Enabling resilient, safe, and secure highway transportation systems in the era of vehicle automation and electrification

CAEM Graduate Seminar

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RESEARCH & PARTNERSHIPS
Data Science Institute

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- Mingfeng Shang
- Jun Zhao

Roots for Resilience

- Tina Johnson
- Michele Cosi
- Jeff Gillan
- Tyson Swetnam
- My cohort
- And all others who contributed to the learning environment

Motivation

What is a *Resilient* Transportation System

- Systems today face increasing uncertainty
  - Inclement weather 🌧️
  - Cyber threats 💻
  - Evolving vehicle technologies 🚙 ⚡
- ***Resilience:***
  - Ability to withstand, adapt, and recover from disruptions
- Achieving this requires data-driven insight into systems

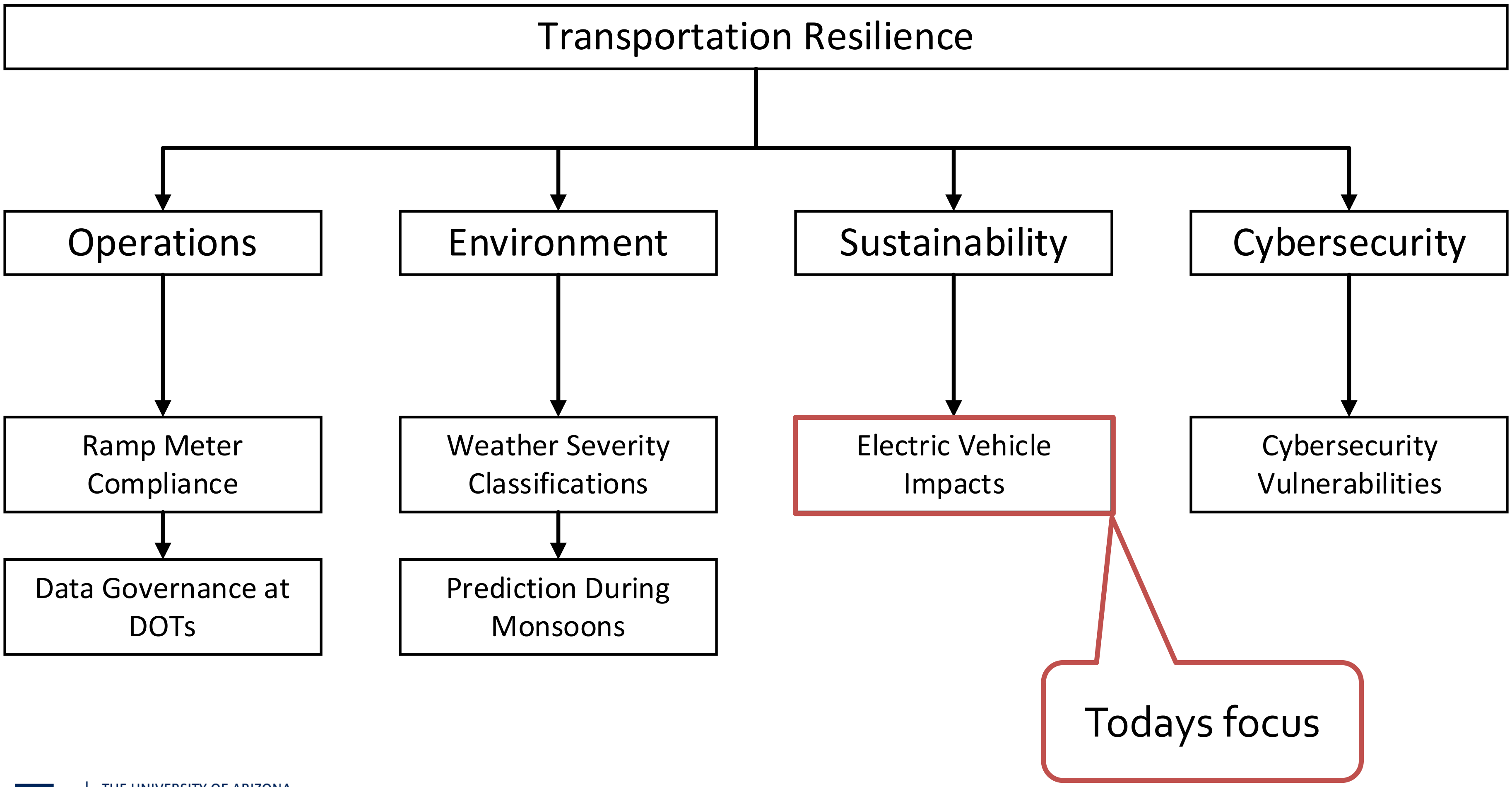
Motivation

Defining Transportation Resilience

- Encompasses multiple dimensions:
  - ***Operational resilience:*** managing incidents, congestion, and data quality
  - ***Environmental resilience:*** weather and climate adaptation
  - ***Cyber resilience:*** protecting connected vehicle networks
  - ***Sustainability resilience:*** long-term efficiency, safety, and environmental balance

My Research

Multi-Dimensional View of Transportation Resilience

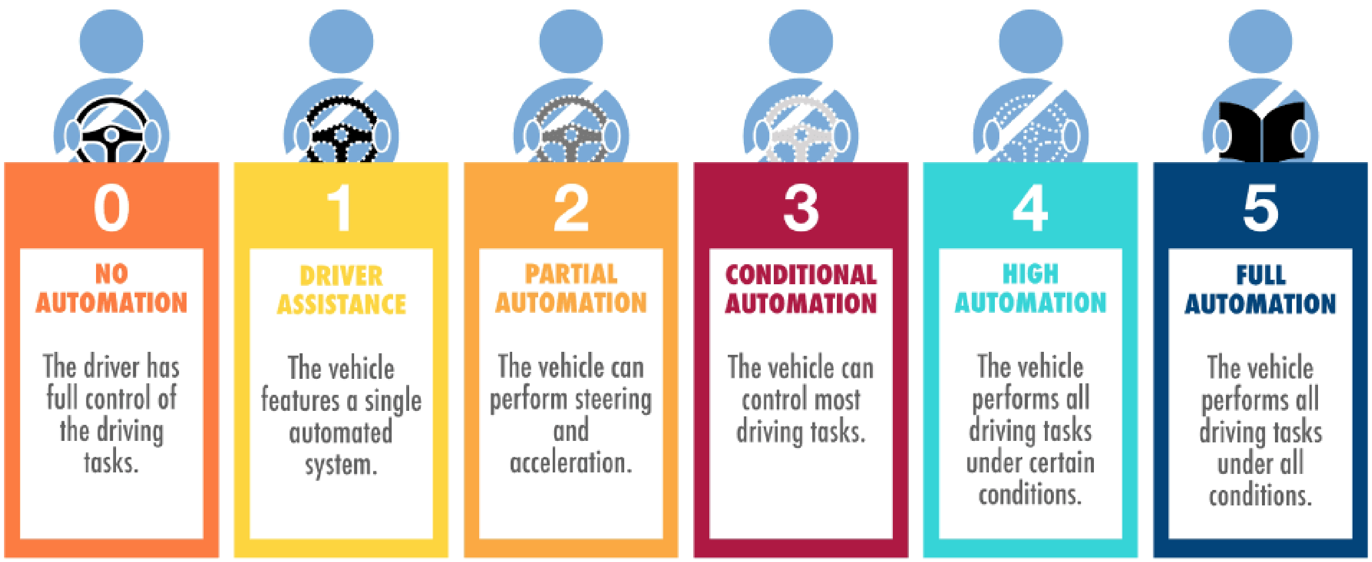


Impacts of Driver-Assistance-Enabled Electric Vehicles on Safety, Mobility, and the Environment: An Empirical Study

Background

Evolution of Vehicle Automation

- SAE defines 5 levels of automation (L1 → L5)
- L5 automation aims for safer, more efficient mobility
- Current commercial vehicles: Levels 1–2 (ACC)
  - Driver supervision still essential



SAE: Society of Automotive Engineers
ACC: Adaptive Cruise Control

Background

Reality of Automation Benefits

- L5 (***fully automated***) projected to:
  - ↑ Throughput
  - ↑ String Stability
  - ↓ Energy Efficiency
- L1–L2 (***ACC-equipped***) may degrade flow:
  - ↓ Throughput
  - ↓ String Stability
  - ↑ Fuel use/emissions

