# Traffic Impacts of Automated Driving Feature – Evidence from Field Experiments

Xiaowei (Tom) Shi, Ph.D.
Assistant Professor

Department of Civil and Environmental Engineering
University of Wisconsin – Milwaukee

Oct $6^{th}$, 2023

UNIVERSITY of WISCONSIN
UWMILWAUKEE | Institute for PHYSICAL INFRASTRUCTURE and TRANSPORTATION

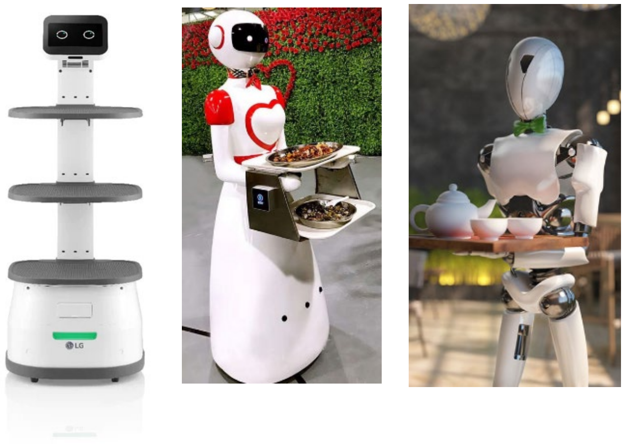
# Rapid Development of AVs


Automated passenger car

Automated transit

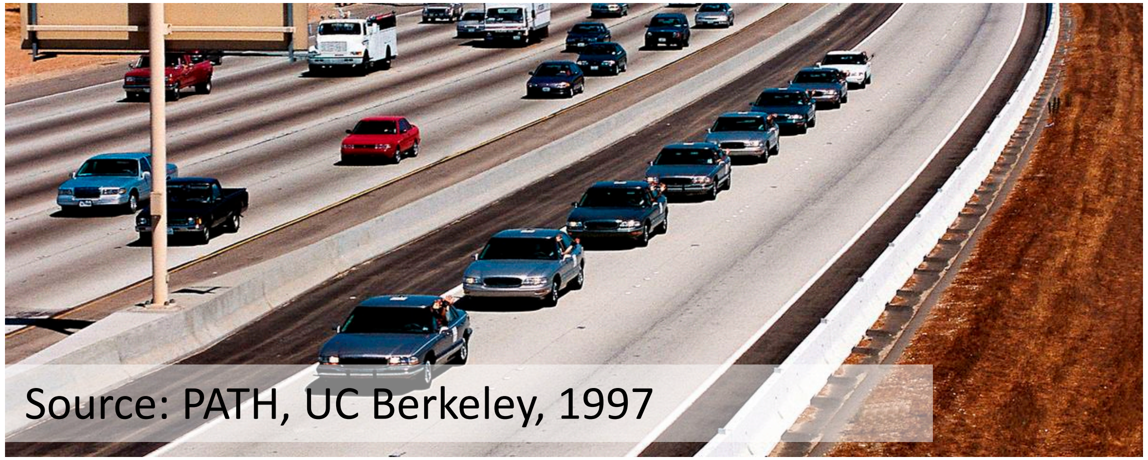
Automated truck


Automated taxi



Food delivery robot!

# High Hopes on AVs




- Mobility: capacity **tripled** (Varaiya, 1993; Ioannou 1997) ; **quadrupled** (Karaaslan, 1990)
- Energy efficiency: save **+25~50%** energy (Vahidi & Sciarretta, 2018)
- Traffic stability: **No** traffic congestion (Chien, 1997).

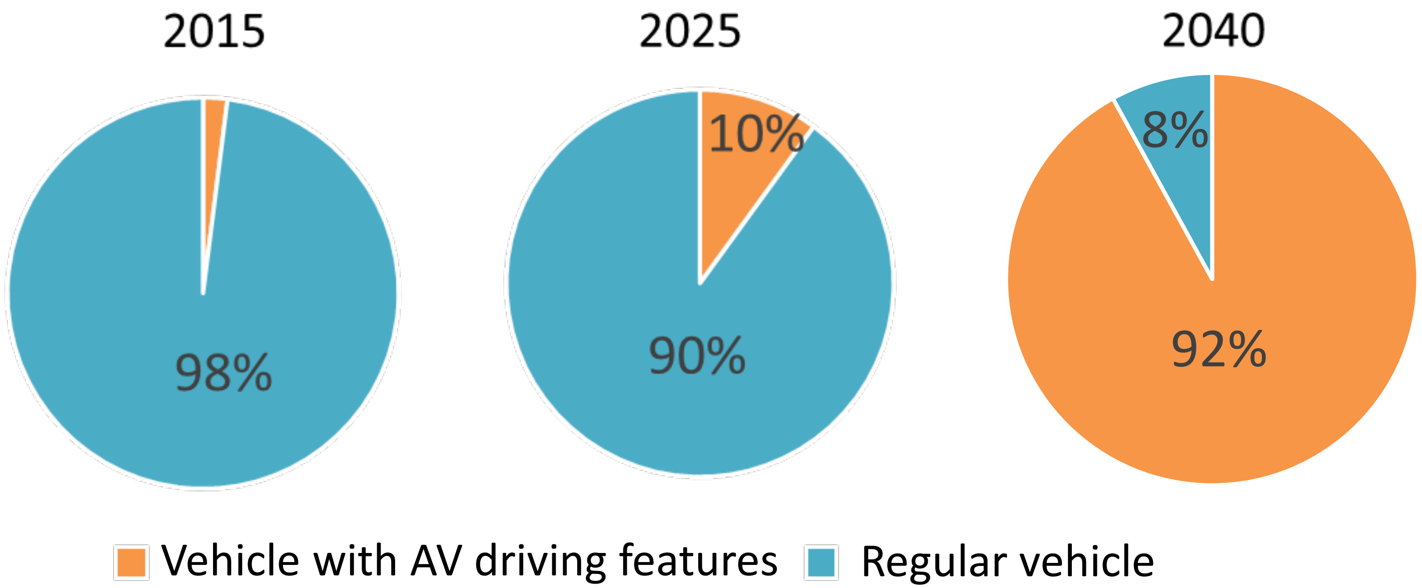
} High Hopes on AVs

Ioannou, P. ed., 1997. Automated highway systems. Springer Science & Business Media.
Vahidi, A. and Sciarretta, A., 2018. Energy saving potentials of connected and automated vehicles. Transportation Research Part C: Emerging Technologies
Shladover, S.E., 2007. PATH at 20—History and major milestones. IEEE Transactions on intelligent transportation systems
Karaaslan, U., Varaiya, P., Walrand, J., 1991. Two proposals to improve freeway traffic flow. Proc. Am. Control Conf.
Chien, C., Zhang, Y., Petros A. L, 1997. Traffic Density Control for Automated Highway Systems. Automatica.

