Trade-off Between Safety, Mobility and Energy Efficiency of Automated Vehicles

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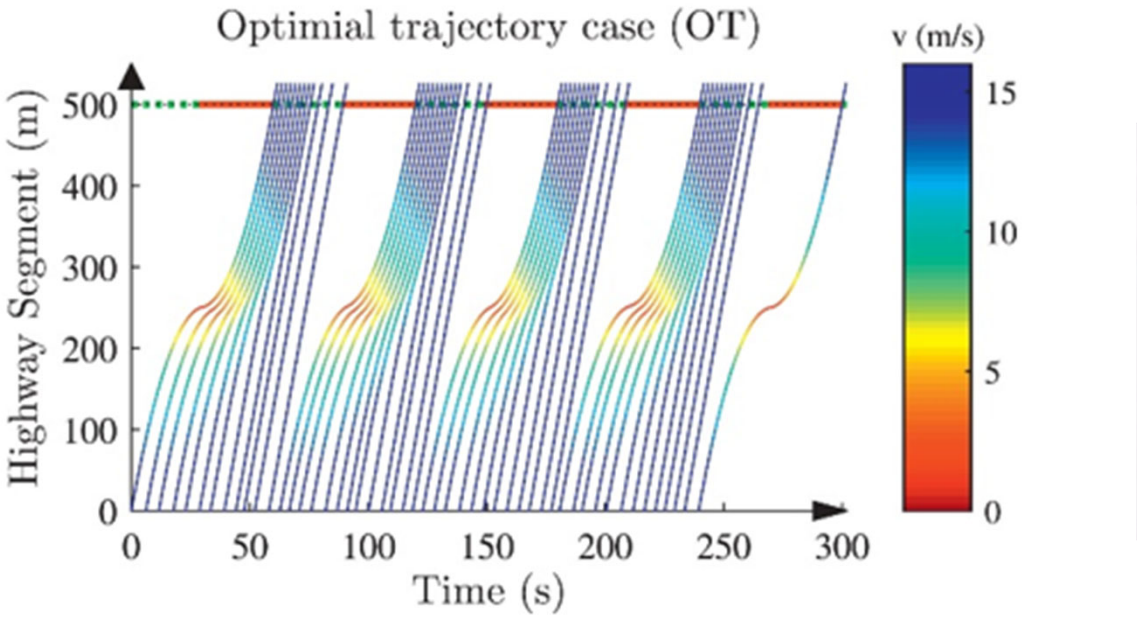
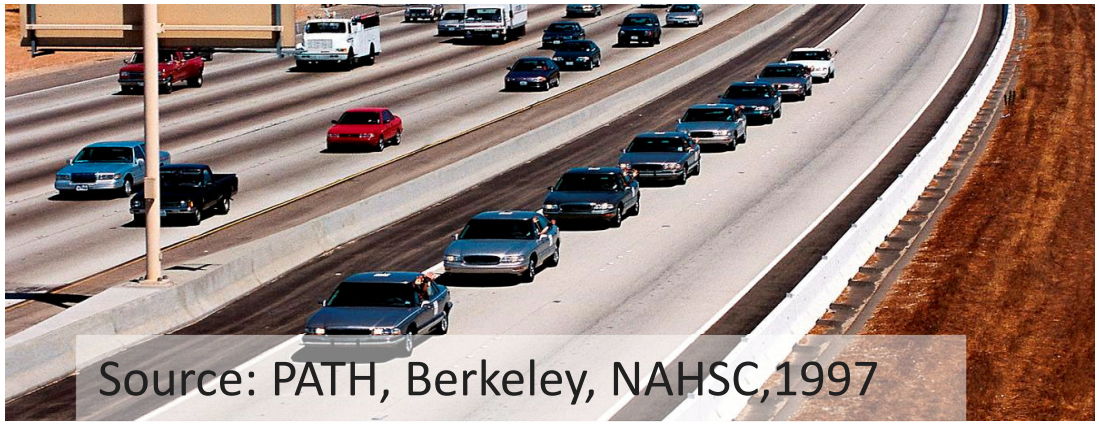
Vision of CDA

- Complicated coordination of vehicles, infrastructure and control units



High Hopes on Connected Automated Vehicles (CAVs)

- Safety: >94% reduction of crashes (Winkle, 2016)
- Mobility: capacity tripled (Varaiya, 1993; Ioannou 1997) ; quadrupled (Karaaslan, 1990)
- Energy efficiency: +25~50% (Vahidi & Sciarretta, 2018)

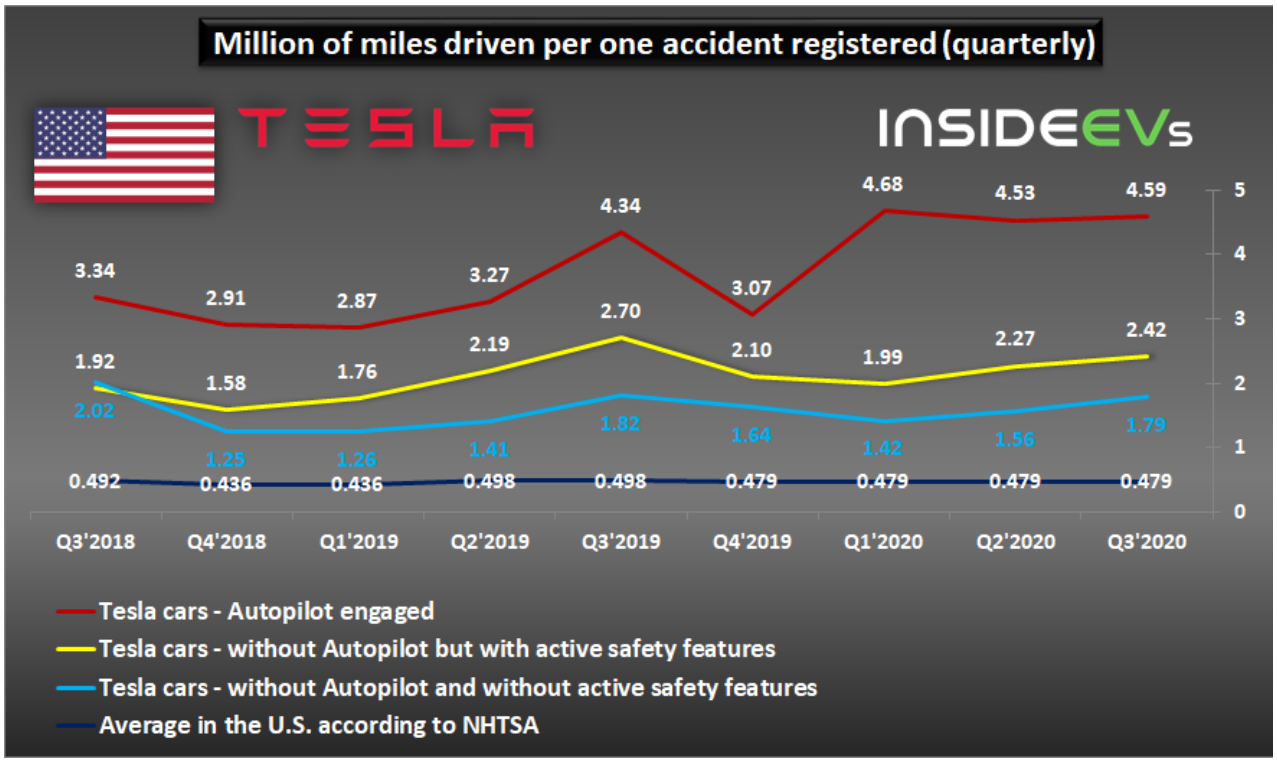


Deployed Technology

- Advanced Driver-Assistance Systems (ADAS)
  - Longitudinal – adaptive cruise control (ACC)
- Production automated vehicle (AVs) market penetration rates
  - 2% in 2015 -> 10% in 2025 -> 40% in 2040.