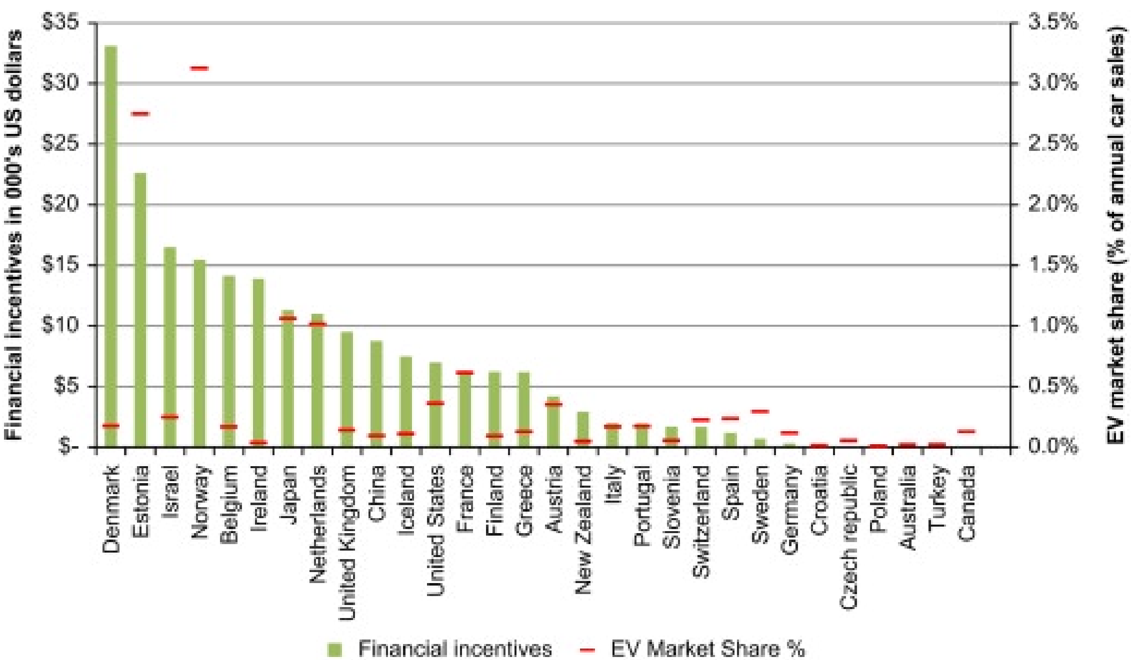
Level	Throughput	String Stability	Energy/Emission
L5	↑	↑	↓
L1-L2	↓	↓	↑

String Stability: the ability of a platoon of vehicles to dampen, not amplify, small speed disturbances

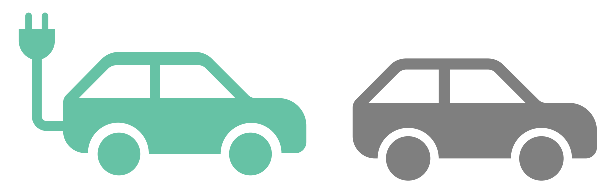
Parallel Trends

Electrification of Transportation

- EVs gaining market share alongside ICEVs
- Many EVs also equipped with ACC systems
- Electrification + automation = new behavioral dynamics



Mixed Traffic



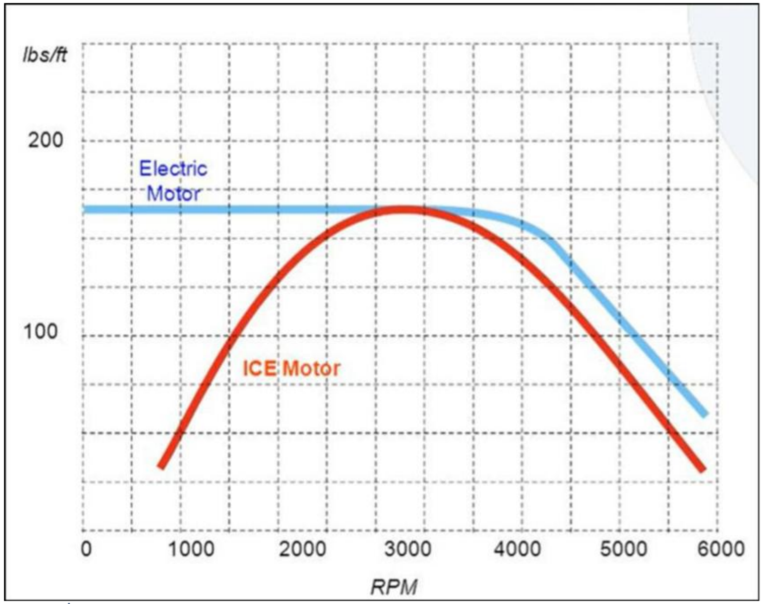
EVs ICEVs

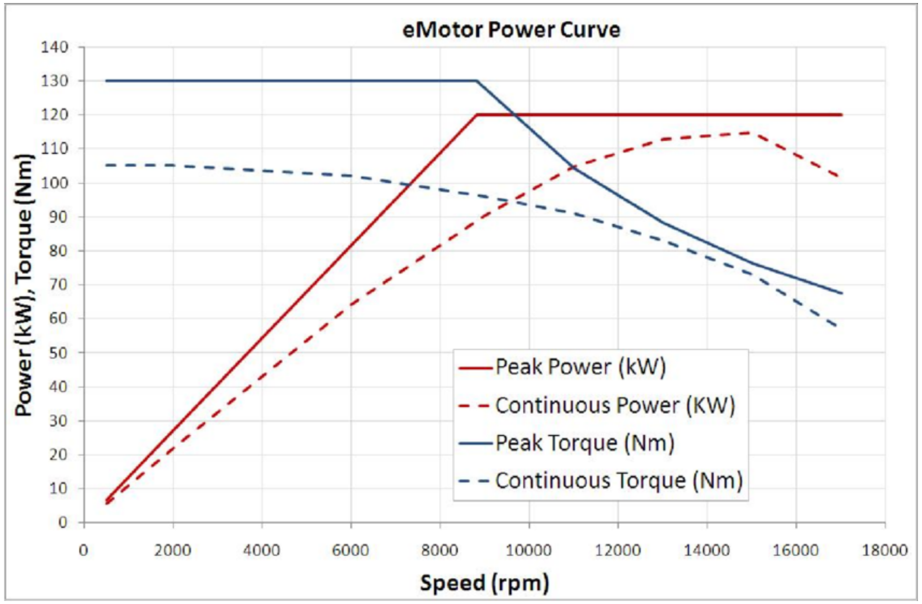
EV: Electric Vehicles
ICEV: Internal Combustion Engine Vehicles

Parallel Trends

Why EVs Behave Differently

- ***Regenerative braking:*** smoother, quicker deceleration
- ***Instant torque:*** faster response to traffic changes
- ***Possible effect:***
  - Potentially different car-following and traffic flow impacts





Extending Prior Research

Building Toward Empirical Validation

- Prior work: understanding of microscopic behaviors
  - acceleration, headway, and speed
- Our research: extends to macroscopic outcomes
  - traffic flow, stability, and emissions
- Earlier studies relied primarily on calibrated simulations
  - (e.g., Zare et al., Aguilar et al.)
- Our contribution: empirical analysis that captures
  - Real-world noise and disturbances
  - Behavioral variability
  - Data-driven validation of automation and electrification effects

Challenges in Empirical Analysis

Scarcity of high-fidelity datasets with both EVs and ICEVs

Datasets often lack consistency or experimental control

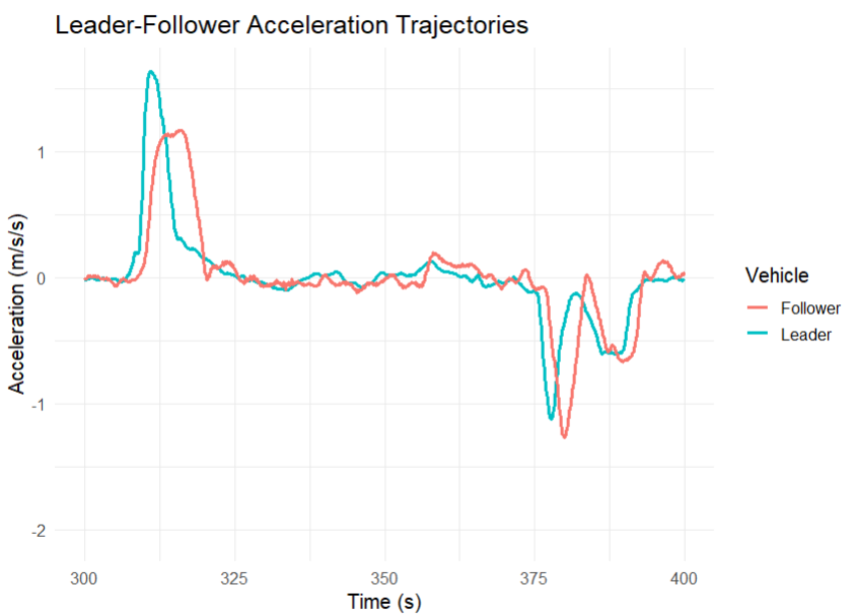
Lead vehicle trajectory control is a major issue

