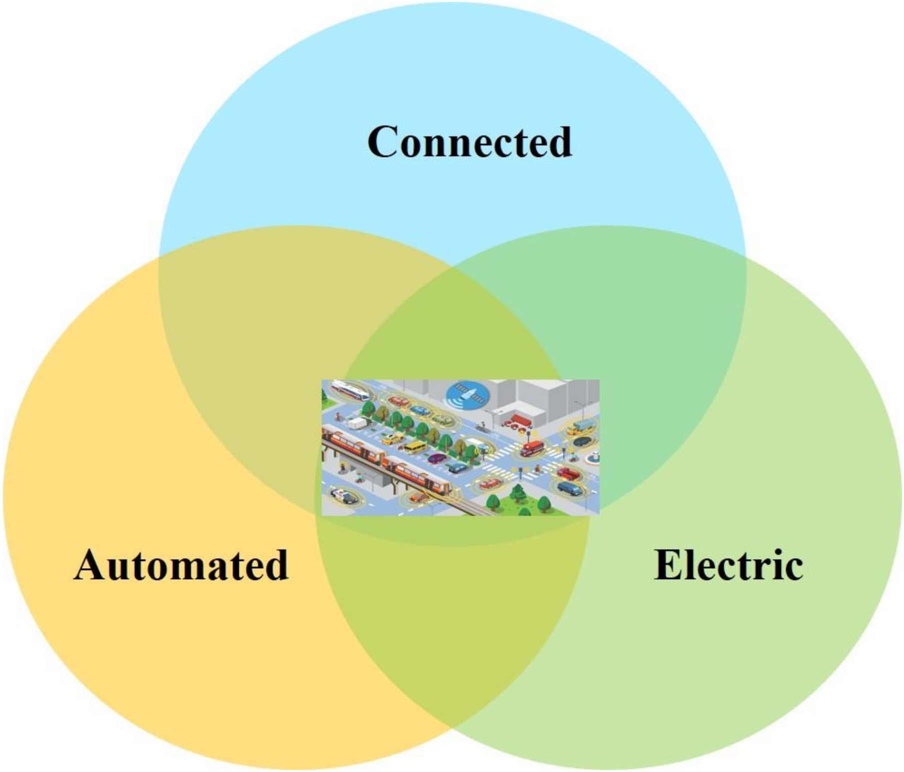
Charging Decision Making for Automated Electric Vehicles

Zonggen Yi, Ph.D.
Energy Storage and Advanced Vehicles Department
Idaho National Laboratory

Automated Electric Vehicles



Convergence of the ***Electric Propulsion Systems*** and ***Automated Vehicles***:

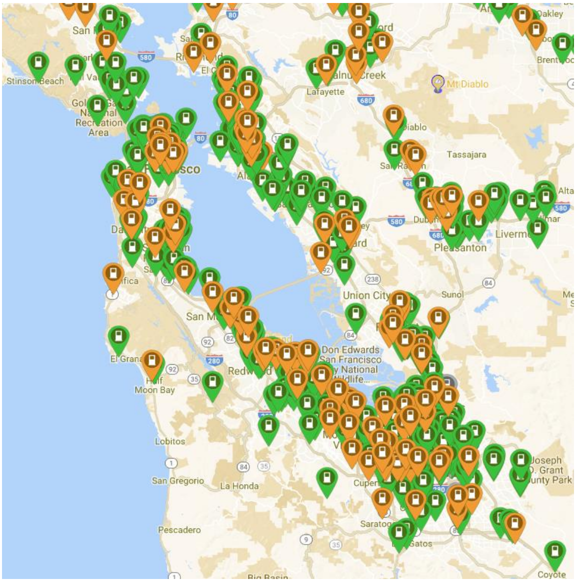
- Electric vehicles have inherent advantages when it comes to fuel savings and reducing the impact on the environment.
- It is easier for computers to drive electric vehicles.
- The lower operating cost of a battery-electric vehicle is a much bigger factor.

Hybrid vs Electric

- ***General Motors*** affirmed its commitment to battery-electric propulsion with the goal of “Zero emissions; Zero crashes; Zero congestion”.
- ***Tesla*** is pursuing the all-electric program for its “fully self-driving cars”.
- ***Waymo*** is using Chrysler Pacifica minivans that are plug-in hybrid electric.
- ***Uber*** is also opting for hybrids, having recently placed an order for plug-in hybrid Volvo XC90 SUVs.

Source: https://www.theverge.com/2017/12/12/16748024/self-driving-electric-hybrid-ev-av-gm-ford

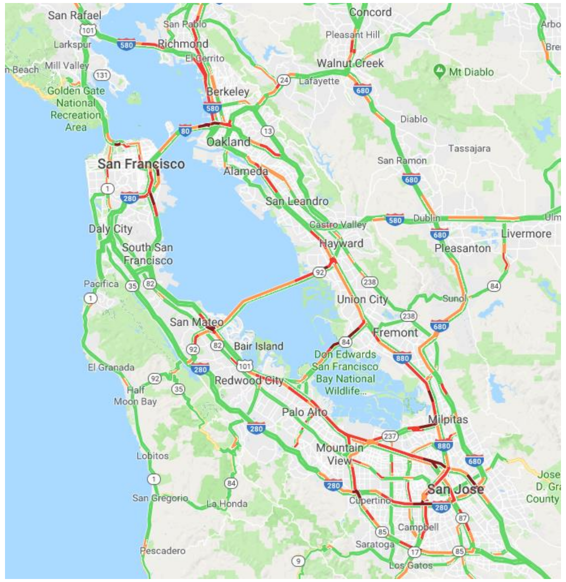
Energy Management of Automated Electric Vehicles



Energy Consumption
Eco-driving/Eco-routing

Energy Management of Automated EVs

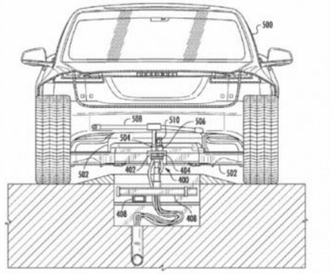
Energy Recharging
Charging Decision Making