Deployed Technology - Safety

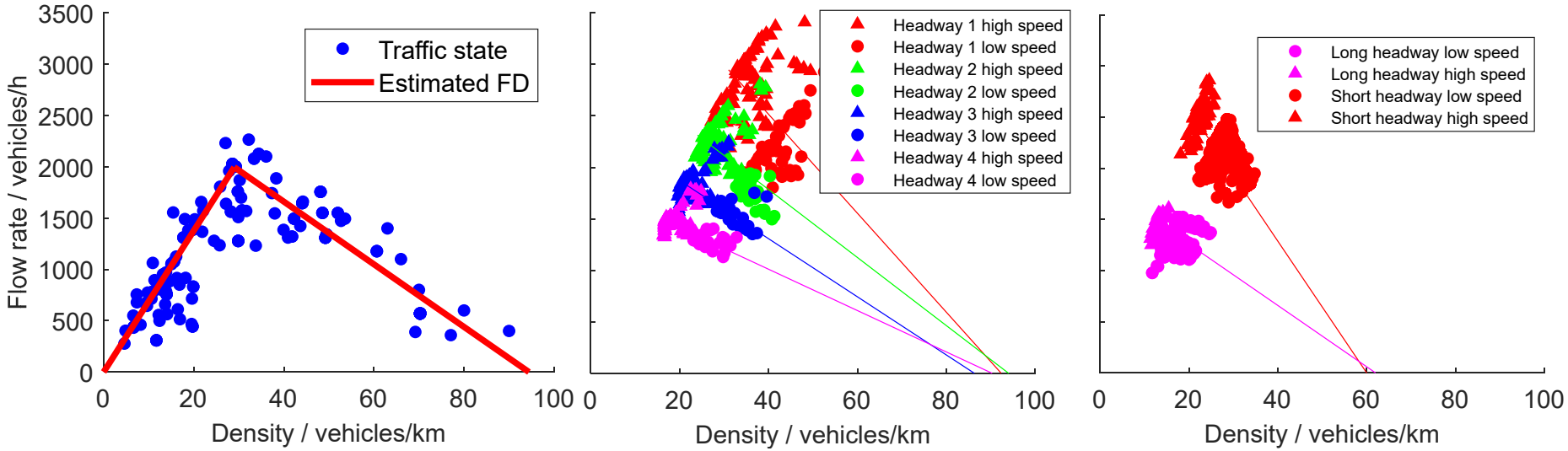
- Tesla Autopilot: -80~90% crashes



Close to Target: >94% reduction

Deployed Technology – Mobility

- HV benchmark fundamental diagram
- Comparable or even smaller capacity, depending on the customized headway settings



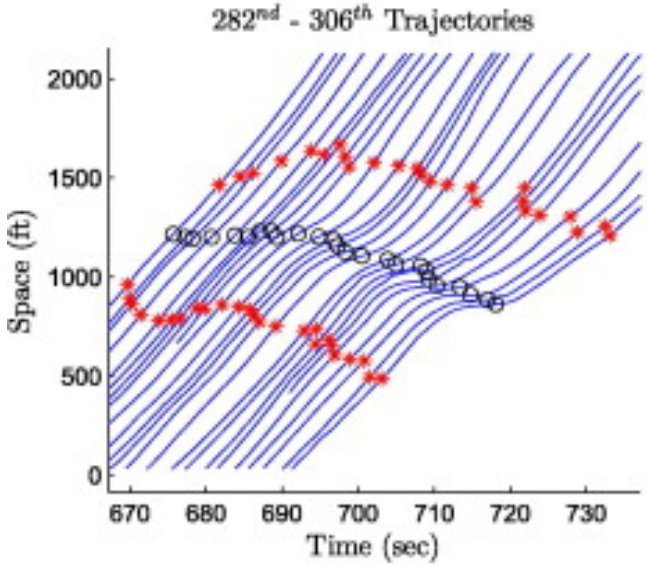
Human-driven Vehicles (HVs) | ACC Automaker 1 | ACC Automaker 2

Far from the Target: Multiply Capacity

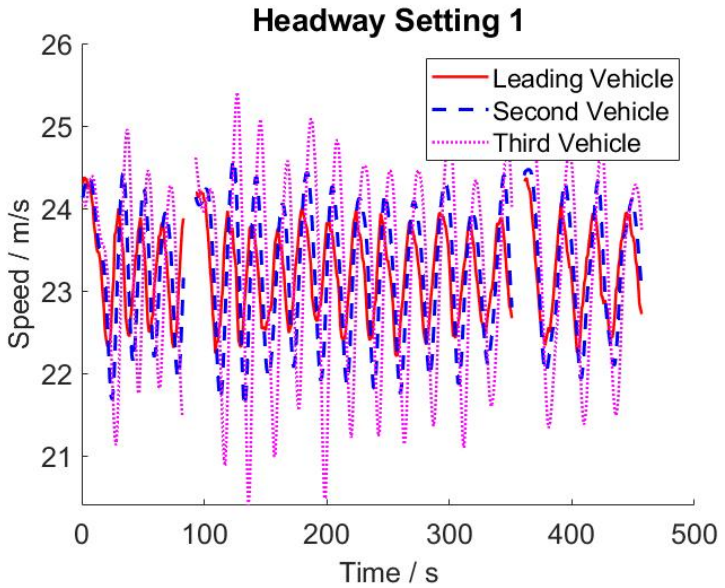
Ref: Shi, X., & Li, X. (2021). Shi, X., & Li, X. (2021). Constructing a fundamental diagram for traffic flow with automated vehicles: Methodology and demonstration. TR Part B, 150, 279-292.

