ANTICIPATING A WORLD OF AUTOMATED VEHICLES:

Cost, Energy, & Urban System Implications

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Part 1

Forecasting Americans' Plans for Acquiring & Using Self-driving, Shared (& Electric) Vehicles

2017 U.S. Survey

- **n = 1,426** complete, adult **respondents, weighted** to match **U.S. population**.
- Questions about current & coming **vehicle & travel choices**
- Focus on **electric**, **autonomous**, & **shared** vehicles & rides
  - EVs, CAVs, SAVs, & DRS (**dynamic ride-sharing**)

- **Questions** provide values for **regression models** used in **fleet-evolution simulation.**

Results: AV & SAV Technology

- **32.4% prefer an AV for next vehicle**, *if price premium neglected*.
- If vehicle is **capable of both human (HV) & autonomous (AV) driving**, average respondent believes he/she would use **AV mode** for **36% of travel distance**.
- **WTP** for **full AV technology** is nearly **$1,000 higher** if HV capability maintained.
- **What if SAVs exist** at $0.50 to $2 per mile? Will people still use private cars?

Vehicle Ownership Preference	$2/mile	$1/mile	$0.50/mile
NOT OWN personal vehicle **RELY primarily on SAVs**	3.6%	4.3%	4.4%
NOT OWN vehicle, Use **COMBO of SAVs & other modes**	3.6%	3.7%	4.1%
Rely primarily on other modes, like **Bike, Walk & Transit**	10.7%	9.2%	7.5%
MOSTLY USE SAVs but still own 1+ vehicles	7.5%	8.5%	**12.5%**
SOME SAV USE Rely primarily on **personal vehicle(s)**	**29.3%**	**31.2%**	**32.4%**
NO SAV USE Rely primarily on **personal vehicles**	**44.5%**	**42.5%**	**38.3%**

Results: SAVs + Policy Opinions

- Respondents state **average WTP for SAVs = $0.44/mile**.
- **49% select dynamic ride-sharing (DRS)** at **40% discount** vs. "private" SAV.
- Just **19%** say their **SAV rides** will be **DRS**, assuming a **40% discount**.

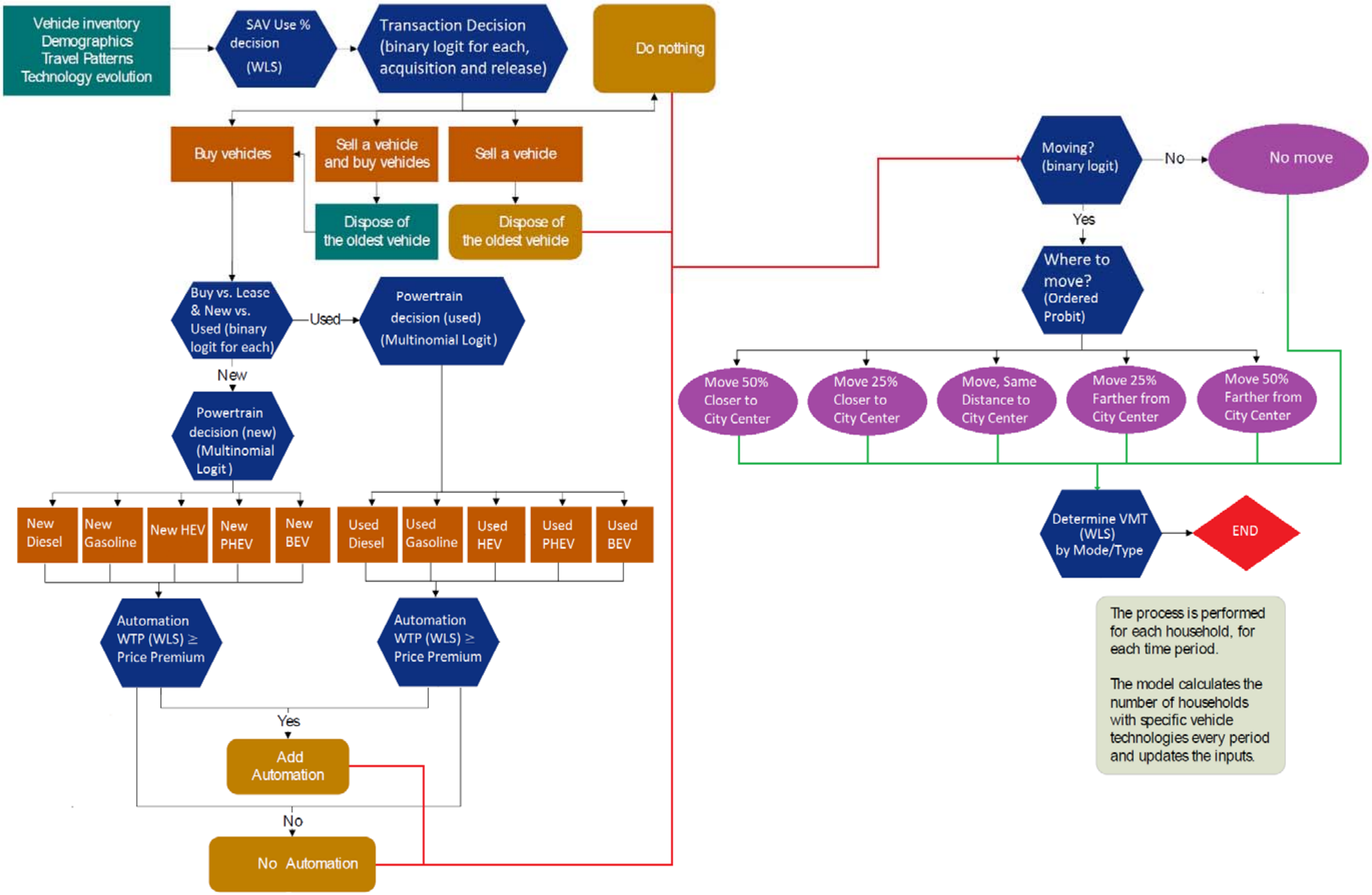
Will you do some things more often if SAVs are available?	Very Likely	Somewhat Likely	Neither Likely nor Unlikely	Somewhat Unlikely	Very Unlikely
I will go places where parking is an issue more often, like downtown.	14.7%	**26.5%**	16.6%	9.3%	32.9%
I will use public transit more often, with SAVs as a backup	7.3%	**19.7%**	20.5%	14.3%	38.3%
I will use bikeshare or walk more, with SAVs as a backup	5.4%	**17.1%**	22.5%	13.8%	41.2%