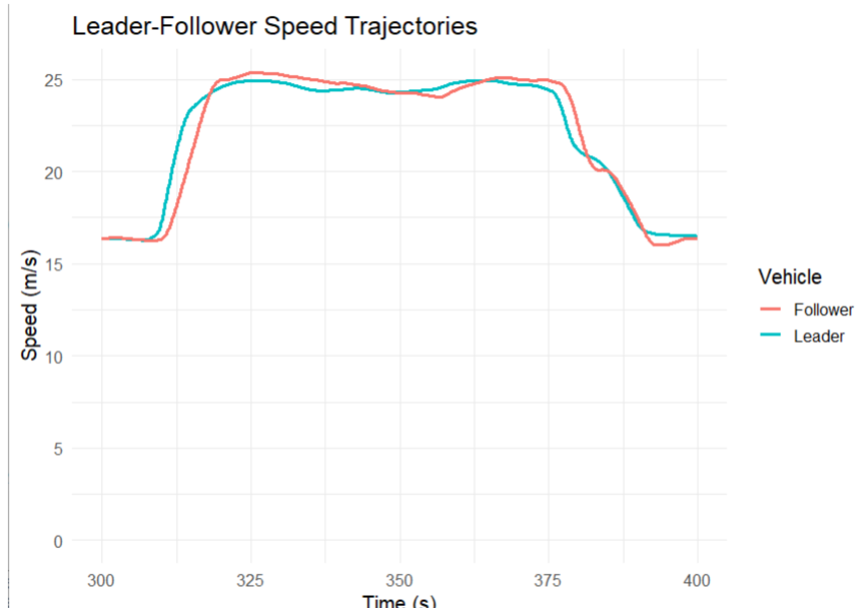
Without comparable scenarios, analysis becomes unreliable

Overcoming Challenges

The OpenACC Dataset

- Includes both EVs and ICEVs under consistent conditions
- Diverse range of ACC-equipped vehicles
- High-resolution data for analyzing car-following and flow
- Widely validated in autonomous driving studies





Applying R4R Concepts

Open Science & Open Data

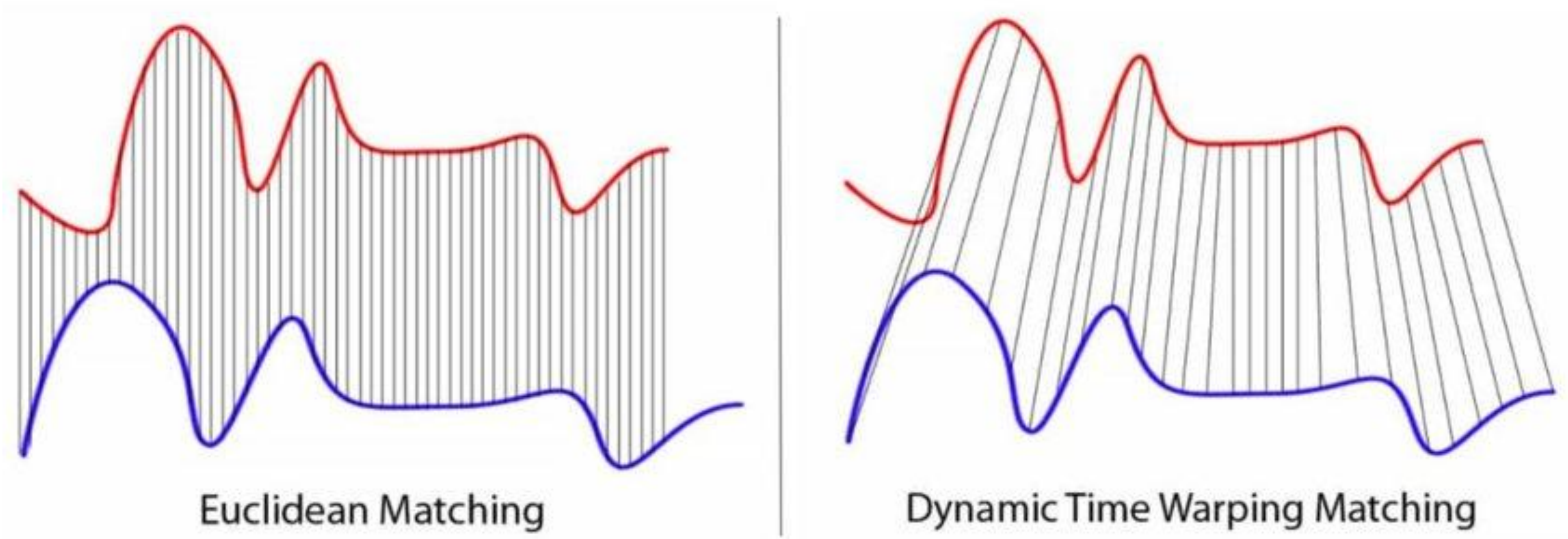
- Used an openly available dataset (OpenACC) to support transparent and reproducible analysis
- Followed open science practices learned in R4R:
  - Data documentation
  - Licensing awareness
  - Ethical reuse

- Annotated the dataset and data management workflows
- Prepared analysis outputs for open sharing

Overcoming Challenges

Ensuring Fair Comparisons

- DTW: time-series alignment technique
- Matches sequences with varying speed or duration
- Ensures equivalent car-following conditions for comparison
- Supports rigorous EV vs. ICEV behavioral analysis



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DTW: Dynamic Time Warping

Applying R4R Concepts

Reproducibility Through Conda & Documentation

- Managed analysis scripts with Git/GitHub to track code evolution and ensure reproducibility
- Used a Conda environment to maintain consistent package versions for DTW and emissions modeling
- Documented processing steps for transparent, open workflows
- Ensured analysis can be re-run on another machine

Motivation

Study Contributions

Empirical analysis using real-world OpenACC dataset, not simulations

Framework for evaluating safety, efficiency, and sustainability impacts

DTW-based method for trajectory matching to ensure robust comparisons

A Framework for Empirical Analysis

Analytical Framework

Linking Efficiency, Safety, and Environment

Roadway safety: collision risk under mixed traffic

- Time-to-Collision
- Deceleration Required to Avoid Crash

Traffic efficiency: smoothness and stability of flow

- Average Speed Variation
- Velocity-Spacing Curves

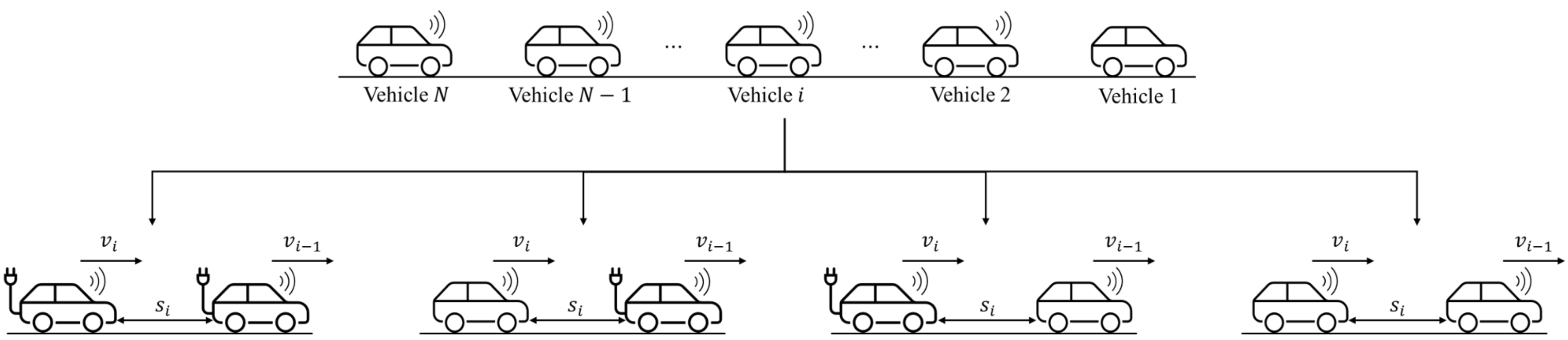
Environmental impact: indirect impacts of traffic smoothness