Deployed Technology – Energy

- ACC energy efficiency slightly better than HVs



HV

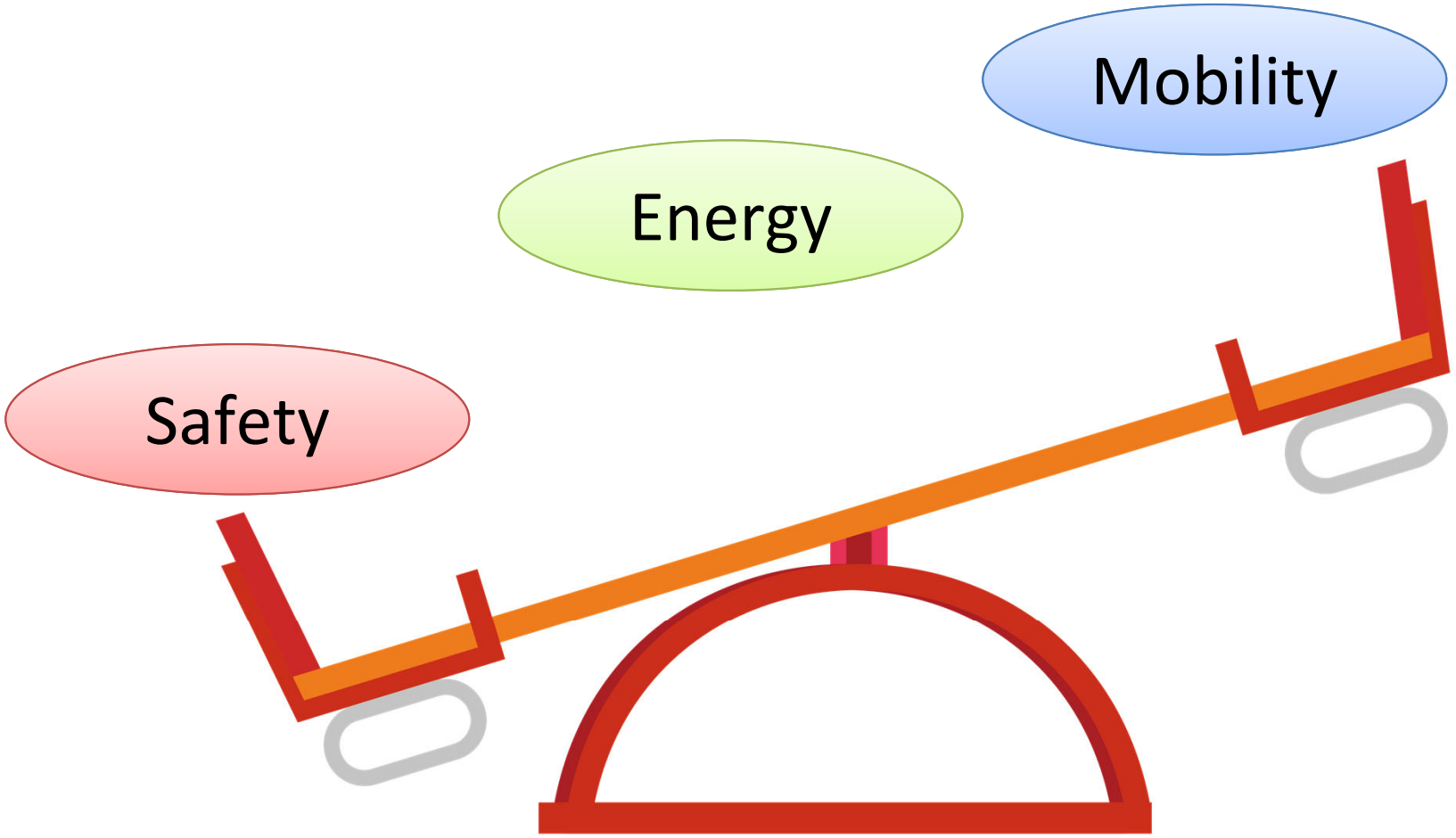


ACC

Remains Room for Improvement

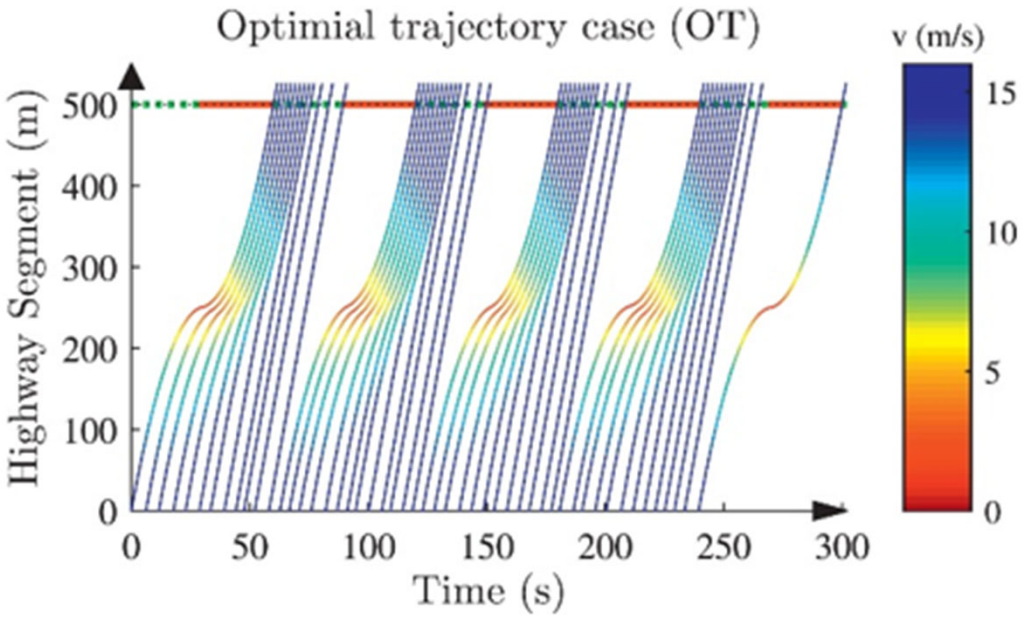
Source: Shi, X., Yao, H. Liang, Z. & Li, X. (2022) An Empirical Study on Fuel Consumption of Commercial Automated Vehicles. Transportation Research Part D, 106, 103253. https://doi.org/10.1016/j.trd.2022.103253

