A Disaggregated Approach for Predicting the Equity Impacts of Autonomous Vehicles

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DREXEL UNIVERSITY College of Engineering

Drexel CAM Lab

Drexel Connected & Automated Mobility Lab

System
use optimization & AI to model, analyze, and optimize mobility systems

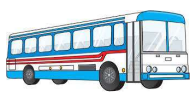
Technology
integrate modeling & experimentation to test emerging vehicle technologies

Impact
leverage data analytics to unravel the social impacts of existing & emerging mobility systems

Today's focus

Applications

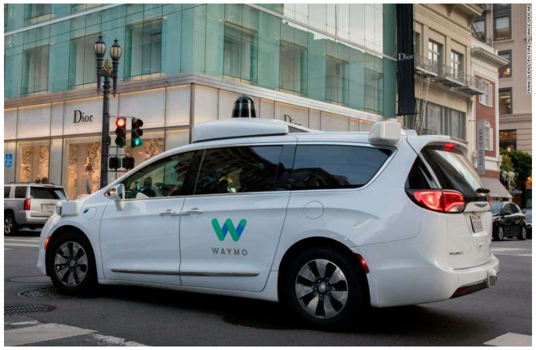

connected, auto-mated, modular vehicles


transit


shared mobility

Connected & Automated Vehicles (CAVs)

- Mobility: capacity **quadrupled** (Karaaslan, 1990)
- Energy: ↓ by up to **60%** (Stephens et al., 2016)
- Equity: mobility issue for **83%** people over 65 (Stopher et al., 2021)



Ref:
Karaaslan, U., Varaiya, P., & Walrand, J. (1991, June). Two proposals to improve freeway traffic flow. In 1991 American Control Conference (pp. 2539-2544). IEEE.
Stephens, T. S., Gonder, J., Chen, Y., Lin, Z., Liu, C., & Gohlke, D. (2016). Estimated bounds and important factors for fuel use and consumer costs of connected and automated vehicles (No. NREL/TP-5400-67216). National Renewable Energy Lab.(NREL), Golden, CO (United States).
Stopher, P., Magassy, T. B., Pendyala, R. M., McAslan, D., Arevalo, F. N., & Miller, T. (2021). An Evaluation of the Valley Metro–Waymo Automated Vehicle RideChoice Mobility on Demand Demonstration, Final Report (No. FTA Report No. 0198). United States. Department of Transportation. Federal Transit Administration.

CAV Reality – Equity

- Most discussions are qualitative, few quantitative evidence.

Accessible to some

Accessible to all

Research Question

- Will the costs and benefits of AVs be distributed equitably to system users?