New Opportunities for Automated Electric Vehicles

Connected Automated EVs

Automatic Charging Station



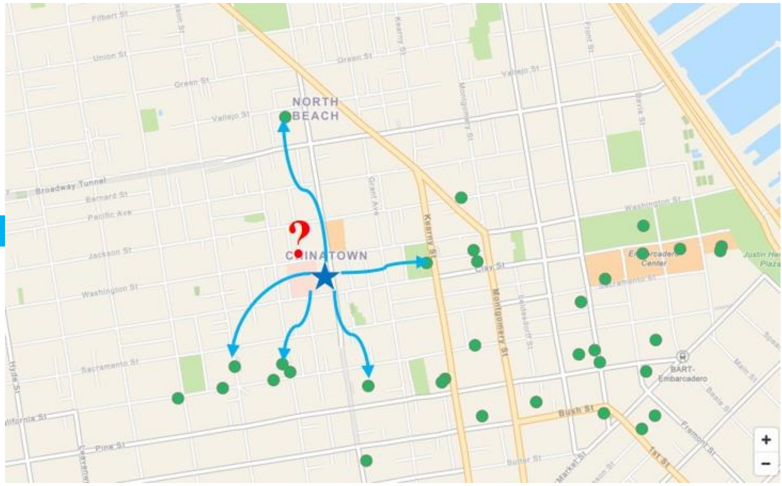
Source: http://www.ipwatchdog.com/2015/06/18/wireless-induction-charging-is-coming-to-electric-vehicles/id=58756/

Source: https://patents.google.com/patent/US9527403

Automatic Charging Decision Making

- An automatic decision making process is necessary for recharging of automated electric vehicles
- Remove the challenge of co-locating charging infrastructure with driver destinations
- Utilize real-time charging station status information

Connected Charging Station Network



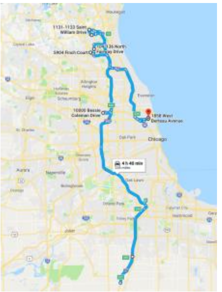
Benefits

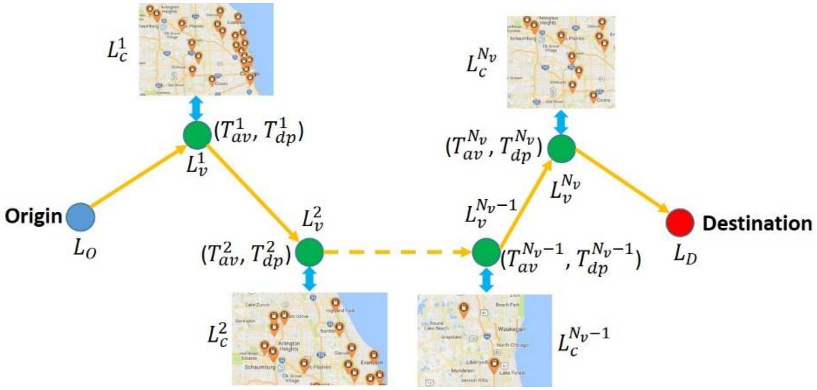
- Ensure sufficient battery energy to meet travel needs
- Minimize the energy/time/money cost of charging actions
- Facilitate the charging control and vehicle/grid integration

Automatic Charging Decision Making Framework

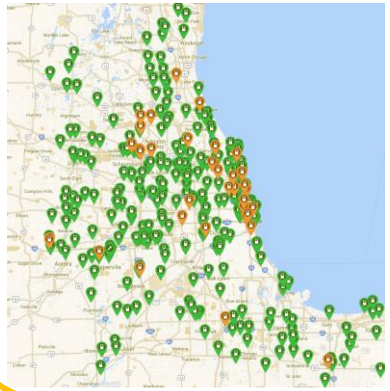
Travel/Itinerary Information

- Visited locations
- Staying time



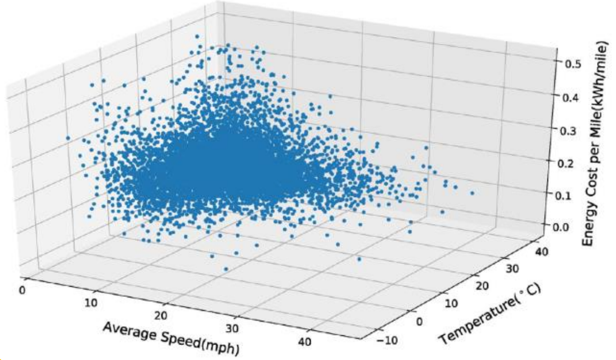


Nearby Charging Station Network



- Location
- Availability

EV Energy Consumption Model



Multi-Stage Dynamic Programming

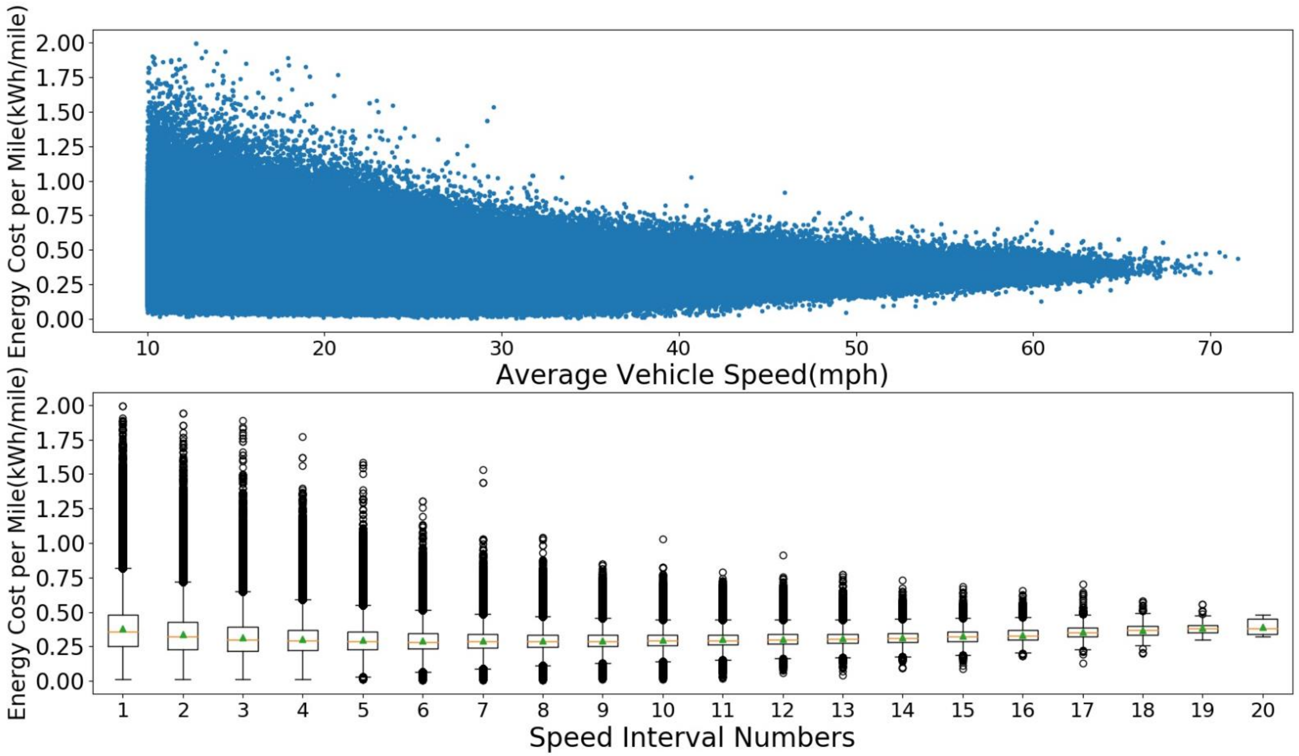
$$
\begin{aligned}
\min_{a[1],\ldots,a[N_v]} \quad & f(s[0], a[0], 0) + \sum_{k=1}^{N_v} f(s[k], a[k], k) \\
\text{s.t.} \quad & s[0] = S_0 \\
& s[k-1] = s[k] - \sum_{i=1}^{N_c^k} E_c^i[k] x^i[k] + E_{tc}^{(k-1,k)} + 2\sum_{i=1}^{N_c^k} E_{cc}^i[k] x^i[k] \\
& P_d[k] \le s[k] \le C_p \\
& 0 \le E_c^i[k] \le E_{upr}^i[k] \\
& x^i[k] = 0 \text{ or } 1, \text{ and } \sum_{i=1}^{N_c^k} x^i[k] \le 1 \\
& k = 1, \ldots, N_v
\end{aligned}
$$

