# The Promise of an Efficient and Sustainable Transport System: An Investigation into Automated Vehicles

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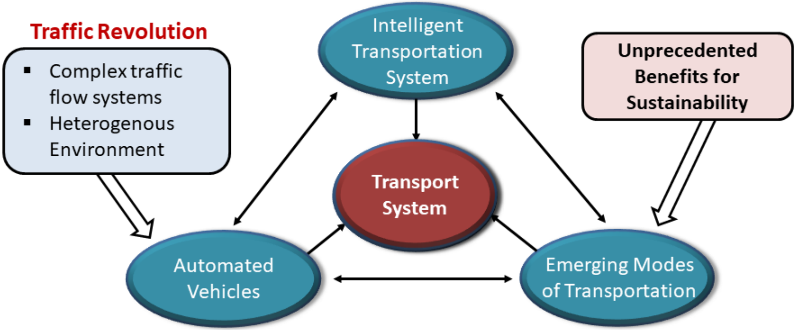
# Outline

1. Motivation and Research Framework
2. Emerging Modes of Transportation: Automated Vehicles
    - Automated Vehicles: Implications on Transportation Operation
    - Automated Vehicles: Adoption Patterns, Competition, and Environmental Implications
3. Conclusions

# Motivation & Research Framework

# The New Transportation System

- New dimensions of complexity is shaping our transport system



# The Transportation Sector: Environmental Insights

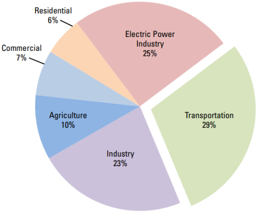


**Figure 1:** Share of U.S GHG Emissions by Sector, 2019 [1]

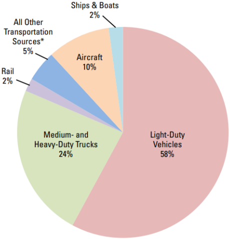


**Figure 2:** Share of U.S. Transportation Sector GHG Emissions by Source, 2019 [1]

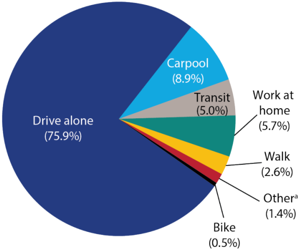
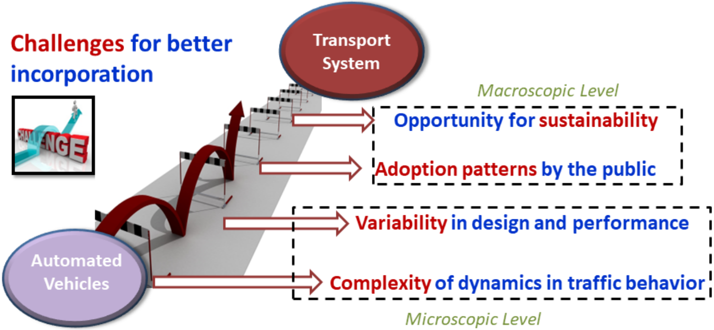


**Figure 3:** Commute share by Mode, 2019 [2]

- Most polluting sector in the US; overtaking the power sector
- On-road vehicles and driving alone are major contributors to transport pollution

# Challenges

- To realize the full potential of automated vehicles and incorporate them into our system, an analysis into their behavior and impacts is needed



# Research Objectives

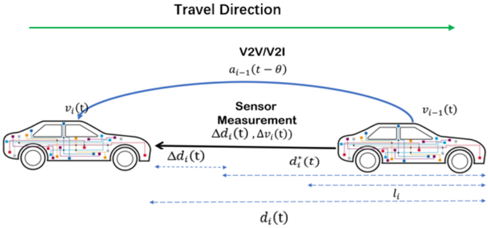
**Overarching Goal**

Guide the design and deployment of Automated Vehicles in ways that are not myopic but consider system-level benefits