The elderly

Low-income population

Rural residents

Focus of This Study: AV Equity Impacts

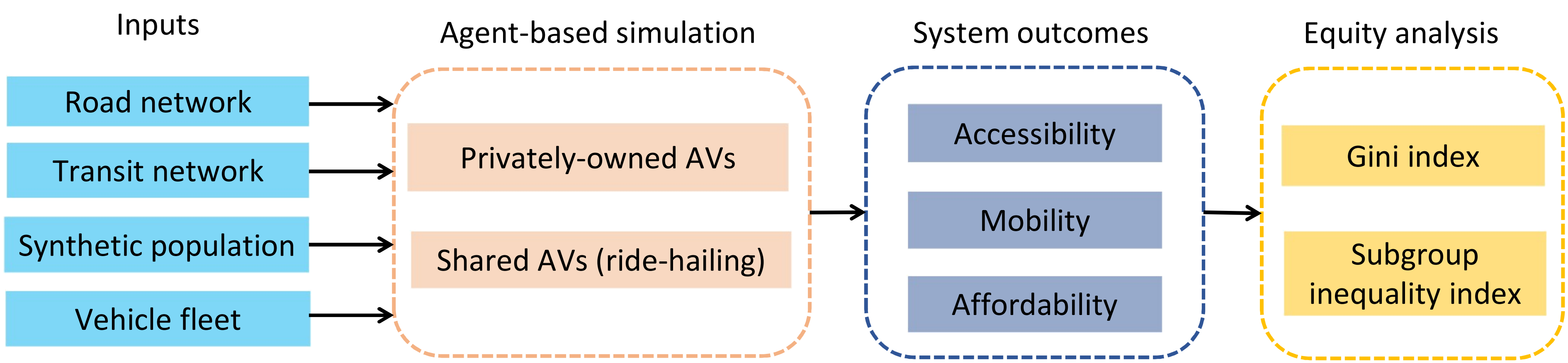
Accessible to some

Accessible to all

FHWA needs quantitative evidence for policymaking

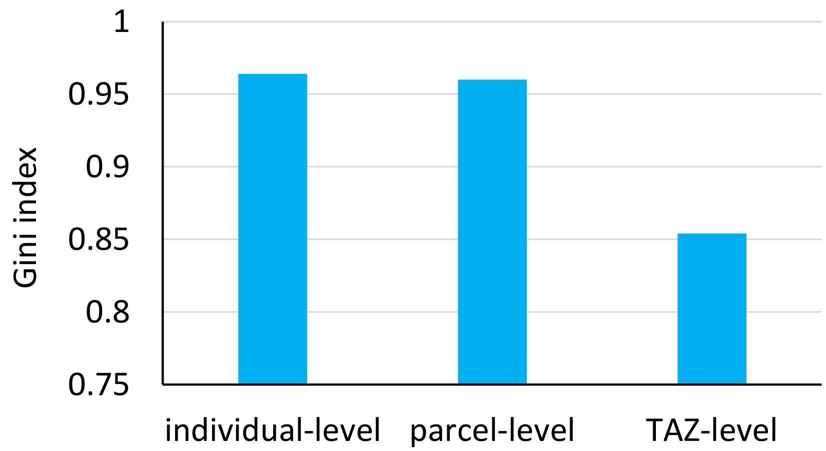
Funded project: Automated Vehicle Access, Mobility and Affordability for System Users

A Disaggregated Modeling Approach



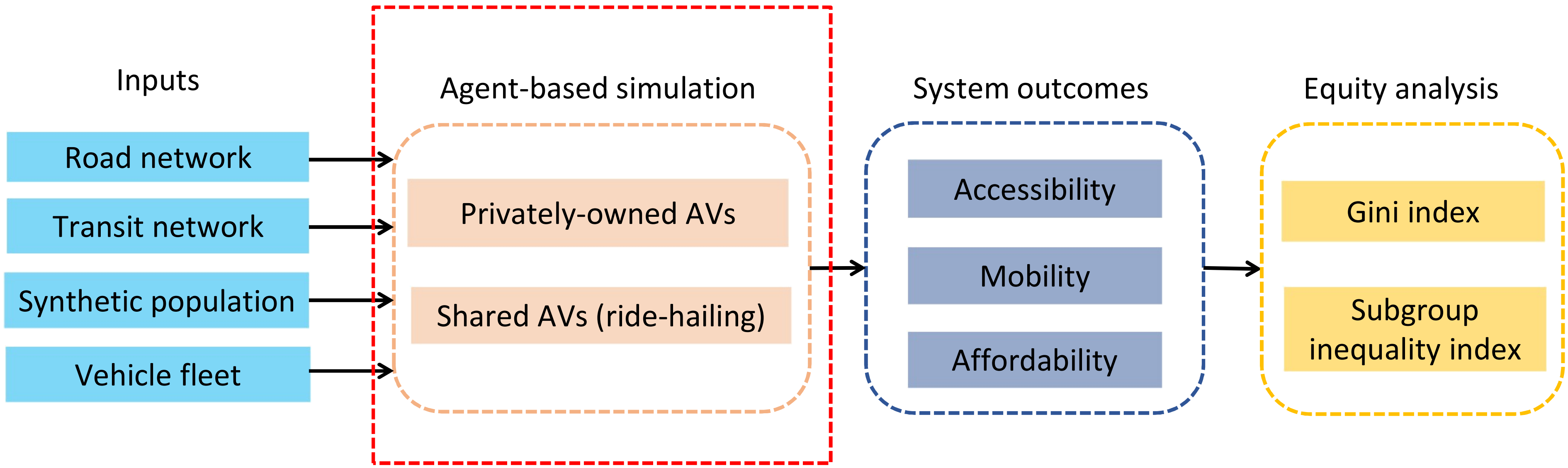
Why Disaggregated Approach?

- Existing modeling works on AV equity impacts: data aggregated to zonal levels, e.g., Cohn et al. (2019), Lee and Kockelman (2022).
- Our previous study on bike-sharing equity in southern Tampa (Chen et al. 2020): data aggregation hides individual differences in access to bike-sharing services.



Ref: Cohn, J., Ezike, R., Martin, J., Donkor, K., Ridgway, M., & Balding, M. (2019). Examining the equity impacts of autonomous vehicles: a travel demand model approach. Transportation research record, 2673(5), 23-35.
Lee, J., & Kockelman, K. M. (2022). Access benefits of shared autonomous vehicle fleets: focus on vulnerable populations. *Transportation research record*, *2676*(11), 568-582.
Chen, Z., Guo, Y., Stuart, A. L., Zhang, Y., & Li, X. (2019). Exploring the equity performance of bike-sharing systems with disaggregated data: A story of southern Tampa. Transportation research part A: policy and practice, 130, 529-545.

