# Connected and Automated Vehicles: Improving Safety and Efficiency Across the Scales

**Gábor Orosz**

**University of Michigan, Ann Arbor**

# Motivation

**Connectivity** and **automation** of road vehicles
may improve **safety, energy efficiency,** and **mobility**

# Connectivity + Automation

VEHICLE SYSTEM DYNAMICS
2020, VOL. 58, NO. 5, 672–704
https://doi.org/10.1080/00423114.2020.1741652

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## Connected and automated road vehicles: state of the art and future challenges

Tulga Ersal [a], Ilya Kolmanovsky[b], Neda Masoud [c], Necmiye Ozay[d], Jeffrey Scruggs[c], Ram Vasudevan [a] and Gábor Orosz [a,c]

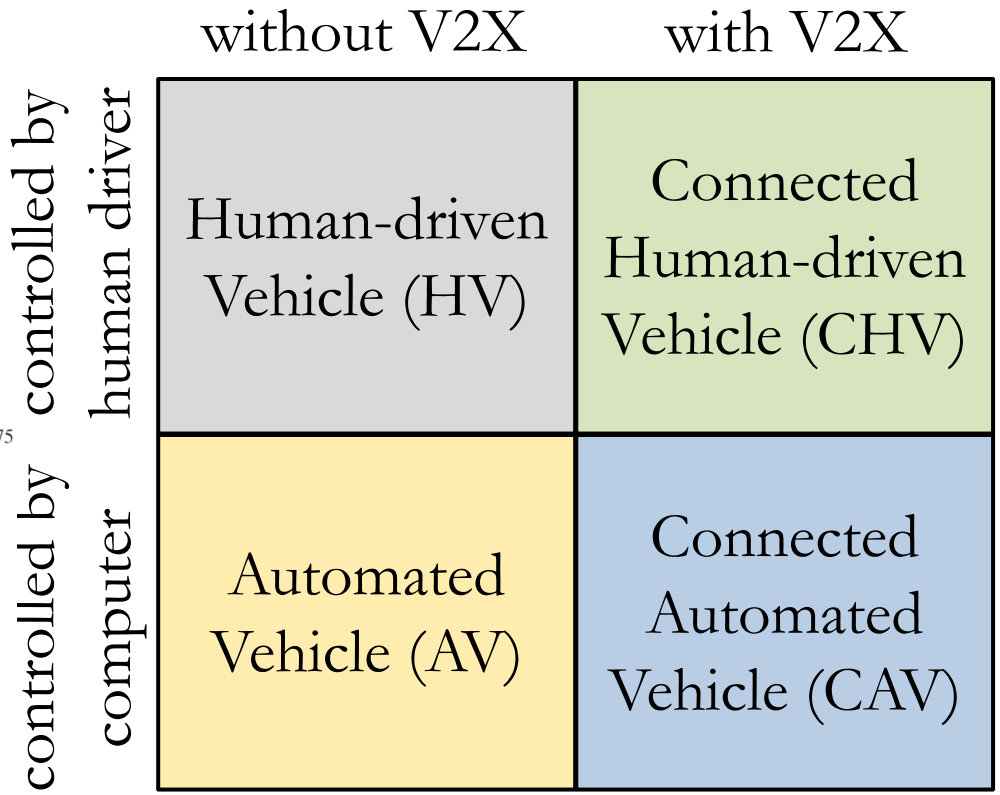
[a]Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA; [b]Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI, USA; [c]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA; [d]Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, USA

IEEE TRANSACTIONS ON INTELLIGENT VEHICLES, VOL. 8, NO. 1, JANUARY 2023

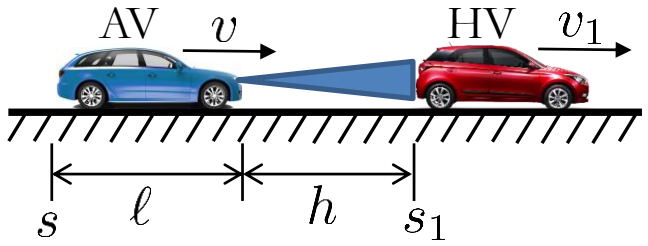


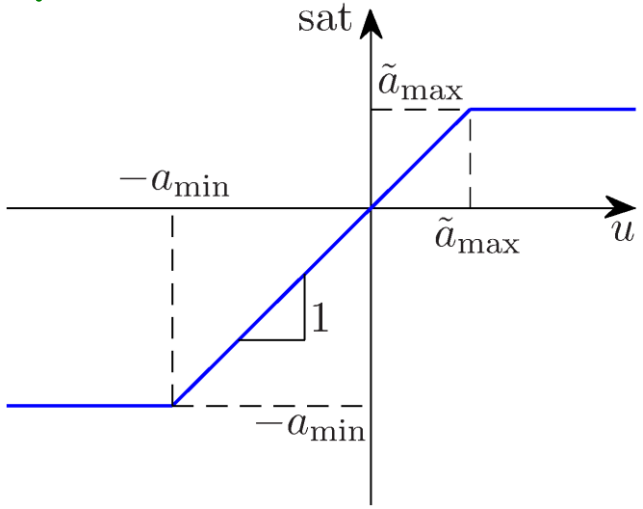
## Connectivity-Based Delay-Tolerant Control of Automated Vehicles: Theory and Experiments

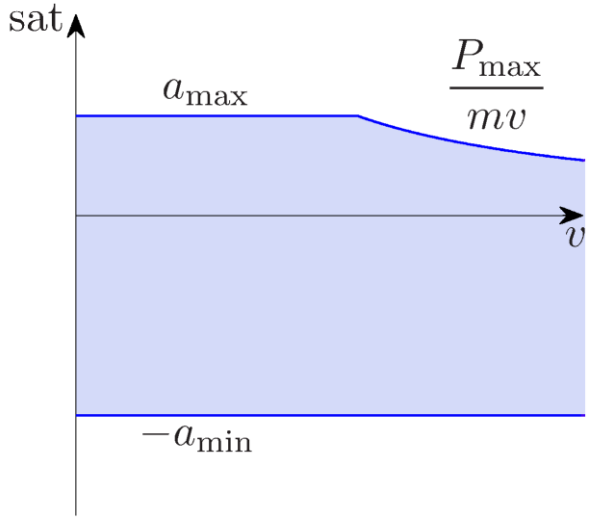
Sándor Beregi, Sergei S. Avedisov, Chaozhe R. He, Dénes Takács, and Gábor Orosz



# Adaptive Cruise Control (ACC)



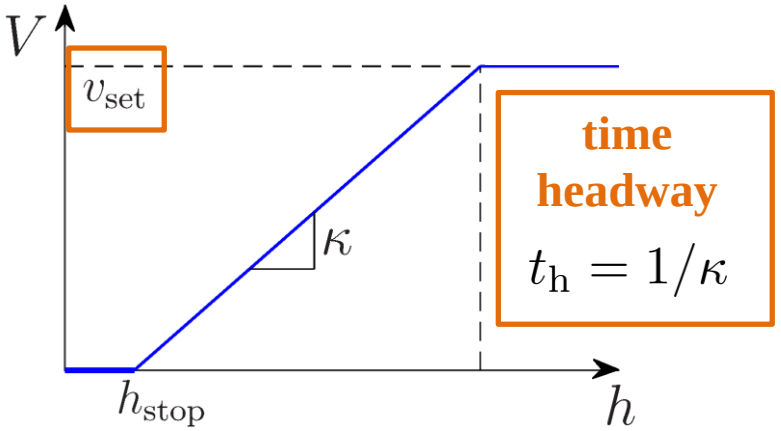




## Simplified vehicle model

$$\begin{cases} \dot{h}(t) &= v_1(t) - v(t) \\ \dot{v}(t) &= \mathrm{sat}\big(u(t-\tau)\big) \end{cases}$$

## Desired behavior

- match velocity to preceding vehicle
- adjust velocity according to range policy