Performance Imbalance



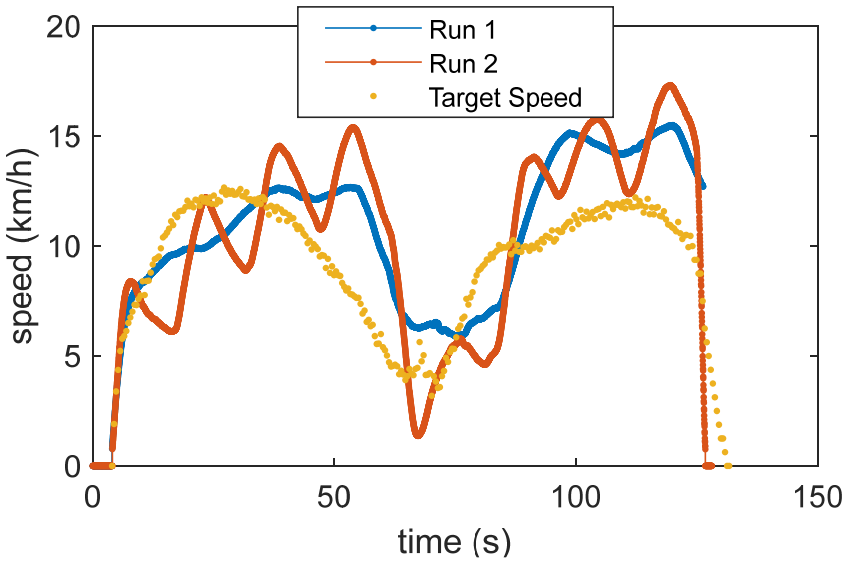
Vision of CDA

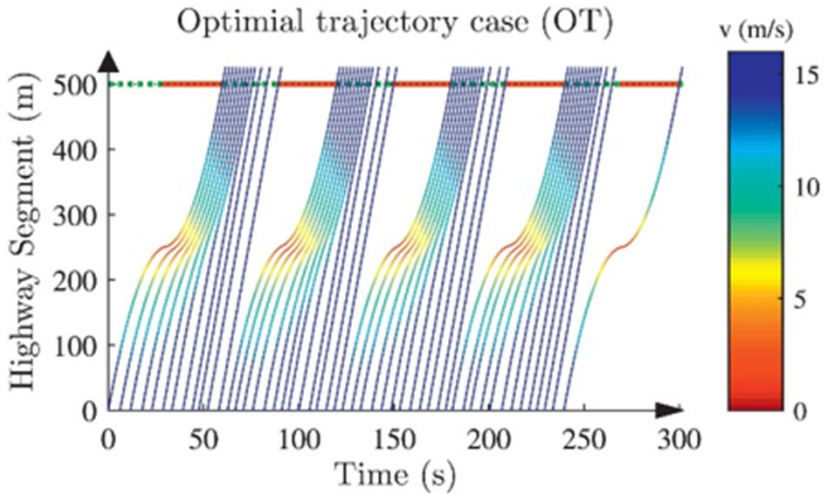
- Complicated coordination of vehicles, infrastructure and control units
- Needs for precise control of automated vehicle (AV) trajectory



Experiment with Production AVs

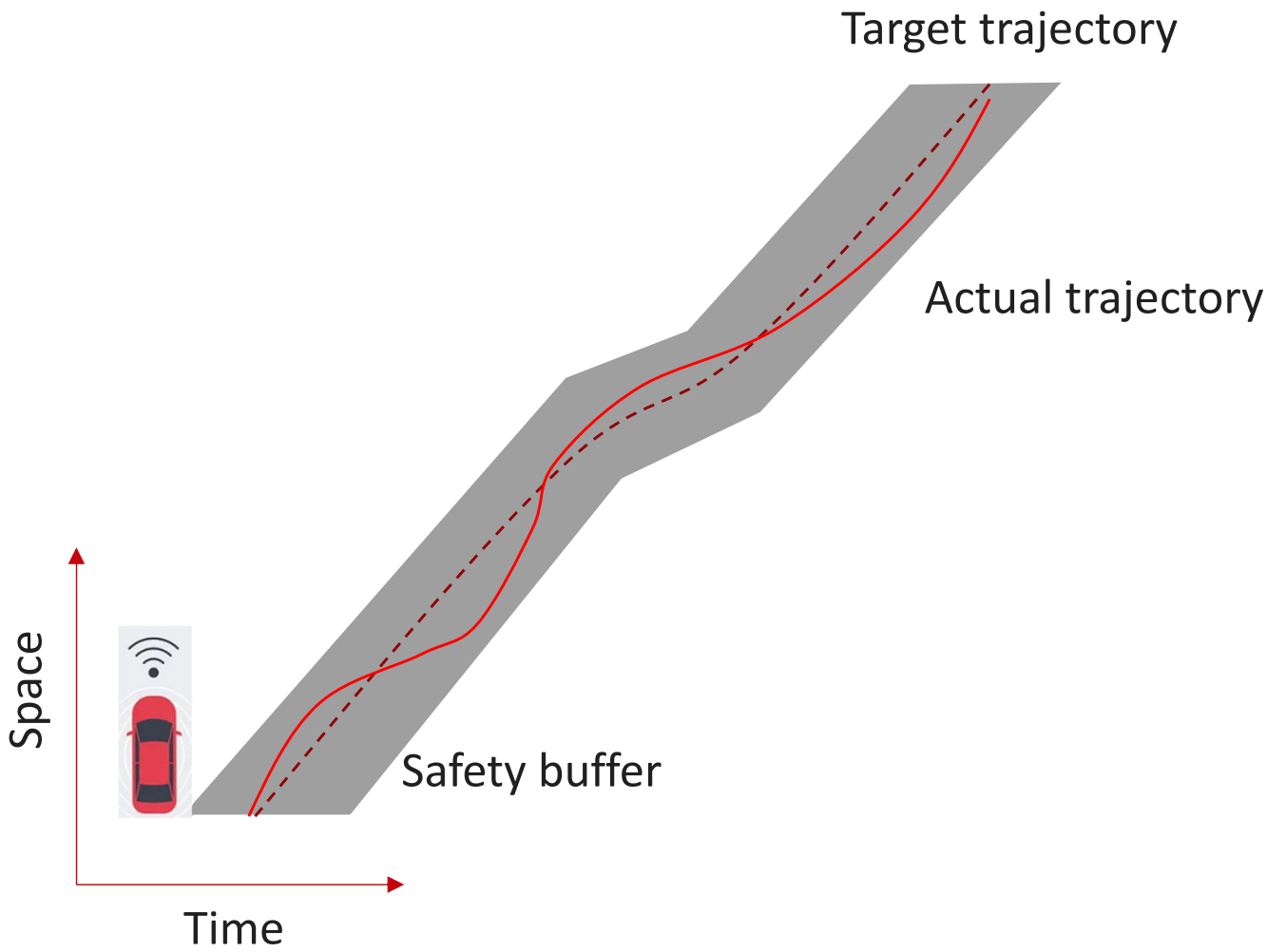
- Significant gaps between target and actual speeds
- Inconsistent speed profiles across different runs