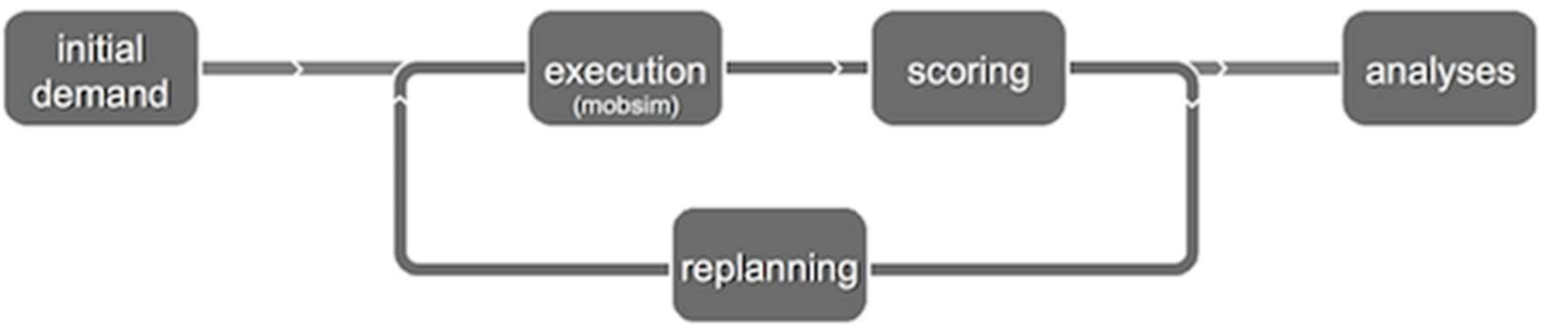
A Disaggregated Modeling Approach



Agent-Based Simulation (ABS)

- Mesoscopic network simulation model

MATSim
Multi-Agent Transport Simulation



ABS: Simulating Private & Shared AVs

- Individuals would use private AVs even if shared AV services are available (Haboucha et al., 2017).
- MATSim built-in AV module only considers shared AVs.

av 12.0 API

The automated (autonomous) vehicle contrib is structured as follows:

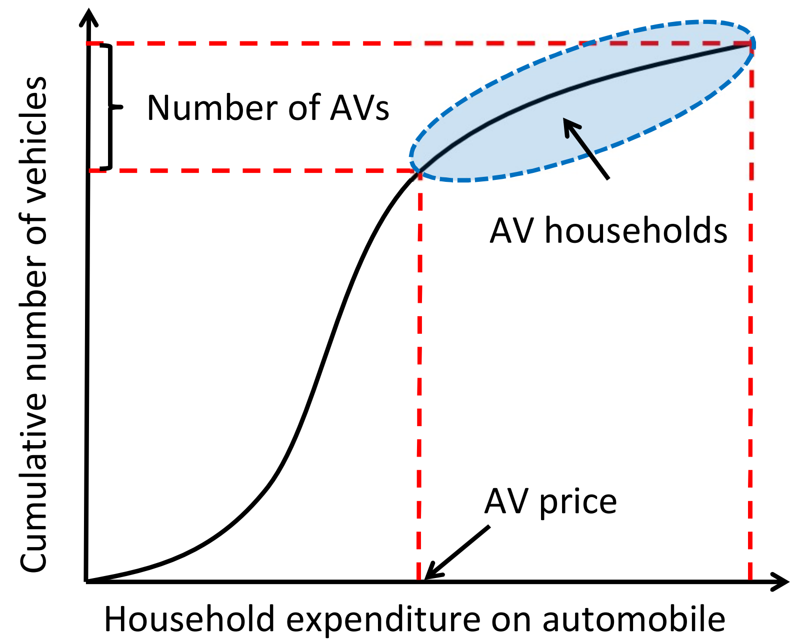
- org.matsim.contrib.av.robotaxi: Simulation of large-scale autonomous taxi fleets
- org.matsim.contrib.drt: Basic packages for DRT simulation (with our without drivers)
- org.matsim.contrib.intermodal: Intermodal routing between pt and different modes, such as autonomous taxi fleets.

- We extended this module to consider private AVs: treat private AVs as part of the shared AV fleet but only shared among household members

Ref: Haboucha, C. J., Ishaq, R., & Shiftan, Y. (2017). User preferences regarding autonomous vehicles. Transportation Research Part C: Emerging Technologies, 78, 37-49.