## Simplest ACC algorithm

$$u = \alpha\,(V(h) - v) + \beta(v_1 - v)$$

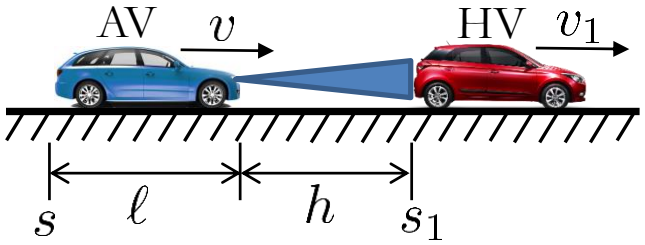
## Equilibrium

$$v_1^* = v^* = V(h^*)$$

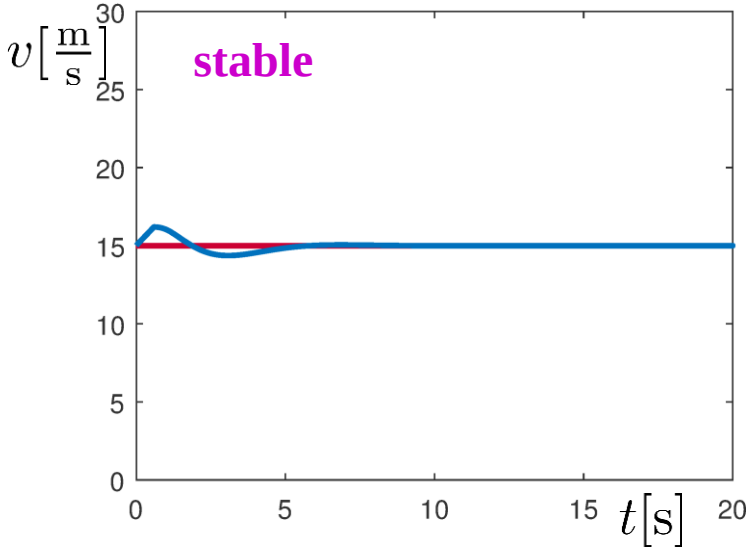
## Transfer function $\tilde{v}_1 \to \tilde{v}$

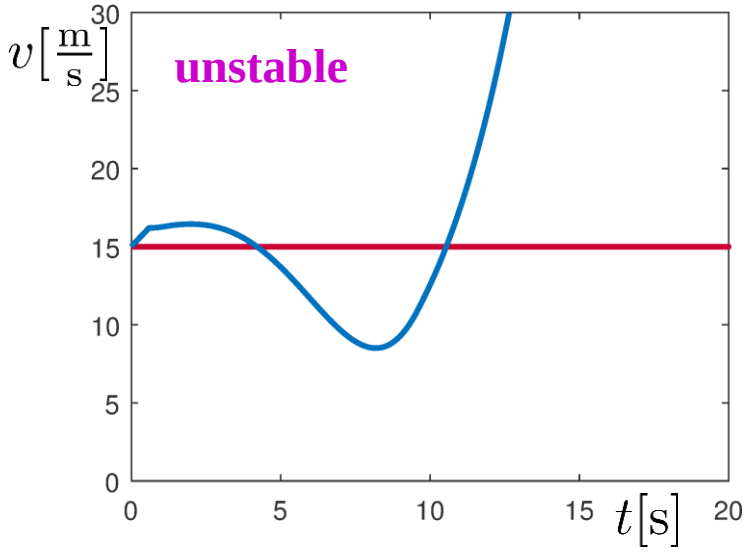
$$T(s) = \frac{\beta s + \alpha\kappa}{s^2 \mathrm{e}^{s\tau} + (\alpha+\beta)s + \alpha\kappa}$$

# Adaptive Cruise Control (ACC)

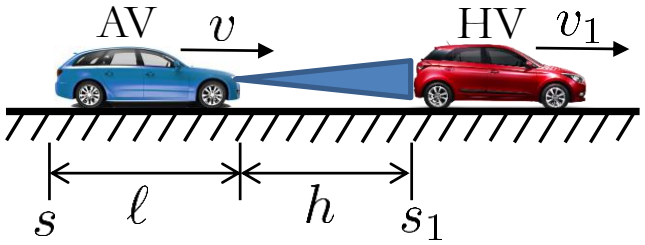



## Plant stability



# Adaptive Cruise Control (ACC)



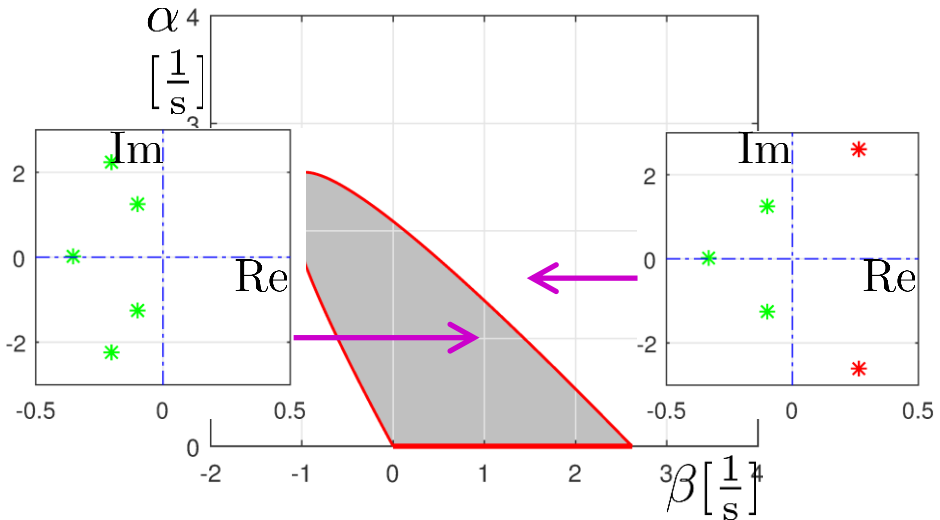

## Plant stability

$$s^2 e^{s\tau} + (\alpha + \beta)s + \alpha\kappa = 0 \quad \Rightarrow \quad s_1, s_2, \ldots s_\infty$$

$$\mathrm{Re}(s_k) < 0, \quad \forall k \in \mathbb{N}$$

## Stability chart

$$\tau = 0.6[\mathrm{s}]$$



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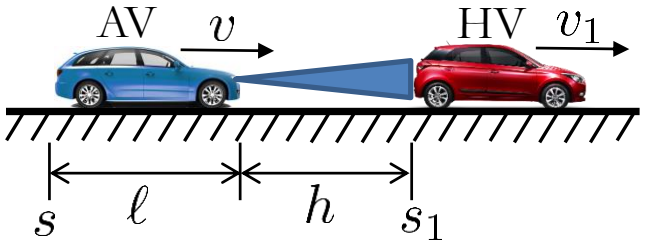
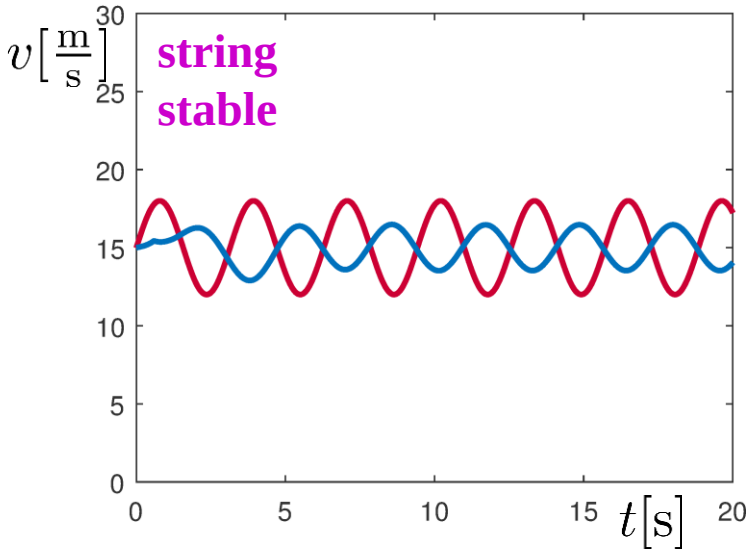
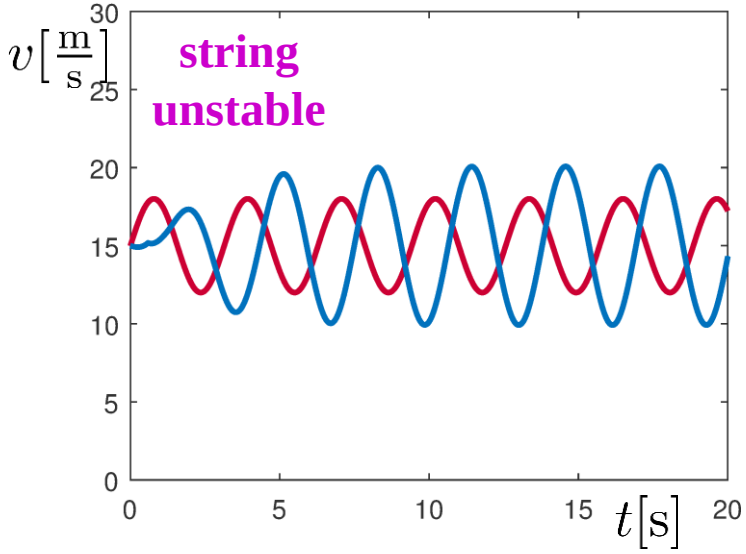



## String stability



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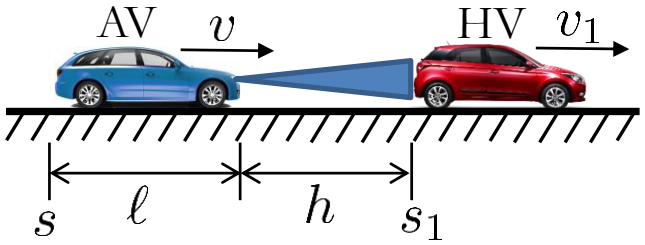