# How Far Are We From the Targets?

❖ Deployment status of AV technologies

- No production AVs yet!
- Only a few premium production vehicles are equipped with AV driving features (i.e., ADAS - Advanced Driver Assistance Systems).
- 2% in 2015 -> 10% in 2025 -> 92% in 2040.
- **Pure AV traffic flow situation still is far from now!**

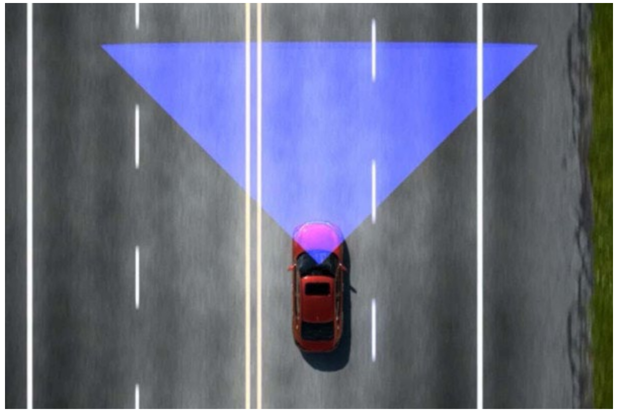


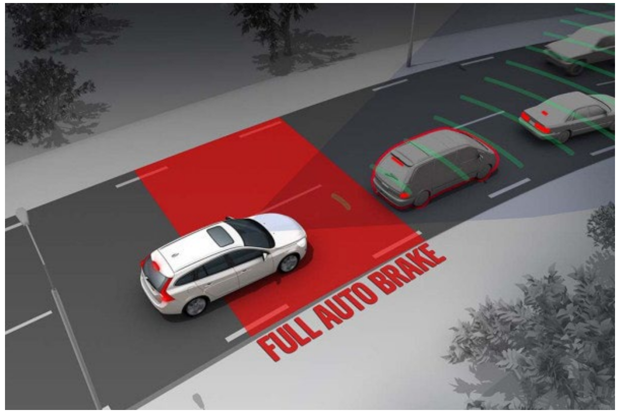

Calvert, S.C., Schakel, W.J., van Lint, J.W.C., 2017. Will automated vehicles negatively impact traffic flow? J. Adv. Transp. 2017.
https://www.consumerreports.org/automotive-technology/how-much-automation-does-your-car-really-have-level-2-a3543419955/

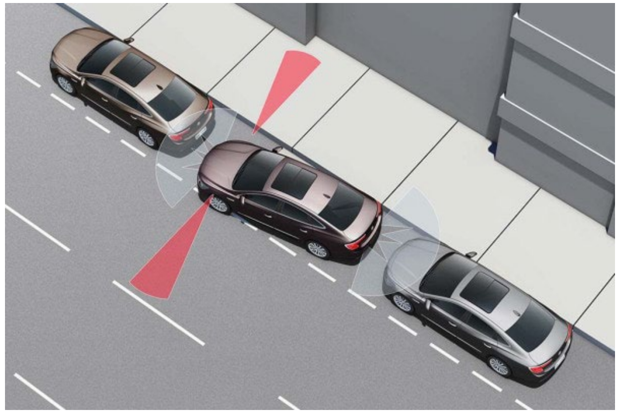
# Can We Still Study the Impacts of AVs?

❖ Advanced AV driving features

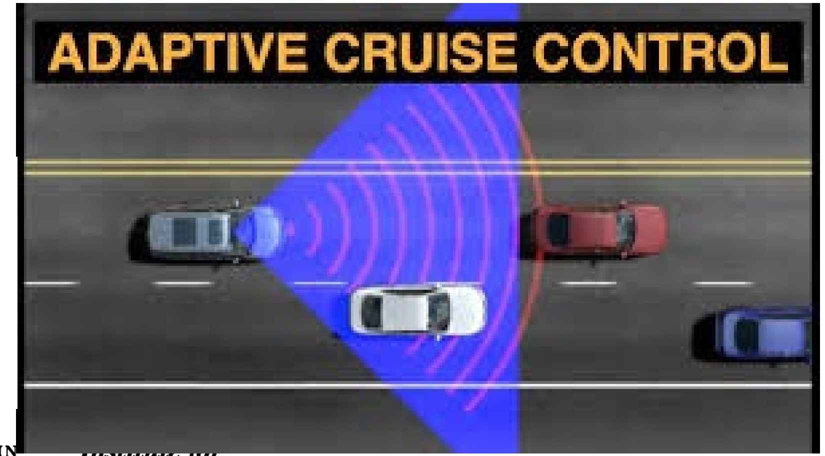
- Lane keeping, emergency braking, automatic parking, etc.
- **Longitudinal – adaptive cruise control (ACC) system (Automation L1 - L5)**