- Respondents believe **~20% of AV travel** should be **allowed empty** – for both **SAV fleets & private AVs**!
- **24.8%** believe **empty travel** should always be **banned or heavily tolled**.

Fleet Evolution

- **Simulation** through **year 2050** using MATLAB.
- Decisions via series of **regression models** (calibrated using survey results & MNL, ordered probit, & WLS specifications).
- Includes **vehicle acquisition & release**, **SAV use**, **home location**, & **VMT by mode & vehicle type** (powertrain & automation alternatives).
- ***7 scenarios*** include different rates of **AV technology price reductions** & **WTP for AVs retaining an HV option**.

Household Fleet Microsimulation



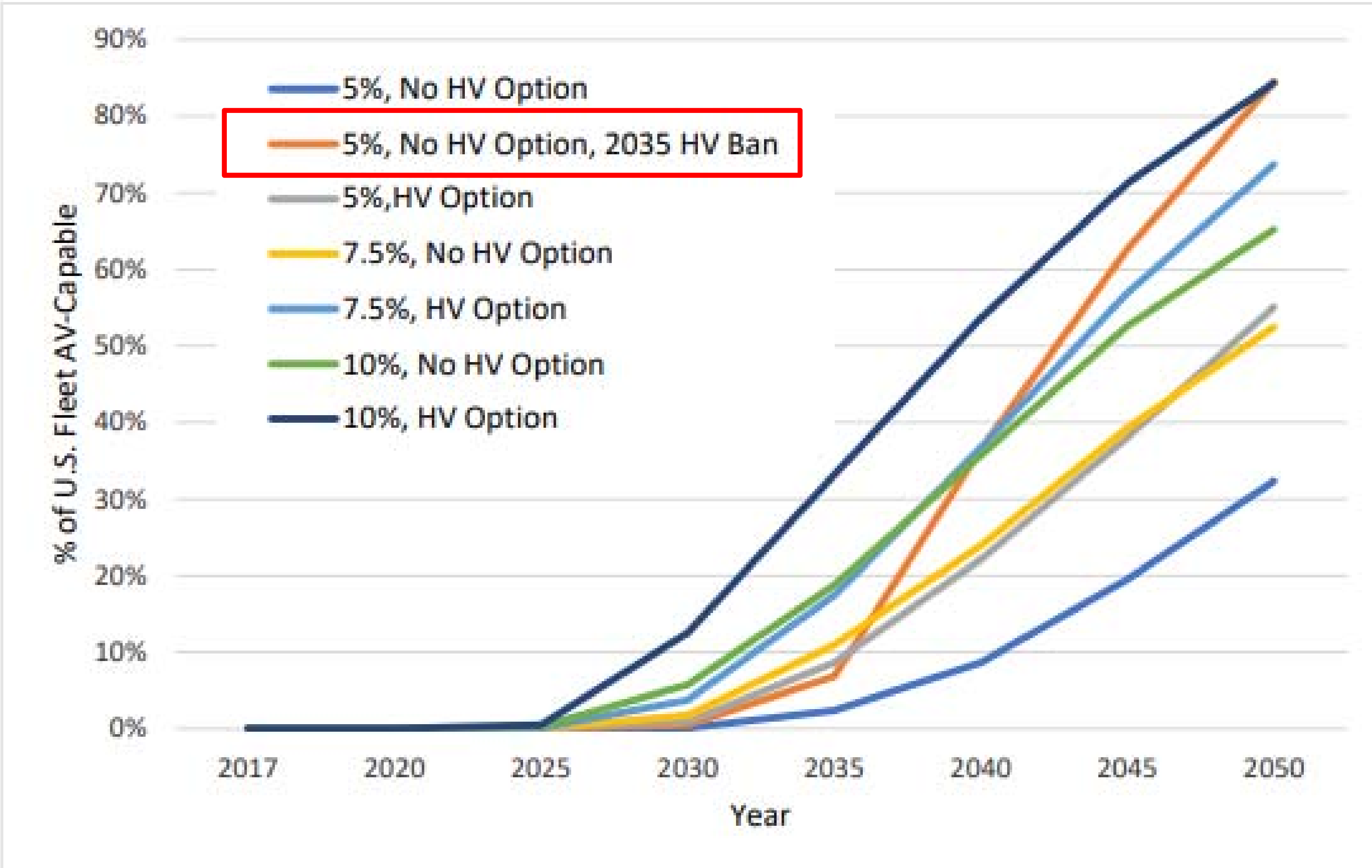
The process is performed for each household, for each time period.

The model calculates the number of households with specific vehicle technologies every period and updates the inputs.

Predicted **Household** **Fleet in 2035 & 2050**

Scenario	2035 % AV	2035 % HV	2050 % AV	2050 % HV
5%/yr AV Price Decline + HV Capability	8.6%	91.4%	55.1%	44.9%
5% Decline + No HV Capability	2.4%	97.6%	32.4%	67.6%
7.5%/yr AV Price Decline + HV Capability	17.4%	82.6%	73.7%	26.3%
7.5% Decline + No HV Capability	11.0%	89.0%	52.5%	47.5%
10%/yr AV Price Decline + HV Capability	33.2%	66.8%	84.3%	15.7%
10% Decline + No HV Capability	18.8%	81.2%	65.2%	34.8%

- ***Much*** **higher AV adoption rates if HV option is retained**.
- **Pricing decline assumptions are key** in future-year adoption levels.