Optimized Charging Strategies

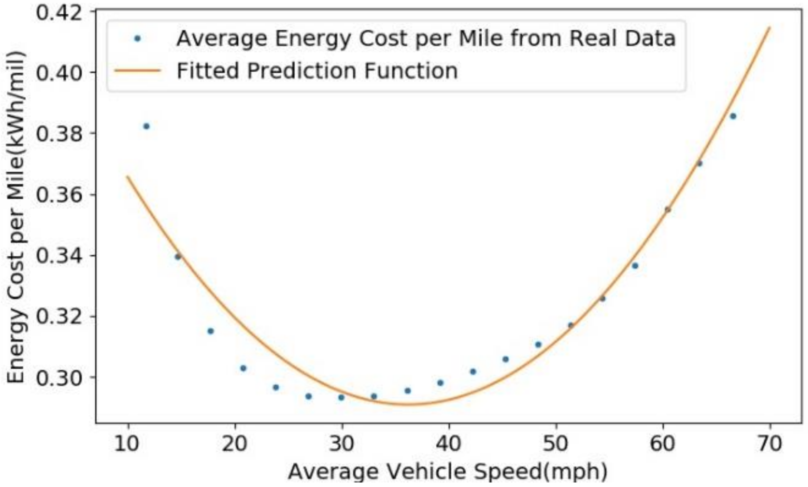
- Charging location
- Charging energy amount
- Charging time interval

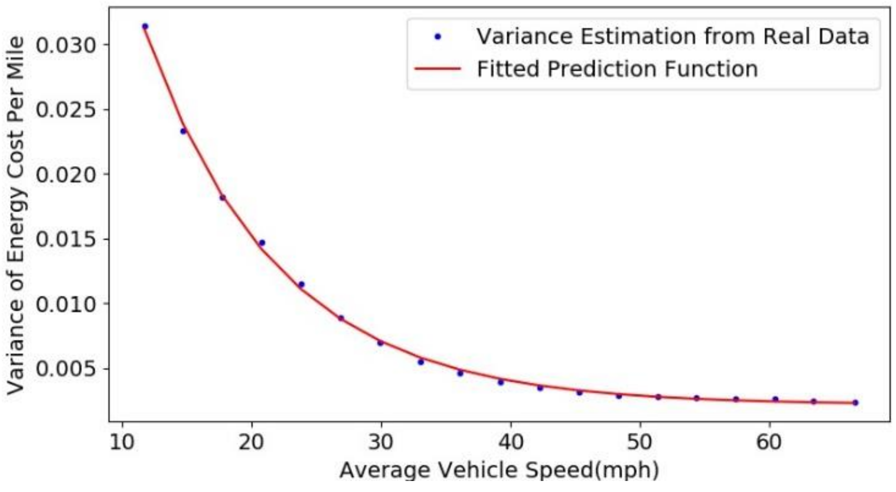
Data-Driven EV Energy Consumption Modeling

- **Energy cost per mile (kWh/mile) distribution**



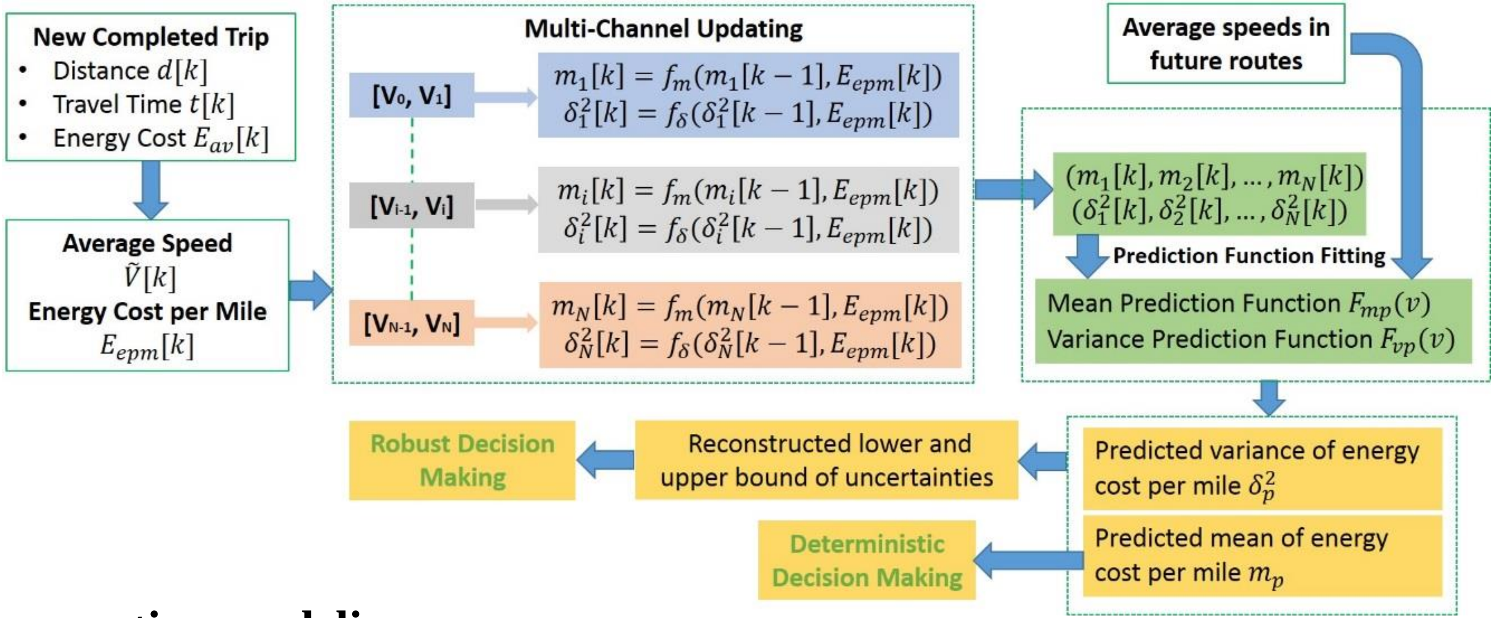
- **A stochastic model for Nissan Leaf**