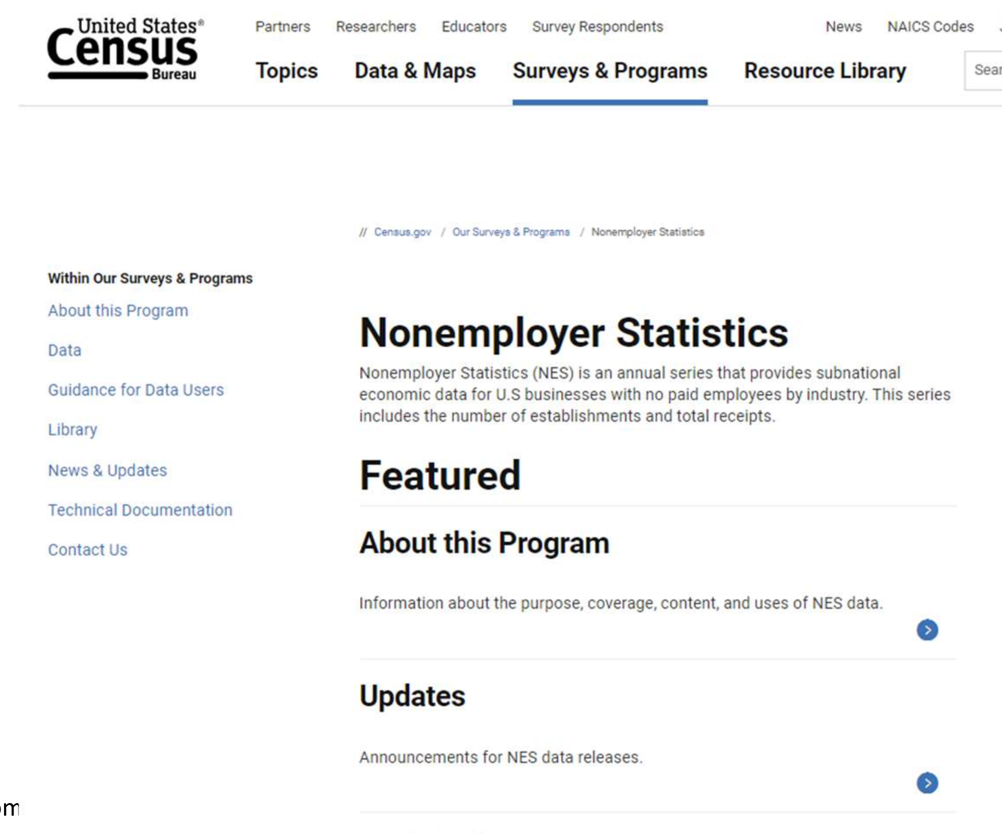
ABS: Estimating Private AV Ownership

- households ranked by historical expenditures on automobiles and also categorized into groups based on annual household income
- AV households are selected by preferentially assigning private AVs to those households who had higher expenditures on vehicles in the past



ABS: Estimating Shared AV Fleet

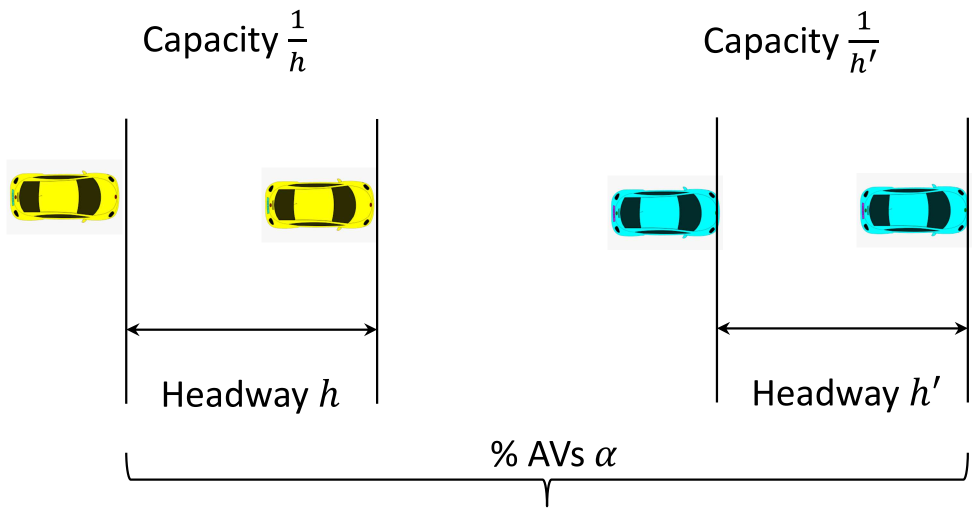
- the total number of ride-hailing vehicles not available
- # non-employer establishments under industry group 4853 (Taxi and Limousine Services) as a surrogate



Ref: Haboucha, C. J., Ishaq, R., & Shiftan, Y. (2017). User preferences regarding autonom

ABS: Modeling AV Impact on Roadway Capacity

- A simple analytical model based on Ghiasi et al. (2017)



We assume that $h = 2h'$

$\alpha = 1$ for managed AV lanes and the AV market penetration rate for other lanes

Average headway $h(1-\alpha) + h'\alpha$ Capacity $\frac{1}{h(1-\alpha)+h'\alpha}$

Ref: Ghiasi, A., Hussain, O., Qian, Z. S., & Li, X. (2017). A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method. Transportation Research Part B: Methodological, 106, 266-292.