How to Handle Imperfect Control

- Safety buffer



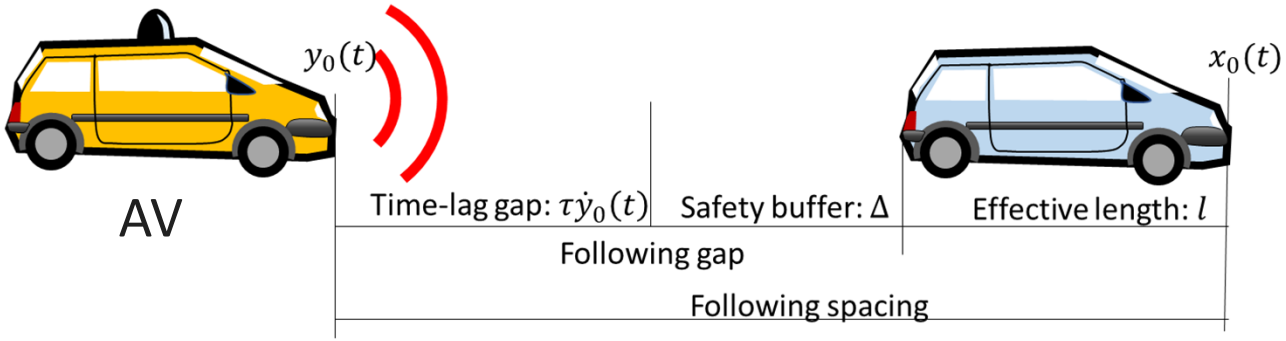
Tradeoff Analysis

- Reactive AV car following control

$$\ddot{y}_0(t) = \kappa[(x_0(t) - y_0(t)) - (\Delta + \tau\dot{y}_0(t))]$$

  - $y_0(t)$ lead vehicle trajectory; $x_0(t)$ subject AV trajectory; κ control sensitivity; Δ safety buffer (safety); τ reaction time (mobility);

- Theorem: control sensitivity $\downarrow \Rightarrow$ safety buffer $\uparrow$ $\Rightarrow$ mobility $\downarrow$



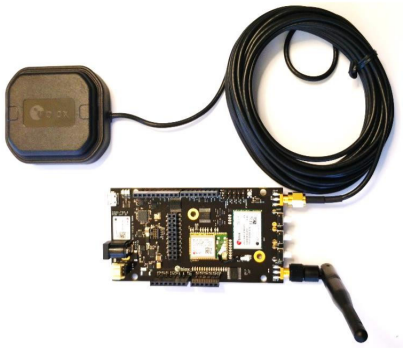
Li, X. Trade-off between safety, mobility and stability in automated vehicle following control: An analytical method. Transportation Research Part B, under revision; http://dx.doi.org/10.13140/RG.2.2.28804.35204

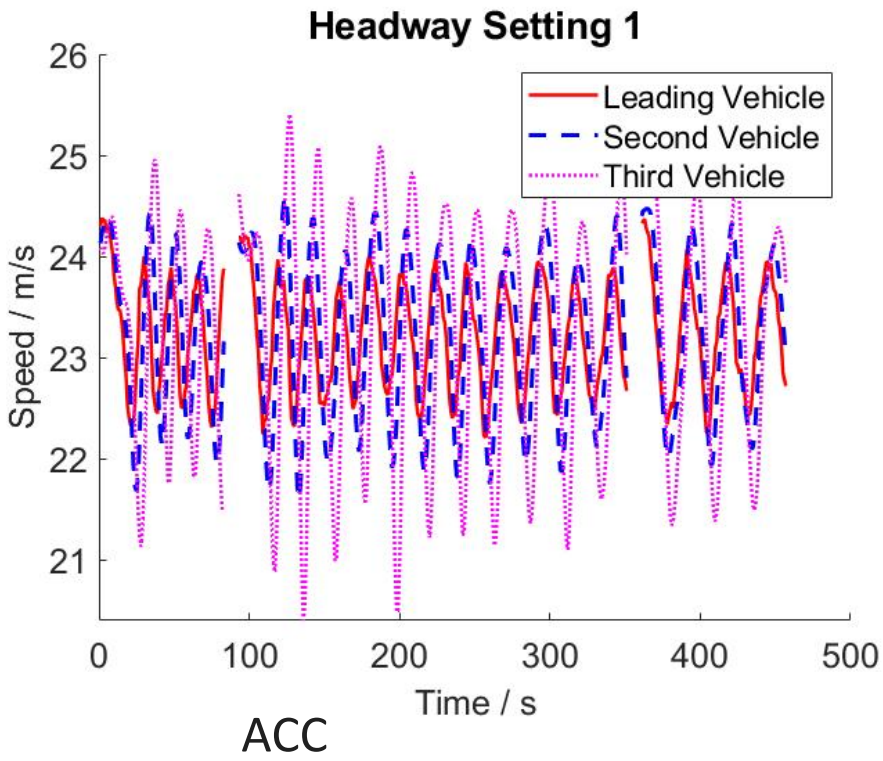
Summary of the Results

- Mobility↑(τ ↓) ⇒ Safety↓ (Δ ↑)
- Mobility↑(τ ↓) ⇒ Traffic Oscillation↓(TF^* ↑, ω^* ↑)⇒ Energy Consumption ↑

Verification with Field Studies

- Production AV Following Tests





ACC

Verification with Field Studies

- Mobility ↑ ⇒Control sensitivity ↑ ⇒ Safety ↓ & Energy Consumption ↑

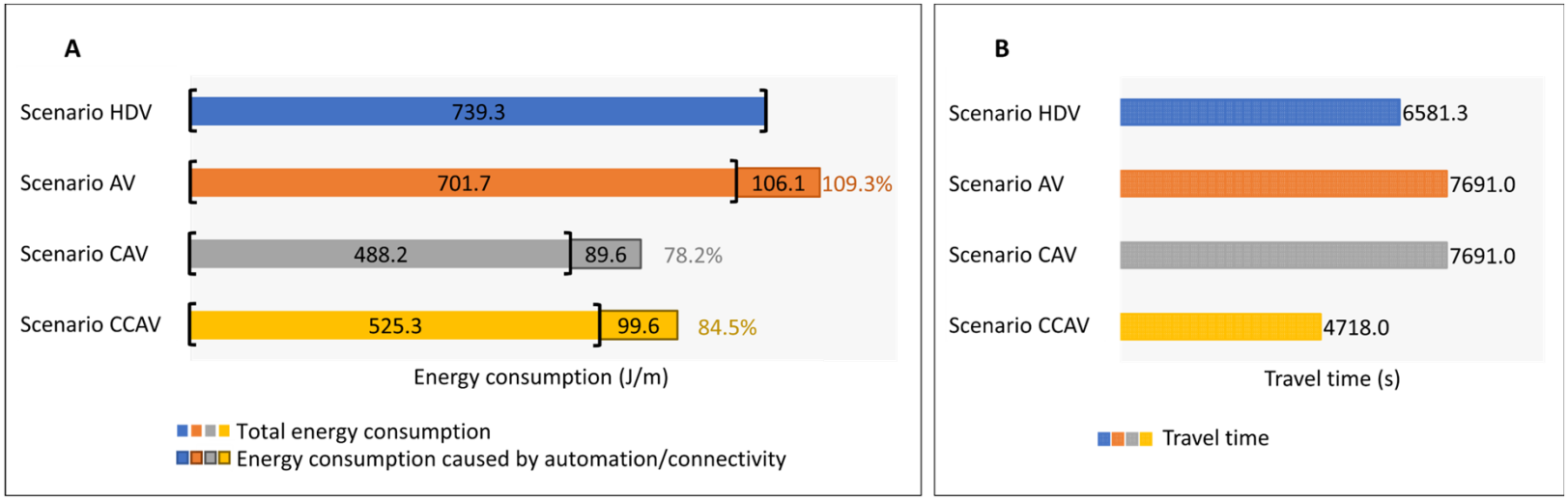
	τ (s)	k	Δ (m)	R^2_{adj}
High Speed-Headway Setting 1	0.83	0.10	4.83	0.87
High Speed-Headway Setting 2	1.21	0.10	4.40	0.95
High Speed-Headway Setting 3	1.61	0.09	3.31	0.92
High Speed-Headway Setting 4	2.17	0.07	0.66	0.84
Low Speed-Headway Setting 1	0.79	0.12	7.28	0.92
Low Speed-Headway Setting 2	1.14	0.09	6.36	0.90
Low Speed-Headway Setting 3	1.52	0.08	5.92	0.83
Low Speed-Headway Setting 4	2.09	0.08	4.97	0.82

