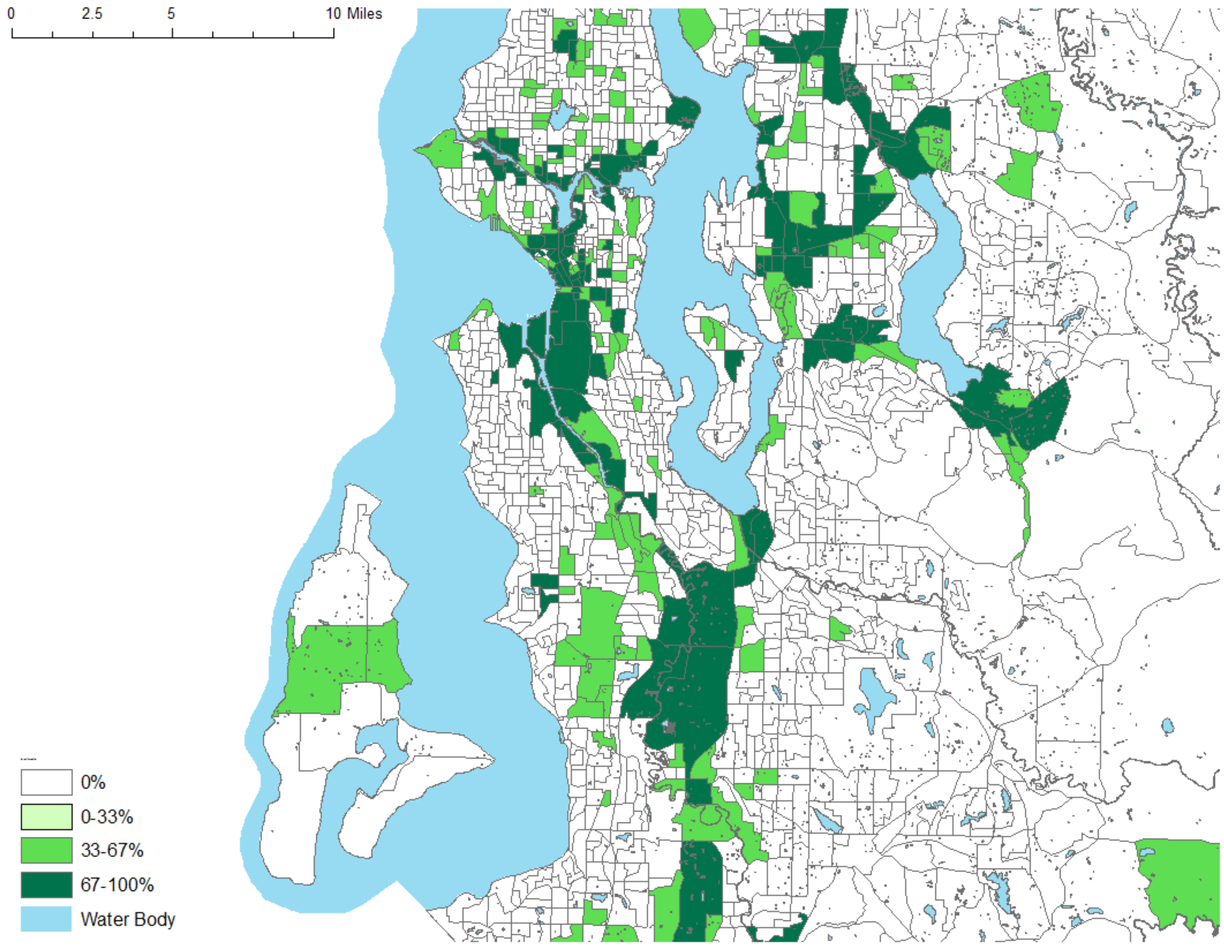
Results: Level 4 Automation

- $930,000 Charger Owner
- $940,000 Total Costs
  - Commuter costs remain bounded by walking distance
- 680 Chargers
  - 3.5 Trips per charger
  - 13% Utilization