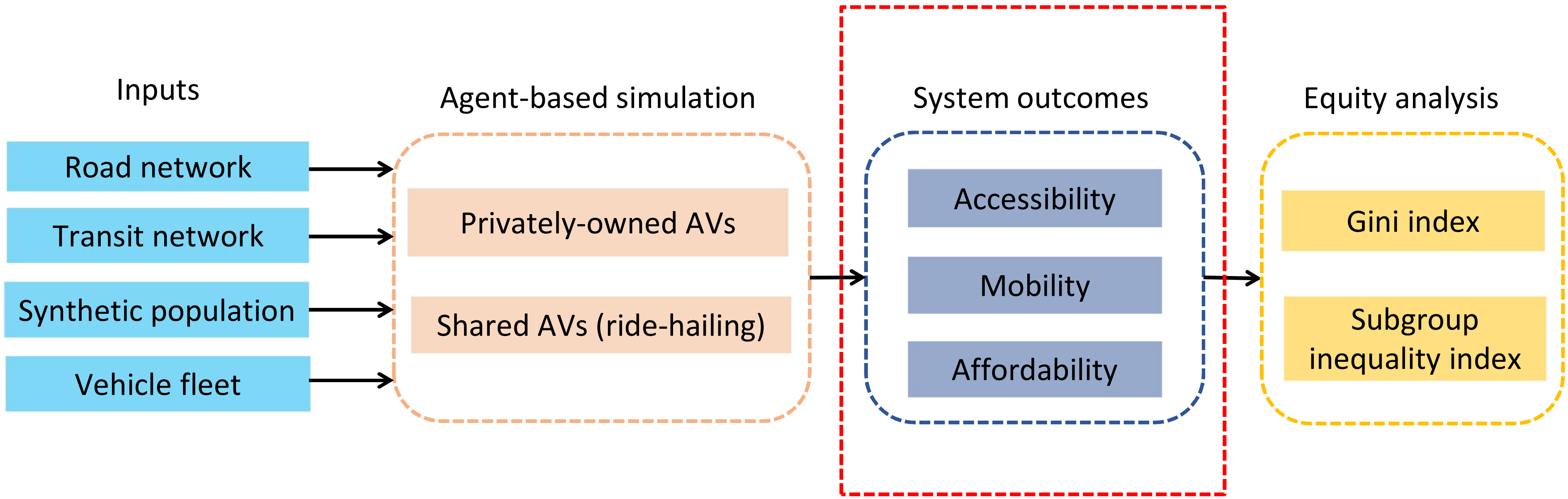
ABS: Modeling AV Impact on Driving Behaviors

- A critical benefit of AVs that is frequently claimed by businesses is that AVs improve mobility of seniors and children who cannot drive (National Highway Traffic Safety Administration, 2017).
- Removed all escort trips from the travel itineraries of all individuals.
- Customized MATSim's utility scoring functions to consider individual sociodemographics, e.g., minimum driving age.

escorting kids to schools

Ref: National Highway Traffic Safety Administration. (2017). Automated driving systems 2.0: A vision for safety. Washington, DC: US Department of Transportation, DOT HS, 812, 442.