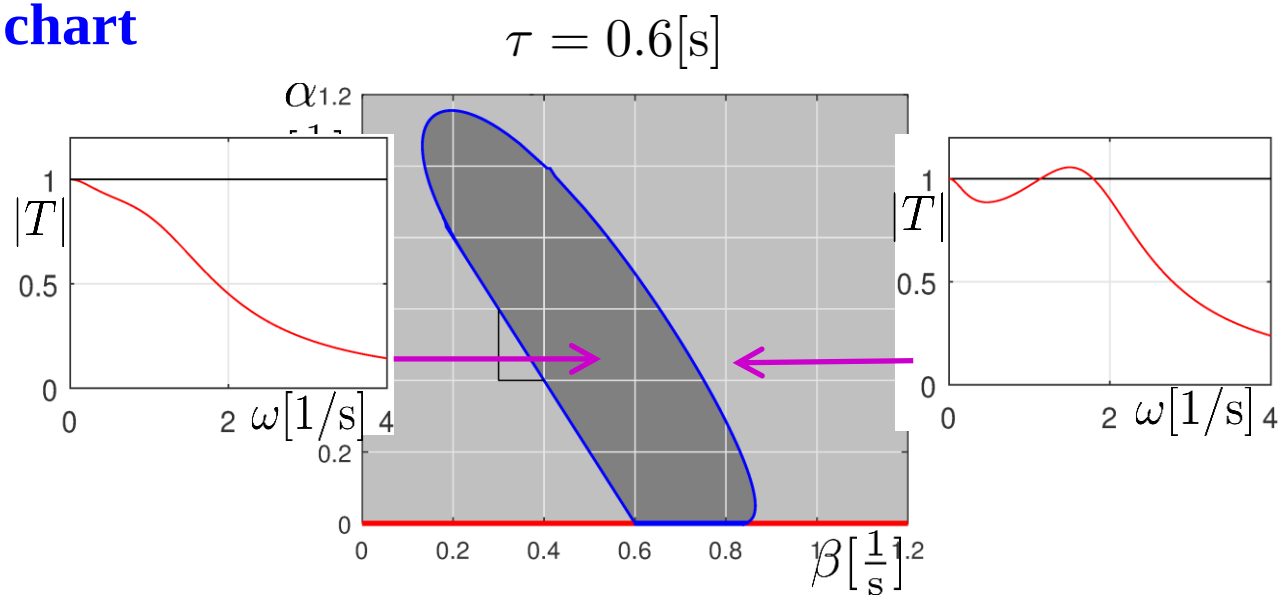

## String stability

$$|T(\mathrm{j}\omega)| < 1, \quad \forall \omega > 0$$

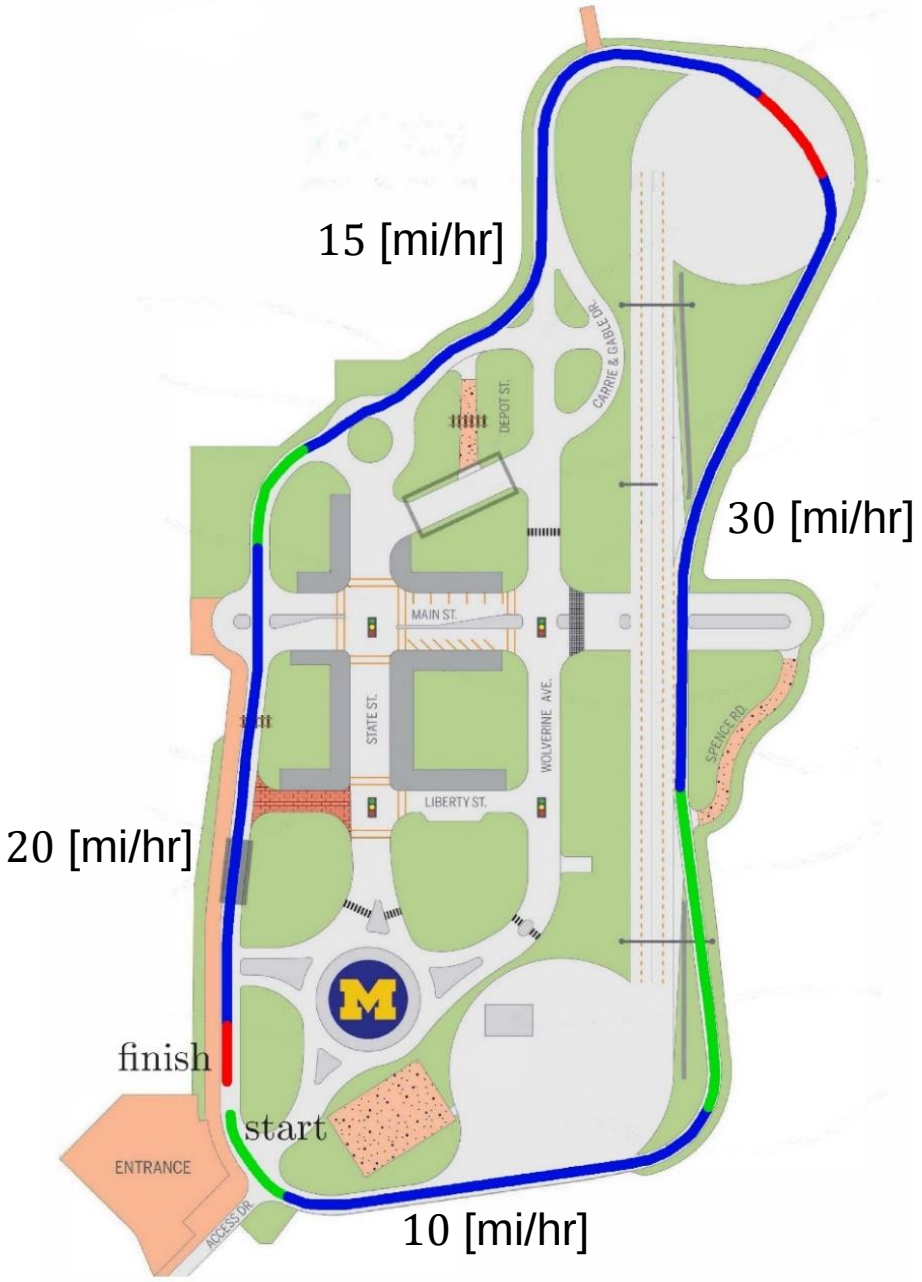
## Critical delay / time headway

$$\tau_{\mathrm{cr}} = \frac{t_{\mathrm{h}}}{2}$$

## Stability chart



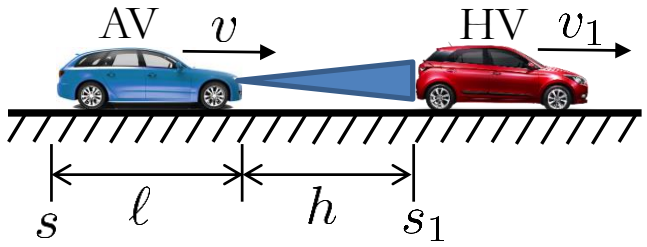
# Adaptive Cruise Control (ACC) - Experiments