Data-Driven EV Energy Consumption Modeling

- **Multi Channels Prediction Model Construction and Real-time Update**



Promising energy consumption modeling

✓ ***Data-driven modeling*** can provides a uniform format, which is independent from specific vehicle parameters, and is easy to handle real-world uncertainties.

✓ ***Stochastic modeling*** for real-world uncertainties provides the capability of decision making process to achieve robust strategies.

✓ ***Real-time updating*** is necessary to handle the dynamics of real world traffic and other environmental conditions.

Dynamic Programming for Charging Decision Making

- **Multi-Stage Charging Decision Making Modeling**

Deterministic (Average) Modeling

$$\min_{a[1],\ldots,a[N_v]} \quad f(s[0],a[0],0)+\sum_{k=1}^{N_v} f(s[k],a[k],k)$$

$$\begin{aligned}
\text{s.t.} \quad & s[0]=S_0\\
& s[k-1]=s[k]-\sum_{i=1}^{N_c^k} E_c^i[k]x^i[k]+E_{tc}^{(k-1,k)}+2\sum_{i=1}^{N_c^k} E_{cc}^i[k]x^i[k]\\
& P_d[k]\le s[k]\le C_p\\
& 0\le E_c^i[k]\le E_{upr}^i[k]\\
& x^i[k]=0 \ \text{ or } \ 1, \ \text{ and } \sum_{i=1}^{N_c^k} x^i[k]\le 1\\
& k=1,\ldots,N_v
\end{aligned}$$

Robust Modeling

$$\min_{a[1],\ldots,a[N_v]} \ \max_{\substack{E_{tc}^{(k,k+1)}\in[E_{lw}^k,E_{up}^k]\\ E_{cc}^i[k]\in[E_{lw}^i[k],E_{up}^i[k]]}} f(s[0],a[0],0)+\sum_{k=1}^{N_v} f(s[k],a[k],k)$$

$$\begin{aligned}
\text{s.t.} \quad & s[0]=S_0\\
& s[k-1]=s[k]-E_c[k]+E_{tc}^{(k-1\to k)}+2\sum_{i=1}^{N_c^k} E_{cc}^i[k]x^i[k]\\
& P_d[k]\le s[k]\le C_p\\
& 0\le E_c^i[k]\le E_{upr}^i[k]\\
& E_c[k]=\sum_{i=1}^{N_c^k} E_c^i[k]x^i[k]\\
& x^i[k]=0 \ \text{ or } \ 1, \ \text{ and } \sum_{i=1}^{N_c^k} x^i[k]\le 1\\
& k=1,\ldots,N_v
\end{aligned}$$

Energy Cost Prediction

- One-step prediction

$$P_d[k]=E_{tc}^{(k,k+1)}$$

- Two-step prediction

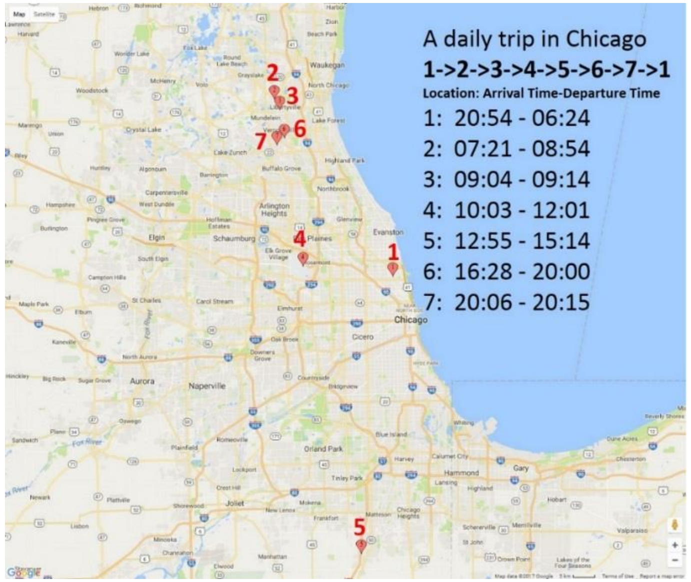
$$P_d[k]=E_{tc}^{(k\to k+1)}+E_{tc}^{(k+1,k+2)}$$

Objective Function: (Energy, Economy, etc.)

$$f(s[k],a[k],k)=\sum_{i=1}^{N_c[k]} E_c^i[k]P_r^i[k]x^i[k]+\lambda\sum_{i=1}^{N_c[k]} E_{cc}^i[k]x^i[k]$$