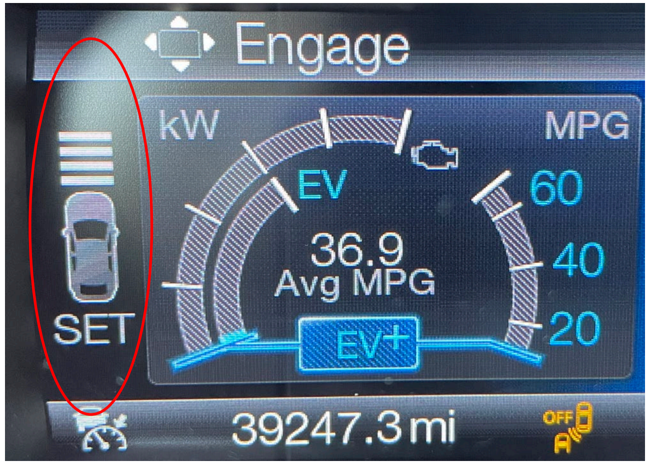


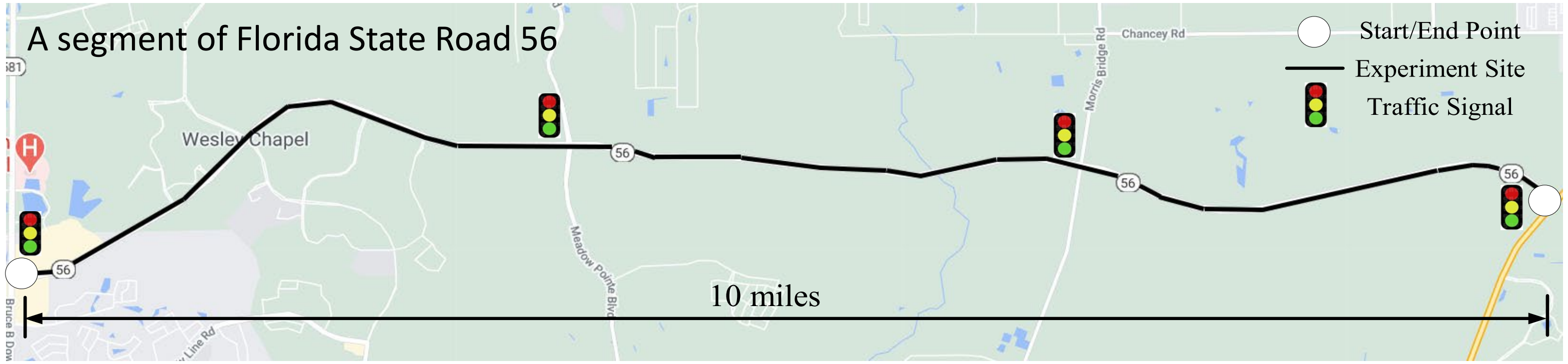
Millimeter-wave Radar

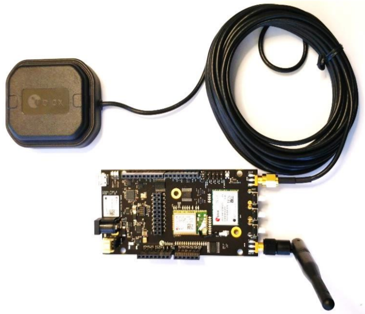


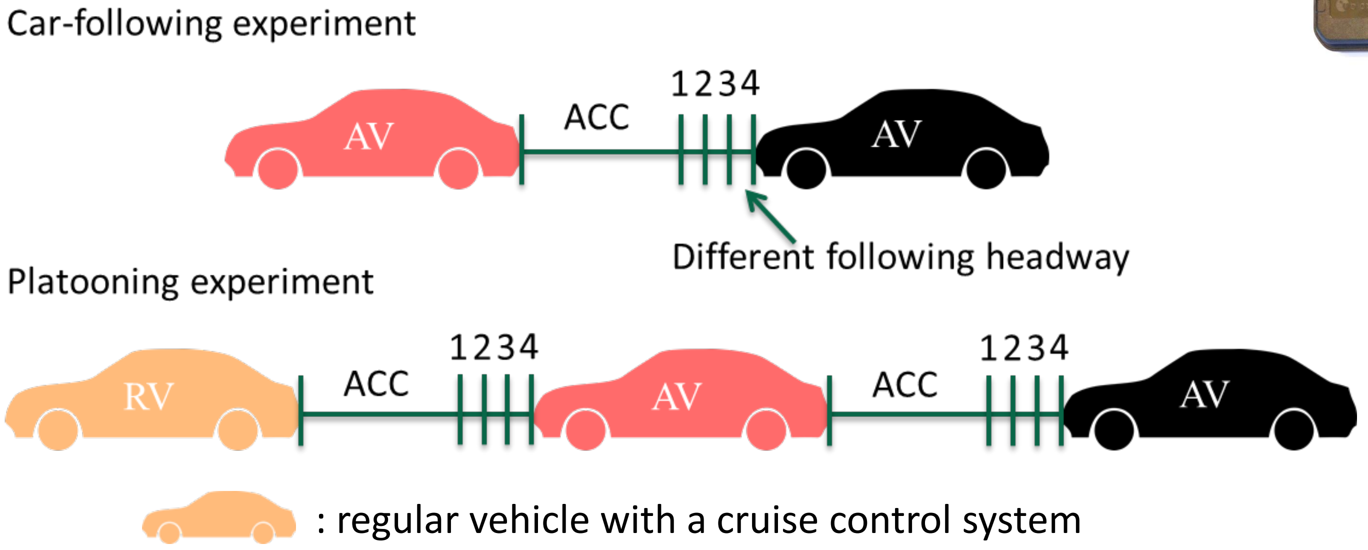




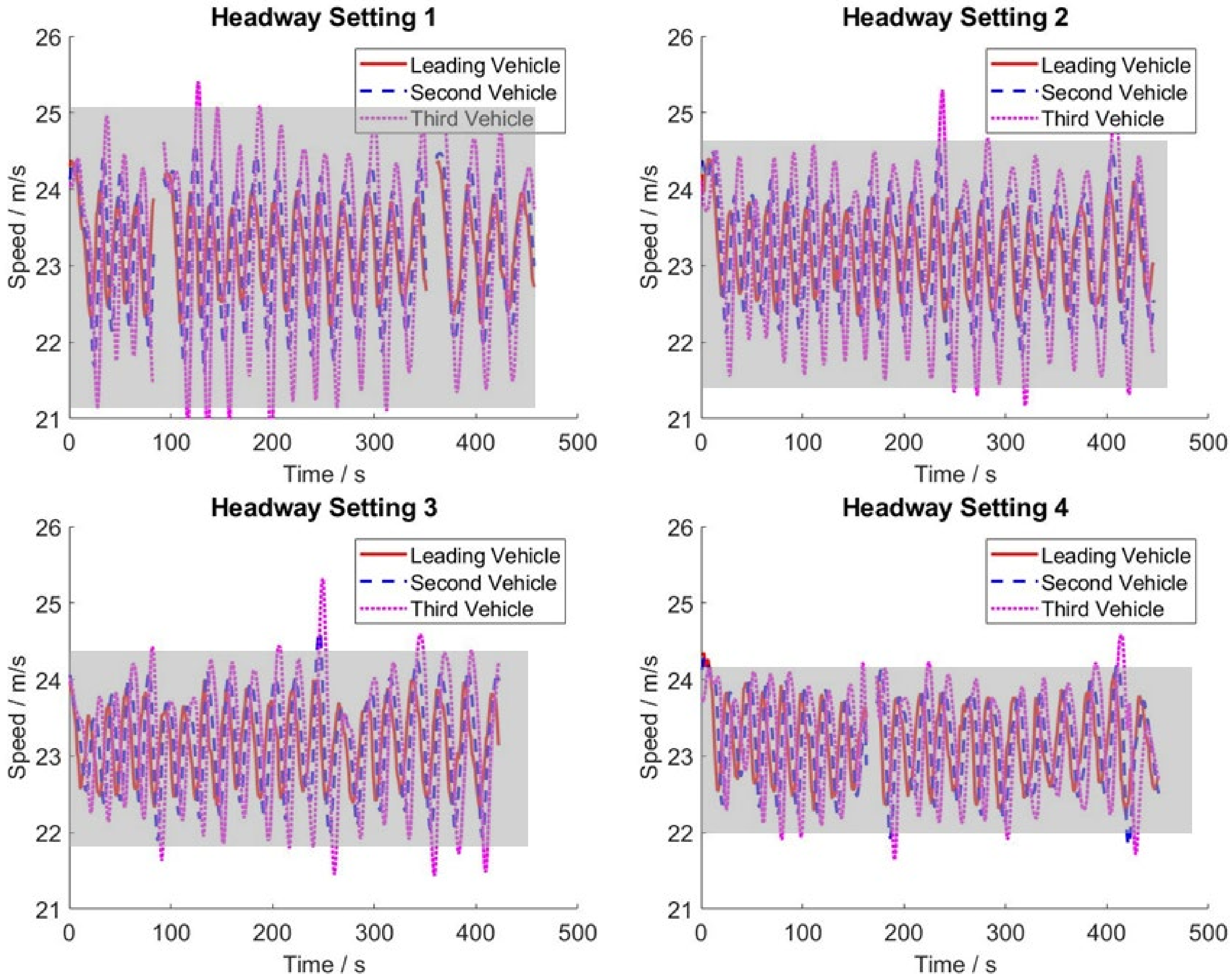
# ACC Trajectory Data Collection





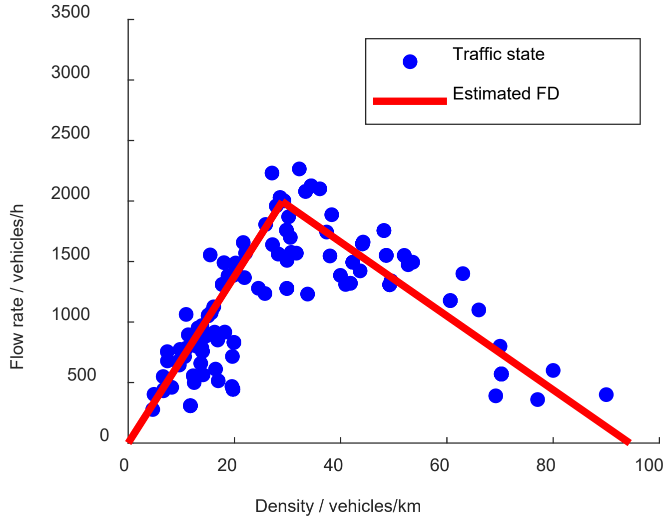
# ACC Trajectory Data Illustrations



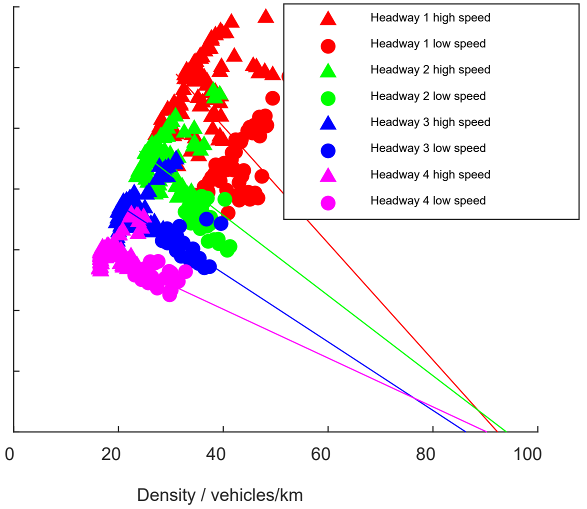

Headway setting ↑,
speed variation range ↓

# Deployed Technology - Mobility

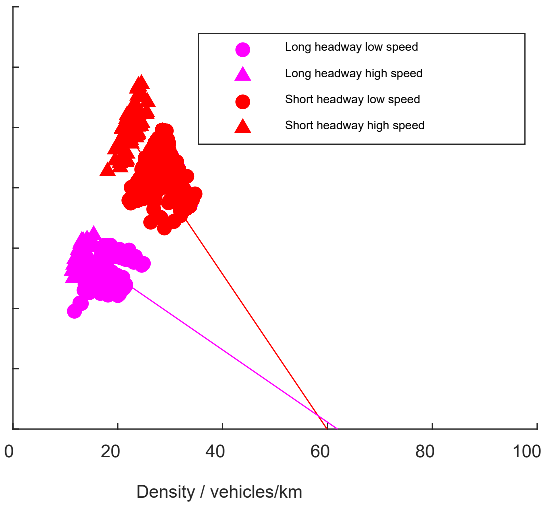