AV **Ownership Shares by US Households** Over Time, across 7 Scenarios

Mileage Splits in 2035 & 2050

	SAVs in 2035		Privately-Held Cars 2035		SAVs in 2050		Privately-Held Cars 2050	
Scenario vs. Year	*2035 DRS*	*Private SAV*	*2035 AV*	*HV*	*2035 DRS*	*Private SAV*	*2050 AV*	*2050 HV*
(1) 5% Decline + HV Capability	5.6%	11.0%	9.6%	73.8%	12.1%	23.3%	39.8%	24.9%
(2) 5% Decline + No HV Capability	5.6%	11.0%	3.3%	80.2%	12.1%	23.3%	25.1%	39.4%
(3) 7.5% Decline + HV Capability	5.6%	11.0%	17.7%	65.7%	12.1%	23.2%	50.1%	13.6%
(4) 7.5% Decline + No HV Capability	5.8%	11.2%	12.1%	71.0%	12.5%	23.8%	39.3%	24.3%
(5) 10% Decline + HV Capability	5.5%	10.8%	31.5%	52.2%	12.0%	23.1%	57.3%	7.7%
(6) 10% Decline + No HV Capability	5.6%	10.9%	19.8%	63.8%	12.0%	23.1%	47.1%	17.9%

- Total SAV use is 16% & then 35% of **VMT.** Private SAV is **double** that of DRS.
- VMT per vehicle is **higher** for AVs than HVs, due to lower vehicle age.

Conclusions

- **Americans' willingness to give up vehicle ownership** is low, even among those who expect to rely mostly on SAVs.
- **Proactive policies** to **limit empty driving** are **needed to moderate congestion** from empty VMT. Americans appear unwilling to limit such driving.
- **AV price drops** & **WTP to retain human-driving** option are **key to AV adoption rates.**
- Overall **home locations not significantly affected** by these transport technologies.

Caveat: Changing **demographics** (e.g., aging of the population) can affect results.

Part 2
Agent-Based Models for Shared AVs

- **Less than 20%** of newer (& 15% of all) personal vehicles are in-use at peak times, even with 5-minute pickup & drop-off buffers.
- **Car-sharing** programs like Car2go & ZipCar have expanded quickly, with the number of U.S. users doubling every year or two, over the past decade.
- **Shared Autonomous Vehicles** (**SAVs**) can help overcome car-sharing barriers, like **return-trip certainty** & **vehicle access** distances.

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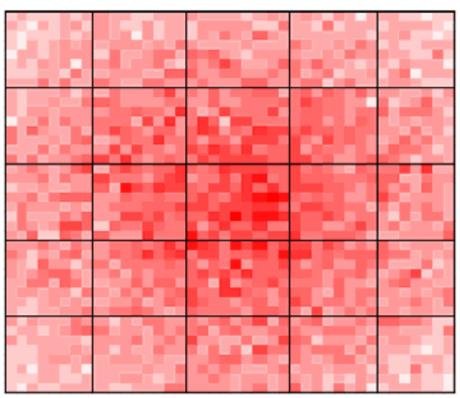
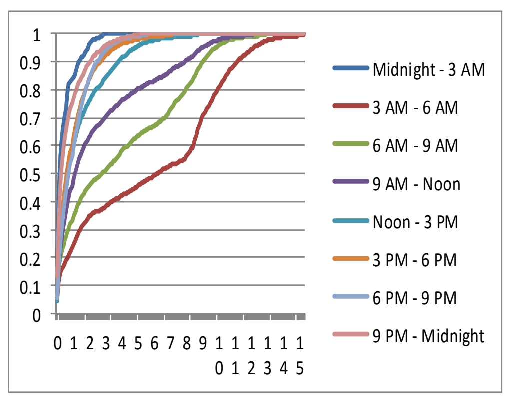
Agent-Based **Model Framework**

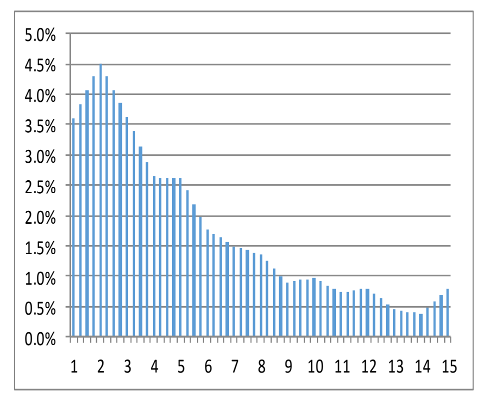
- Grid-based 10 mi x 10 mi urban area with **0.25-sq. mile zones**.
- **Trip generation**:
  - Poisson-based PK & OP counts for **trip generation**, **every 5 minutes**.
  - Higher **trip production & attraction** rates closer to city center.
  - **Mostly round-trip** travel, with 78% travelers returning via SAVs.
  - Random **departure times & trip distances** (2009 NHTS).
- SAVs travel at **fixed speeds**, with **5 min.** intervals.