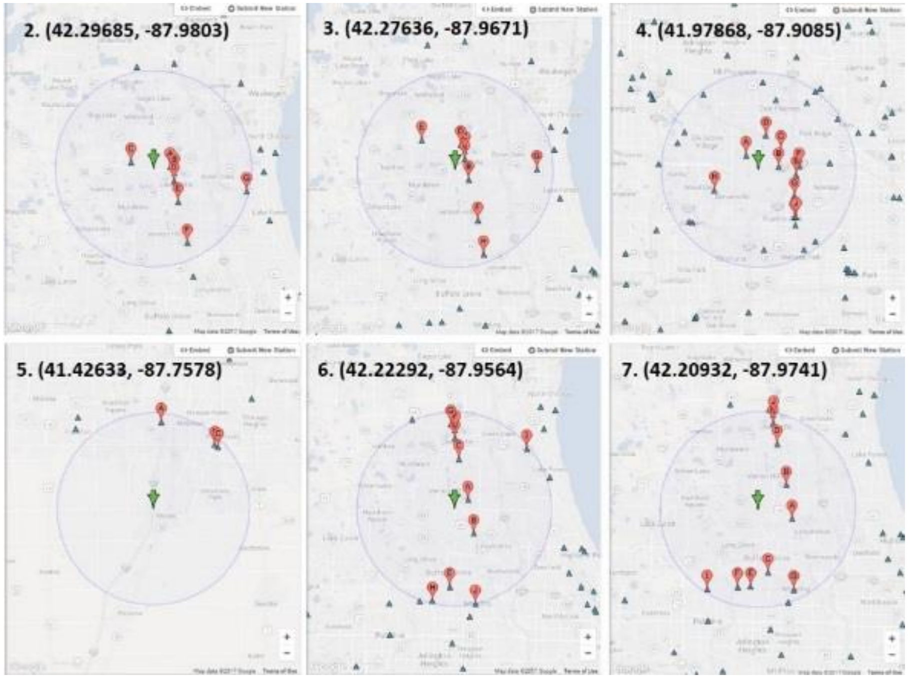
Results for Personal Automated EVs Scenario

Itinerary Information



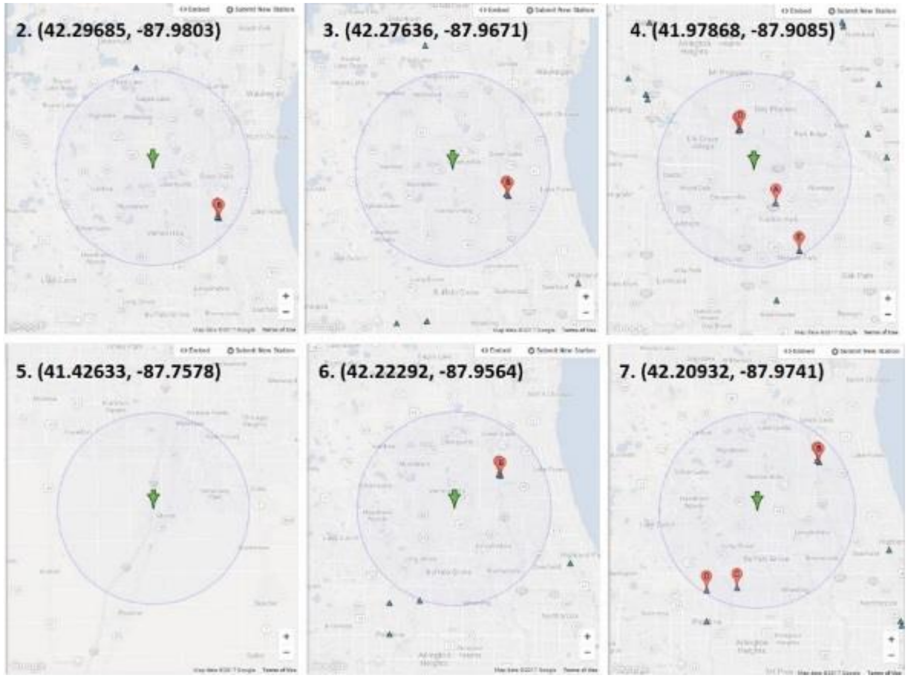
A single daily itinerary in Chicago

Level 2 Charging Stations



Nearby public charging station distribution (within 3 miles)