- HV benchmark fundamental diagram
- **Comparable** or **even smaller** capacity, depending on the customized headway settings




Human-driven Vehicles (HVs)




ACC Automaker 1



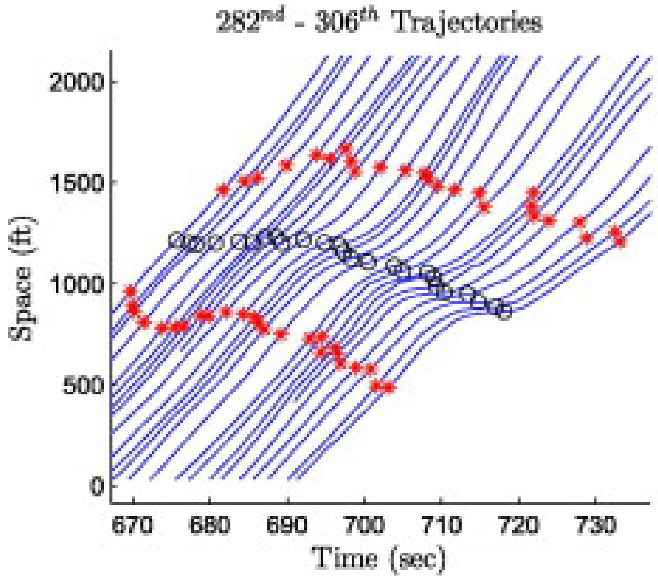

ACC Automaker 2

**Far from the target: multiply capacity by two to three times!**

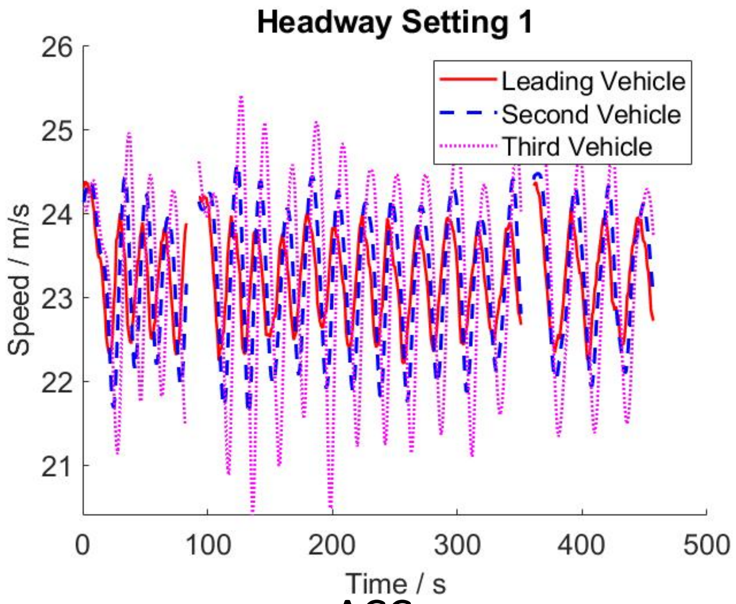
Shi, X. and Li, X., 2021. Constructing Fundamental Diagram for Traffic Flow with Automated Vehicles: Methodology and Demonstration. Transportation Research Part B.