# Part 1:

# Automated Vehicles and their Implications on Transportation Operation

# Analysis of Automated Vehicles Behavior



## Automated Vehicle Behavior

1. What governs their behavior logic?
2. How can we translate their driving mechanisms into the traffic-level operational impact

# The Asymmetric Behavioral (AB) Model

## Principal Idea

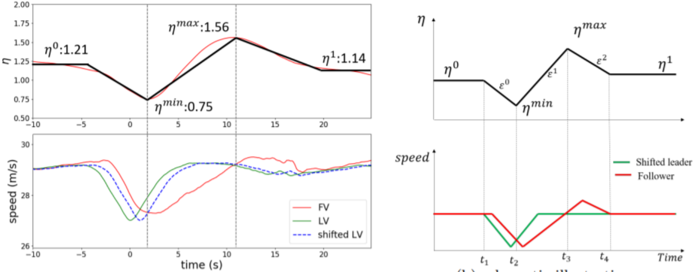
Physics-based car-following model: Vehicle's temporal deviation in time gap ($\tau$) or constant minimum spacing ($\delta$) from its equilibrium position as defined by Newell, expressed through parameter $\eta_i(t)$

$$y_i(t) = y_{i-1}(t - \eta_i(t)\tau) - \eta_i(t)\delta \tag{1}$$

where $y_i$ and $y_{i-1}$ are the positions of vehicle $i$ and its leader $i-1$

$\eta(t)$ : Highlights key aggregate characteristics and trends that influence the disturbance propagation (magnitude, direction and duration of different phases, reaction to the leader trajectory)

# Emperical Analysis on Commercially Available Automation Technologies



(a) observed evolution

(b) schematic illustration

- Reaction patterns of AB model ($\eta(t)$ evolution) can capture main characteristics of controller design and explain the governing physical behavior

# Control Logic of Automated Vehicles

The system state is described by: $\boldsymbol{x}_i(t) = [\Delta d_i(t), \Delta v_i(t), a_i(t)]^T$

- Deviation of actual spacing from equilibrium spacing: $\Delta d_i(t) = d_i(t) - d_i^*(t)$
- Speed difference between leader and follower: $\Delta v_i(t) = v_{i-1}(t) - v_i(t)$
- Acceleration: $a_i(t)$

The control input $u_i(t)$ is then formulated as:

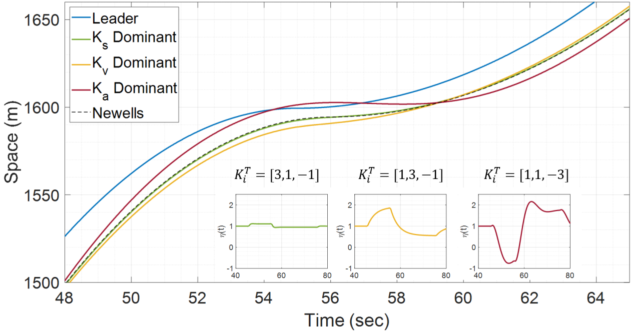
$$\begin{aligned} u_i(t) &= \boldsymbol{K}_i^T \boldsymbol{x}_i(t) \\ \boldsymbol{K}_i^T &= [k_{si}, k_{vi}, k_{ai}] \end{aligned} \tag{2}$$

- $k_s$: Feedback gain for the deviation from equilibrium spacing
- $k_v$: Feedback gain for the speed difference
- $k_a$: Feedback gain for the acceleration

$\boldsymbol{K}_i^T$ denotes the regulation magnitude for each component; **governs the vehicle behavior**

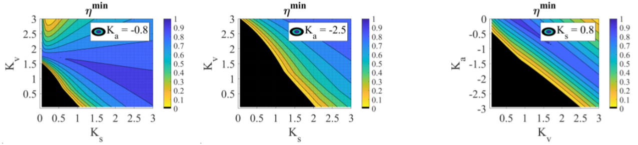
# Analysis of Control Mechanisms and Behavior

How the control logic you design impacts the driving behavior of an AV.