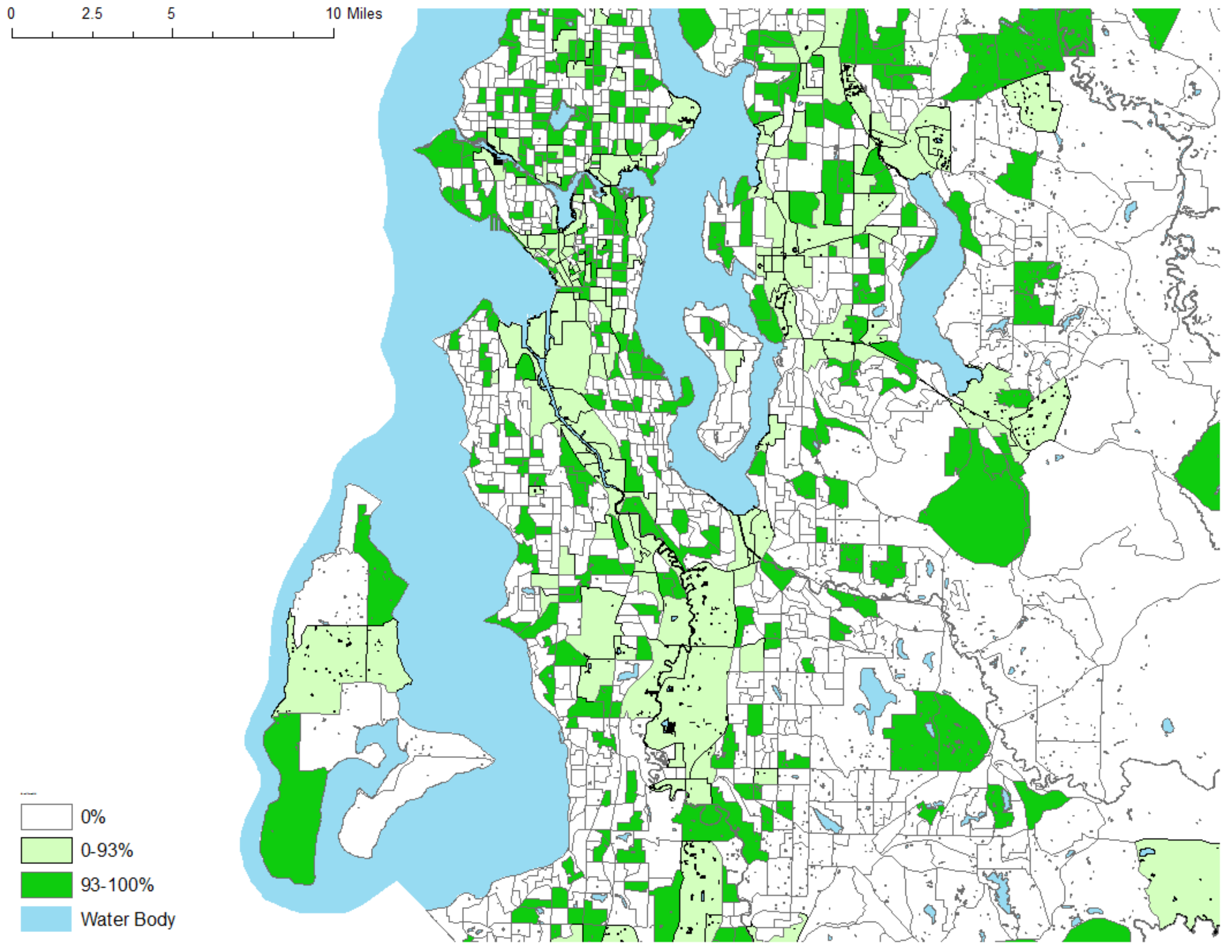
Results: Level 5 Automation

- $440,000 Charger Owner
- $540,000 Total Costs
  – Commuter Costs increased by a factor of 10
- 330 Chargers
  – 7.5 Trips per charger
  – 27% Utilization