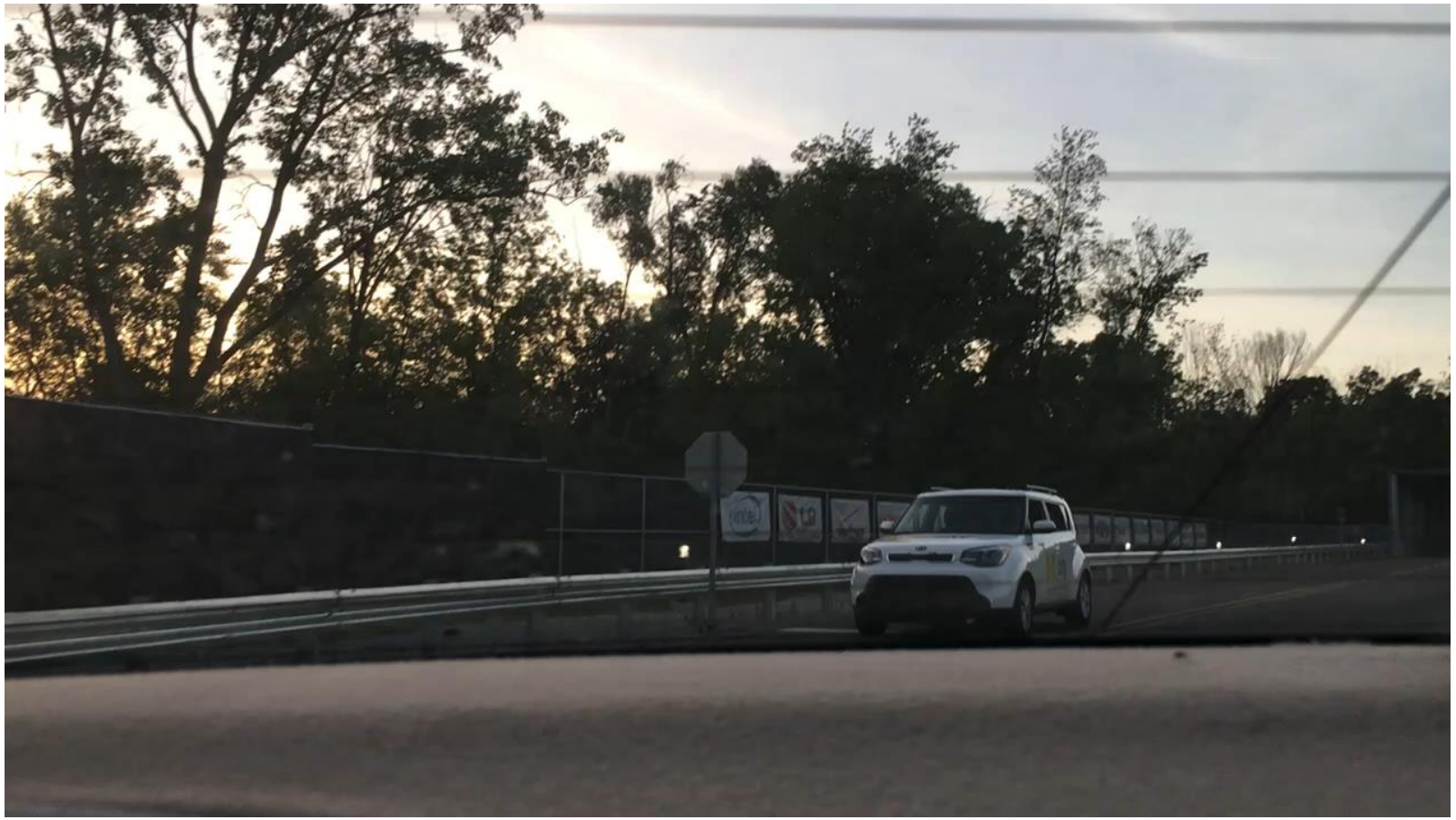



Acceleration

Constant Speed

Braking



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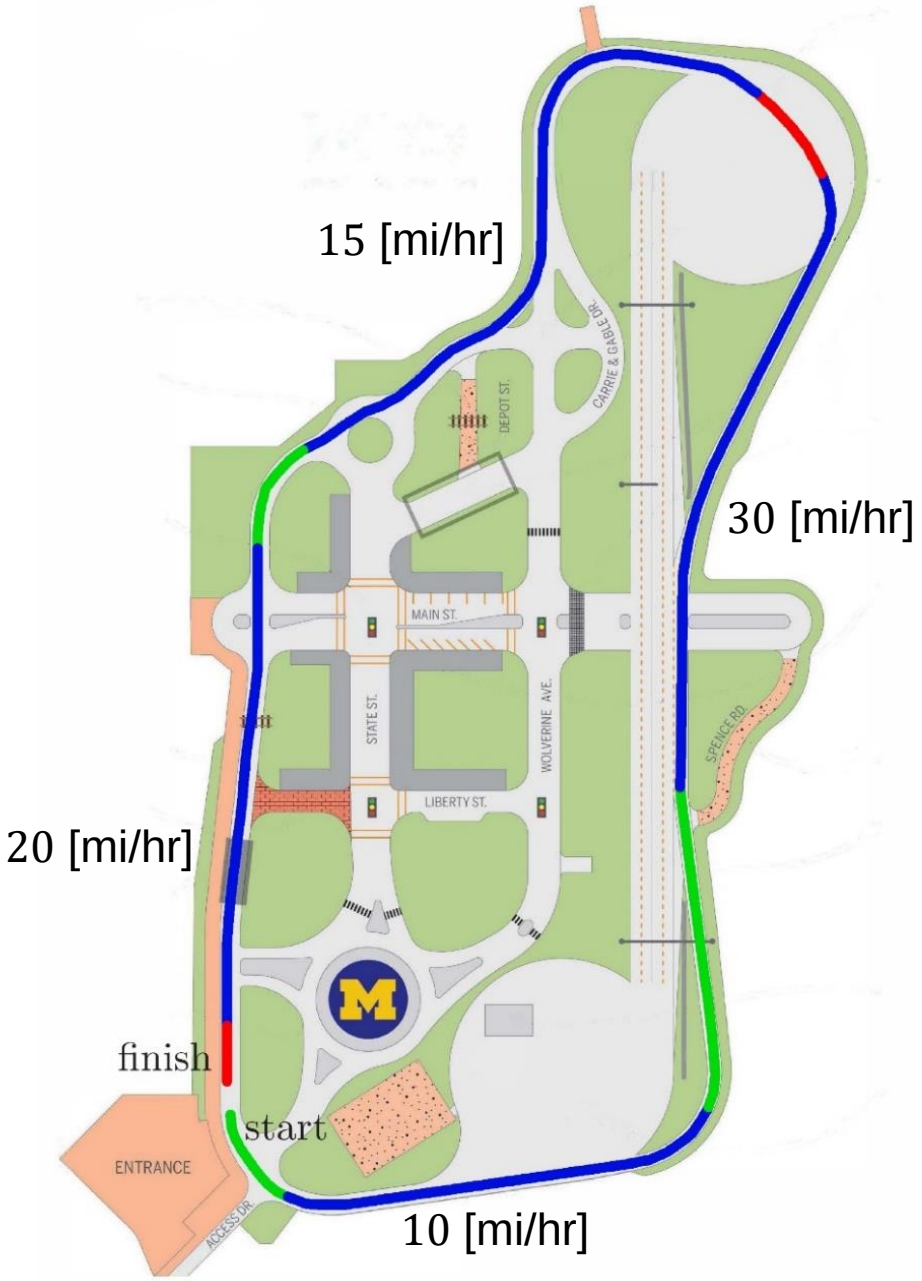