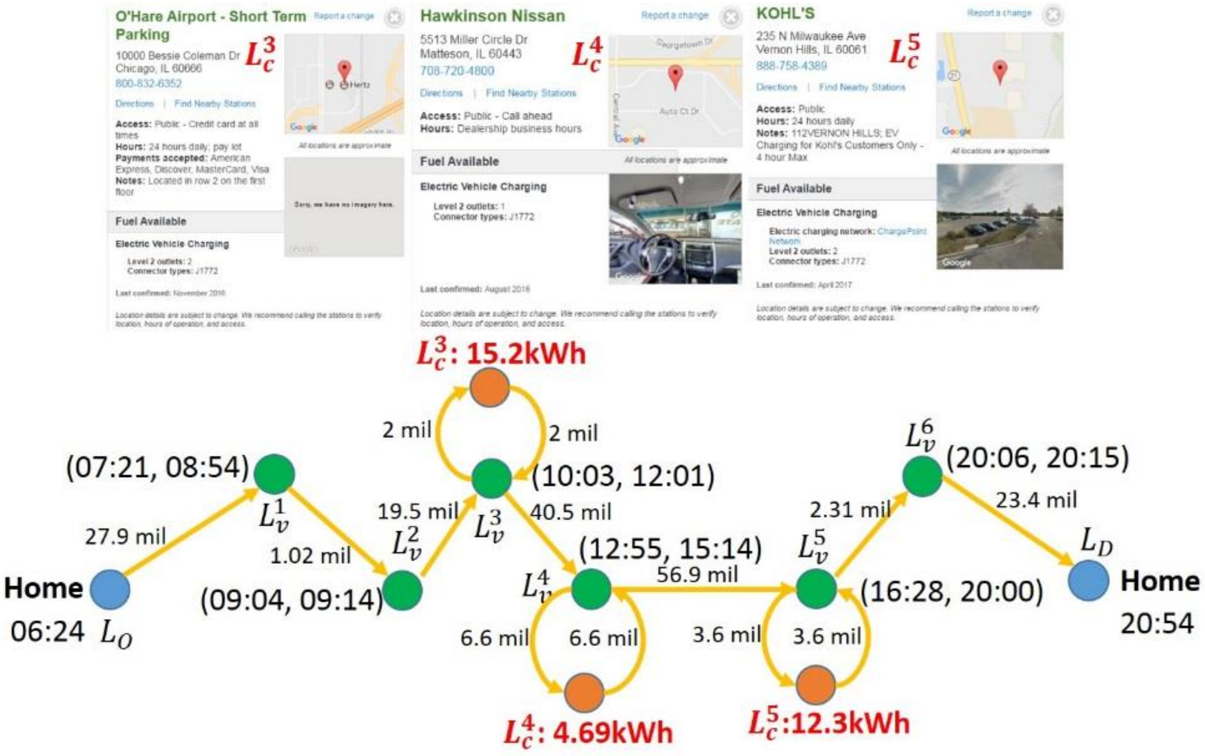
DC Fast Charging Stations Distribution



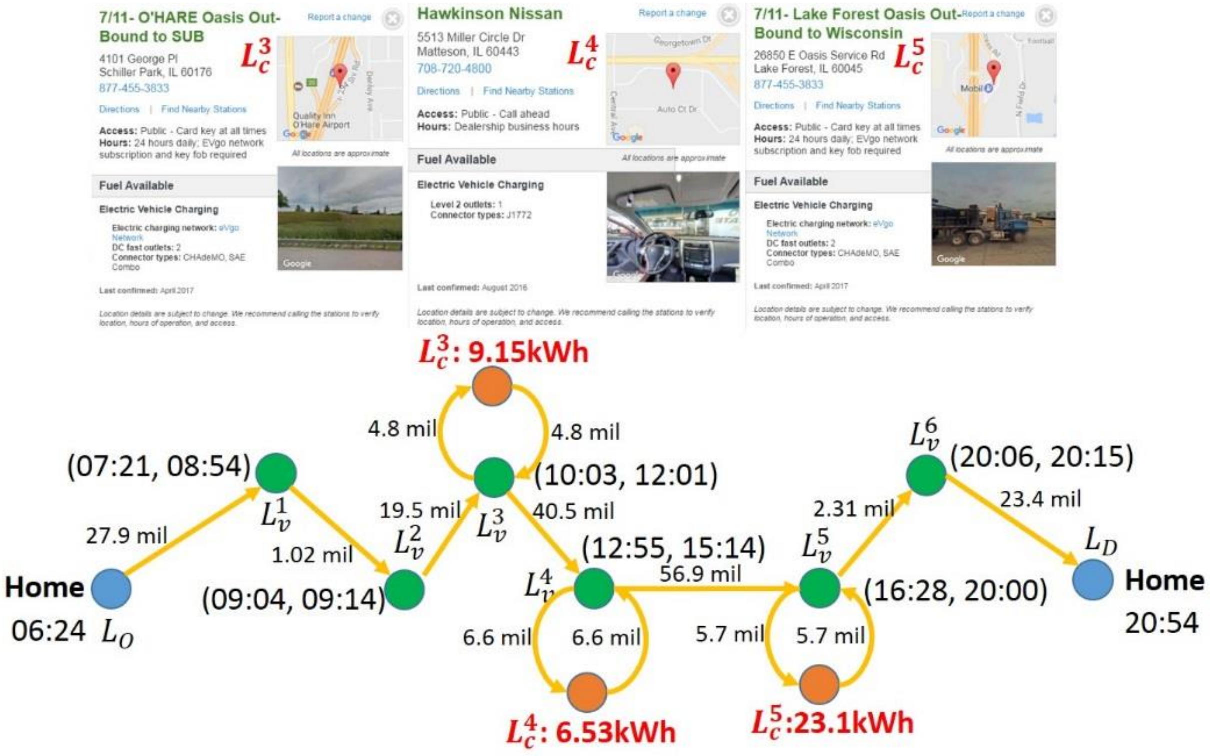
Charging power: 50kW

Results for Personal Automated EVs Scenario

Average Decision Making for Charging Strategies

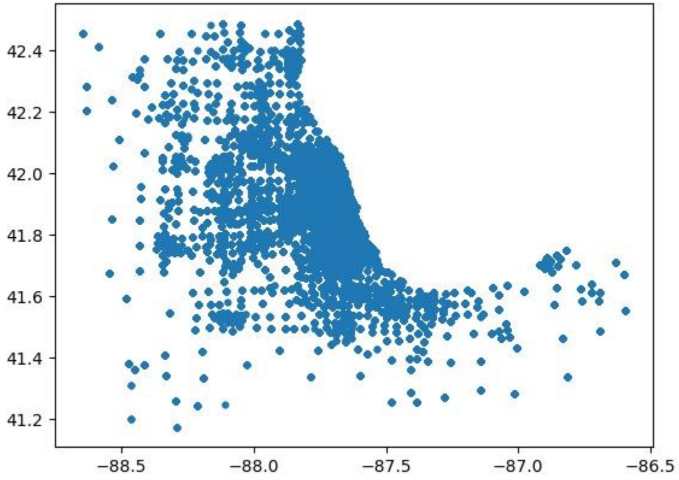


Robust Decision Making for Charging Strategies

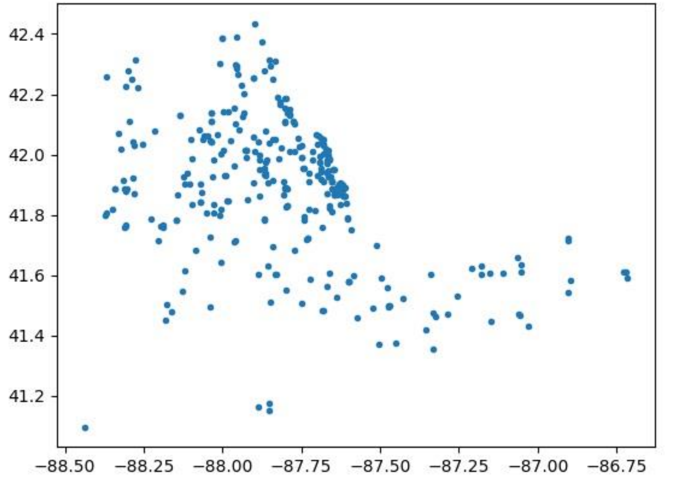


Results for Personal Automated EVs Scenario

Visited Locations

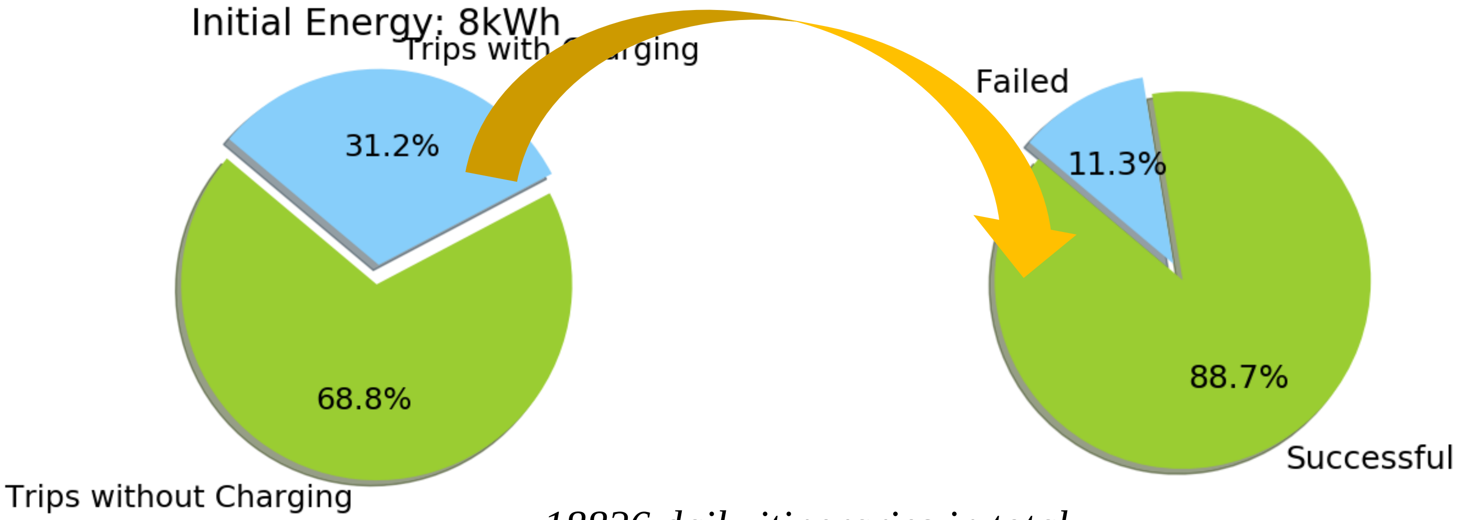


Public Charging Station Locations



Data: *Travel Tracker Survey* from the Chicago Metropolitan Agency for Planning (CMAP)

Source: http://www.cmap.illinois.gov/data/transportation/travel-survey



18826 daily itineraries in total

Failed: Itineraries cannot be achieved with enough energy using charging decision making algorithm.
Successful: Itineraries are achieved successfully by using charging decision making algorithm.