	T=18	T=20	T=22	T=24	T=26
Headway 1	1.304	1.553*	1.505	1.515	1.478
Headway 2	1.378	1.460*	1.403	1.446	1.424
Headway 3	1.270	1.215	1.440*	1.253	1.352
Headway 4	1.142	1.199	1.201	1.148	1.208*

Shi, X. & Li, X. (2021). Empirical study on car following characteristics of commercial automated vehicles with different headway settings. Transportation Research Part C, 128, 103134. https://doi.org/10.1016/j.trc.2021.103134

Energy Performance

- Field AV data (Shanghai, China) in an urban environment
- Production AV energy performance may be inferior to human drivers, due to delay & stops at intersections

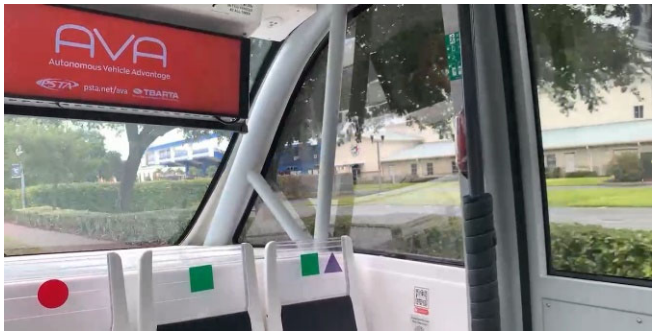


Qu, X, Zhong, L., Zeng, Z., Tu, H., Li, X. "Automation and connectivity of electric vehicles: Energy boon or bane?" ***Cell Reports***, forthcoming.

People's Acceptance of AV

- AV Shuttle Demonstration in Dunedin, Florida.
- May to July 2022.
- Interviewed 161 people before and after them taking an open road AV shuttle ride.