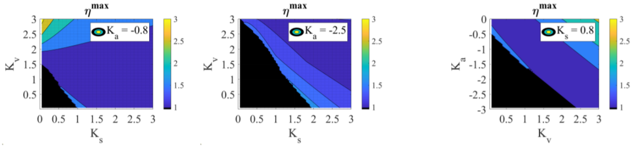


| $K_i$ | Coefficient | Controller Command | Effect of $\lvert k_i\rvert\uparrow$ |
|---|---|---|---|
| $k_s$ | $\Delta d_i(t)$ | Maintain the target spacing | Pushes towards neutral behavior |
| $k_v$ | $\Delta v_i(t)$ | Match the leader's speed | Generates responsive behavior (concave-convex pattern) |
| $k_a$ | $a_i(t)$ | Minimize acceleration | Resists acceleration change (convex-concave pattern) |

# Range of Behavior from an Automated Vehicle



(a) $\eta^{min}$; $K_v$ vs. $K_s$; ($K_a$=-0.8) (b) $\eta^{min}$; $K_v$ vs. $K_s$; ($K_a$=-2.5) (c) $\eta^{min}$; $K_a$ vs. $K_v$



(d) $\eta^{max}$; $K_v$ vs. $K_s$; ($K_a$=-0.8) (e) $\eta^{max}$; $K_v$ vs. $K_s$; ($K_a$=-2.5) (f) $\eta^{max}$ mapping; $K_a$ vs. $K_v$

- There exists a tradeoff between safety, efficiency, and stability from an AV control logic
- A significant commercial ACC vehicles and self-driving systems have undesired traffic-level properties

# Dealing with the Uncertain

### What about real-life operations?

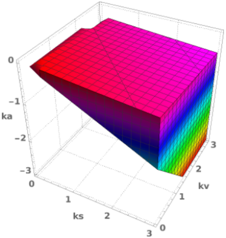
- Discrepancy between desired performance and realized performance from controller given and uncertainty of the physical world
- Stochastic control parameters can affect traffic-level performance of an AV

# Some Stochastic Parameters of Importance

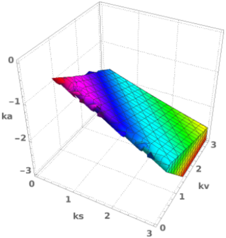
**Lower Level Design: General Longitudinal Vehicle Dynamics**:

$$\dot{a}(t) = \frac{-1}{T_L} a(t) + \frac{K_L}{T_L} u(t) \tag{3}$$

Actuation Lag ($T_L$), $K_L$ (the ratio between demanded and realized acceleration), and response time ($\tau^*$) can significantly shrink the attainable stability region for the AV and can be stochastic in real-time operation:



(a) $[T_L^l, T_L^u] = [0, 0.1]$



(b) $[T_L^l, T_L^u] = [0, 1]$

# Addressing Uncertainties in the Physical World

## Real-time Parameter Estimations using Sensor Data

Gauge the AV car-following performance in real-time and preserve performance against real-time uncertainty that are unaccounted for in the vehicle control algorithm

**Bayesian approach to parameter estimations**

$$\min_{K_L^t, T_L^t} \quad -\left(\log P(K_L^t, T_L^t) + \sum_{i}^{N_{\tilde{t}}} \log P(\dot{a}_i | a_i, u_i, K_L^t, T_L^t)\right) \tag{4}$$

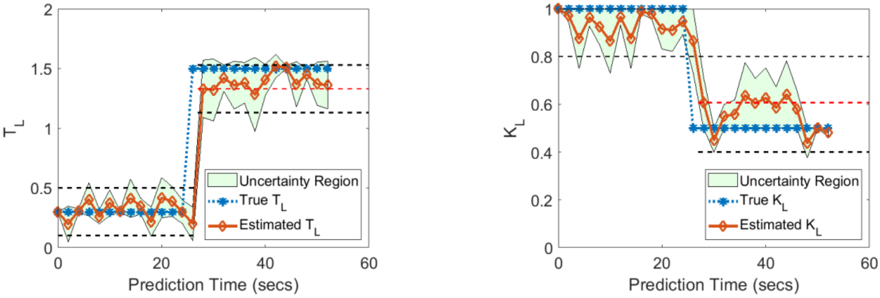
where $\log P(\dot{a}_i | a_i, u_i, K_L^t, T_L^t)$ is written as the log Gaussian likelihood, $-\frac{1}{2}\log\sigma^2 - \frac{1}{2\sigma^2}\left(\dot{a}_i - \dot{a}(t)\right)^2$. Using the log Gaussian likelihood comes with the assumption that $\epsilon(t) \sim \mathcal{N}(0, \sigma^2)$, where $\epsilon(t)$ is the additive error/noise parameter.