Reduction in Number of Chargers: Level 0-4 Vehicle Automation

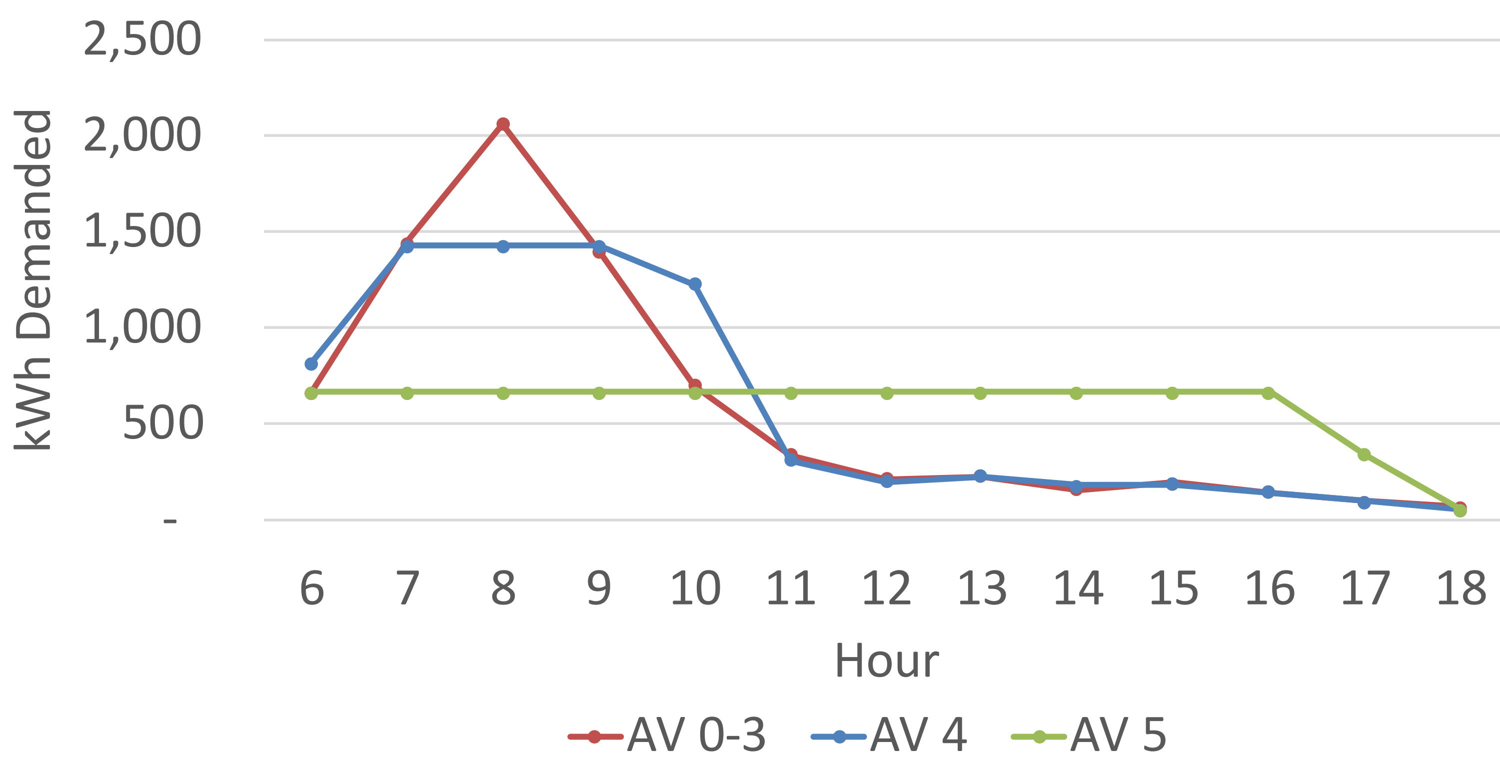


Reduction in Number of Chargers: Level 0-5 Vehicle Automation



Automation Enables Demand Smoothing

- Assume 35 kWh / 100 mi



Implications

- Optimizing EV infrastructure for AVs enables smoothing of peak EV electric demand
- Similar results could be gained through smart charging technology
  - Though those have their own cost structures and technical limitations

Implications

- Automation allows for considerable decreases in the total chargers and charger owner cost
  - Number of chargers reduced from 1,900 to 330
  - $1.8 M to $440,000
- But shifts a portion of the costs to commuters
    - How do we best incentivize the social good without harming travelers?

Limitations

- Traffic demand taken direct from HHTS
  - Demand is shown to be more concentrated than reality
  - Demand is much smaller than reality
- Poor real estate data