# Deployed Technology - Energy

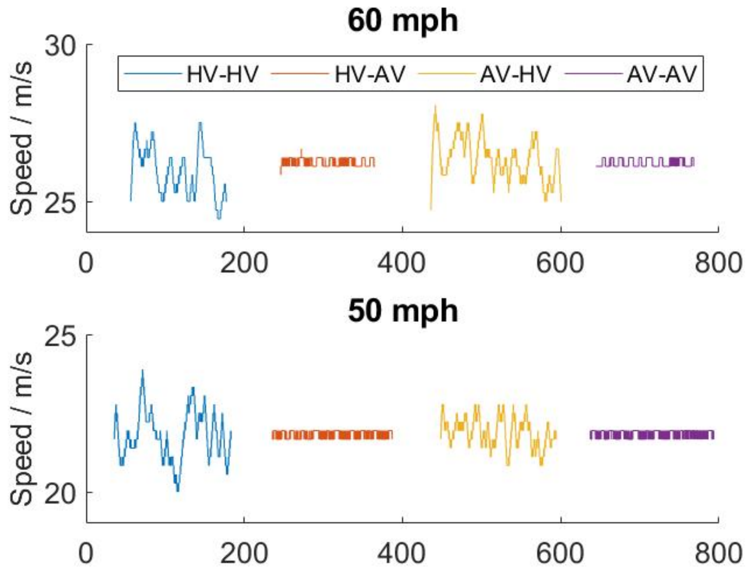
- **Acceleration/deceleration** requires **more energy** than **constant speed**
- String unstable traffic (stop-and-go traffic) -> traffic oscillation amplification
- ACC also amplifies oscillation




HV




ACC




**Only slightly better than HV, remains room for improvement!**

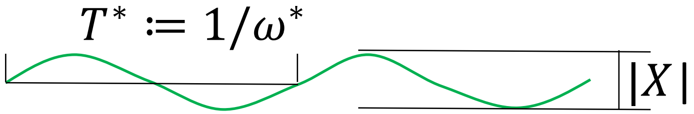
Shi, X., Yao, H. Liang, Z. & Li, X. 2022. An Empirical Study on Fuel Consumption of Commercial Automated Vehicles. Transportation Research Part D

# Deployed Technology - Stability

Transfer function: $TF(\omega) := \frac{Y(j\omega)}{X(j\omega)} = \frac{\kappa}{-\omega^2 + \kappa + i\kappa\tau\omega}, \forall \omega \in \mathbb{R}^+$

| | $k\tau^2$ | $w^*$ | Stability | $T^*$ (s) |
|---|---|---|---|---|
| **High Speed-Headway Setting 1** | 0.07 | 0.31 | Unstable | 19.99 |
| **High Speed-Headway Setting 2** | 0.15 | 0.31 | Unstable | 20.58 |
| **High Speed-Headway Setting 3** | 0.24 | 0.29 | Unstable | 22.04 |
| **High Speed-Headway Setting 4** | 0.35 | 0.25 | Unstable | 25.39 |
| **Low Speed-Headway Setting 1** | 0.07 | 0.34 | Unstable | 18.62 |
| **Low Speed-Headway Setting 2** | 0.11 | 0.29 | Unstable | 21.78 |
| **Low Speed-Headway Setting 3** | 0.19 | 0.28 | Unstable | 22.77 |
| **Low Speed-Headway Setting 4** | 0.37 | 0.26 | Unstable | 23.90 |

All estimated ACC models are **string unstable -> Traffic congestion**




Although ACC is string unstable, **time lag ($\tau$) ↑**,
**the ACC traffic stability ↑** in terms of the **oscillation cycle time** and **speed variation** (verified with both theoretical analysis and field experiments).