Trip Generation



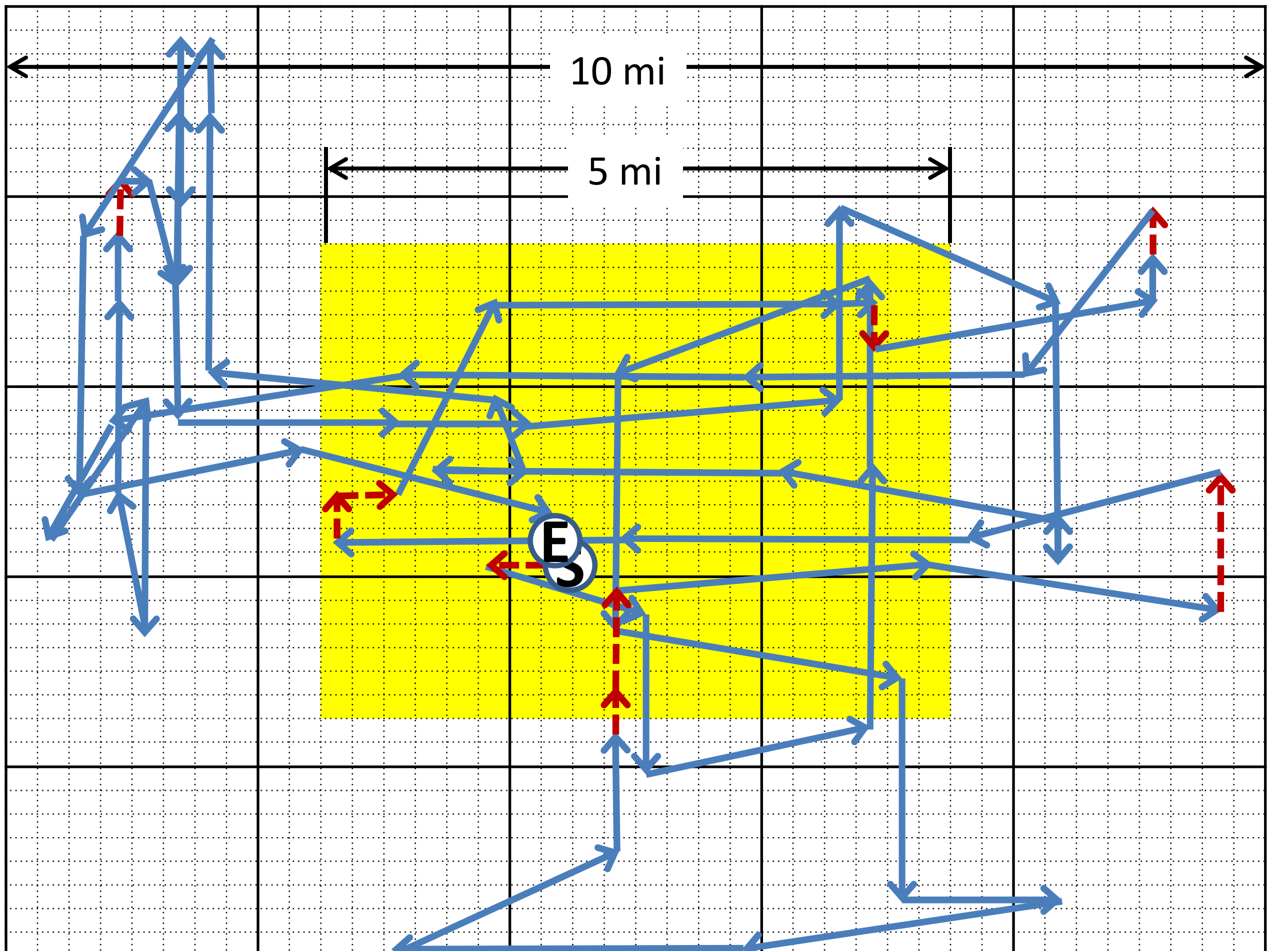
Dwell Times (hrs.)



Trip Distances (mi.)

Example: One SAV's 24-hour Journey

- **Urban Core**
  Higher AM Trip Attraction
- Outer Periphery
  Higher PM Trip Attraction
- **Red Arrows**
  SAV Relocation
- **Blue Arrows**
  Serving Riders



Case Study Results

- **100 days were simulated** to assess SAV travel implications.

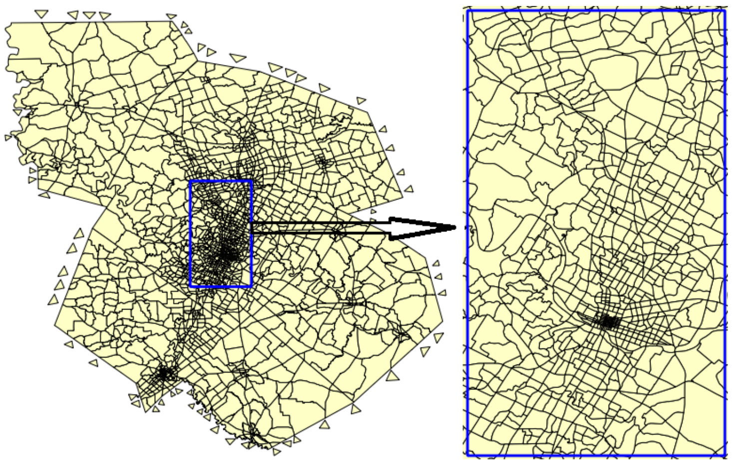
Scenario Results

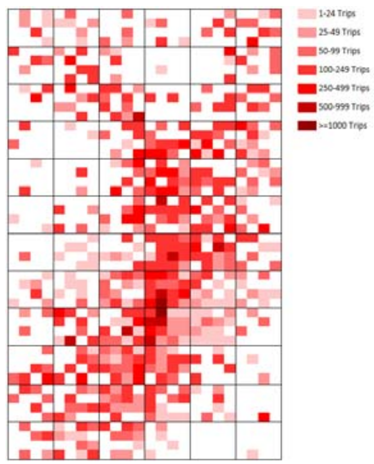
- **Each SAV** replaced **9 to 13 conventional vehicles**.
- Avg. **wait time ≈ 2.8 min.**
- **11% new/induced** (empty-vehicle) **travel.**
- Yet **5% to 50%** (GHG vs. VOCs) life-cycle **emissions reductions**, thanks to **smaller vehicles,** fewer **cold starts**, & less **parking** infrastructure!