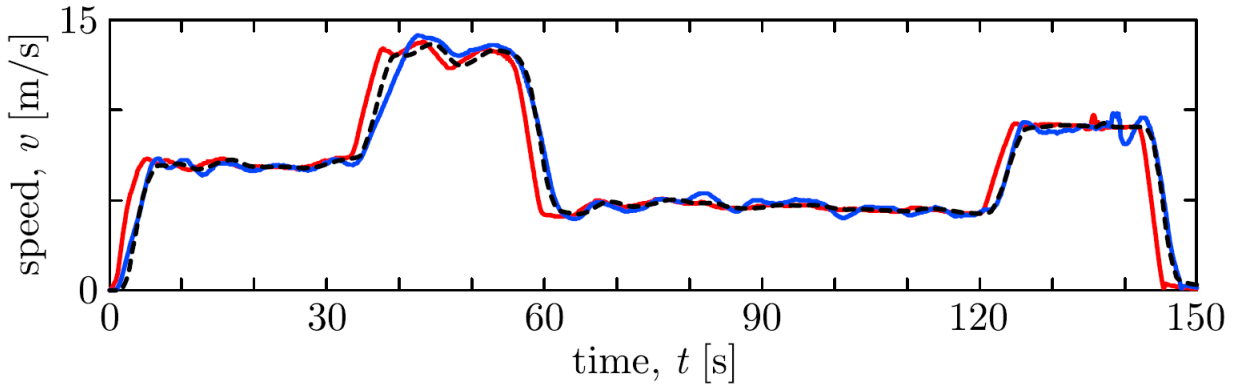


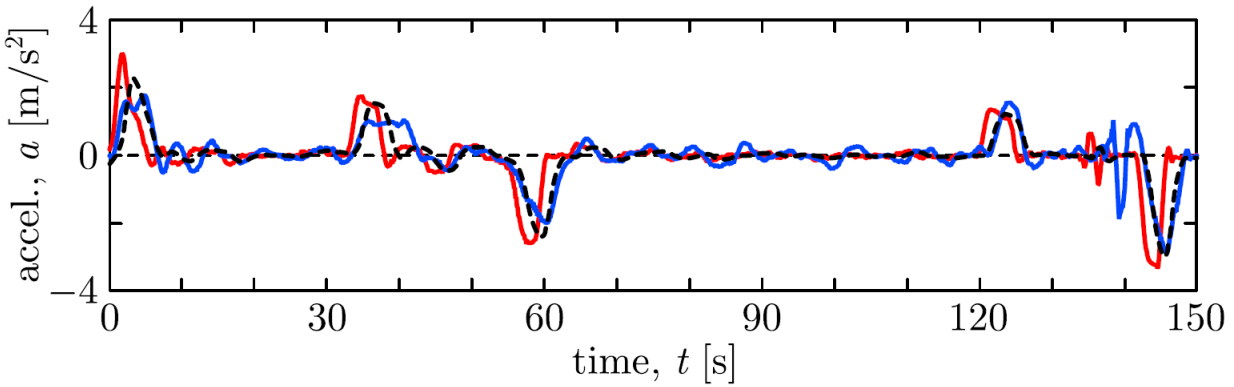


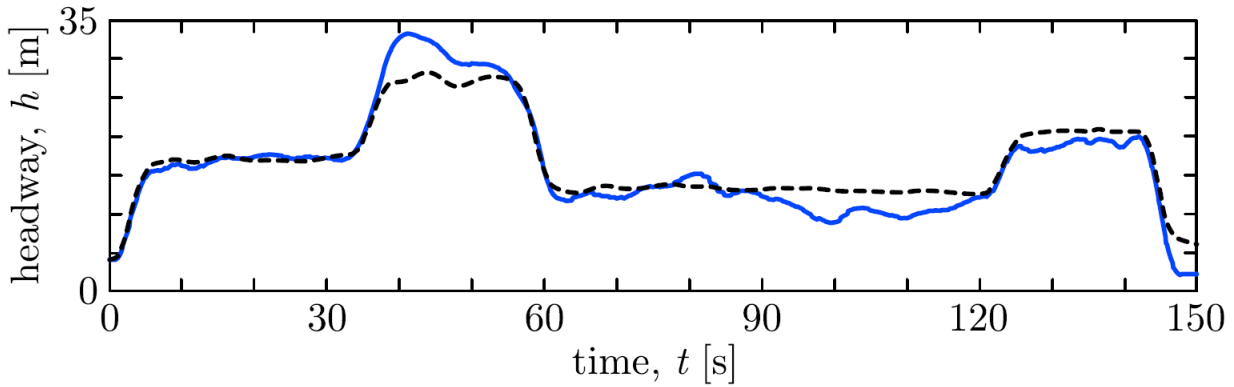

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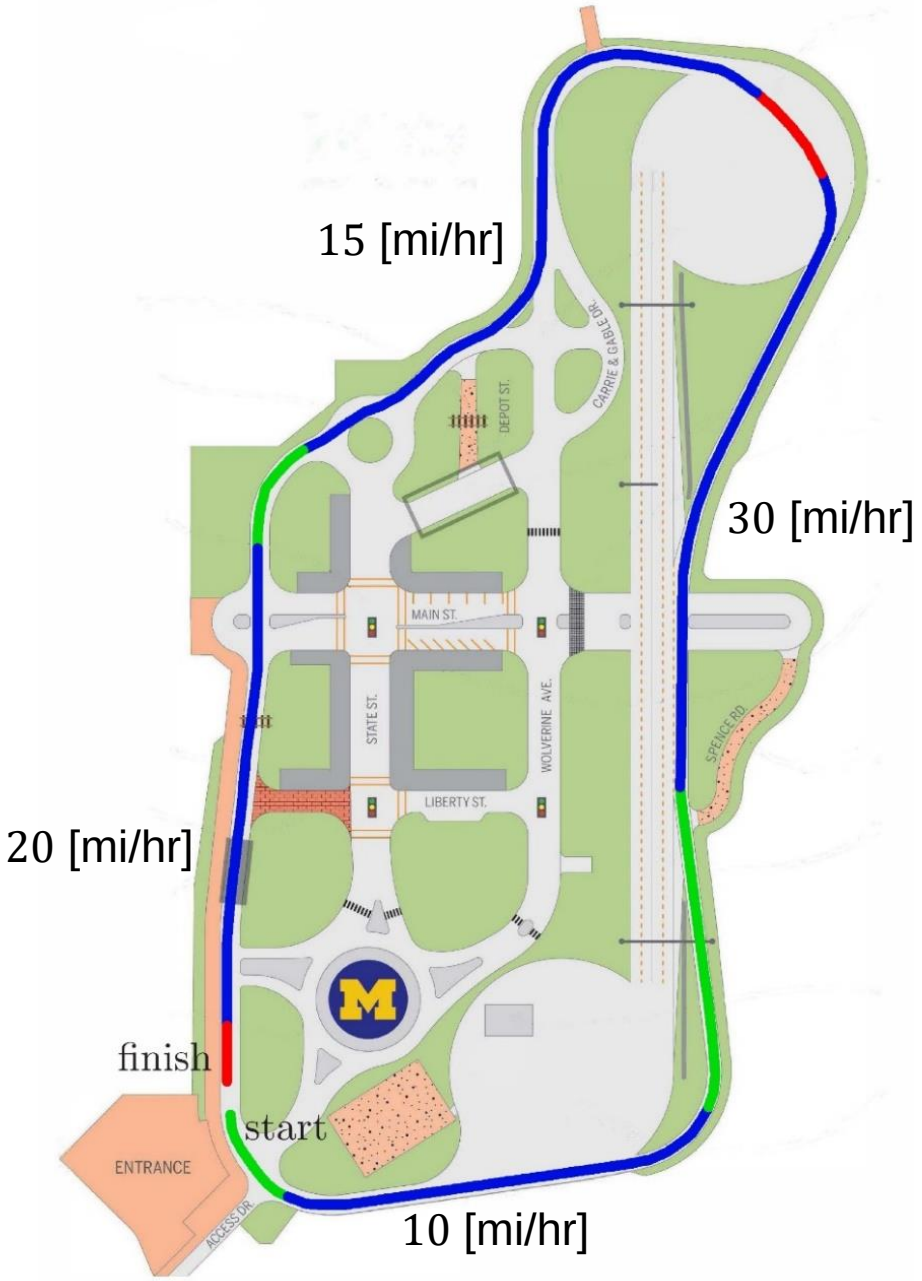