- Fuel Consumption
- Emissions

Processing Trajectory Data

Platoon Decomposition

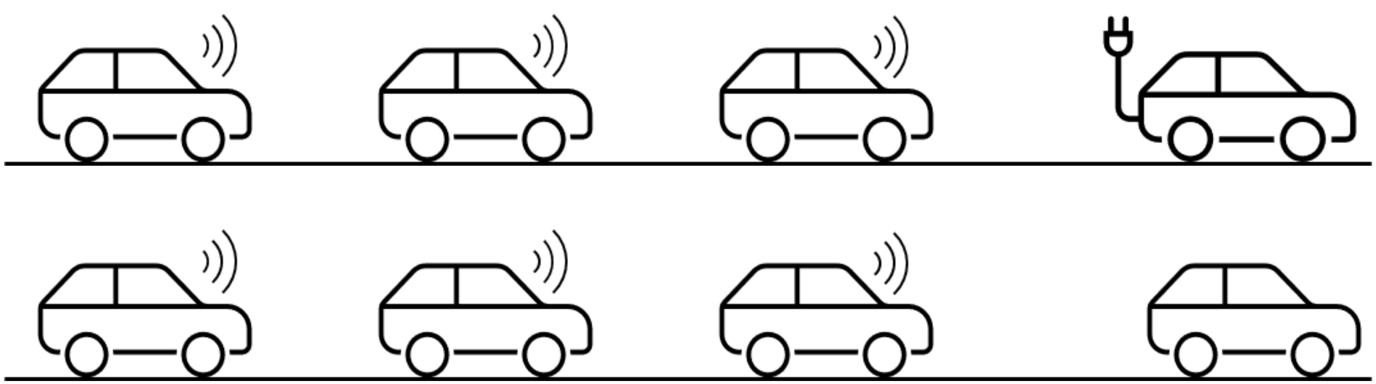
- ***Efficiency & Safety:***
  - Examined individual leader–follower pairs
  - Vehicles serve as a leader and a follower



Processing Trajectory Data

Platoon Decomposition

- ***Efficiency & Safety:***
  - Examined individual leader–follower pairs
  - Vehicles serve as a leader and a follower
- ***Environmental Impacts:***
  - Focused on platoons with ICEVs as followers
  - Compared cases where leaders are EVs vs. ICEVs



Safety Metrics

Time-to-Collision (TTC)

- Measures time until impact at current speeds
- Used widely in autonomous vehicle safety assessment
- Higher TTC $\rightarrow$ lower risk
- Smaller TTC $\rightarrow$ higher risk

$$\text{TTC}_i^t = \begin{cases} \dfrac{s_i^t}{-\Delta v_i^t}, & \text{if } \Delta v_i^t < 0 \\ \infty, & \text{otherwise} \end{cases}$$

- TTC_i^t: Time to collision for vehicle i at time t
- s_i^t: Spacing (distance) between between vehicle i and it's leader at time t
- Δv_i^t: Instantaneous speed difference between vehicle i and it's leader at time t

Safety Metrics

Deceleration Required to Avoid Crash (DRAC)

- Braking intensity required to prevent crash
- Higher DRAC → dangerous driving behavior
- Lower DRAC → safer driving behavior

$$\text{DRAC}_i^t = \begin{cases} \frac{\left(\Delta v_i^t\right)^2}{s_i^t}, & \text{if } \Delta v_i^t < 0 \\ 0, & \text{otherwise} \end{cases}$$

- DRAC_i^t: Deceleration required to avoid a collision for vehicle i at time t
- s_i^t: Spacing (distance) between between vehicle i and it's leader at time t
- Δv_i^t: Instantaneous speed difference between vehicle i and it's leader at time t

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Safety Metrics

Critical Event Rate

- A critical event occurs when:
  - TTC < threshold
  - DRAC > threshold
- Interpretation
  - Lower $p_{\text{crit}} \rightarrow$ safer driving behavior
  - Enables comparison of safety across experiments

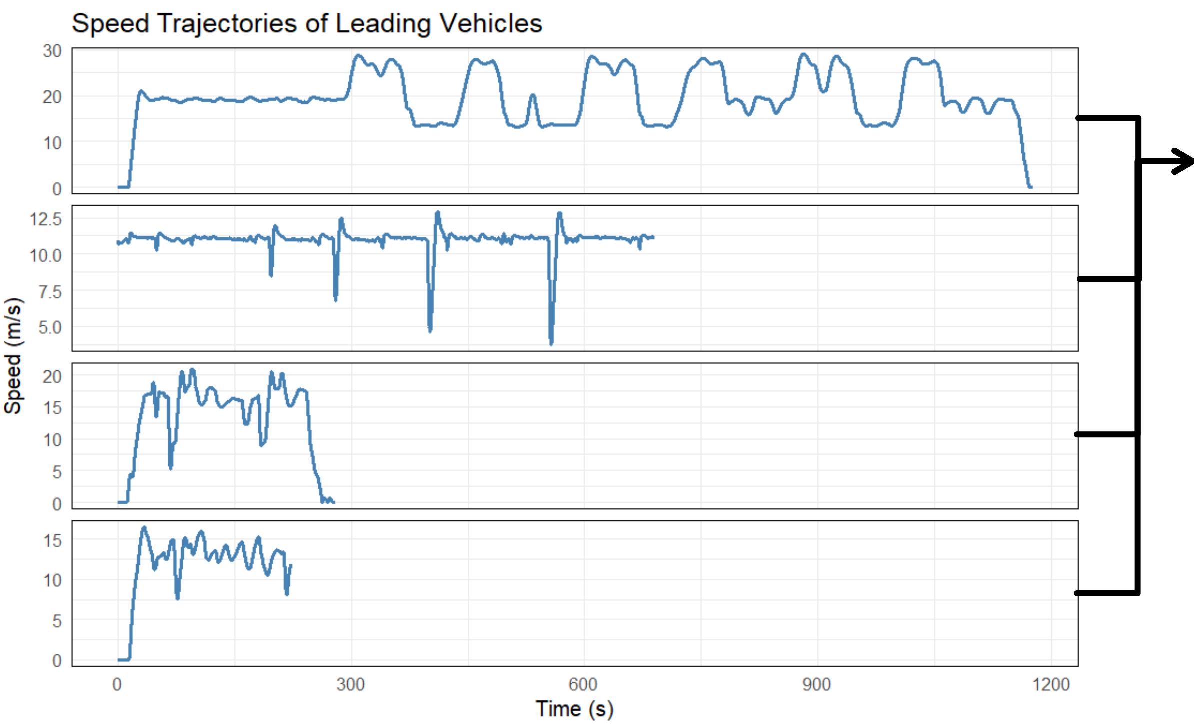
$$p_{\text{crit}} = \frac{c_{\text{crit}}}{p_{\text{total}}} \times 100\%$$

- p_{crit}: Proportion of critical events in an experiment
- c_{crit}: Number of instances where risk is indicated
- p_{total}: Total number of evaluated instances in the experiment

Efficiency Metrics

Aligning Similar Trajectories

- Efficiency varies with driving conditions
  - Need fair EV vs. ICEV comparison
- DTW aligns similar leader speed-time trajectories
- Compute efficiency metrics on the most similar trajectories



Compute DTW distances between all trajectories

Select most similar trajectories (lowest DTW distance)

Compute efficiency metrics for followers of selected trajectories

Efficiency Metrics

Average Speed Variation (ASV)

- Measures oscillation intensity in vehicle speed
- High ASV → unstable, stop-and-go flow
- Low ASV → smoother, more efficient driving