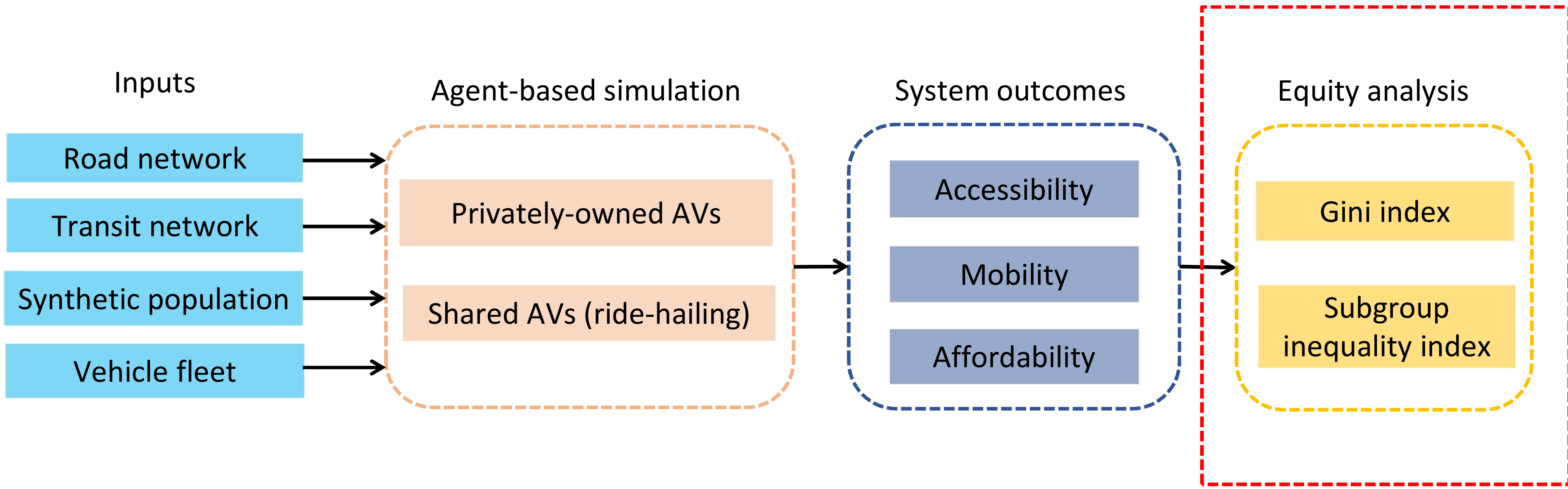
A Disaggregated Modeling Approach



Transportation System Outcomes

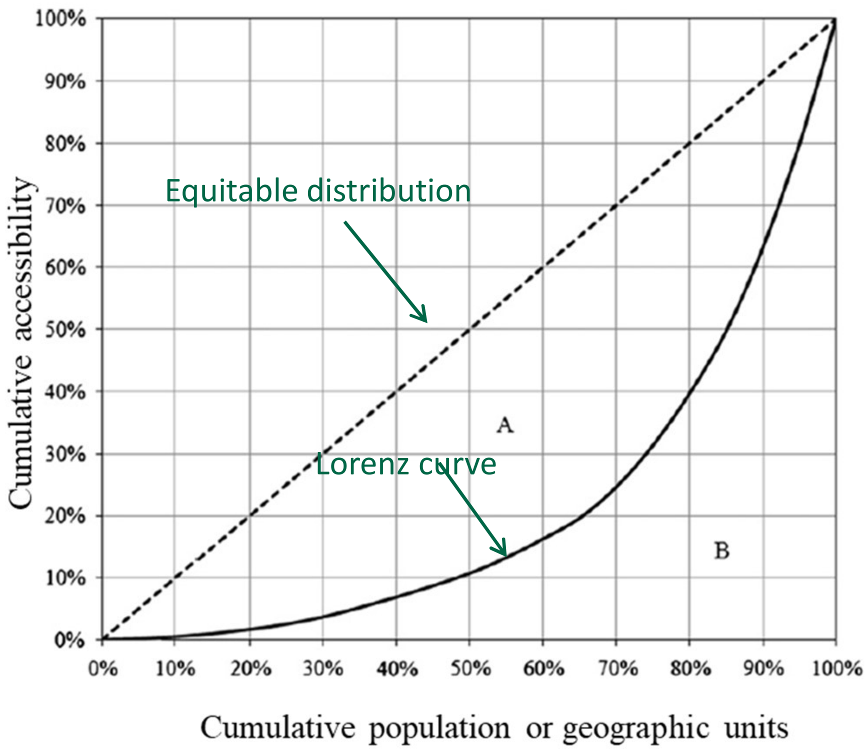
- **Accessibility:**
  - the potential of each individual to access, within a certain time threshold, those locations of their typical daily activities (as represented by the daily travel itinerary): jobs, schools, recreational activities
  - 1 if the travel time of this trip is no more than a given time threshold, and otherwise 0
- **Mobility:**
  - the amount of travel on the system as a proxy for ease of travel
  - we use person miles traveled per day as the indicator
- **Affordability:**
  - financial costs often determine which users benefit from technologies
  - we use the travel cost per dollar of household income to quantify affordability

A Disaggregated Modeling Approach



Gini Index

Does not consider population subgroups



Gini index = $\frac{A}{A+B}$

0: most even

1: most uneven

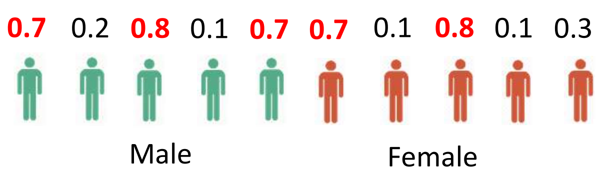
Subgroup Inequality Index

$$SII_r = \log(\frac{\hat{Y}_r}{Y_r})$$

SII_r: the extent to which members in subgroup r are disproportionally distributed among the population with accessibility above the population average

$\hat{Y}_r$: the fraction of the population that belongs to subgroup r with an accessibility level above the population average

Y_r: the fraction of the population that is subgroup r



$$SII_{\text{male}} = \log\left(\frac{\hat{Y}_{\text{male}}}{Y_{\text{male}}}\right) = \log(\frac{3/5}{5/10}) = 0.08$$