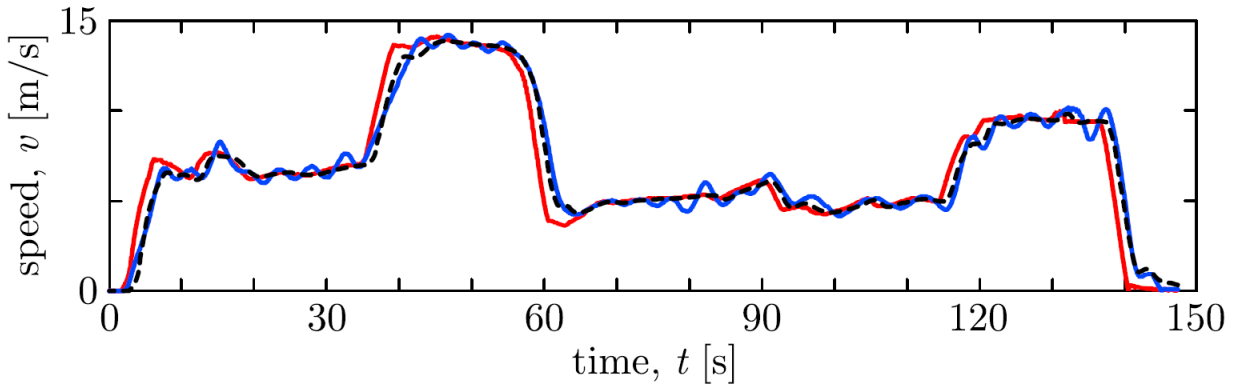


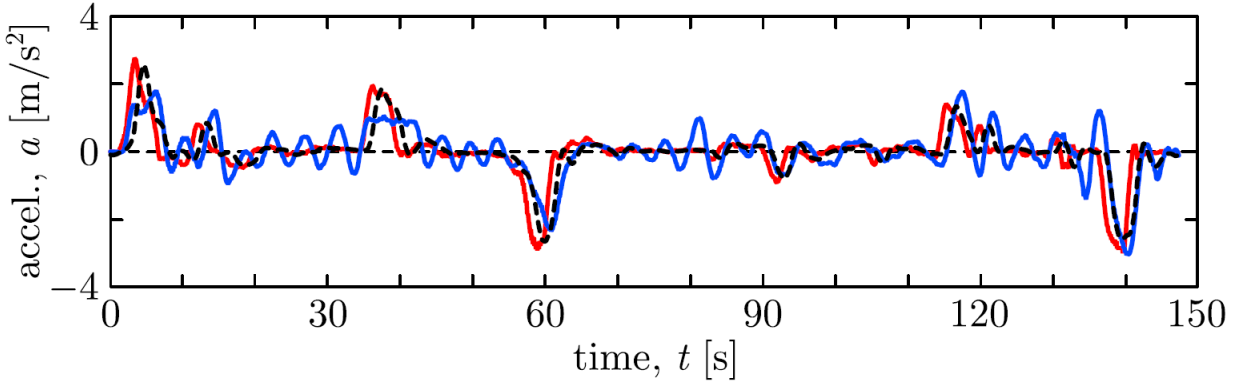


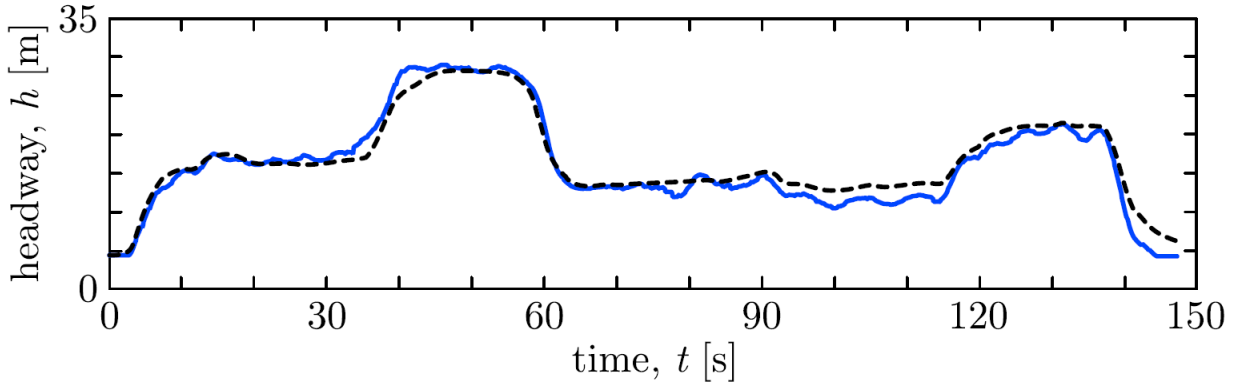

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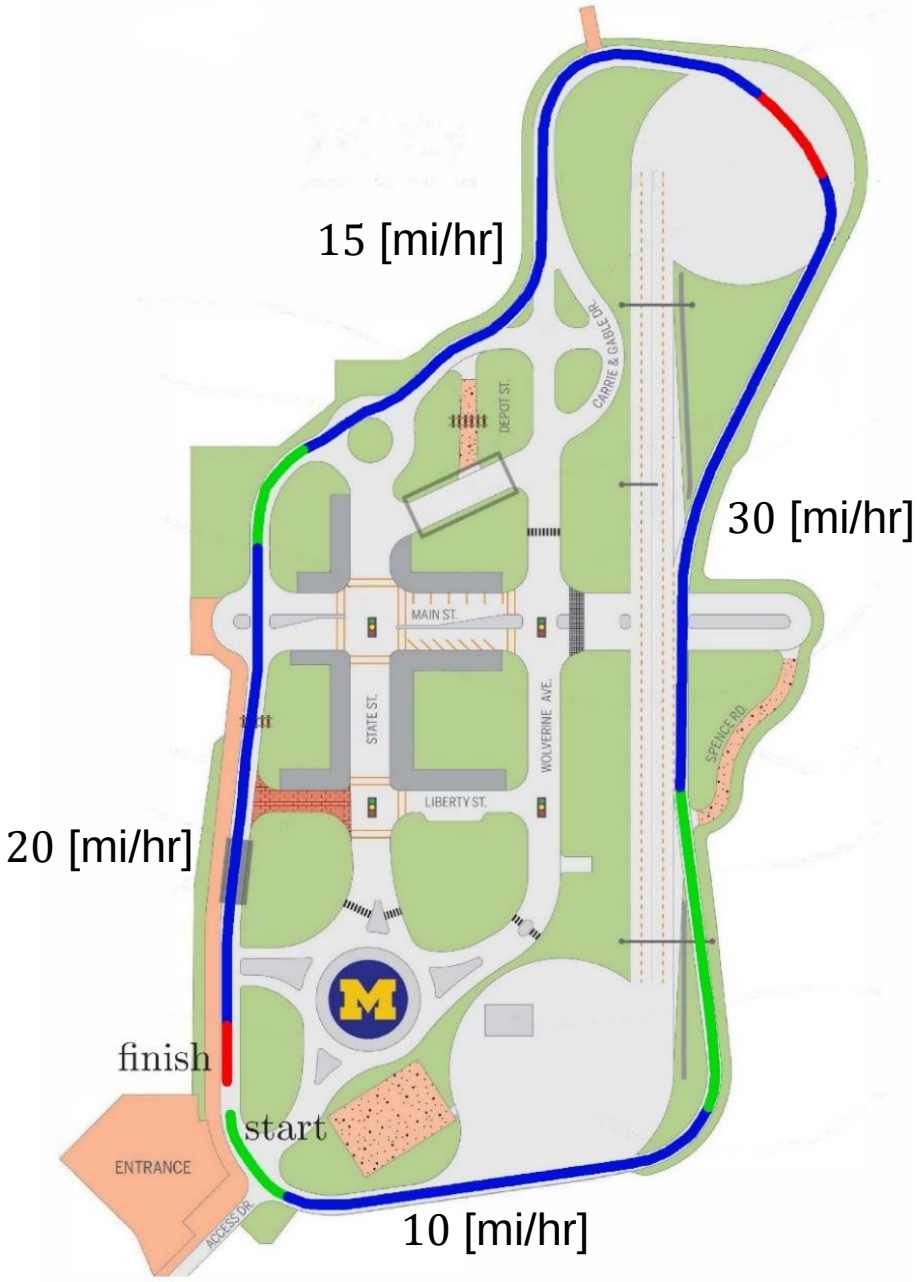
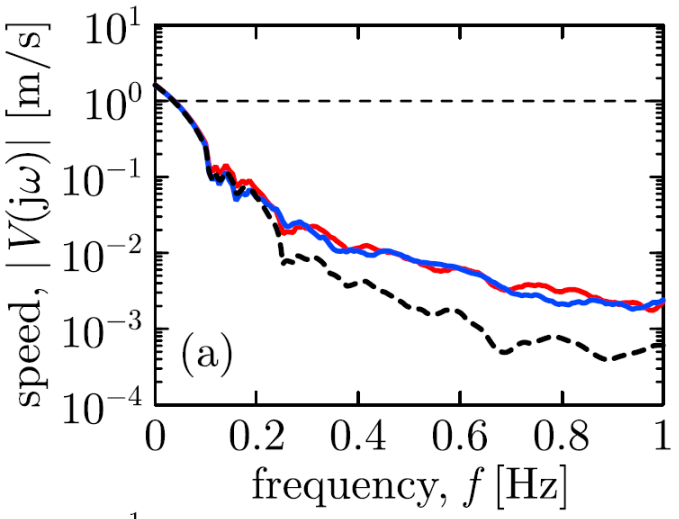
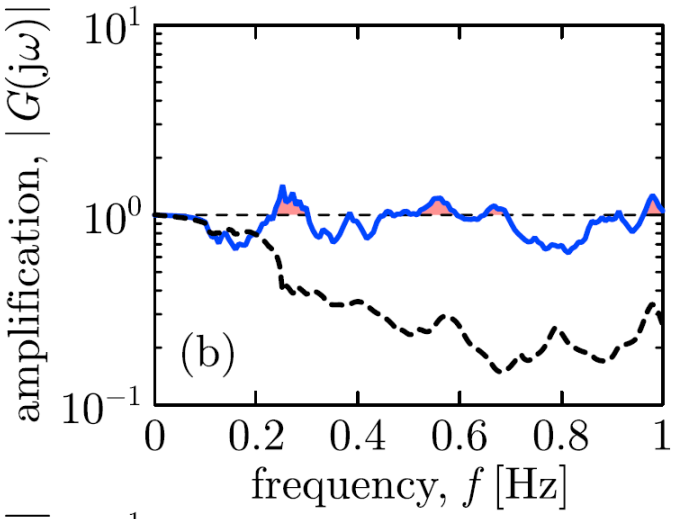
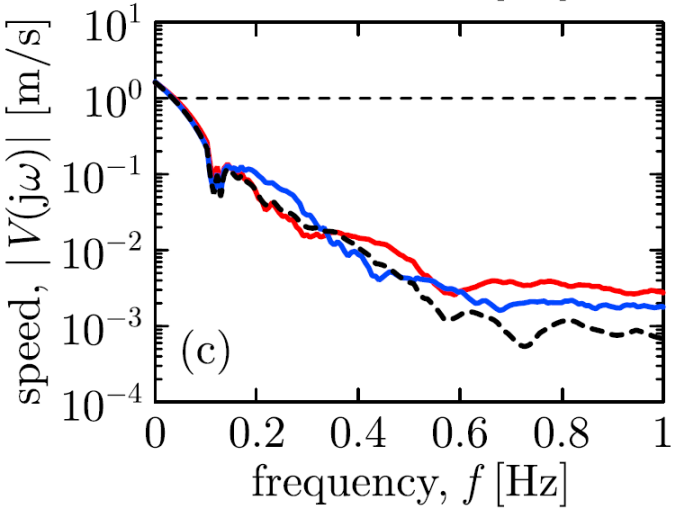
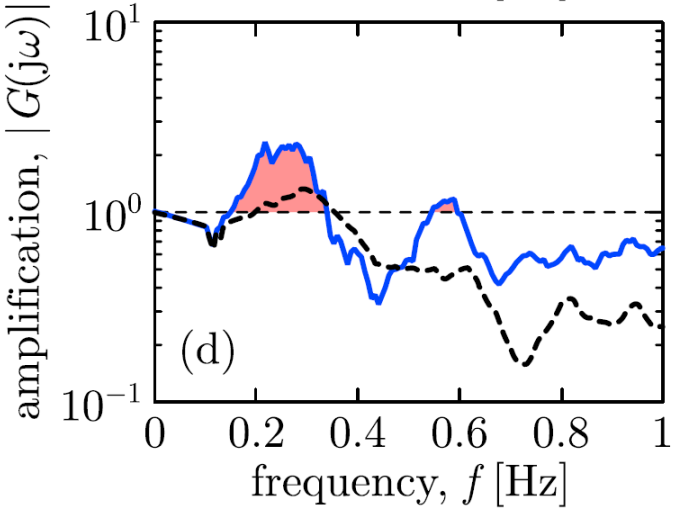