**Stochastic Gradient Langevin Dynamics (SGLD) solution**

$$\nabla(K_L^t, T_L^t) = \frac{\eta_t}{2}\left(\nabla \log P(K_L^t, T_L^t) + \frac{N_{\tilde{t}}}{n}\sum_{i=1}^{n} \nabla \log P(\dot{a}_i | a_i, u_i, K_L^t, T_L^t)\right) + \epsilon_t \tag{5}$$

$$\epsilon_t \sim \mathcal{N}(0, \eta_t \boldsymbol{I}) \tag{6}$$

# Real-time Parameter Profiling



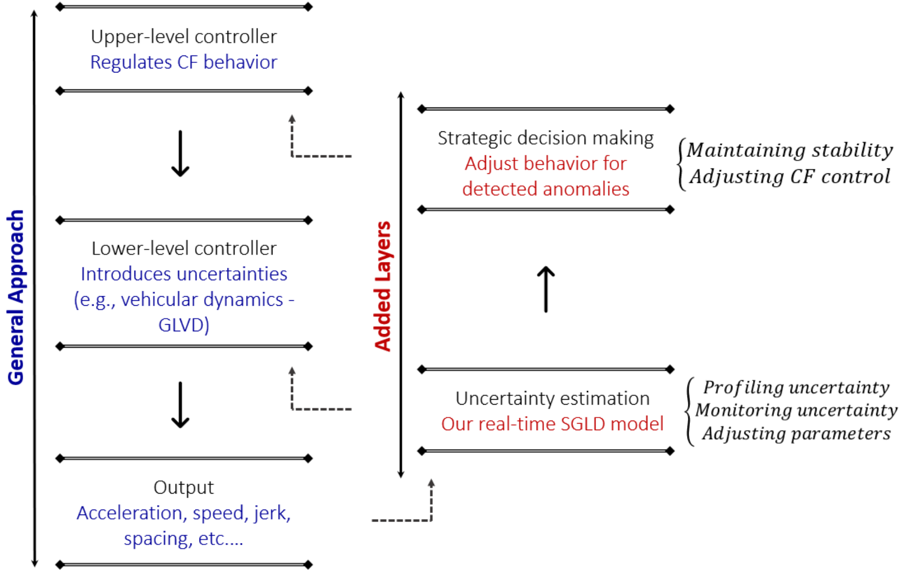
(a) Estimation and monitoring profile of $T_L$

(b) Estimation and monitoring profile of $K_L$

## Estimation Profiles

Use real-time information (sensor data) to detect abnormalities in $T_L$ & $K_L$. This allows for adjusting our knowledge of these parameters in the controller, as well as taking strategic decisions to benefit the stability of traffic.

# The Real-time Strategic Approach



**General Approach**

Upper-level controller
Regulates CF behavior

Lower-level controller
Introduces uncertainties (e.g., vehicular dynamics - GLVD)

Output
Acceleration, speed, jerk, spacing, etc....