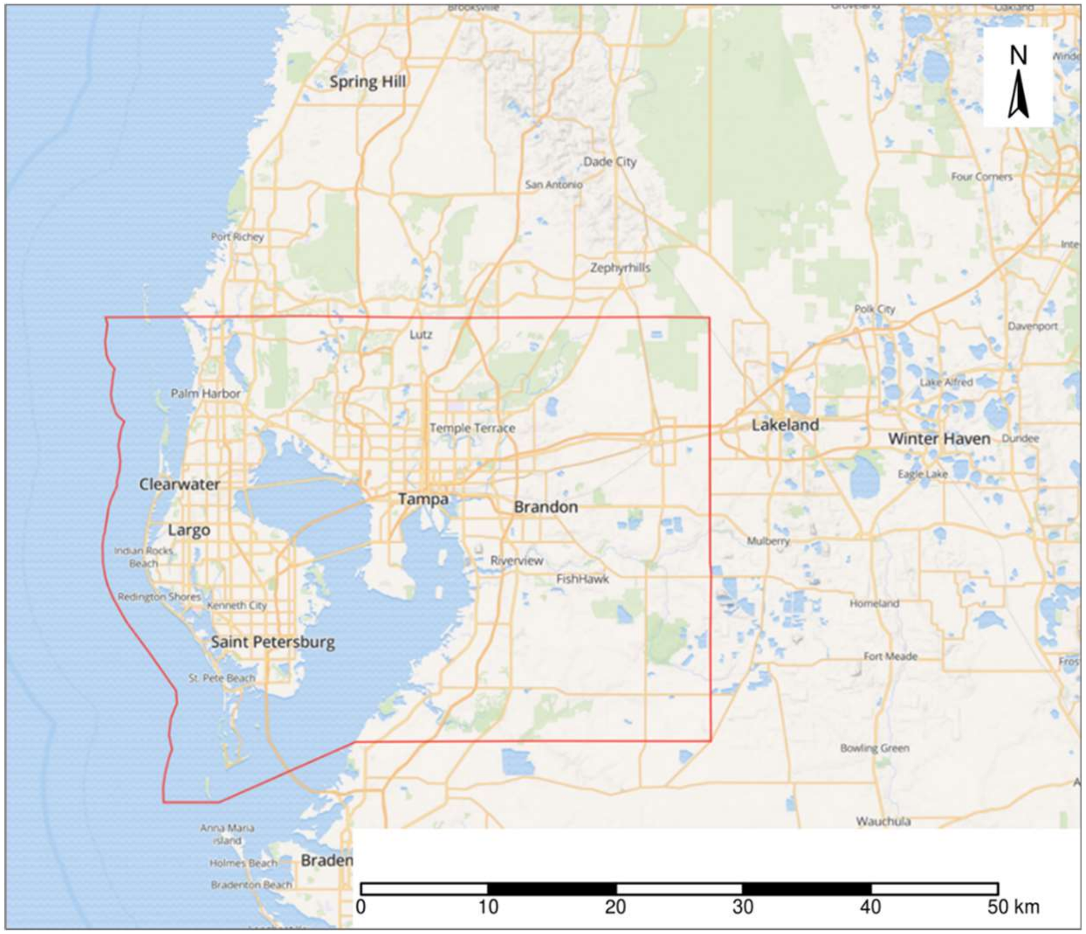
Above 0; overrepresented

$$SII_{\text{female}} = \log\left(\frac{\hat{Y}_{\text{female}}}{Y_{\text{female}}}\right) = \log(\frac{2/5}{5/10}) = -0.10$$

below 0; underrepresented

Case Study: Study Area

- Hillsborough and Pinellas Counties
- highly diverse population demographics
- Stakeholder interests (companies testing AV models)



Case Study: Study Scenarios

- Five potential future scenarios based on the US Federal Highway Administration's (FHWA) previous scenario planning study for connected and automated vehicles

Scenario	Business as Usual	Niche Growth	Steady Growth	AVs are Common	Managed Lanes
Market penetration rate of AVs (%)	0	5	20	50	50
Effective increase in roadway capacity (%)	0	2.6	11.1	33.3	33.3
Minimum age to drive alone (years)	16	12	12	12	12
Includes dedicated AV lanes	No	No	No	No	Yes
Ratio of the operating cost for an AV vs a conventional automobile	N/A	2.52	1.66	1.04	1.04

Case Study: Focus Population

rural population

low-income households

low-income working families

people 65 years of age and older

females

Results: Summary Statistics

- Mean commute time first increased and then decreased
- All types of accessibility considered first decreased and then increased
- # trips & miles travelled increased; travel cost/income decreased

Indicator	Scenario: Business as Usual	Niche Growth	Steady Growth	AVs are Common	Managed Lanes
Commute time (min)	39.3	42.7	38.6	32.8	30.7
Number of trips	4.21	4.05	4.01	3.94	3.94
Job accessibility	0.53	0.52	0.53	0.57	0.6
School accessibility	0.75	0.74	0.77	0.82	0.84
Social accessibility	0.65	0.64	0.67	0.72	0.74
Miles traveled (miles/day)	20.9	20.2	19.4	18.1	17.8
Travel cost/income (%)	15	17.3	15.8	14.5	14.4

Results: Gini Index

- Accessibility: First more equal then more equal
- Mobility: More unequal
- Affordability: not much affected
- Mobility and affordability more unequal than accessibility

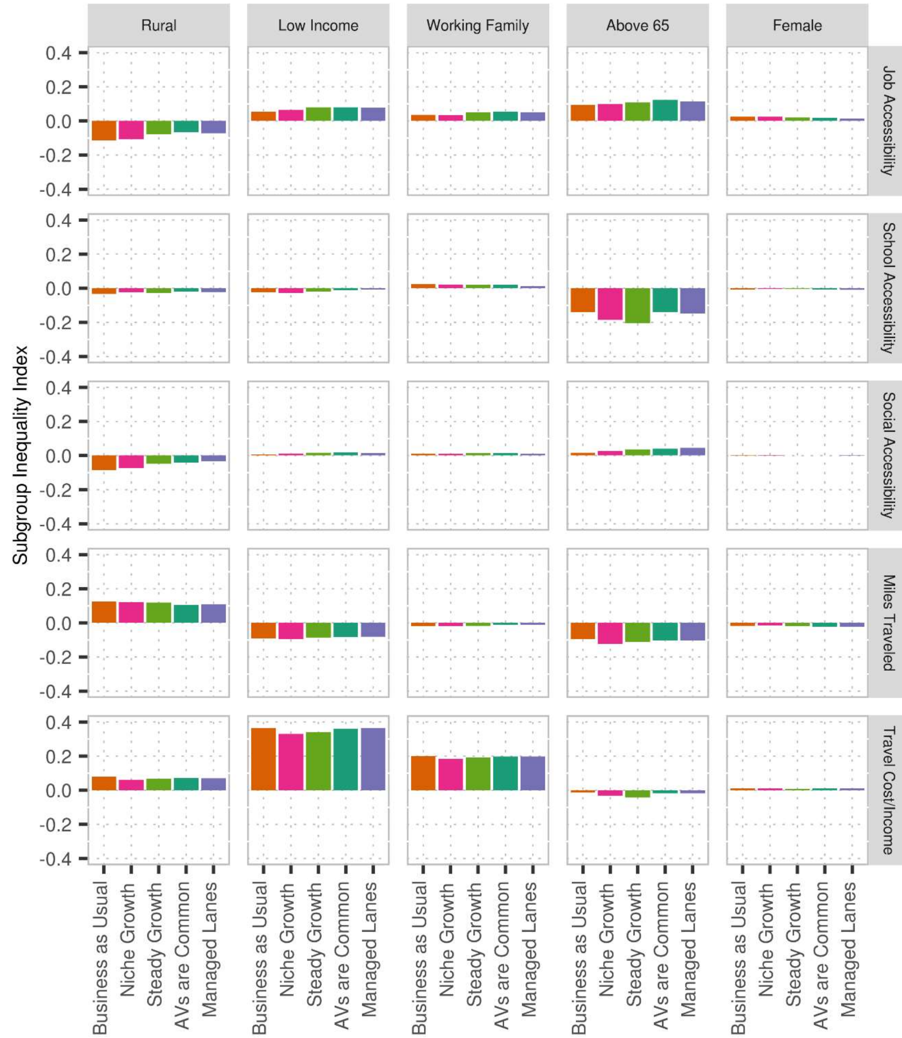
Gini index values (% change compared with the Business as Usual scenario in parenthesis)