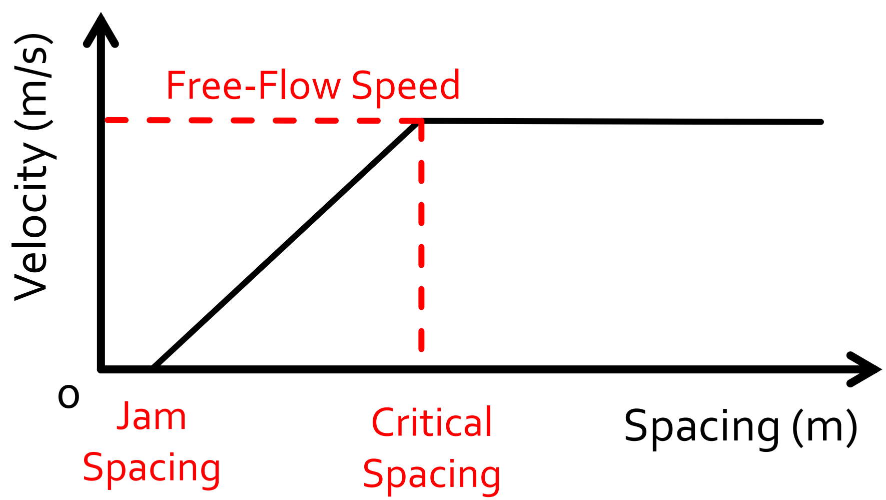
$$\text{ASV}_i = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \left| v_i^t - v^* \right| dt$$

- ASV_i: Average speed variance for vehicle i
- t_1, t_2: Start and end times of the observation period
- v_i^t: Instantaneous speed of vehicle i at time t
- v^*: Desired (or target) cruising speed of vehicle i

Efficiency Metrics

Velocity–Spacing (v–s) Curves

- Models speed adjustments based on spacing
- Critical spacing: spacing where vehicles can no longer maintain free-flow speed
- Smaller critical spacing → aggressive
- Larger critical spacing → cautious behavior



Environmental Metrics

Fuel Consumption and Pollutant Emission

- ***Goal:*** Estimate fuel consumption/emissions from trajectories
- Method:
  - Based on Ahn et al. (2002) ***VT-Micro model***
  - Uses instantaneous speed and acceleration levels
- Outputs:
  - Fuel Consumption
  - Hydrocarbons (HC)
  - Nitrogen Oxides (NO_x)
  - Carbon Monoxide (CO)

Applying R4R Concepts

Scaling Analysis with High-Performance Tools

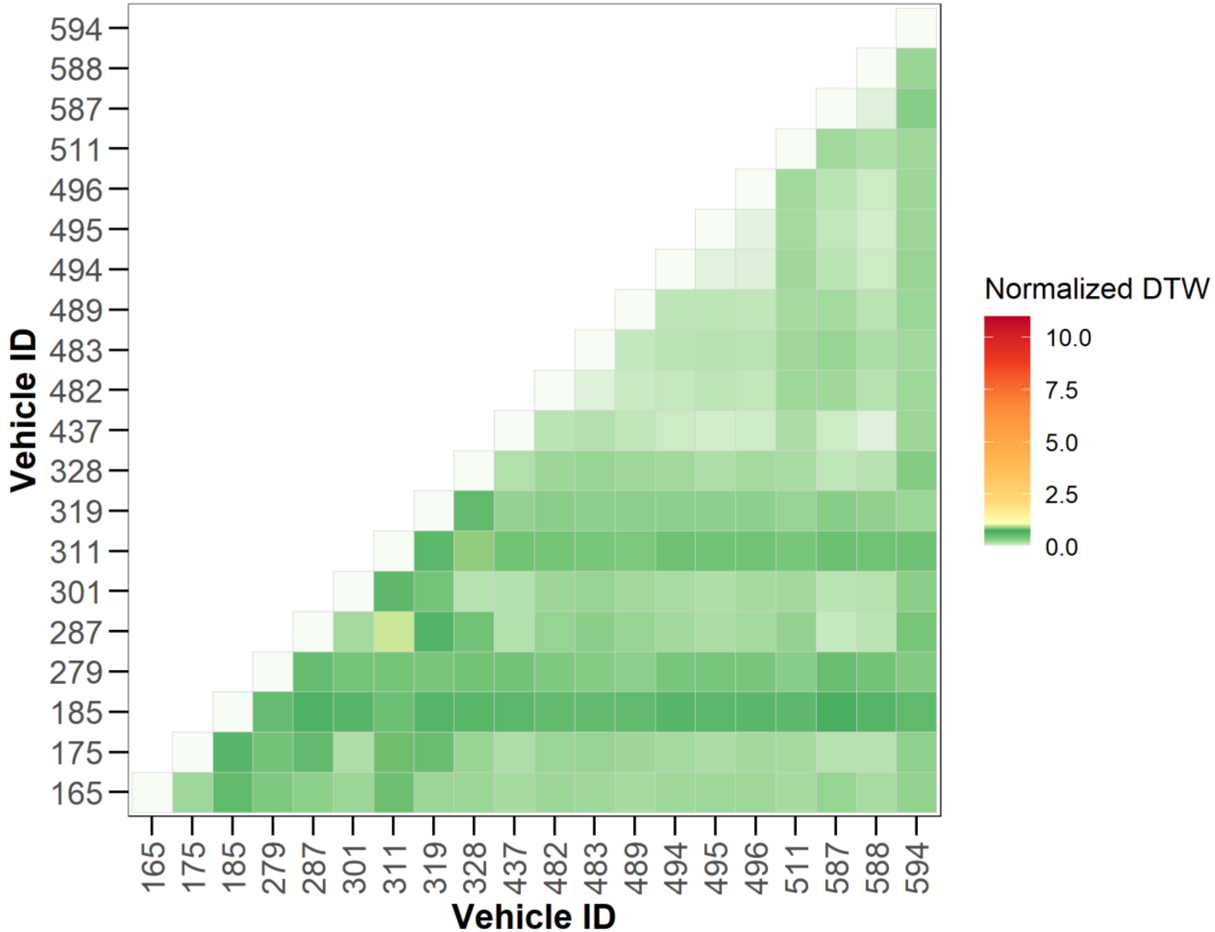
- Utilized high-performance computer (HPC) for large-scale DTW alignment and emissions modeling
- Leveraged remote computing to reduce processing time from hours to minutes

Numerical Results

Efficiency

Trajectory Similarity Analysis

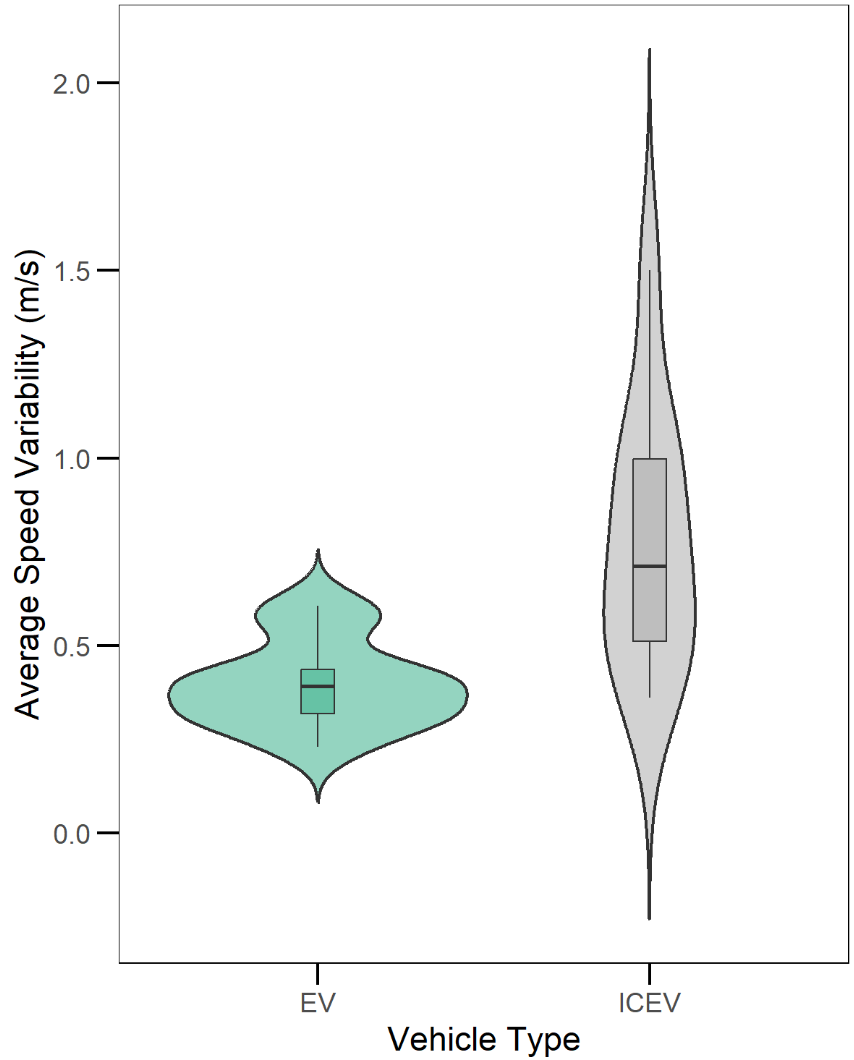
- DTW aligns trajectories of lead–follower pairs
- Green = high similarity; red = low similarity
- 20 vehicle pairs (10 EVs, 10 ICEVs) selected for balanced comparison