**Added Layers**

Strategic decision making
Adjust behavior for detected anomalies

$\begin{cases} \textit{Maintaining stability} \\ \textit{Adjusting CF control} \end{cases}$

Uncertainty estimation
Our real-time SGLD model

$\begin{cases} \textit{Profiling uncertainty} \\ \textit{Monitoring uncertainty} \\ \textit{Adjusting parameters} \end{cases}$

# Part 2:

# Adoption Patterns of Automated Vehicles and their Environmental Implications

# Research Question

**Autonomous Vehicle Adoption**

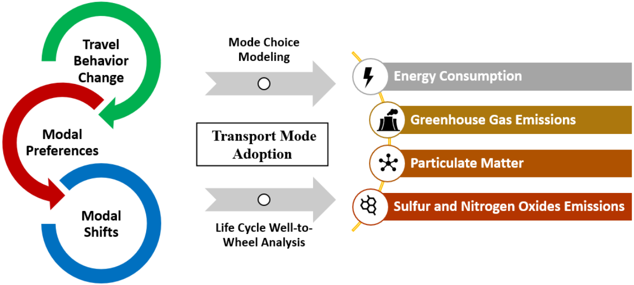
- What are the environmental tradeoffs resulting from the adoption of autonomous vehicles (AVs)?
- If they are available as a mode of transportation, how would their user adoption pattern look like?

# Research Methods

**A. Mode Choice Modeling:** Traveler's probability of choosing a mode of transportation in presence of other modes; informed through survey data

$$\mathcal{P}^n = \int_\beta \frac{e^{\beta_n \mathcal{X}_{ni}}}{\sum_j e^{\beta_n \mathcal{X}_{nj}}} f(\beta, \theta) d\beta \tag{7}$$

**B. Use-Phase Life Cycle Analysis (LCA)**: Quantifying environmental emissions of modes of transportation on a per-mile basis



# Autonomous Vehicle Adoption: Study Results

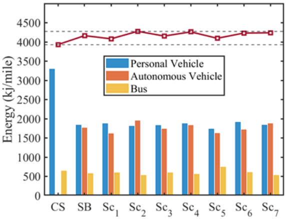
A stated preference survey was deployed to collect data from 805 participants in Madison, Wisconsin.

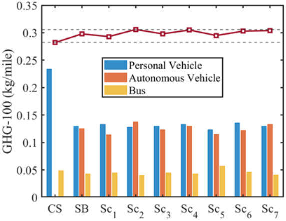
**Major findings:**

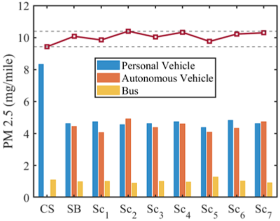
- Autonomous vehicles were a desirable mode of transportation by travelers: reducing ridership of public transport and bicycles (i.e., the bus in Madison)
- Autonomous Vehicles had the lowest estimated value to time (VOT) of (\$16.31/$hr$), as compared to busses (\$26.8/$hr$) and personal vehicles (\$20.4/$hr$).
- Autonomous Vehicle's ability to cut cost, access time, waiting time, and parking where significant contributors to its adoption.

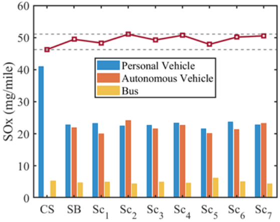
# Autonomous Vehicle Adoption: Study Results

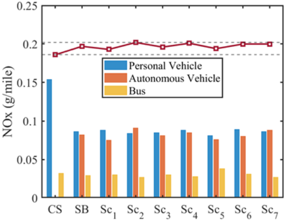
**Environmental Implications of AV's induced modal shifts**: An overall increase in environmental emissions



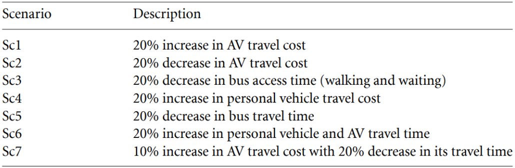




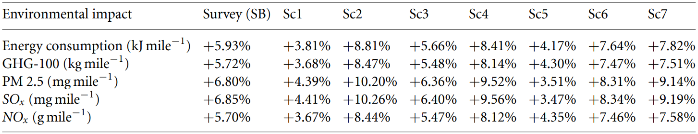




# Environmental Implications of AV's Induced Modal Shifts



| Scenario | Description |
|---|---|
| Sc1 | 20% increase in AV travel cost |
| Sc2 | 20% decrease in AV travel cost |
| Sc3 | 20% decrease in bus access time (walking and waiting) |
| Sc4 | 20% increase in personal vehicle travel cost |
| Sc5 | 20% decrease in bus travel time |
| Sc6 | 20% increase in personal vehicle and AV travel time |
| Sc7 | 10% increase in AV travel cost with 20% decrease in its travel time |