AV shuttle operated by PSTA

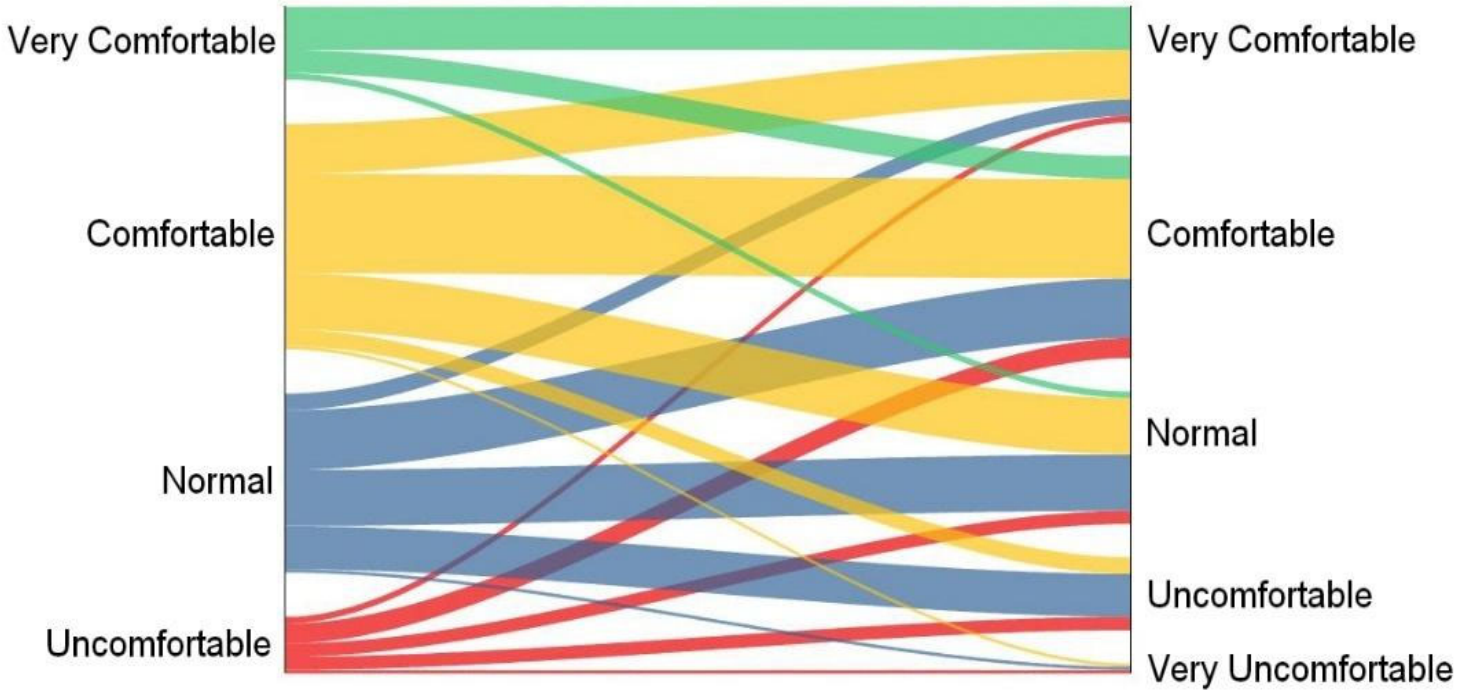


Interior view of AV shuttle

Costumer survey questioner link

People's Acceptance of AV

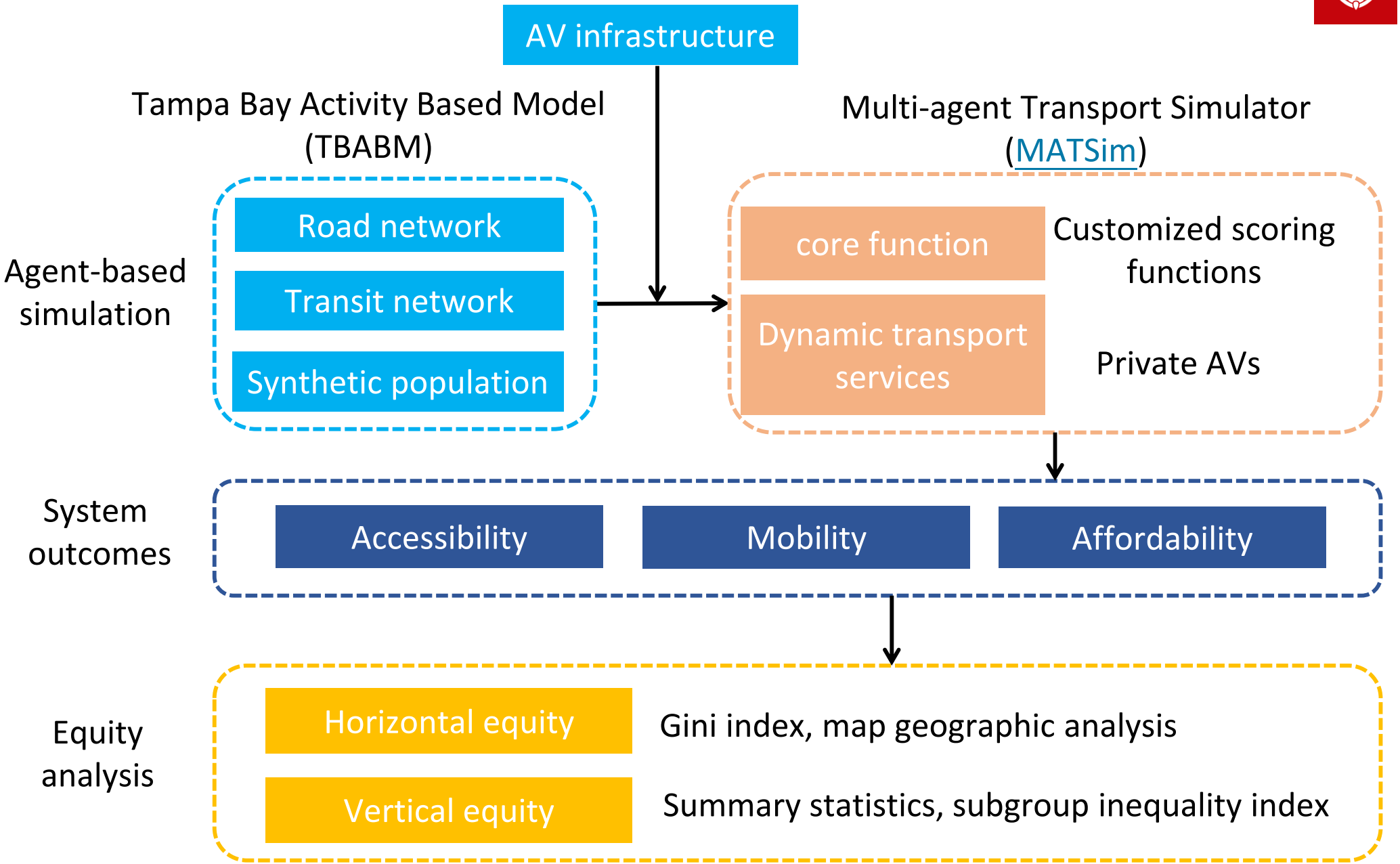
- Hard breaks deteriorate people's acceptance.
- Surrounding drivers feel less comfortable



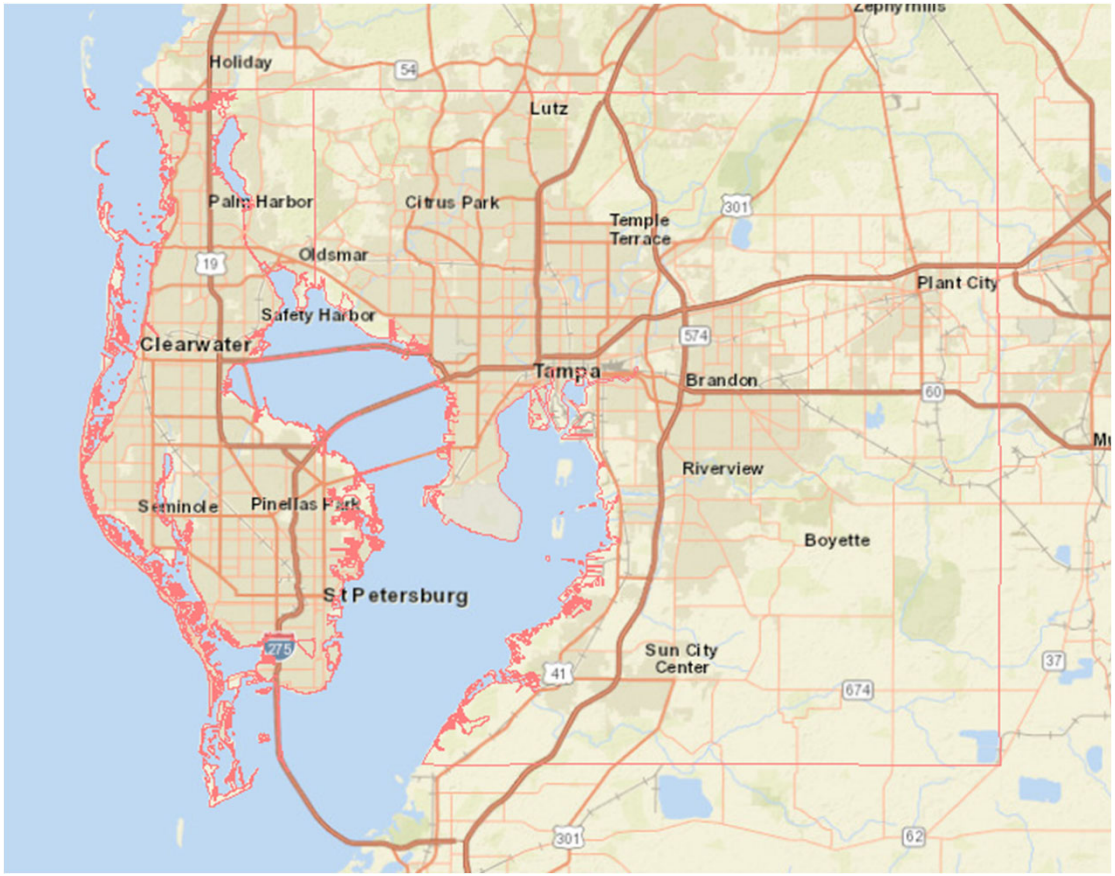
Before the ride

After the ride

AV Equity Analysis



Case Study Application



Geographic extent of Tampa Bay study region (source: Google Maps)

- Simulation area: District 7, FL
- Equity analysis area: Tampa Bay
- Study scenarios (2040):
  - Base scenario: 0% AV
  - AV scenario 1: 10% AV

Results: Horizontal equity – Gini index

	Base scenario	10% AV scenario
Job accessibility	0.26	0.35
School accessibility	0.14	0.24
Social activity accessibility	0.16	0.27
Person miles traveled (miles/day)	0.44	0.46
Travel cost ($/day)	0.43	0.42
Travel cost to income ratio (%)	0.65	0.65

- Mobility, travel cost, and travel cost to income ratio are more unequally distributed compared with accessibility in the base scenario
- Adoption of AV increase the degree of inequality in the distribution of all transportation outcomes considered.