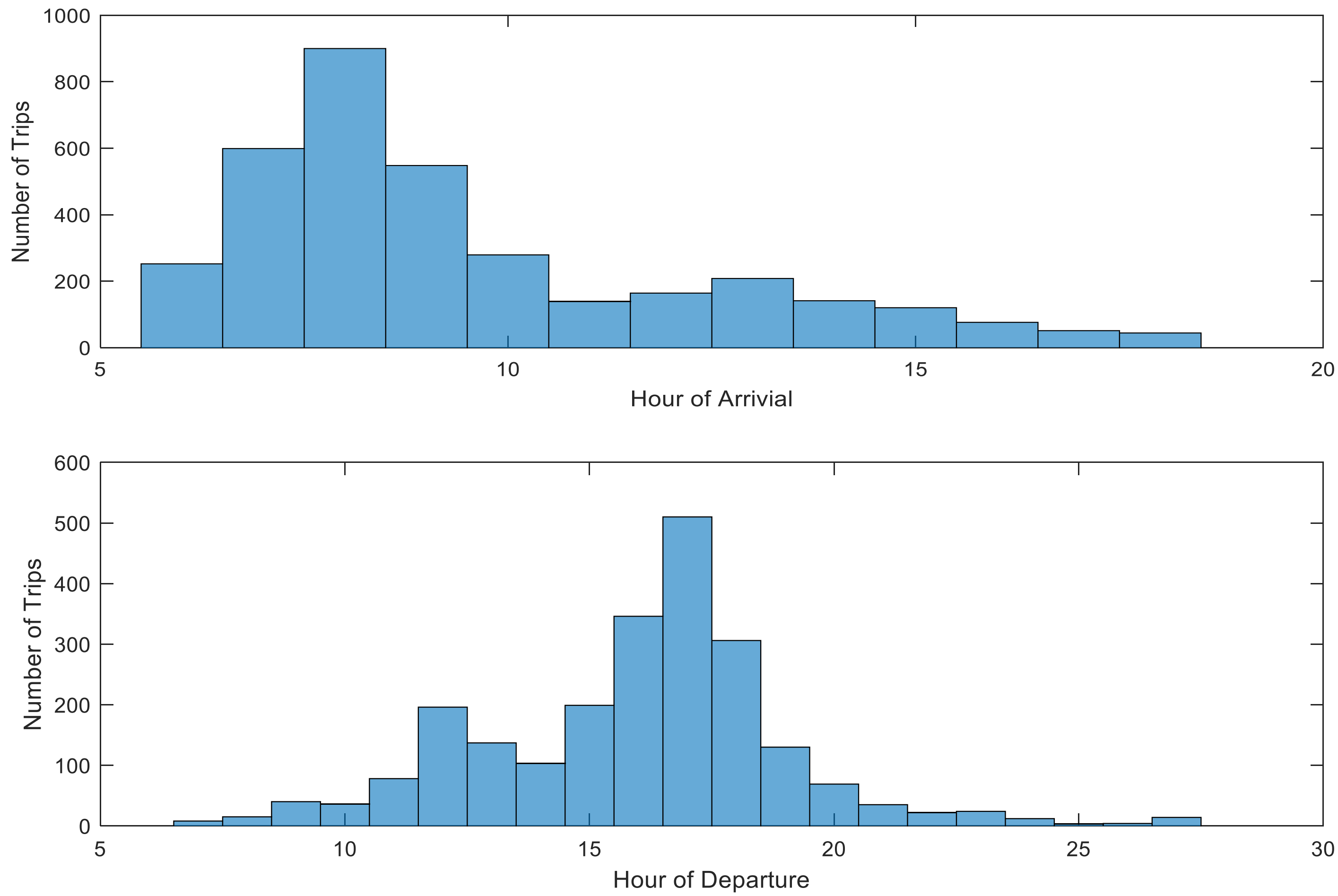
Questions?