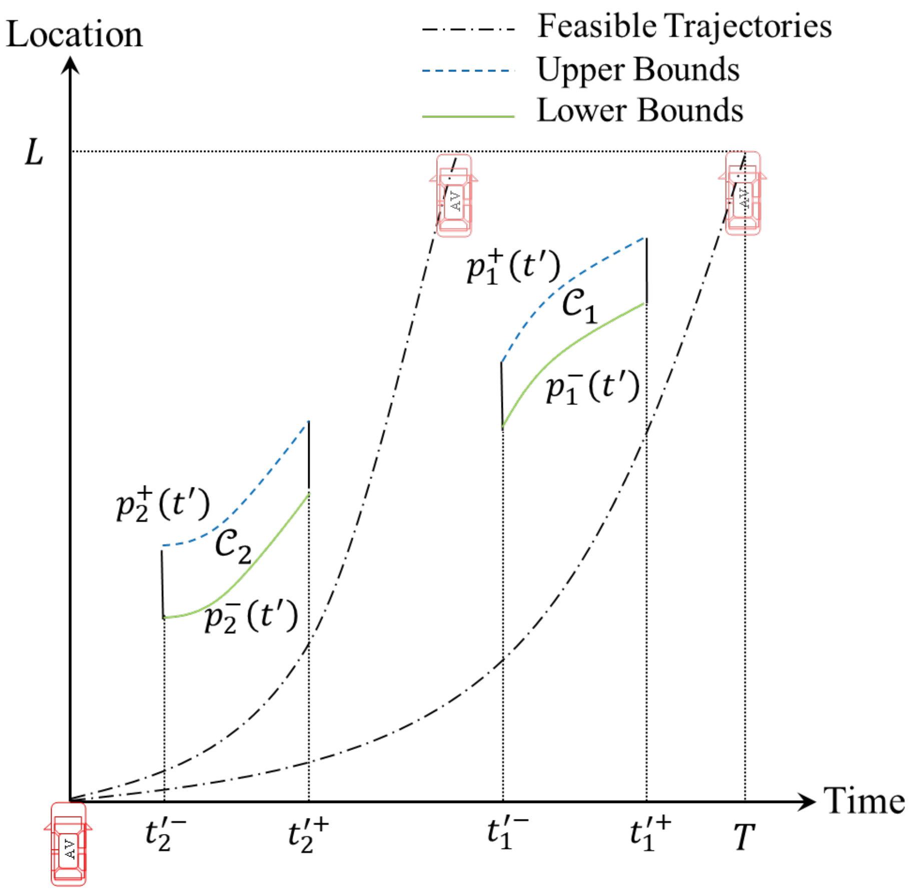
# ACC System Design

| Studied design | | | Minimum headway | | | String stable headway | | |
|---|---|---|---|---|---|---|---|---|
| $\Delta$ (m) | $\tau$ (s) | $g$ (s) | $\Delta^*$ (m) | $\tau^*$ (s) | $g^*$ (s) | $\underline{\Delta}$ (m) | $\underline{\tau}$ (s) | $\underline{g}$ (s) |
| 4.83 | 0.83 | 1.02 | 5.43 | 0.24 | 0.46 | 0.59 | 4.47 | 4.50 |
| 4.40 | 1.21 | 1.38 | 5.43 | 0.24 | 0.46 | 1.10 | 4.47 | 4.52 |
| 3.31 | 1.61 | 1.74 | 5.87 | 0.26 | 0.50 | 1.69 | 4.71 | 4.78 |
| 0.66 | 2.17 | 2.20 | 7.42 | 0.30 | 0.60 | 2.38 | 5.35 | 5.44 |
| 7.28 | 0.79 | 1.24 | 3.81 | 0.26 | 0.51 | 0.72 | 4.08 | 4.13 |
| 6.36 | 1.14 | 1.54 | 4.76 | 0.32 | 0.63 | 1.06 | 4.71 | 4.78 |
| 5.92 | 1.52 | 1.89 | 5.35 | 0.34 | 0.69 | 1.54 | 5.00 | 5.10 |
| 4.97 | 2.09 | 2.40 | 5.20 | 0.34 | 0.68 | 1.72 | 5.00 | 5.11 |

A string stable ACC design will significantly **degrade driving experience**!
Current ACC controller needs to be **further improved**!

**It is our job to make the traffic better!!!**

# Advanced ACC Design




AV trajectory planning (controller design)

Trajectory $x_t$ is subject to the following constraints:

$x_0 = 0,$
$v_0 = \mathcal{v},$
$a_0 = \mathcal{a},$
Initial States

$x_{\mathbb{T}} \geq L,$
Final States

$0 \leq v_t \leq \bar{v}, \forall t \in \mathcal{T},$
$\underline{a} \leq a_t \leq \bar{a}, \forall t \in \mathcal{T},$
Kinetic Limits

$v_t = (x_t - x_{t-1})/\theta, \forall t \in \mathcal{T}\setminus\{0\},$
$a_t = (v_t - v_{t-1})/\theta, \forall t \in \mathcal{T}\setminus\{0,1\},$
Dynamics

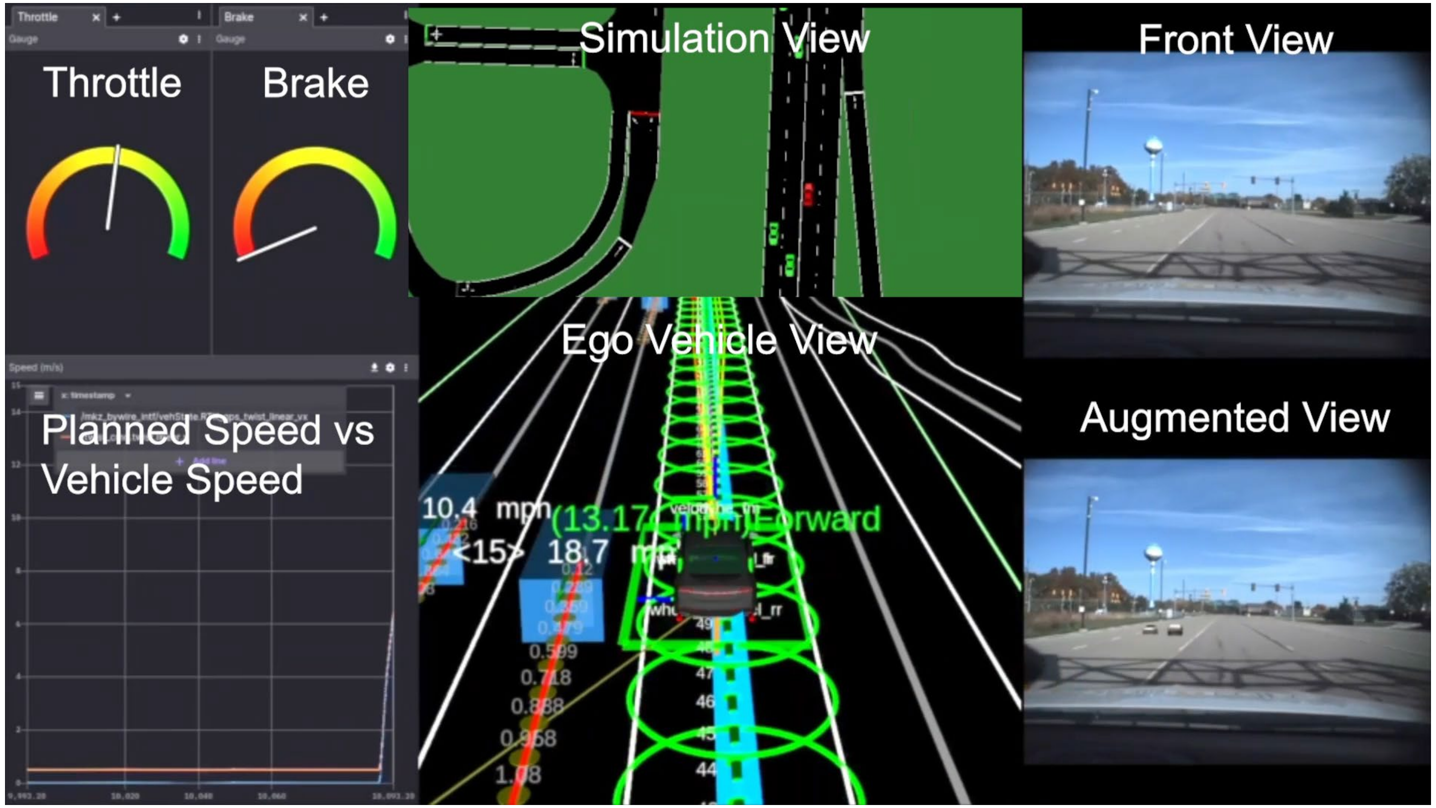
$x_t \leq p_{n,t}^- \text{ or } x_t \geq p_{n,t}^+, \forall t \in \{t_n^-, \cdots, t_n^+\}, n \in \mathcal{N}^o.$ **Safety**