Efficiency
Stability Results

- EV followers:
  - Median ASV = 0.39 m/s
- ICEV followers:
  - Median ASV = 0.66 m/s

- EVs show lower variability and smoother speed control



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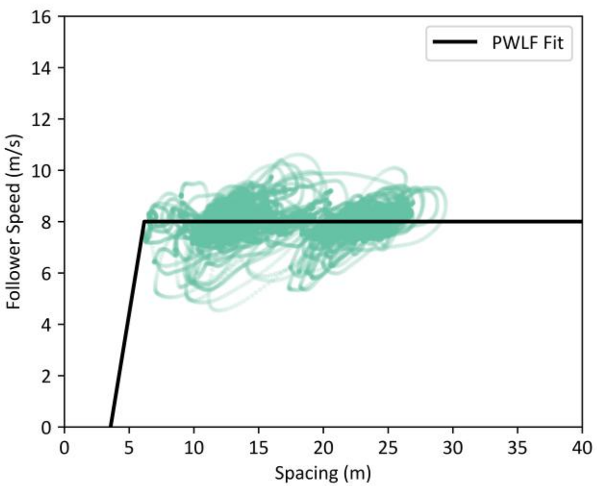
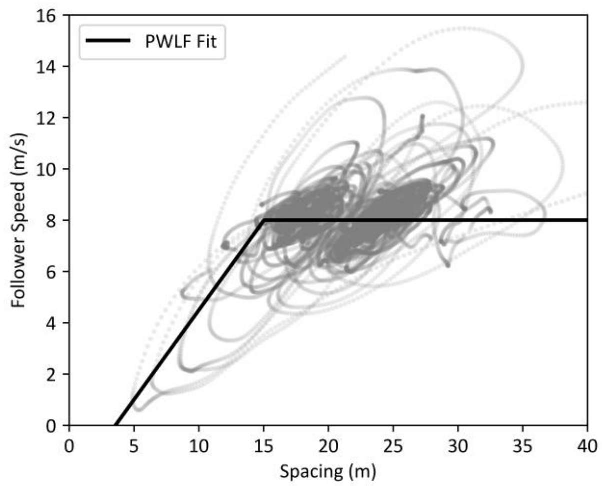
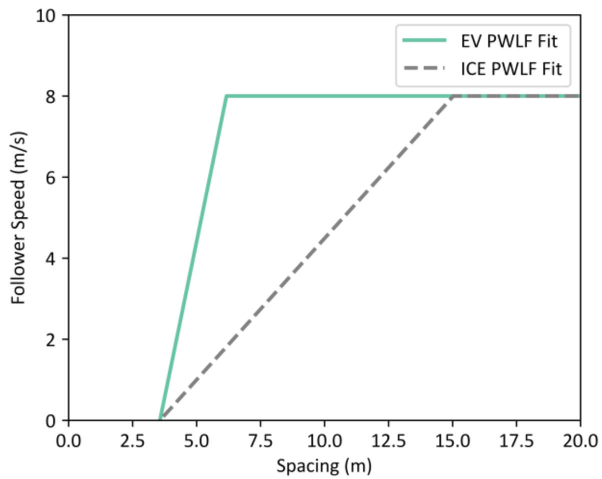
Efficiency

Spacing Behavior

- Piecewise linear models fitted for EV and ICEV followers
- Critical spacing:
  - EV = 6.17 m
  - ICEV = 15.03 m
- EVs: more compact, efficient spacing behavior
- ICEVs: conservative following (larger headways)

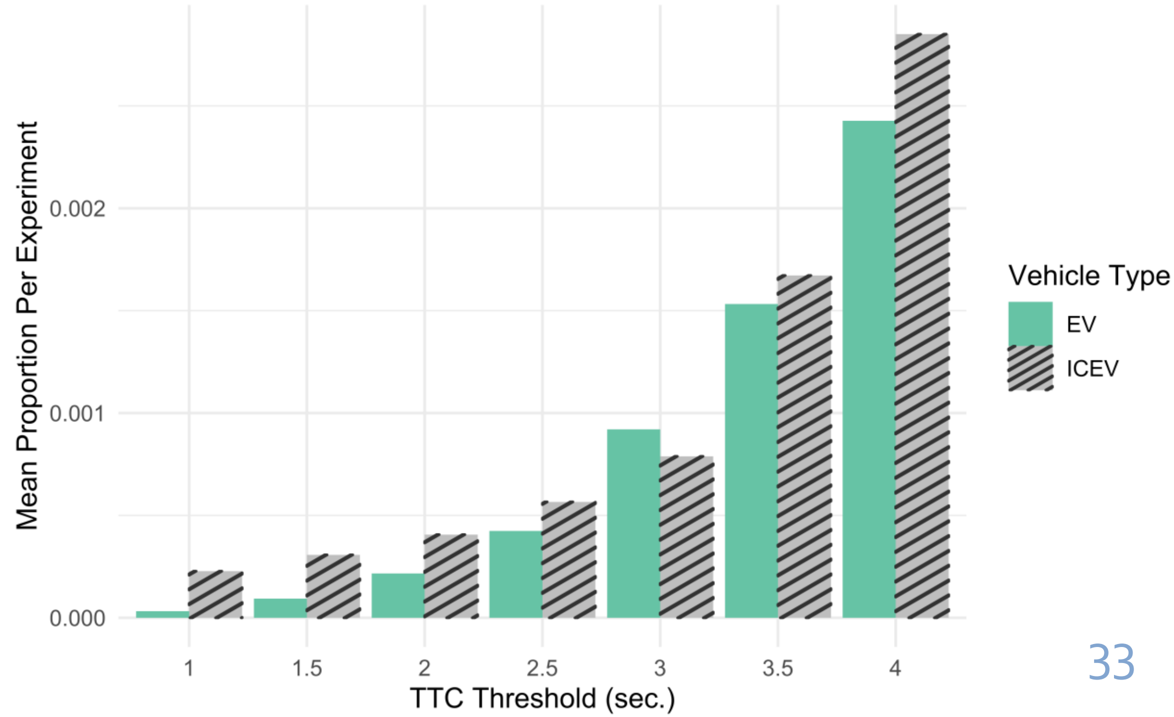






Safety
Time-to-Collision (TTC)

- TTC: Reaction time to potential collision
- *TTC (< 1 s):* EV = 0.0032%, ICEV = 0.0228%
  - 85.8 % reduction
- Evaluated % of time below critical thresholds