Insights

- Do nothing about production AV control
  - ⇒ add sufficient safety buffer
  - ⇒ compromise mobility, energy efficiency as well as equity and people's acceptance against the CDA vision

- Or, do something to improve AV performance?

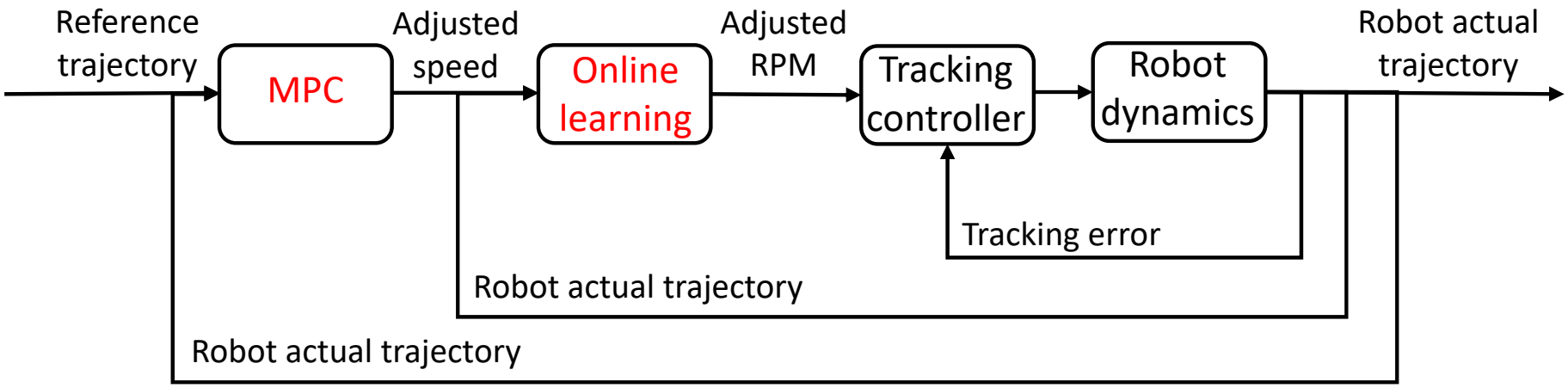
Power Train: Electric Vehicles (EV)

- EVs respond faster and may improve trajectory control precision

	Sensitivity κ	Safety Buffer Δ (m)	Time Lag τ (s)
Electric AV	0.12	1.5	0.92
Hybrid Vehicle	0.11	2.7	1.09
ICE AV	0.1	6.6	1.6

Learning Based Control

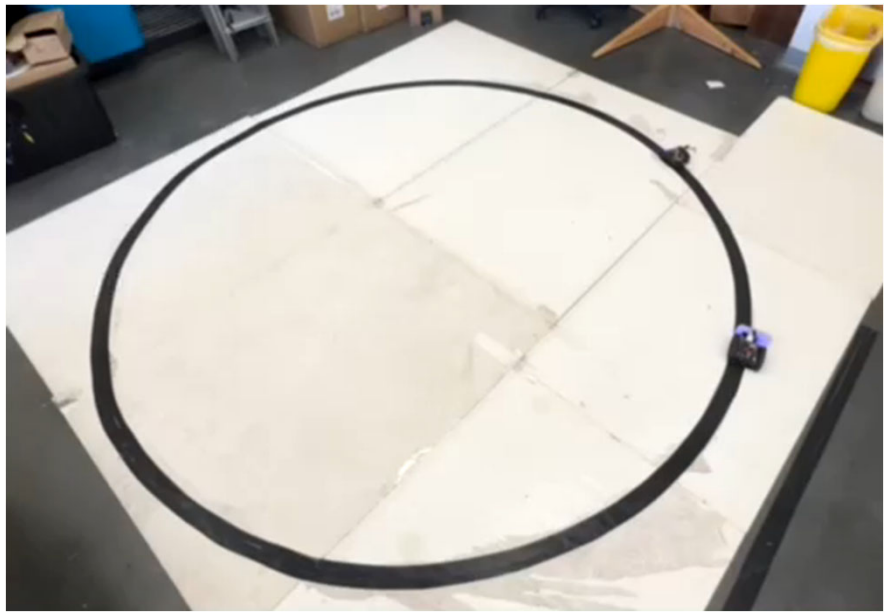
- Model predictive control (MPC) - proactive to future trajectory
- Online reinforcement learning – theoretical speed control to hardware mechanical control; adaptive to varying environment



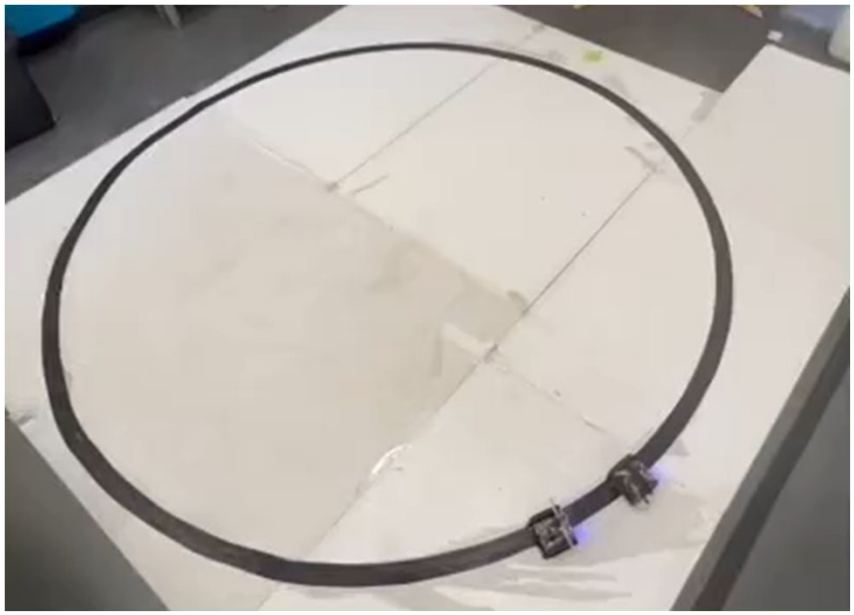
Applications

- Platoon formation & splitting operations

Platoon Formation



Platoon Splitting



Full-Scale Testbed

US DOT CARMA Eco-system

UW-Madison's Efforts

Park Street Smart Corridor

Racine AV Demonstration

Acknowledgements

- Major Collaborators: **Xiaowei (Tom) Shi, Qianwen (Cami) Li,** Ke Ma, Handong Yao, Xiaobo Qu, Amir Ghiasi

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Thank You

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