Parameter	Value
Service area	10 mi. x 10 mi.
Outer trip generation rate	9 trips/cell/day
CBD edge trip generation rate	27 trips/cell/day
CBD core trip generation rate	30 trips/cell/day
Off-peak speed	33 mph
Peak speed	21 mph
AM peak	7 AM - 8 AM
PM peak	4 PM - 6:30 PM
Trip share returning by SAV	78%

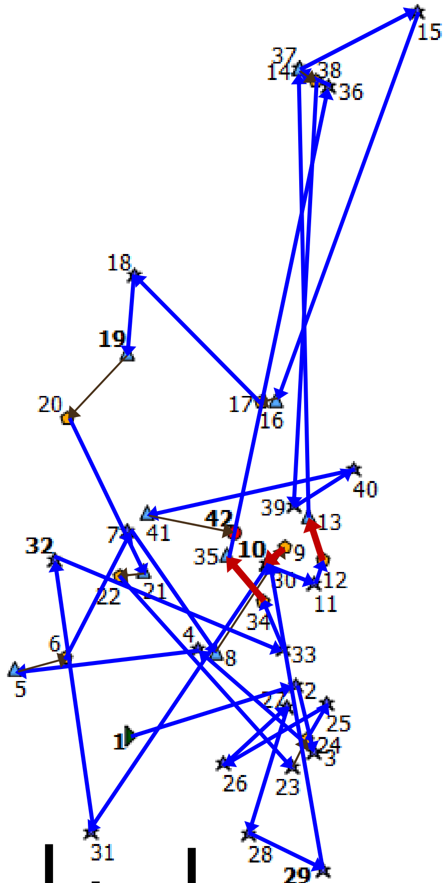
Part 3

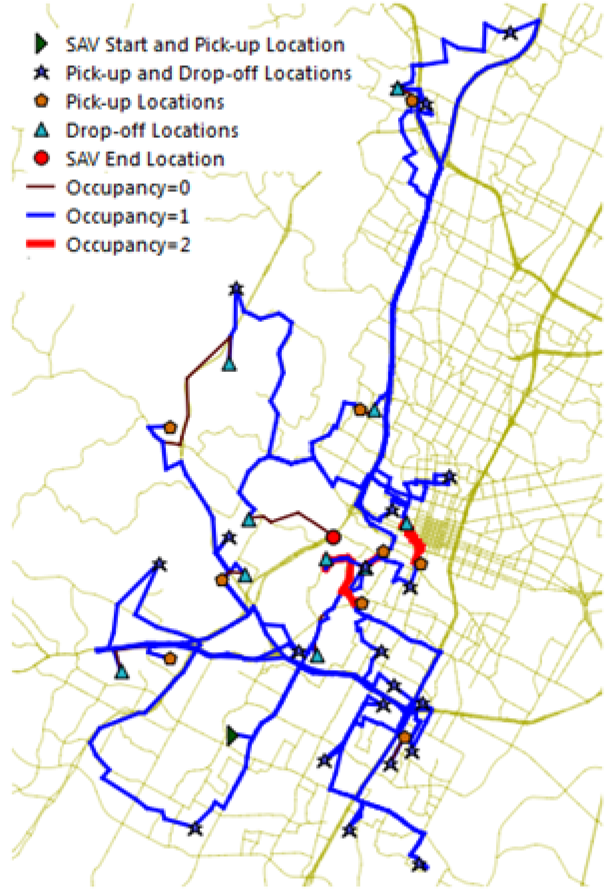
What if SAVs Serve Central Austin, & Offer Dynamic Ride-Sharing (DRS)?