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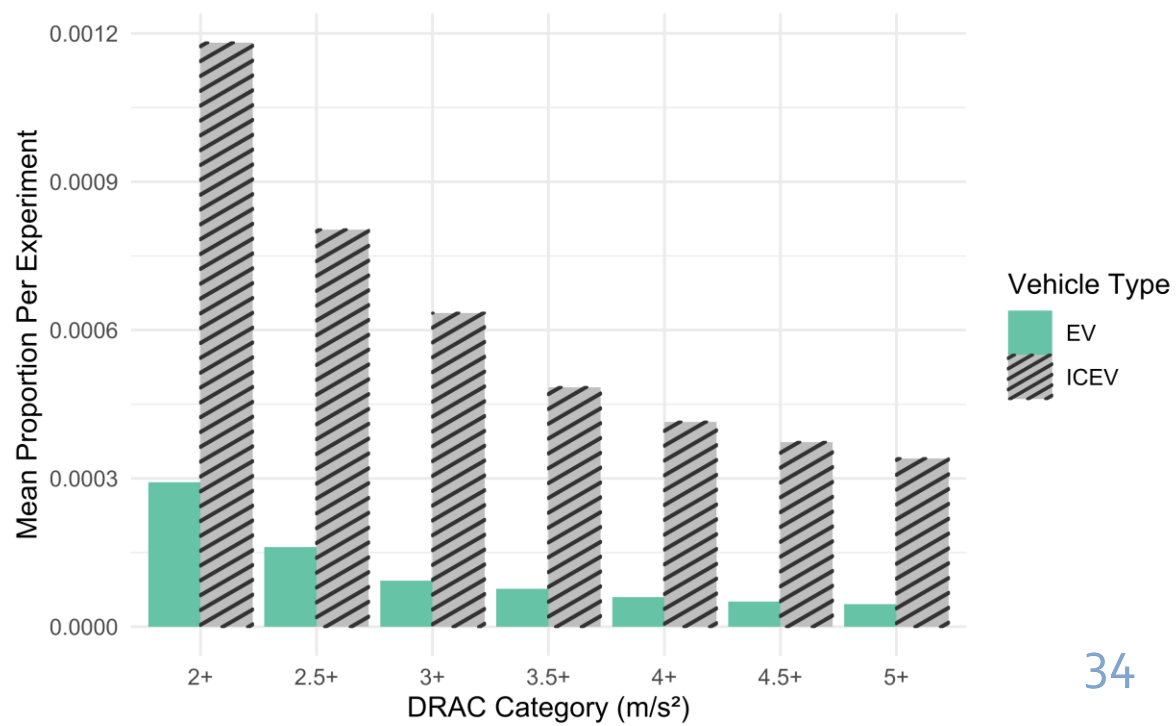
Safety

Deceleration Required to Avoid Crash (DRAC)

- DRAC: Emergency braking demand
- ***DRAC (> 5 m/s²):*** EV = 0.0046%, ICEV = 0.0340%
  - 86.6% reduction
- Evaluated % of time below critical thresholds



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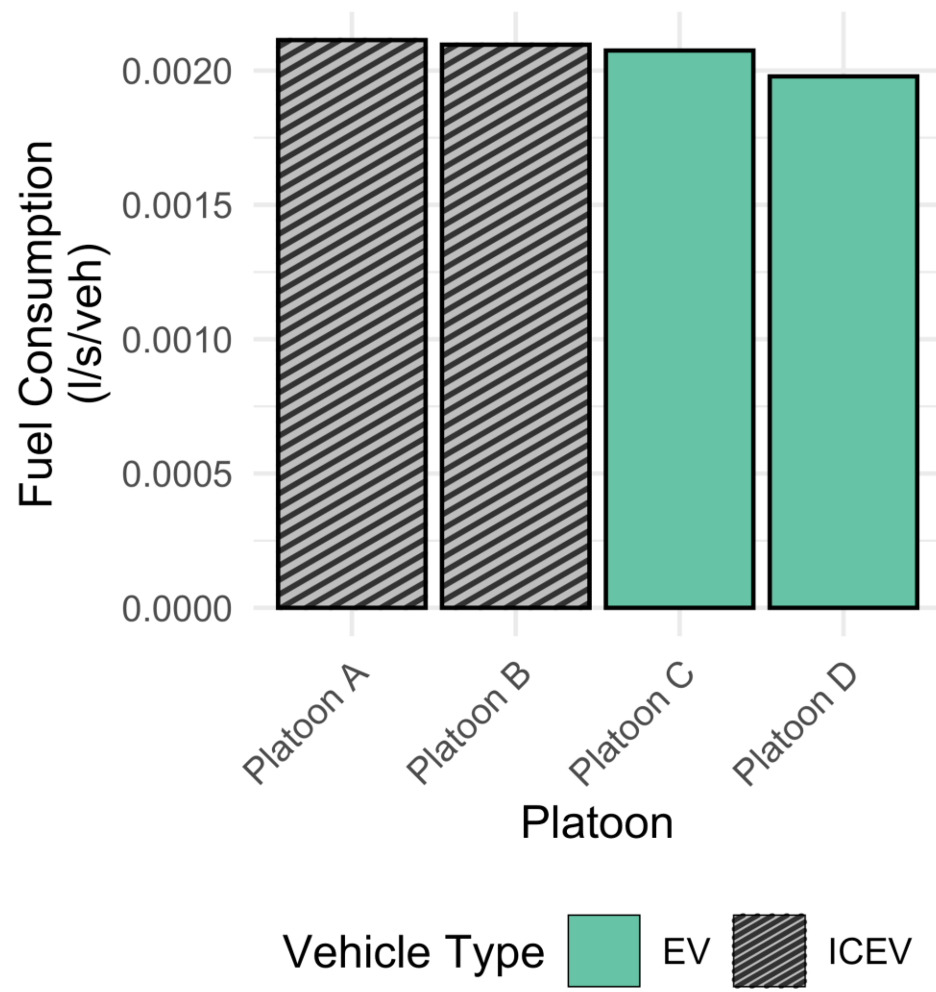
Environmental Analysis

Indirect Impacts

- EV-led platoons reduce emissions by:
  - Fuel consumption: 1–6%



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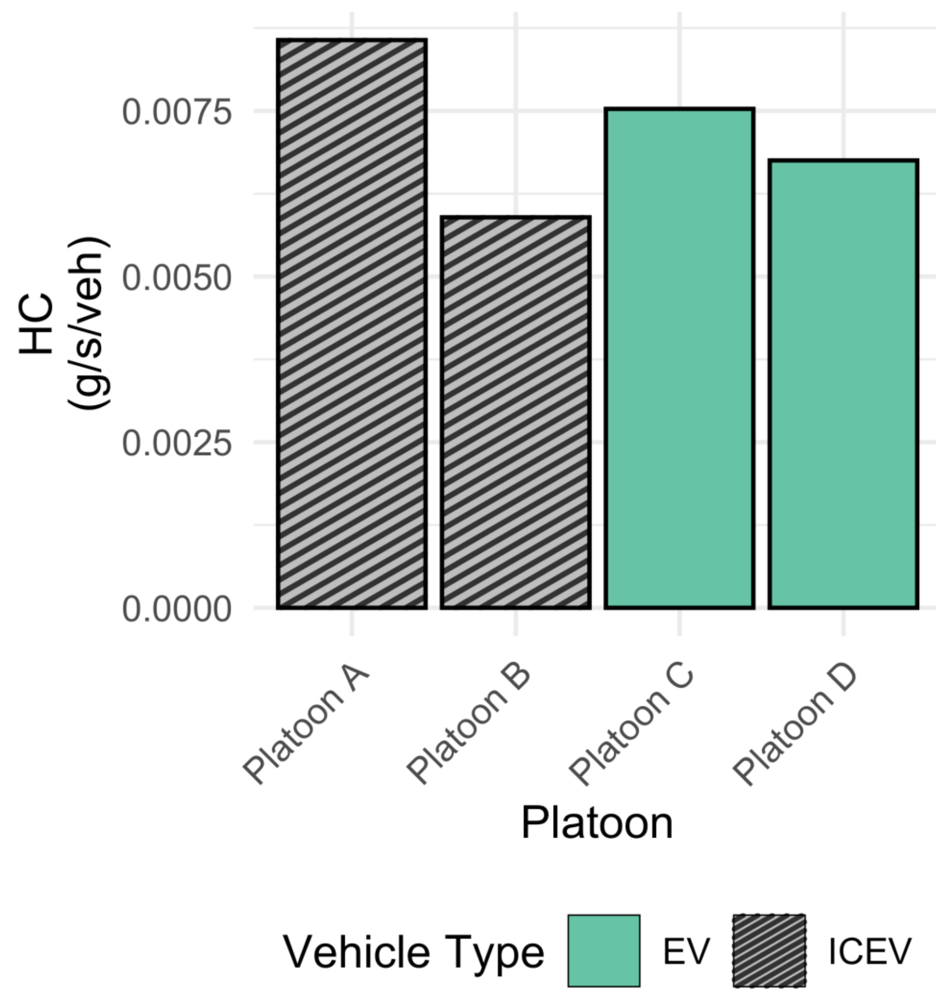
Environmental Analysis