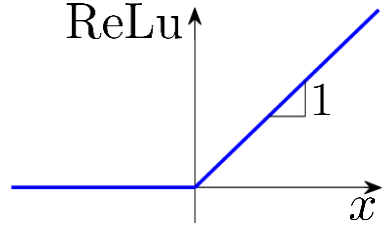



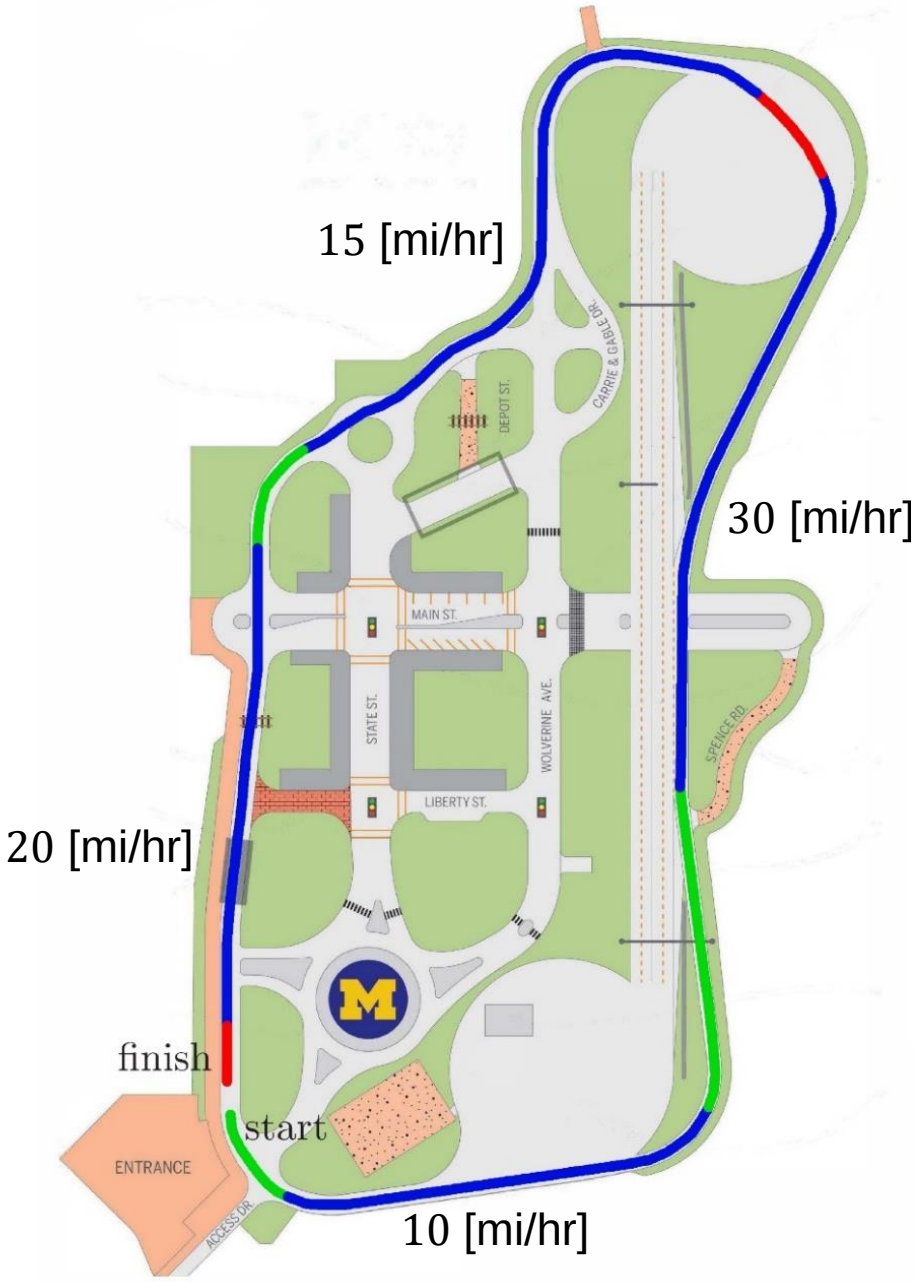



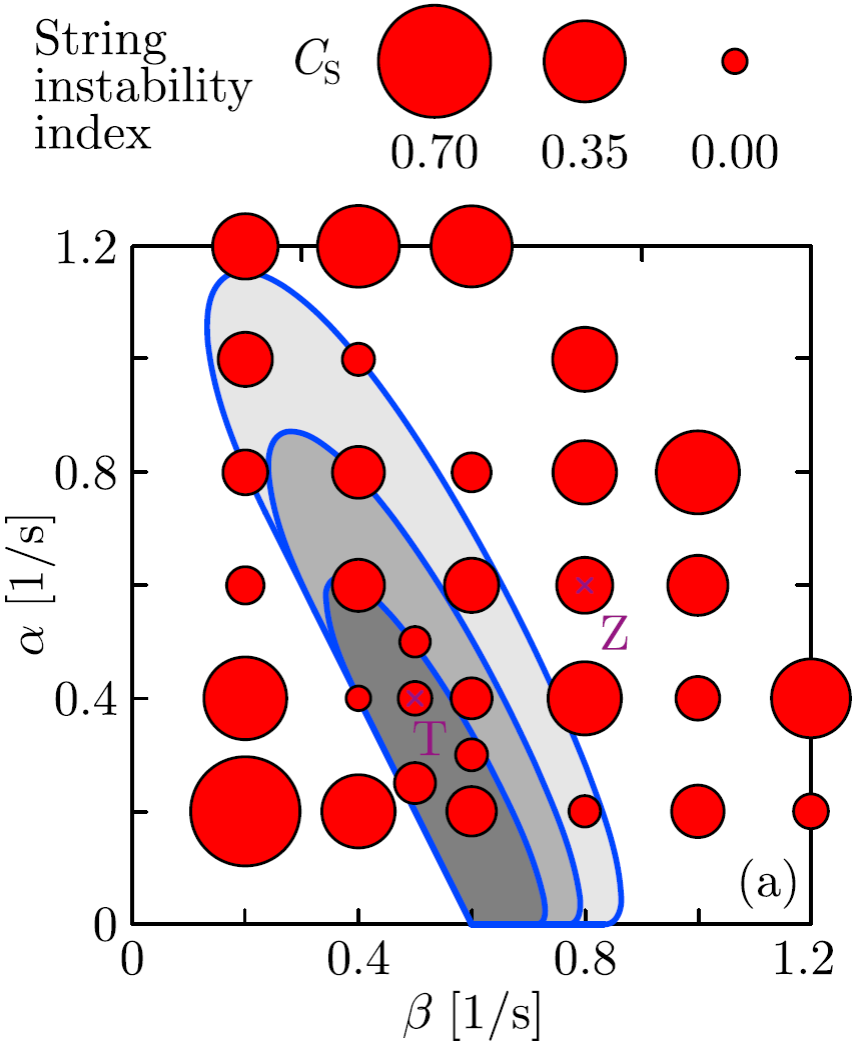

**String instability index**

$$C_{\mathrm{S}} = \int_{f_0}^{f_{\mathrm{end}}} \mathrm{ReLu}\left(\frac{G(f)}{G_1(f)} - 1\right) \mathrm{d}f$$