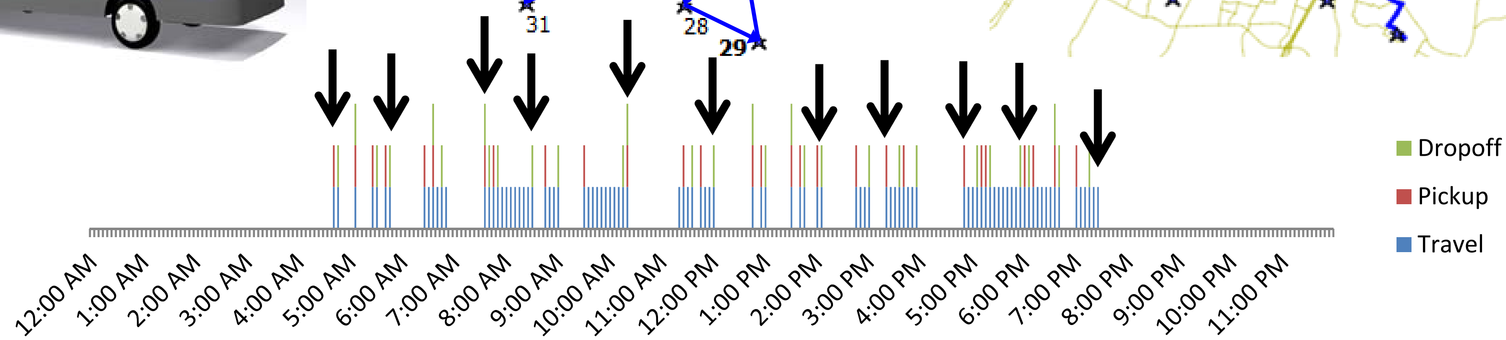




One SAV's 24-hour day







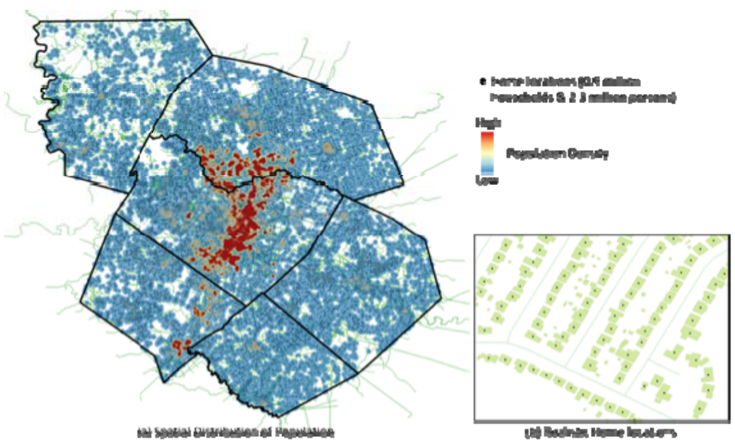
Case Study Results

- **24-hour days simulated** with **56,300 to 270,000 trips** served.
- **Excellent Level of Service** (typ. wait time < 3 min.)
- **1:10 & 1:8 veh. replacement** rates (with & w/o DRS)
- **System pays for itself** with just **$1/mile fares!**
- **Electric vehicles** (**Leaf & Model S**) also tested (with inductive charging), using **100 mi x 100 mi** region.
- **DRS saves more emissions - & VMT** even **falls** (vs. BAU).

Measure	With DRS	Without DRS
SAV fleet size	1,855	2,181
Veh. replacement rate	9.95	8.47
Average wait time	57 sec	47 sec
% Waiting > 10 min.	0.60%	0.33%
5-6 PM avg. wait	3.0 min	2.4 min
Avg. total trip time	14.4 min	13.8 min
New VMT introduced	4.90%	7.92%
# rides shared	5,754	0
% VMT shared	4.50%	0%

Part 4

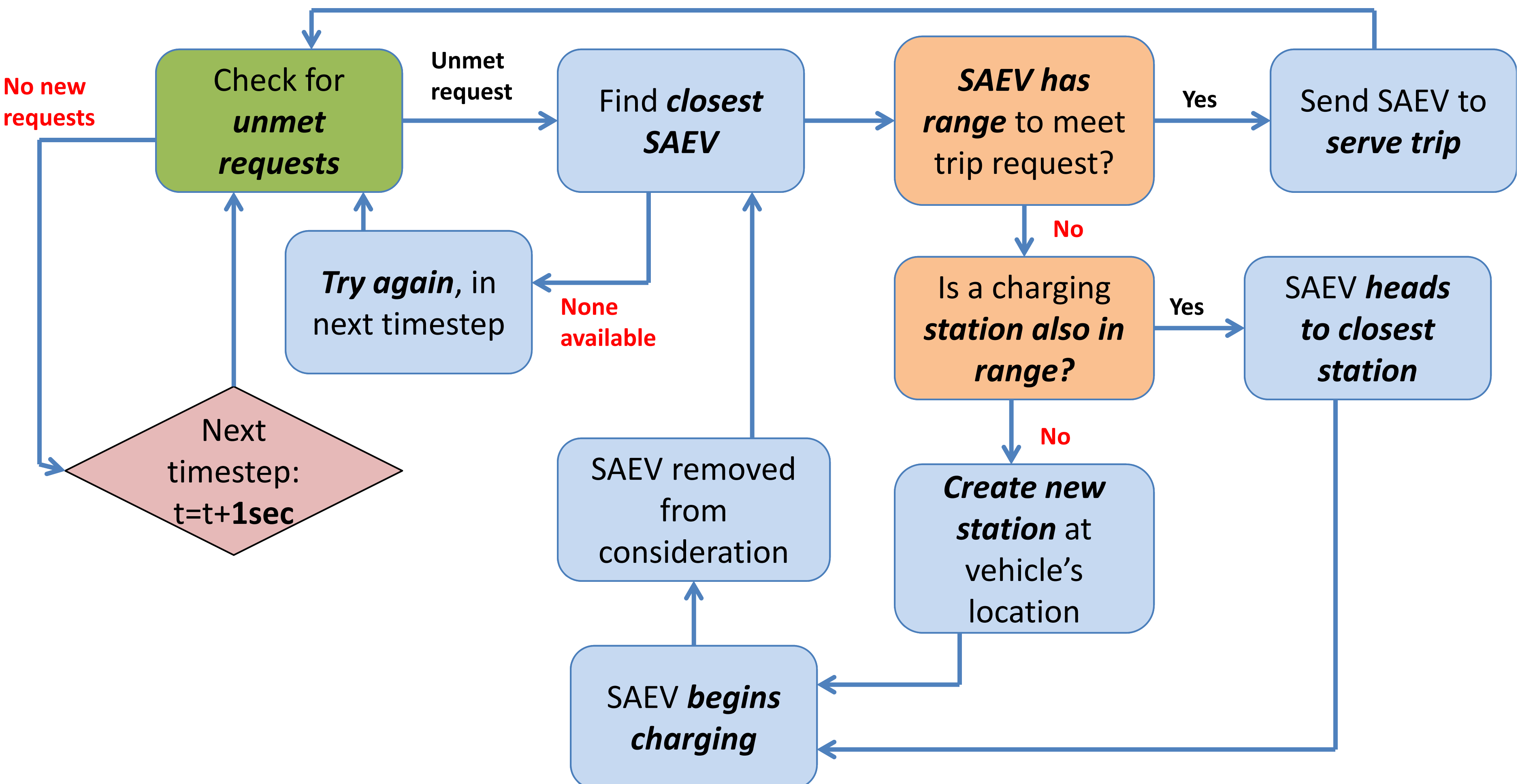
What if SAVs Serve the Entire Region? & Are SAElectricVs?