Reference: Zonggen Yi, and Matthew Shirk. "Data-driven optimal charging decision making for connected and automated electric vehicles: A personal usage scenario." *Transportation Research Part C: Emerging Technologies* 86 (2018): 37-58.

Preliminary Conclusions

- A properly designed intelligent algorithm can ***achieve the recharging decision making automatically*** for future automated electric vehicles.

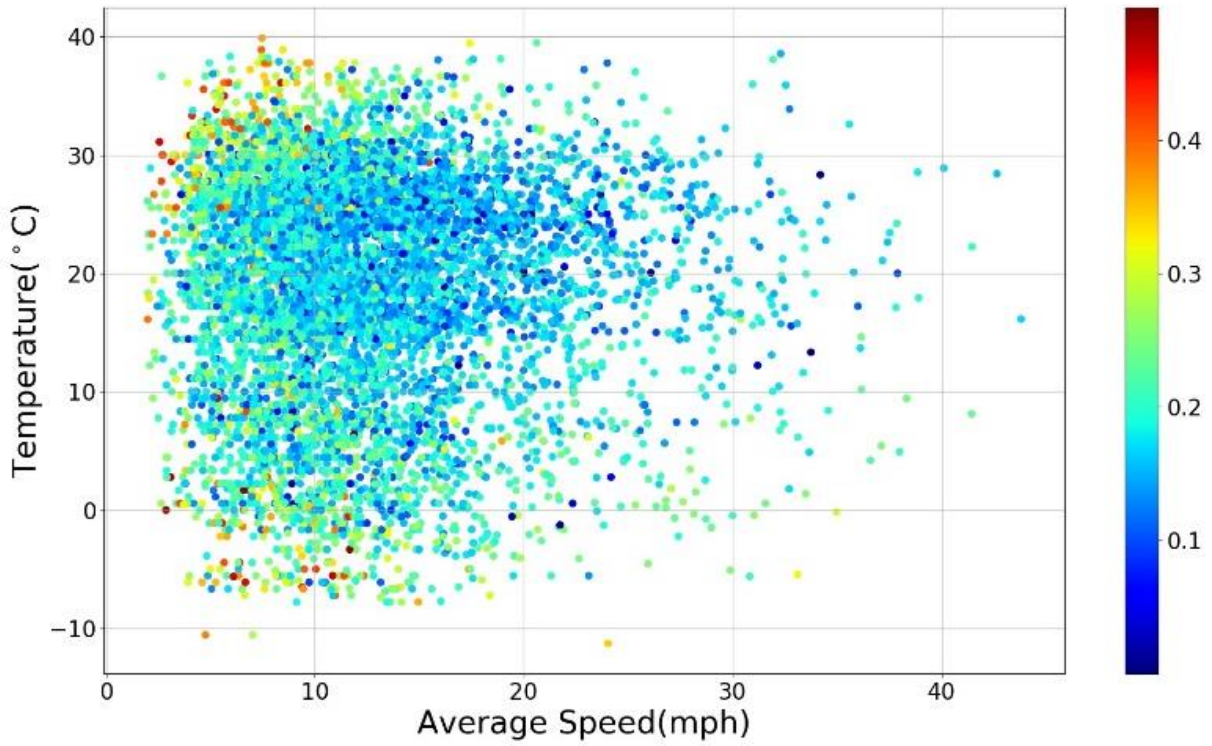
- Automatic charging decision making works well to ***reduce the range anxiety*** even with current existing charging station network and can ***mitigate the pain from electric vehicle charging necessity outside home***.

- More ***available future trip information*** during a long itinerary with several trip segments can help to achieve much better decision making overall.

- Optimized charging strategies can ***minimize the monetary and energy cost of charging actions*** for autonomous vehicles so as to improve the sustainability of future automated electrified transportation.