Appendix Slides

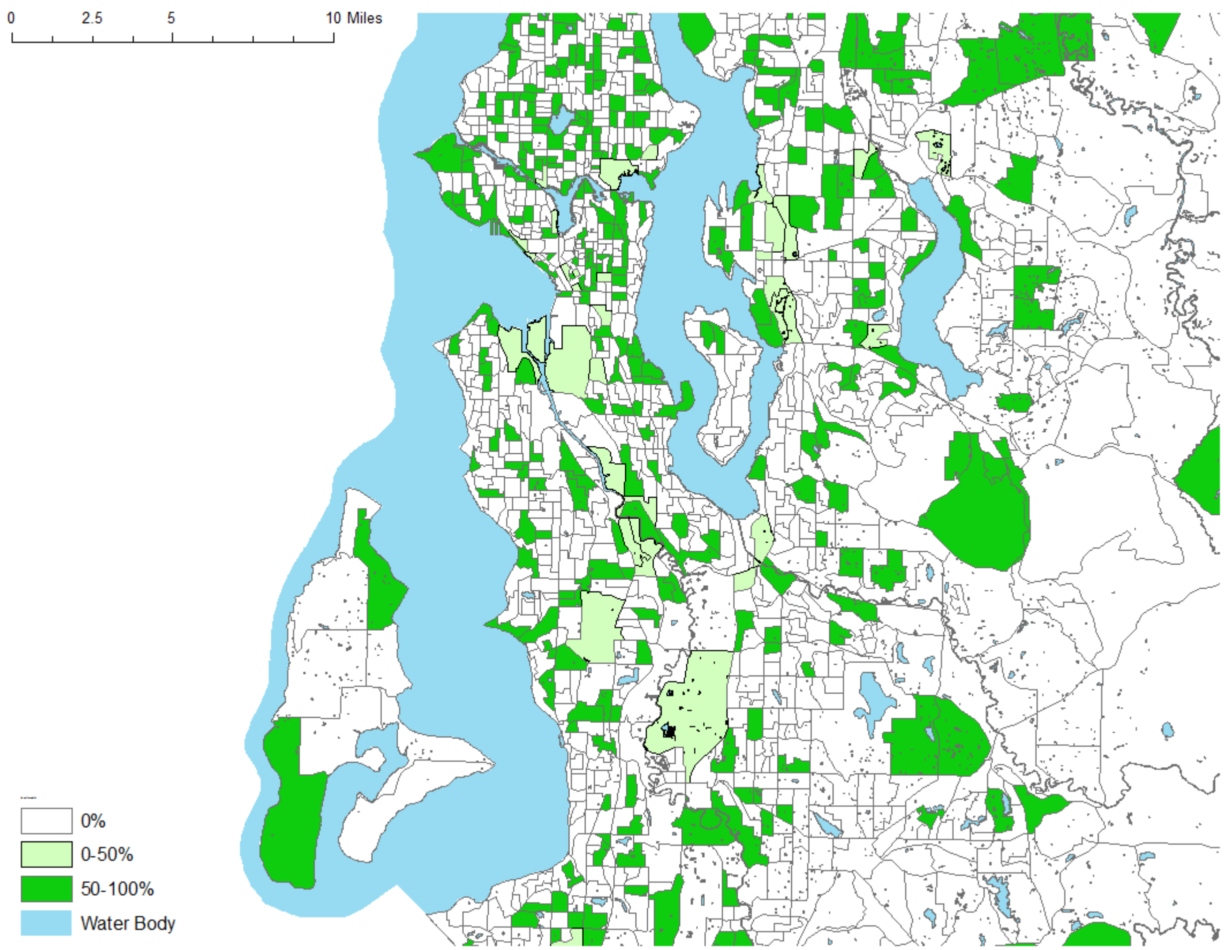
Data Sources

- Infrastructure Costs
  - DOE Report
- GIS Data and Trip Distribution/Characteristics
  - Puget Sound Household Travel Survey
  - Census Bureau
  - King County GIS

Commuter Arrival and Departure Times



Reduction in Number of Chargers: Level 4-5 Vehicle Automation



Optimization Detailed

No Automation (Level 0-3 AV)

- Objective:
  - $\min[\sum_i^I(\sum_j^J\{c_{ij} * y_{ij} * K_i\}) + L]$
- Decisions:
  - y_{ij} =peak parking demand of zone i served in location j, (stations to build in j), integer
- What we Want:
  - $x_j = \sum_i^I y_{ij}$
- Constraints:
  - $\sum_j^J(y_{ij}) = D_i, \forall$ I, (all parking demand served)
  - $\sum_i^I(y_{ij}) \leq x_j, \forall$ j, (charging supply constraint)
  - $y_{ij} \geq 0$ ∀ i ∀ j (non-negativity constraint on parking demand)
  - $x_j \geq 0$ ∀ j (non negative station assignment)
  - $d_{ij} * w_{ij} <= W \; \forall \, i \; \forall \, j$ (maximum walking distance)
- Given:
  - $L = \sum_j^J\left(x_j * (A_j + B) * (A|P,i)\right)$, (owner cost)
  - $c_{ij} = d_{ij} * E * 2 * 260$, (walking costs)
  - $w_{ij} = \begin{Bmatrix} 1, \; if \; y_{ij} > 0 \\ 0, \; else \end{Bmatrix}$, (binary check if anyone walked between i and j)
    - $solved \; as \; \{w_{ij} * 900{,}000 \geq y_{ij}\}$
- Input Parameters:
  - D_i = parking demand at zone i, peak vehicles, count
  - A_j = real estate cost per parking space and charger at location j, $
  - B = costs per charging station, equipment and installation, $
  - d_{ij} = walking distance between zone i and location j, miles
  - E = cost of walking, $ / mile
  - W = maximum walking distance, miles
  - K_i =average number of trips per peak trip in zone i, can be fractional, count
  - $(A|P,i)$ =annuity value of current lump sum, $