Shared Autonomous Electric Vehicles
SAEVs

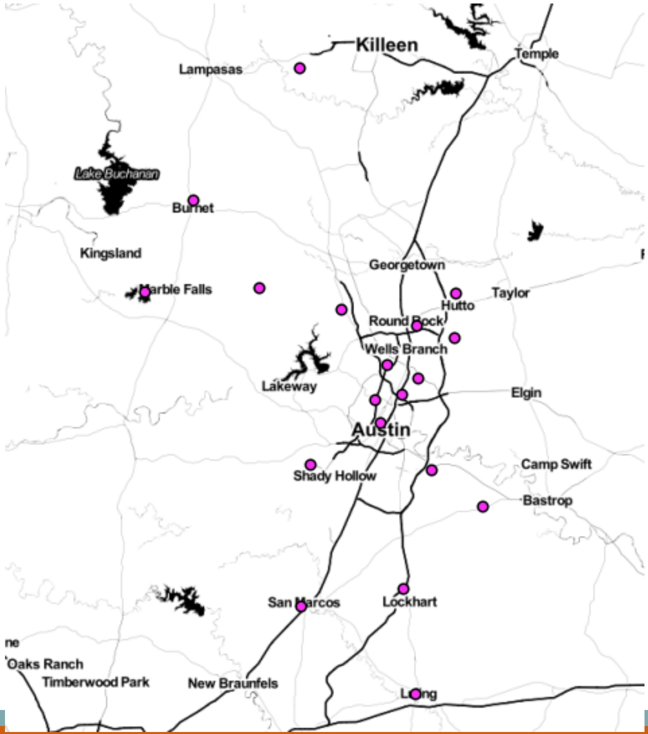
or

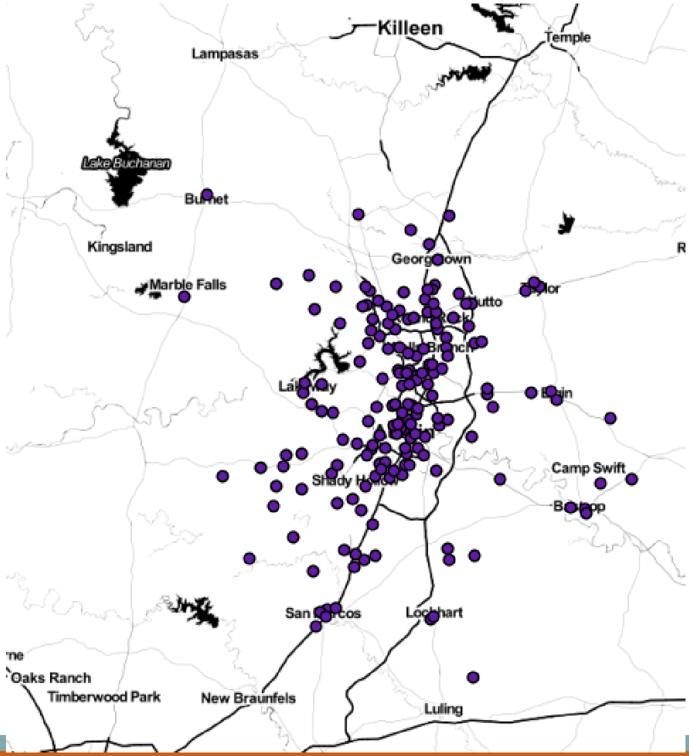
Station Generation via 30-day Initial Run



Charging Station Locations

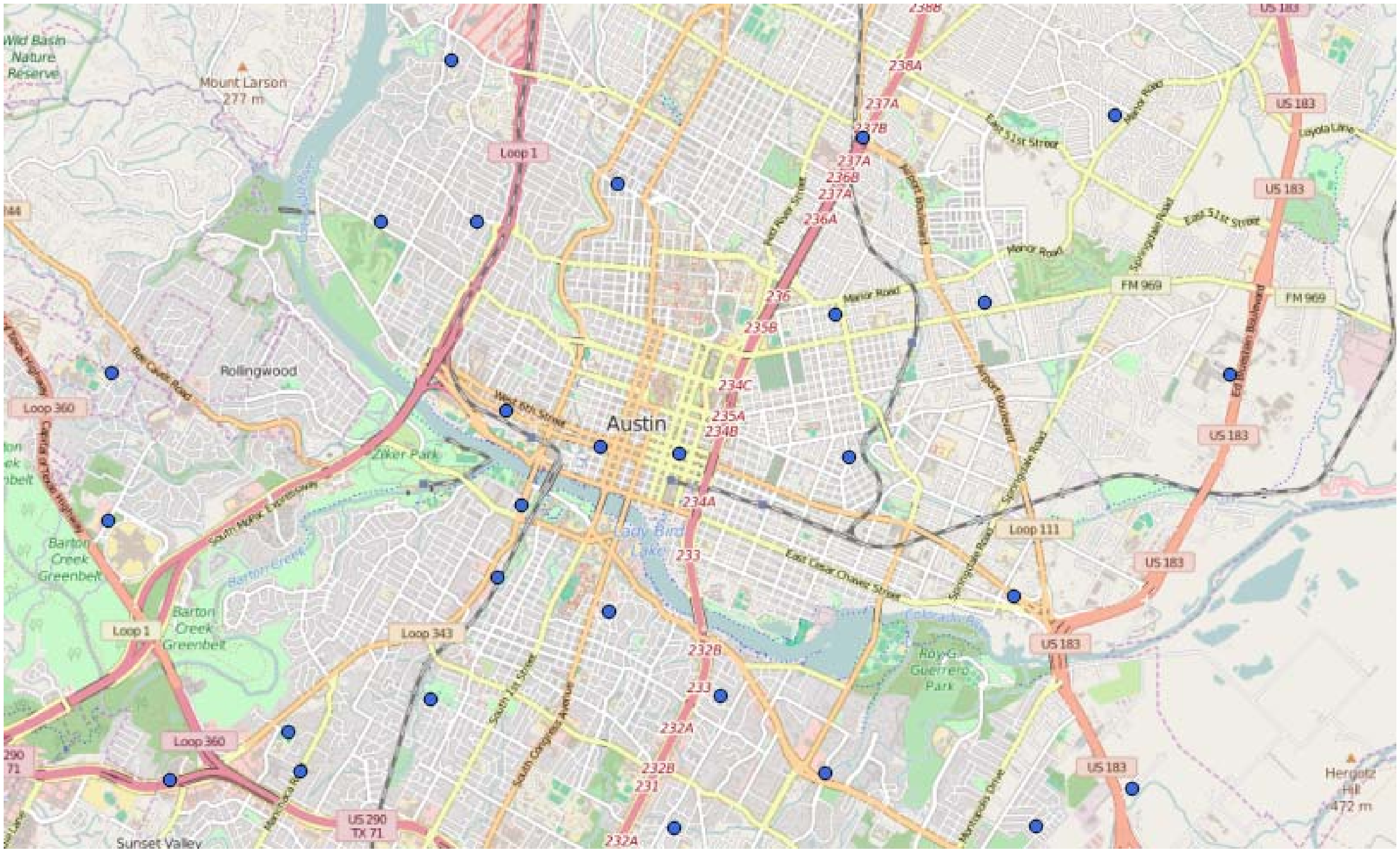
- **Charging stations** generated based on demand.
- Number of charging stations formed is dependent only on **vehicle range**.
- Stations formed for **200-mile range** (left) & **60-mile range** (right)