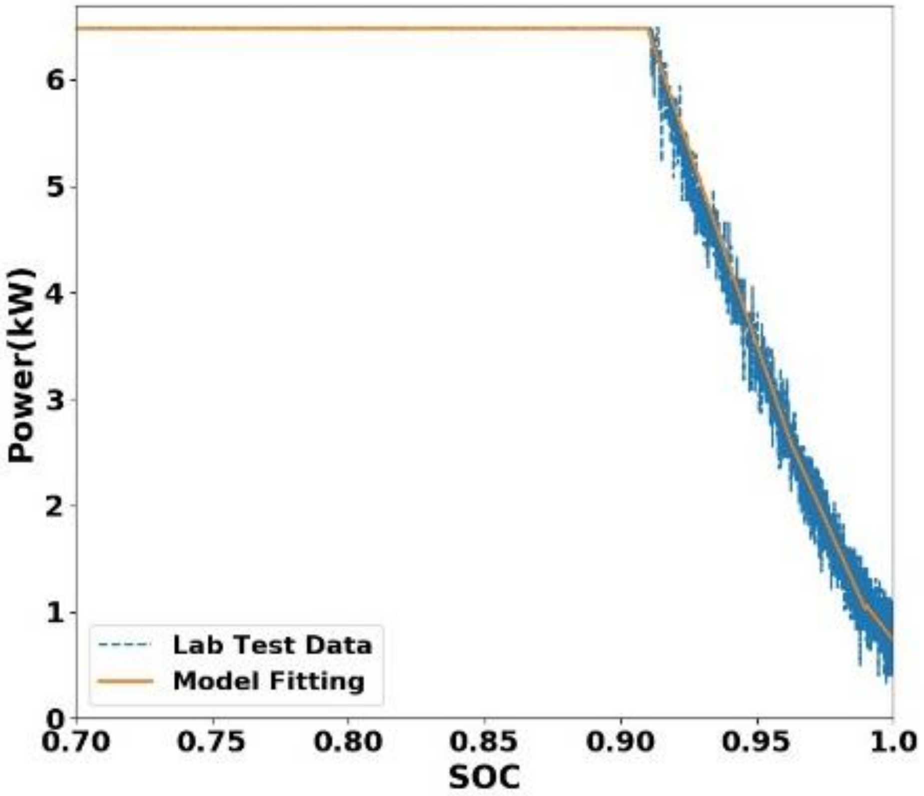
Future Work – Vehicle Level

- **Energy Consumption Dynamics**



Energy cost per mile **of Nissan Leaf Taxi with regard to average vehicle speed and ambient temperature in New York City**

- **Charging Power Dynamics**

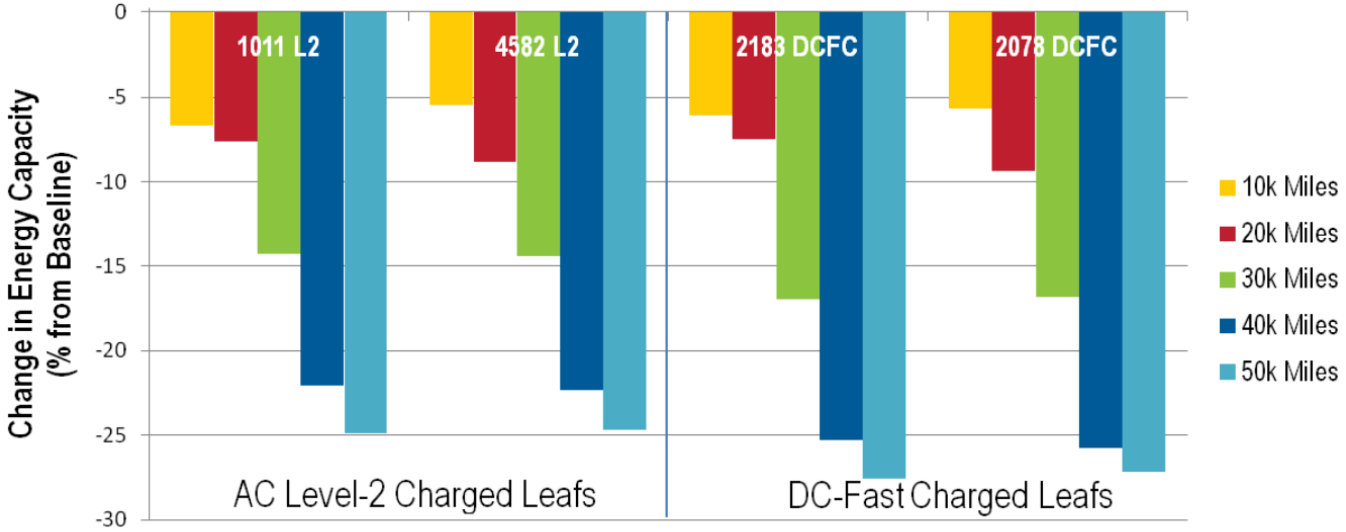


Realistic ***charging power*** **data for a 2015 Nissan Leaf**

Future Work – Vehicle Level

- **Impact of High Power Charging to Battery Life**

A rendering of a *350kW XFC charging station* by Electrek.
Source: https://www.energy.gov/eere/vehicles/downloads/enabling-extreme-fast-charging-technology-gap-assessment



***Percent change in energy capacity* from baseline**
Source: https://www.energy.gov/sites/prod/files/2015/01/f19/dcfc_study_fs_50k.pdf

Future Work – System Level

Spatiotemporal travel demand

MOD
MOBILITY ON DEMAND

Systematic Management for Personal/Shared Automated EV Fleet

Eco-Routing/Eco-Driving

Co-Optimization

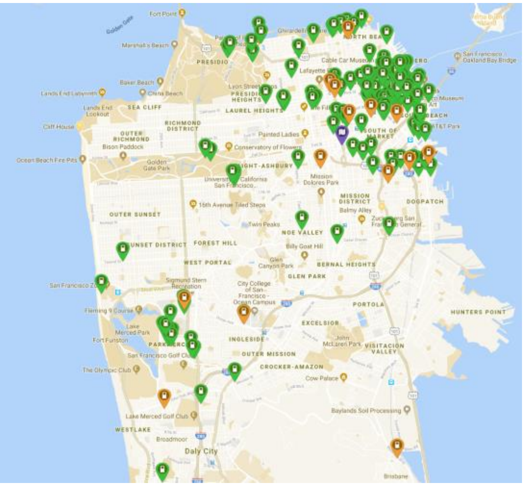
Recharging Decision Making

Centralized vs Decentralized

- Communication cost
- Computing cost

Charging Infrastructure

- Different charging power levels
- Dynamic utilization pattern



Preliminary research:
Zonggen Yi, John Smart, and Matthew Shirk. "Energy impact evaluation for eco-routing and charging of autonomous electric vehicle fleet: Ambient temperature consideration." *Transportation Research Part C: Emerging Technologies* 89 (2018): 344-363.