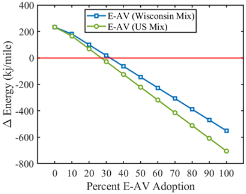


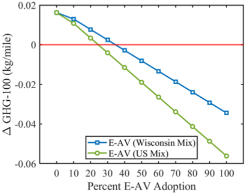
| Environmental impact | Survey (SB) | Sc1 | Sc2 | Sc3 | Sc4 | Sc5 | Sc6 | Sc7 |
|---|---|---|---|---|---|---|---|---|
| Energy consumption (kJ $\text{mile}^{-1}$) | +5.93% | +3.81% | +8.81% | +5.66% | +8.41% | +4.17% | +7.64% | +7.82% |
| GHG-100 (kg $\text{mile}^{-1}$) | +5.72% | +3.68% | +8.47% | +5.48% | +8.14% | +4.30% | +7.47% | +7.51% |
| PM 2.5 (mg $\text{mile}^{-1}$) | +6.80% | +4.39% | +10.20% | +6.36% | +9.52% | +3.51% | +8.31% | +9.14% |
| $SO_x$ (mg $\text{mile}^{-1}$) | +6.85% | +4.41% | +10.26% | +6.40% | +9.56% | +3.47% | +8.34% | +9.19% |
| $NO_x$ (g $\text{mile}^{-1}$) | +5.70% | +3.67% | +8.44% | +5.47% | +8.12% | +4.35% | +7.46% | +7.58% |

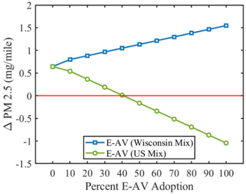
## Environmental Implications:

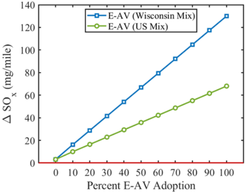
- Adoption of AV's would increase environmental emissions across all categories
- Policies to incentivize public transport usage can reduce impacts of AV adoption; but unable to offset it

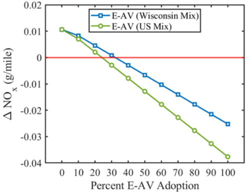
# The Adoption of Electric Autonomous Vehicles







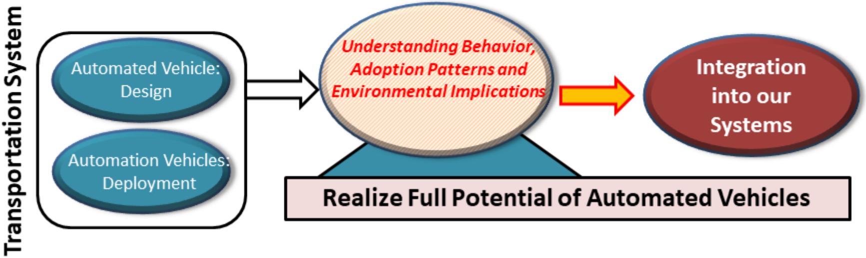




## Electric Autonomous Vehicles adoption

- Can offset the environmental impacts of AV adoption
- Benefits expected are dependent on adoption rates and electricity generation

# Conclusions



Transportation System

Automated Vehicle: Design

Automation Vehicles: Deployment

*Understanding Behavior, Adoption Patterns and Environmental Implications*

**Integration into our Systems**

**Realize Full Potential of Automated Vehicles**

# References I

[1] EPA (2021). Fast facts u.s. transportation sector greenhouse gas emissions 1990-2019.

[2] USDOT (2021). Transportation statistics annual report, 2021. *Bureau of Transportation Statistics*.