Central Austin Station Locations

Assuming **60 mile** range + **4 hour** charge time + **5:1** travelers per SAEV (= 28 stations over 6 x 10 mi area)



Austin SAEV Results

Scenario	Gas SAV	Slow Charge, Short-Range SAEV	Slow Charge, Long-Range	Fast Charge, Long-Range	Fast Charge, Short-Range	Fast Charge, Long-Range, Smaller Fleet
Range (mi)						
Recharge/Refuel Time (min)						
# of Charging/Gas Stations						
Fleet Size (# vehicles)						
Avg. Daily miles per Vehicle						
% of Unserved Trips						
Avg. Daily Trips per Vehicle						
Avg Wait Time Per Trip (min)						
% Unoccupied Travel						
% Travel for Charging						

- **Fleet size is key** to lower **response times**. Tripling fleet (from 9:1 to 3:1 travelers per SAEV) lowers average response times by >75%.
- **Longer charge** times **increase** response times **& unserved trips** rise dramatically.
- **Longer ranges lower empty VMT & shares of unserved** trips.
- Trips in Austin's **urban core served best** (e.g., never exceed 30-min wait times).

SAEV Cost Assumptions

- **Conventional BEV Costs:** \$25,000 (short range) to \$35,000 (long-range)
- **Self-driving Technology Cost:** **\$5,000 to \$25,000** per vehicle
- **Battery Replacement:** \$100 - \$190 per kWh (once per vehicle life)
- **Vehicle Maintenance:** 5.4¢ to -6.6¢ per mile
- **Insurance & Registration:** \$550 - \$2,200 per vehicle-year
- **Electricity:** 8¢ to 20¢ per kWh
- **Level II Chargers:** \$8,000 - \$18,000 each
- **Level II Charger Maintenance:** \$25 - \$50 per year, per charger
- **Fast (Level III) Charger:** \$10,000 - \$100,000 per charger
- **Fast Charger Maintenance:** \$1,000 - \$2,000 per year, per charger
- **Station Properties:** \$1,980 to \$6,900 per vehicle space (based on location)

Financial Results: Costs per Mile

Mid-Range Expected Costs per mile	Hybrid SAV	Slow Charge, Short-Range	Slow Charge, Long-Range	Fast-Charge, Long-Range	Fast-Charge, Short Range	Fast-Charge, Long-Range, Reduced Fleet
Electricity/Fuel	6.39¢/mi	4.51	4.26	4.21	4.57	4.29
Vehicle Maint., Admin + Attendants	18.4¢/mi	19.7	18.6	18.4	19.9	18.7
Charger Costs (Land + Infrastructure)	n/a	3.57	1.35	2.15	6.30	2.20
Vehicle Purchase	19.6¢/mi	27.7	29.4	28.3	25.3	28.4
Battery Costs	n/a	1.58	4.91	4.85	1.60	4.95
Total Costs per Mile	45¢/mi	59¢/mi	59¢/mi	59¢/mi	58¢/mi	59¢/mi
Daily Vehicle Profit ($1/mile fare)	**$234**/ veh-day	$72	**$132**	$170	**$126**	$187
#Trips/vehicle-day	**28** trips/ veh-day	11	23	**28**	24	35
Response time/trip	**4.4** min	9.8	8.8	**5.5**	6.2	9.6

In Conclusion…

- **CAVs** offer **tremendous benefits** for mobility, safety & parking, ***but*** will **add VMT & congestion**.
- **SAVs** offer a **new & exciting** (transit?) mode, with each SAV **replacing ~8 personal vehicles**, for same level of motorized trip-making.
- SAVs add **7-15% extra VMT** (though DRS may reduce VMT).
- Yet SAVs may bring useful **travel-cost savings**, **emissions benefits + profits** for transit providers.
- **Smart system management** practices (like **credit-based congestion pricing**) are also needed, to avoid gridlock, sprawl, greater energy use, & other downsides.

Thank you!

Questions & Suggestions?

30 CAV papers & reports
at www.caee.utexas.edu
prof/kockelman