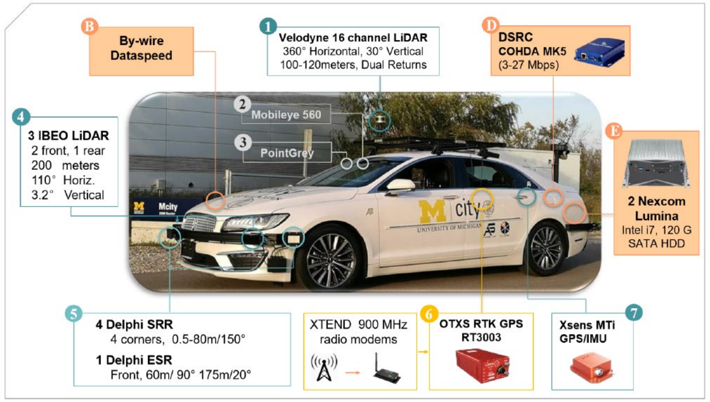
Objective: $\min_{x_t, v_t, a_t} \sum_{t \in \mathcal{T}\setminus\{0\}} (|a_t - a_{t-1}| - w x_t)$ **Mobility & Energy**

**Mixed integer non-linear programming framework!**

# Full-Scale AV Verification

- **Mixed reality platform (hardware-in-the-loop)** - enables the interactions between the simulated traffic and real-world AVs.
- Implement the developed AV trajectory planning algorithm to AVs.




| | ACC | **Proposed** |
|---|---|---|
| Safety | ↓80%~90% | **comparable** |
| Mobility | ↓20%~↑150% | **↑193%** |
| Energy | ↓10% | **↓37%** |