Indicator	Scenario Business as Usual	Niche Growth	Steady Growth	AVs are Common	Managed Lanes
Job accessibility	0.45	0.47 (4)	0.46 (2)	0.42 (-7)	0.39 (-13)
School accessibility	0.25	0.26 (4)	0.23 (-8)	0.18 (-28)	0.16 (-36)
Social accessibility	0.35	0.36 (3)	0.32 (-9)	0.28 (-20)	0.26 (-26)
Miles traveled	0.42	0.44 (5)	0.44 (5)	0.44 (5)	0.44 (5)
Travel cost/income	0.62	0.63 (0)	0.62 (0)	0.63 (2)	0.63 (2)

Note: Values range from 0 to 1, with 0 indicating complete equality, and 1 indicating maximum disparity .

Results: SII

- **Rural residents** consistently had disproportionately lower access to employment, education, and social activities, travelled longer distances, and paid more for transportation.
- **The low-income population** had disproportionately higher access to employment and lower travel distances, but the highest disparity was for affordability.
- **Senior citizens** had disproportionately higher access to employment and travelled less than younger residents.
- No substantial gaps between males and females.



Subgroup inequality index: above 0 overrepresented, below 0 underrepresented

Results: Comparing With Aggregated Analysis

- Gini index values were decreased by the aggregated analysis, meaning that the aggregated analysis hides individual differences that could have been captured in a disaggregated analysis.

Comparison of Gini index values from disaggregated and aggregated analysis

Scenario	Business as Usual		Steady Growth		AVs are Common	
Indicator	Disaggregated	Aggregated	Disaggregated	Aggregated	Disaggregated	Aggregated
Job accessibility	0.45	0.21	0.46	0.21	0.42	0.19
School accessibility	0.25	0.17	0.23	0.16	0.18	0.13
Social accessibility	0.35	0.15	0.32	0.14	0.28	0.12
Miles traveled	0.42	0.14	0.44	0.15	0.44	0.14
Travel cost/income	0.62	0.26	0.62	0.25	0.63	0.26

Results: Comparing With Aggregated Analysis

- The aggregated analysis and the disaggregated analysis agree with each other in the disparity direction (represented by the sign of the SII), but the magnitude of inequality may not be the same.

Comparison of SII values from disaggregated and aggregated analysis

Scenario	Business as Usual		Steady Growth		AVs are Common	
Indicator	Disaggregated	Aggregated	Disaggregated	Aggregated	Disaggregated	Aggregated
Rural	-0.11	-0.28	-0.08	-0.23	-0.07	-0.17
Low income (LI)	0.05	0.06	0.06	0.05	0.08	0.06
LI working family	0.04	0.05	0.03	0.04	0.05	0.05
Above 65	0.09	0.01	0.13	0.02	0.12	0.01
Female	0.02	0.01	0.01	0.00	0.02	0.00

Key Insights

- AV technologies may not generate substantial benefits overall until adoption is wide
- AV technologies have potential to mitigate overall inequality in accessibility but impacts on existing inequities affecting disadvantaged groups may be mixed
  - When the AV market share reached 50% (the Managed Lanes scenario), the Gini index values for school accessibility, social accessibility, and job accessibility decreased by 36%, 26%, and 13%, respectively, from the non-AV scenario.
  - For most of the outcomes for which inequity existed in the Business as Usual scenario, the Managed Lane scenario either improved equity or left it unaffected.
- The impact of AV technologies on inequality in affordability deserves attention in equitable deployment strategies
- Disaggregated analysis is recommended for accurately representing equity impacts

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