Self Parking (level 4 AV)

- Objective:
  - $\min[\sum_i^I(\sum_j^J\{c_{ij} * y_{ij}\}) + L]$
- Decisions:
  - y_{ij} =total trips ending in zone i served in location j, count
- What we Want:
  - $x_j = \frac{(\sum_i^I y_{ij})}{U*q}$, integer
- Constraints:
  - $\sum_j^J \left(y_{mi_{ij}}\right) \geq D_i, \forall$ I, *(all parking demand served)*
  - $\sum_i^I \left(y_{mi_{ij}}\right) \leq Q_j, \forall$ j, (charging supply constraint)
  - $y_{ij} \geq 0$ ∀ i ∀ j (non-negativity constraint on parking demand)
  - $x_j \geq 0$ ∀ j (non−negative station assignment), $integer$
  - $d_{ij} * w_{ij} <= W \; \forall \, i \; \forall \, j$ (maximum walking distance)
- Given:
  - $L = \sum_j^J \left(x_j * \left((A_j + B) * (A|P,i) + C_w\right)\right)$, (owner cost)
  - $c_{ij} = d_{ij} * E * 2 * 260$, (walking costs)
  - $w_{ij} = \begin{Bmatrix} 1, & if\ y_{ij} > 0 \\ 0, & else \end{Bmatrix}$, (binary check if anyone walked between i and j)
    - $solved\ as\ \{w_{ij} * 900{,}000 \geq y_{ij}\}$
  - $Q_j = x_j * U * q$, zone charge capacity, miles
  - $y_{mi_{ij}} = y_{ij} * D_{avg_i}$
- Input Parameters:
  - D_i = parking demand at zone i, peak driver miles
  - D_{avg_i} =mean trip distance for trips ending in zone i, miles
  - A_j = real estate cost per parking space and charger at location j, $
  - B = costs per charging station, equipment and installation, $
  - d_{ij} = walking distance between zone i and location j, miles
  - E = cost of walking, $ / mile
  - W = maximum walking distance, miles
  - U = maximum charger utilization rate, %
  - q =charger capacity, miles per shift
  - $(A|P,i)$ =annuity value of current lump sum, $
  - C_w = cost of wireless AV communication equipment maintenance, $ / year

Self Driving (Level 5 AV)

- Objective:
  - $\min[\sum_i^I(\sum_j^J\{c_{ij} * y_{ij}\}) + L]$
- Decisions:
  - y_{ij} =total trips ending in zone i served in location j, count
- What we Want:
  - $x_j = \frac{(\sum_i^I y_{ij})}{U*q}$
- Constraints:
  - $\sum_j^J \left(y_{mi_{ij}}\right) \geq D_i, \forall$ I, (all parking demand served)
  - $\sum_i^I \left(y_{mi_{ij}}\right) \leq Q_j, \forall$ j, (charging supply constraint)
  - $y_{ij} \geq 0$ ∀ i ∀ j (non-negativity constraint on parking demand)
  - $x_j \geq 0$ ∀ j (non-negative station assignment)
- Given:
  - $L = \sum_j^J \left(x_j * \left((A_j + B) * (A|P,i) + C_w\right)\right)$, (owner cost)
  - $c_{ij} = d_{ij} * F_e * P_{elc} * 2 * 260$, (drop-off/pick-up energy cost, $)
  - $w_{ij} = \begin{Bmatrix} 1, & if\ y_{ij} > 0 \\ 0, & else \end{Bmatrix}$, (binary check if anyone walked between i and j)
    - $solved\ as\ \{w_{ij} * 900{,}000 \geq y_{ij}\}$
  - $Q_j = x_j * U * q$, zone charge capacity, miles
  - $y_{mi_{ij}} = y_{ij} * D_{avg_i}$
- Input Parameters:
  - D_i = parking demand at zone i, peak driver miles
  - D_{avg_i} =mean trip distance for trips ending in zone i, mile
  - A_j = real estate cost per parking space and charger at location j, $
  - B = costs per charging station, equipment and installation, $
  - d_{ij} = walking distance between zone i and location j, miles
  - U = maximum charger utilization rate, %
  - q =charger capacity, miles per shift
  - F_e =fuel economy, kWh / mi
  - P_{elc} =price of electricity, $ / kWh
  - $(A|P,i)$ =annuity value of current lump sum, $
  - C_w =cost of wireless AV communication equipment maintenance, $ / year