# Acknowledgements


- **Collaborators**

Dr. Xiaopeng (Shaw) Li, Professor, University of Wisconsin-Madison

Dr. Henry Liu, Professor, University of Michigan

Dr. Handong Yao, Assistant Professor, University of Georgia

Zhaohui Liang, Graduate Student, University of Wisconsin-Madison

- **Sponsors**

NSF

U.S. Department of Transportation
Federal Highway Administration

Ford

Department of Energy · United States of America

# Thanks for your time!

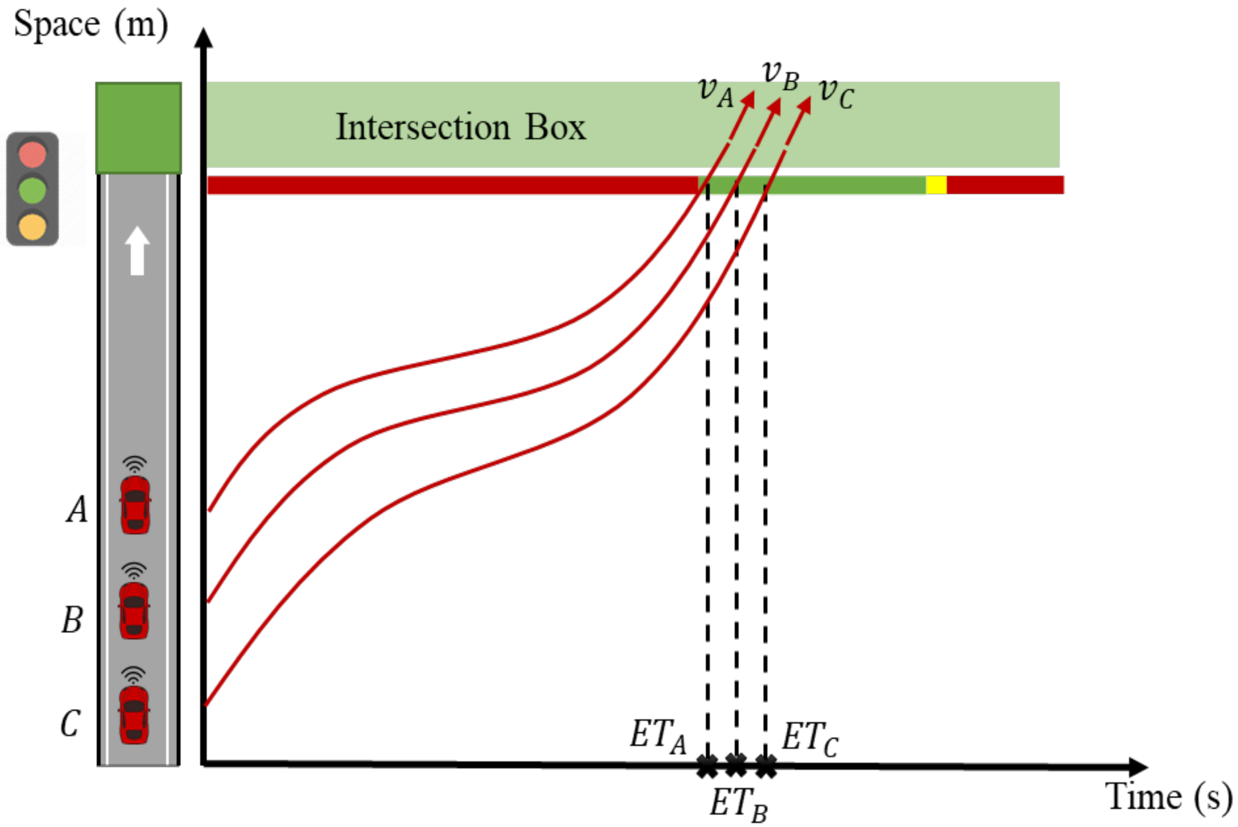
Contact: tomshi@uwm.edu

UNIVERSITY of WISCONSIN
UWMILWAUKEE

*Institute for*
PHYSICAL INFRASTRUCTURE
*and* TRANSPORTATION

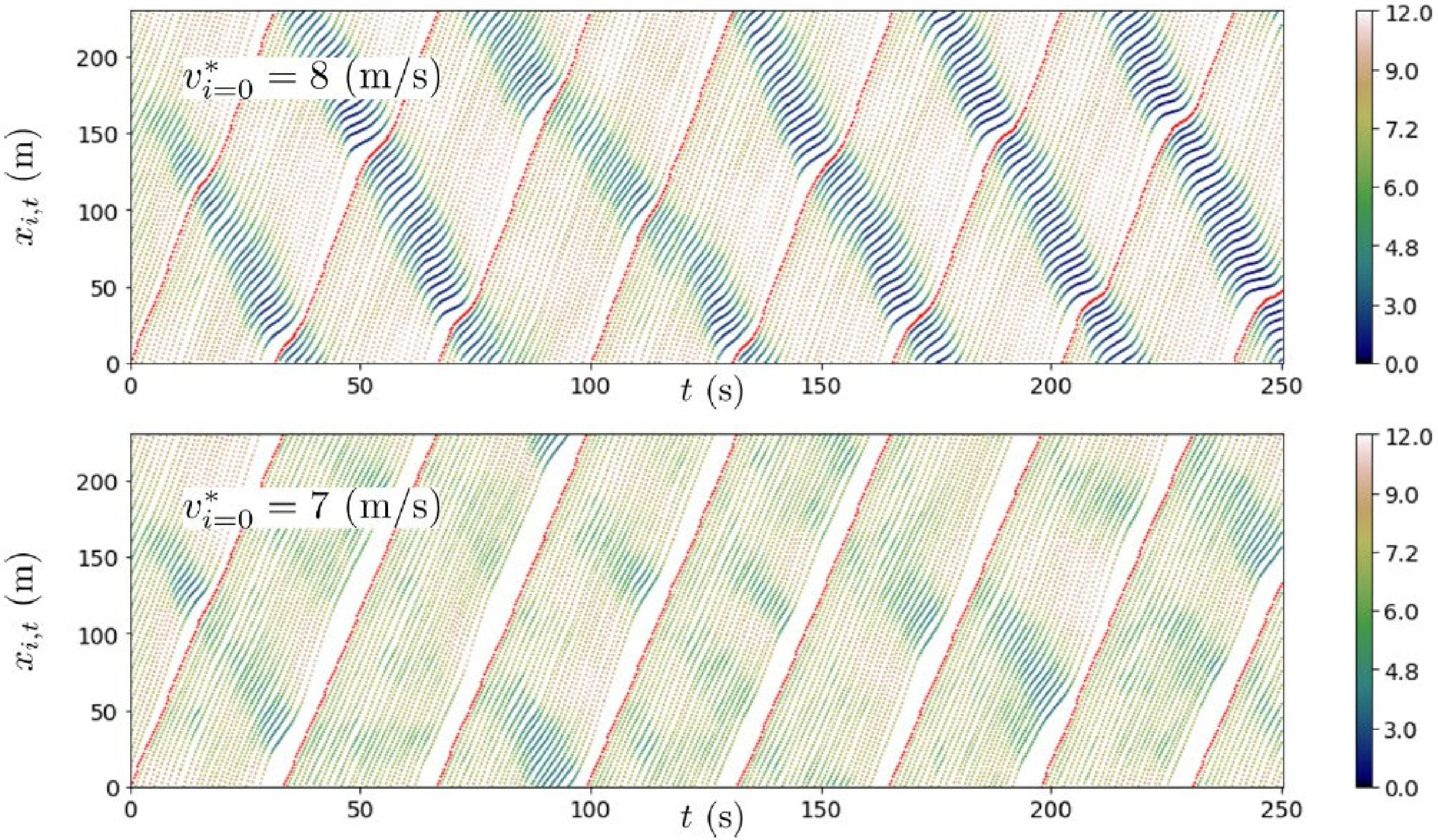
# Development of Vehicle Automation and V2X Communications Technologies


**Multiple AVs trajectory planning** collaborated with **Ford Motor Company**




**GreenWave Speed Advisory** using V2X Communications

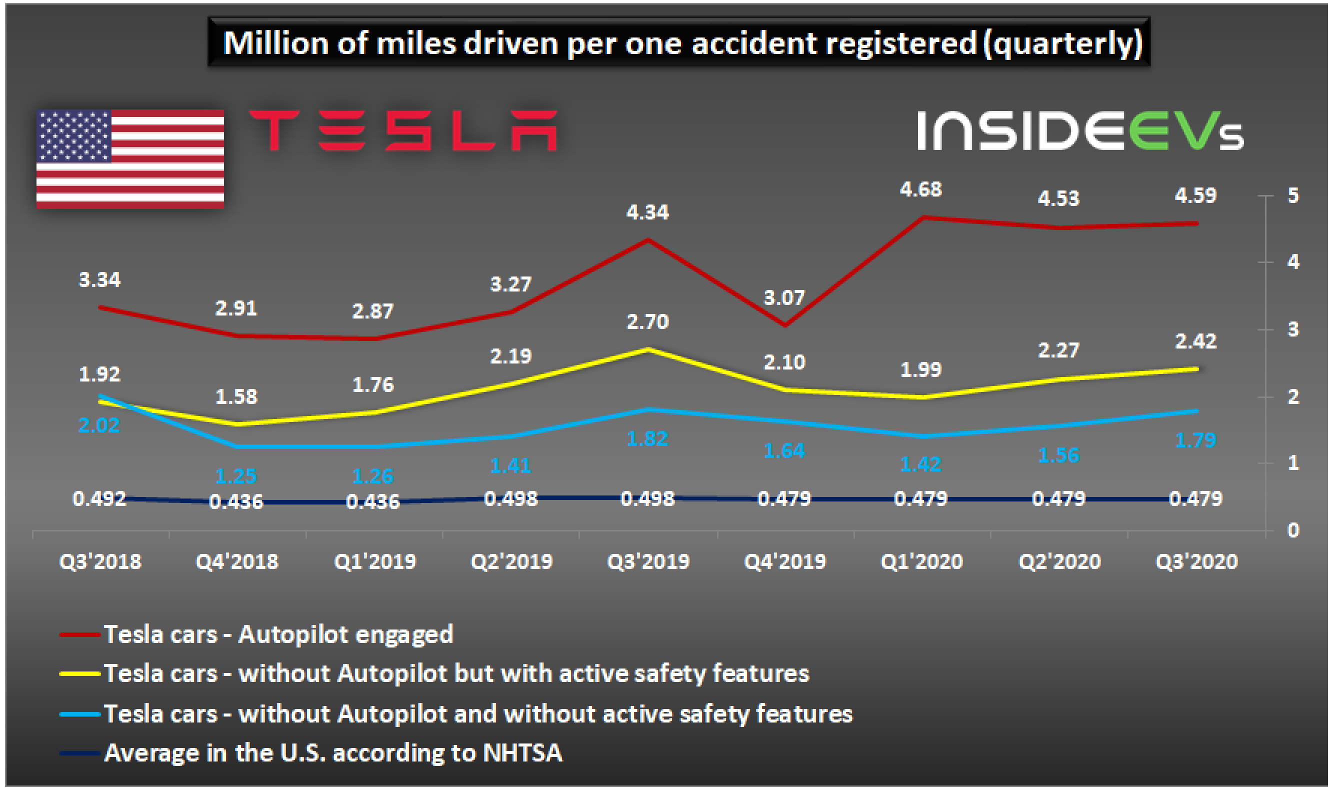
# Shockwave Mitigation Using One Single Vehicle




UNIVERSITY of WISCONSIN
UWMILWAUKEE | Institute for PHYSICAL INFRASTRUCTURE and TRANSPORTATION

# Deployed Technology – ACC Safety

❖ Tesla Autopilot: **-80~90%** crashes




**Close to target: >94% reduction!**