Indirect Impacts

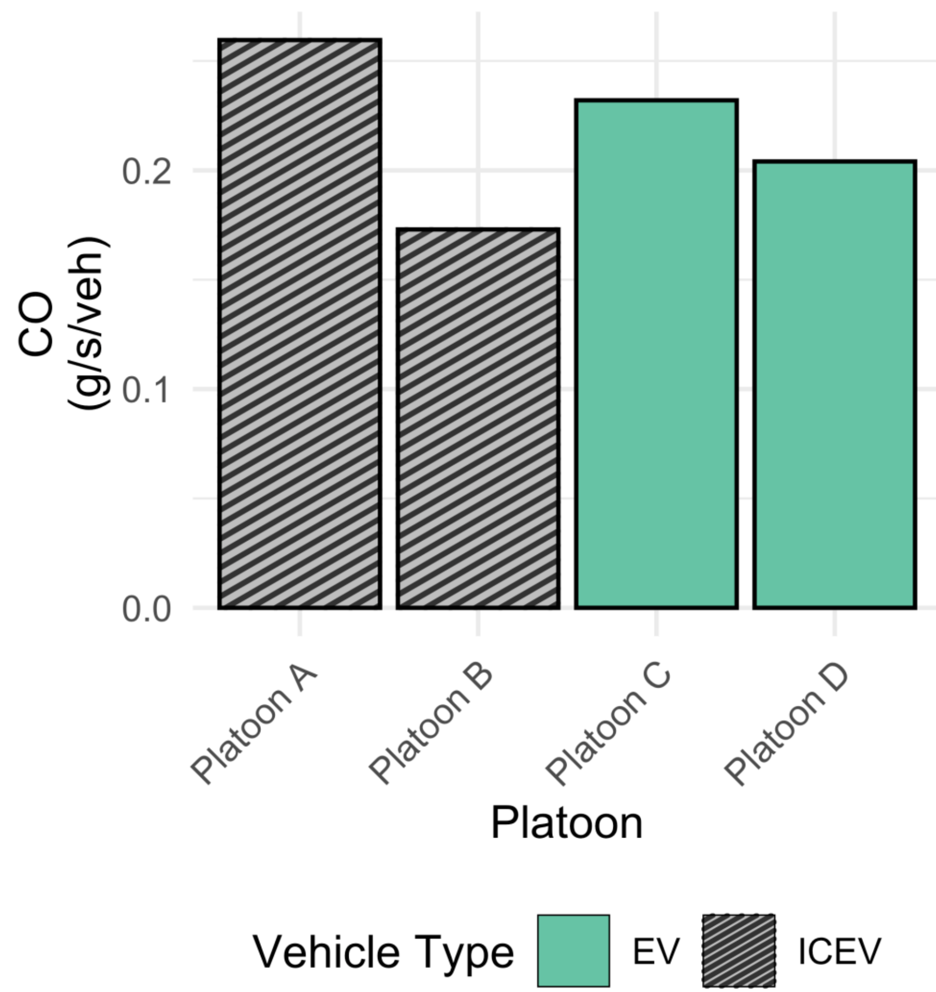
- EV-led platoons reduce emissions by:
  - Fuel consumption: 1–6%
  - HC: 12–21%



Environmental Analysis

Indirect Impacts

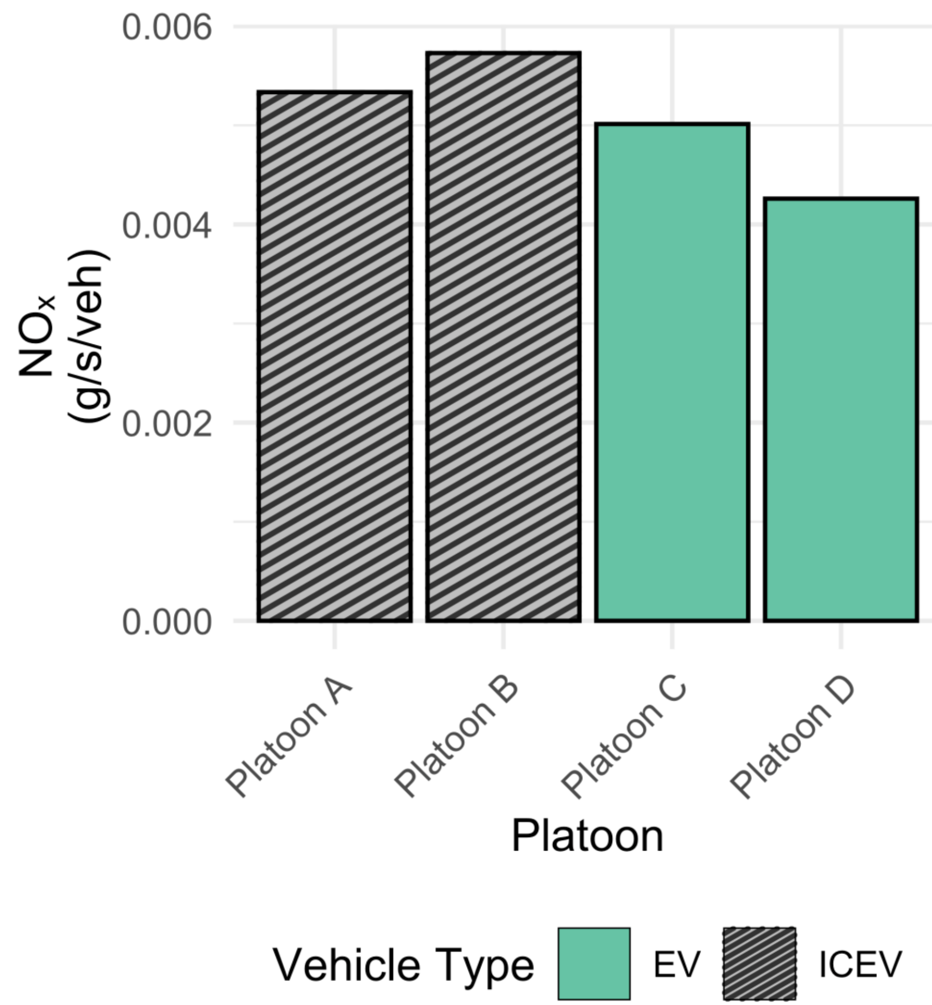
- EV-led platoons reduce emissions by:
  - Fuel consumption: 1–6%
  - HC: 12–21%
  - CO: 10–21%



Environmental Analysis

Indirect Impacts

- EV-led platoons reduce emissions by:
  - Fuel consumption: 1 - 6%
  - HC: 12–21%
  - CO: 10–21%
  - NO_x: 6–26%



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Key Takeaways

Summary of Findings

Efficiency: EVs exhibit smoother and more compact car-following

Safety: 70–85% reduction in critical TTC and DRAC instances

Environment: Up to 25% emission reduction in EV-led platoons

Implication: EVs + ACC outperform ICEVs, suggesting potential system-level benefits

Applying R4R Concepts

Using AI Tools for Research & Coding Support

- LLM prompting techniques were applied to aid in debugging and refining trajectory-preprocessing scripts
- Used LLMs to generate reusable code templates for emissions modeling and visualizations
- Leveraged AI tools responsibly
  - Checking outputs, avoiding hallucinated formulas, and maintaining transparency
- Integrated AI into open, reproducible research workflows

Roots for Resilience (R4R)

“The Roots for Resilience program provides training and support to select graduate students on open, reproducible science, computational infrastructure and AI tools to enhance research focused on environmental and societal resilience.”

R4R Fellowship

Data Science, Open Science, and AI Tools

- Fall-semester fellowship for UA grad students
- Hands-on training in data science, AI, and open science
- $7,000 stipend
- Build cross-department collaborations
- Strengthen research on environmental & societal resilience
- Weekly sessions: Tues & Thurs, 11 AM–1 PM
- Applications due May 31 (next cycle)

R4R Fellowship

Personal Testimonial

The R4R program was an outstanding introduction to open and reproducible science, but what truly stood out was the collaborative community and the practical training. As I transitioned into a more programming- and machine learning–focused research area, the hands-on sessions with GitHub, conda environments, and high-performance computing proved invaluable.

Applying R4R Concepts

Open, Shareable, and Transparent Research

- In the process of organizing the project for public sharing via GitHub
- Repository will include
  - Reproducible scripts with documentation on data preprocessing and environments
  - Followed open science principles to ensure future adaptation and reuse of this work

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Thank you! Questions?

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