# Adaptive Cruise Control (ACC) - Experiments

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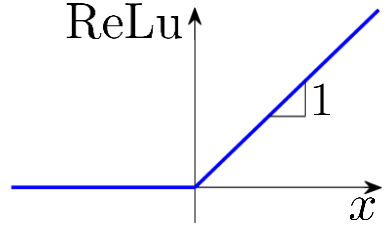
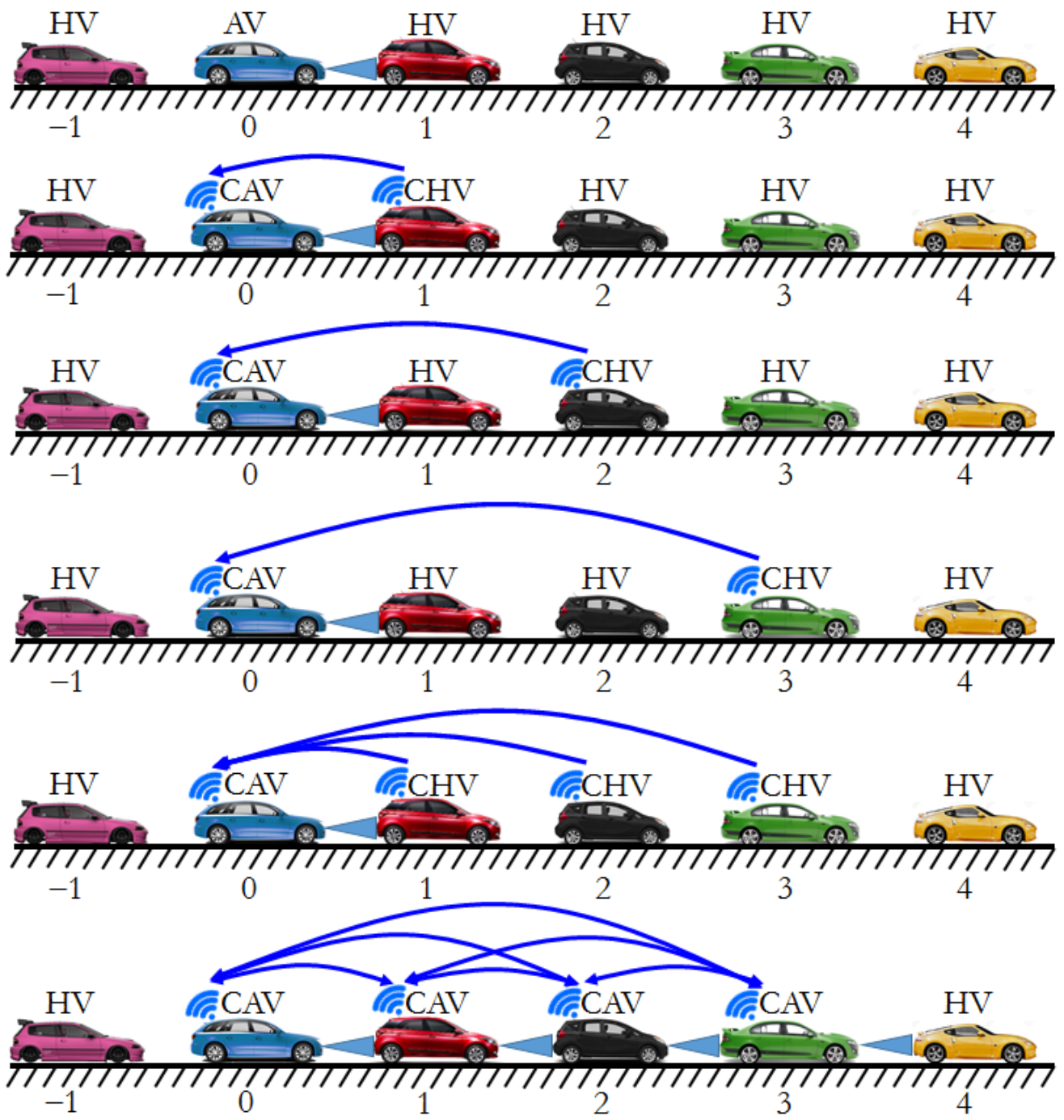


Mixed Traffic

Adaptive Cruise Control (ACC)

Connected Cruise Control (CCC)

Cooperative Adaptive Cruise Control (CACC)



# Connected Cruise Control (CCC)

Transportation Research Part C 46 (2014) 46–64

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

## Dynamics of connected vehicle systems with delayed acceleration feedback

Jin I. Ge *, Gábor Orosz

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VEHICLE SYSTEM DYNAMICS, 2016
VOL. 54, NO. 8, 1147–1176
http://dx.doi.org/10.1080/00423114.2016.1193209

## Connected cruise control: modelling, delay effects, and nonlinear behaviour

Gábor Orosz

Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA





## Optimal Control of Connected Vehicle Systems With Communication Delay and Driver Reaction Time

Jin I. Ge and Gábor Orosz

## Motif-Based Design for Connected Vehicle Systems in Presence of Heterogeneous Connectivity Structures and Time Delays

Linjun Zhang and Gábor Orosz

INTERNATIONAL JOURNAL OF ROBUST AND NONLINEAR CONTROL
*Int. J. Robust Nonlinear Control* 2017; **27**:781–803
Published online 10 August 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/rnc.3600



## Application of Predictor Feedback to Compensate Time Delays in Connected Cruise Control

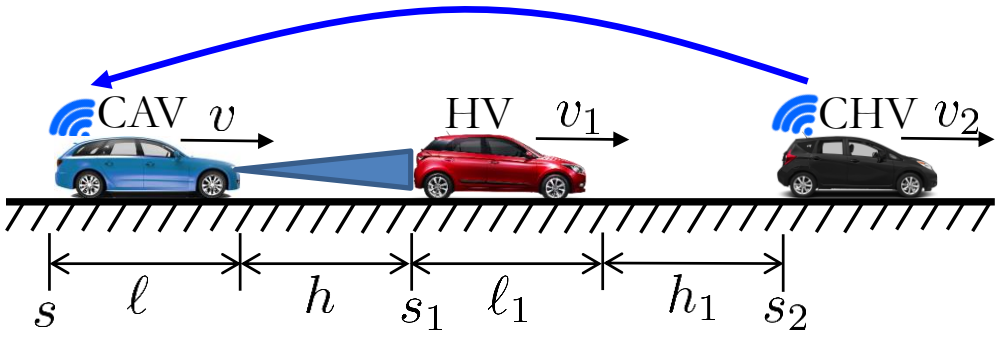
Tamás G. Molnár, Wubing B. Qin, Tamás Insperger, and Gábor Orosz

## Consensus and disturbance attenuation in multi-agent chains with nonlinear control and time delays

Linjun Zhang*,† and Gábor Orosz

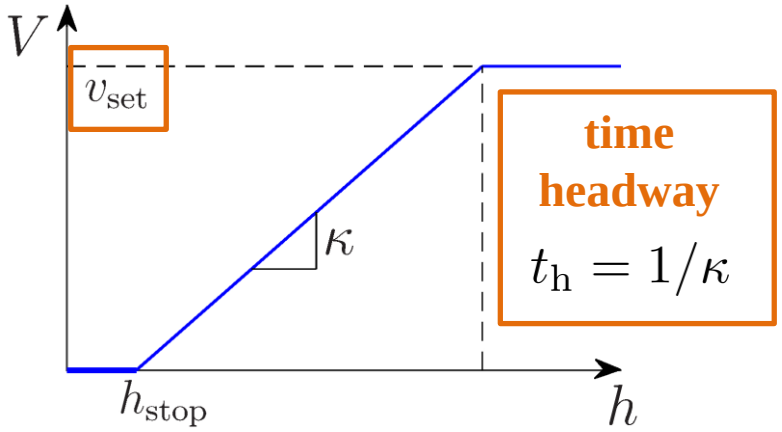
*Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48105, USA*

# Connected Cruise Control (CCC)




## CCC algorithm – going beyond the line of sight

$$u = \alpha\,(V(h) - v) + \beta_1(v_1 - v) + \boxed{\beta_2(v_2 - v)}$$



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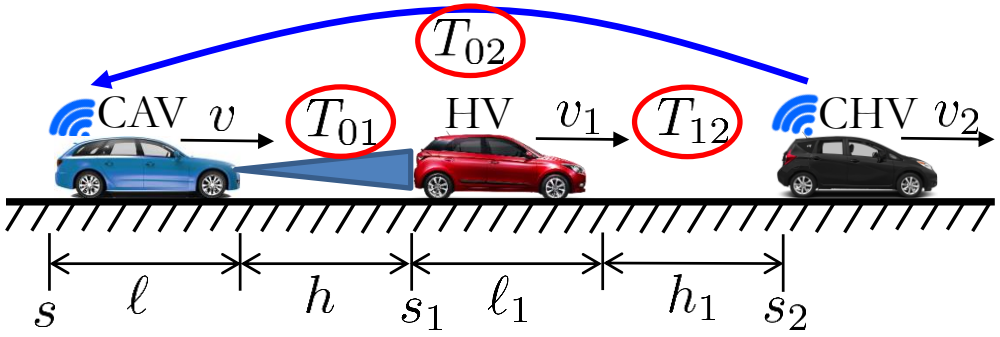



## Link transfer functions

$$T_{ij}(s)$$

## Head-to-tail transfer function

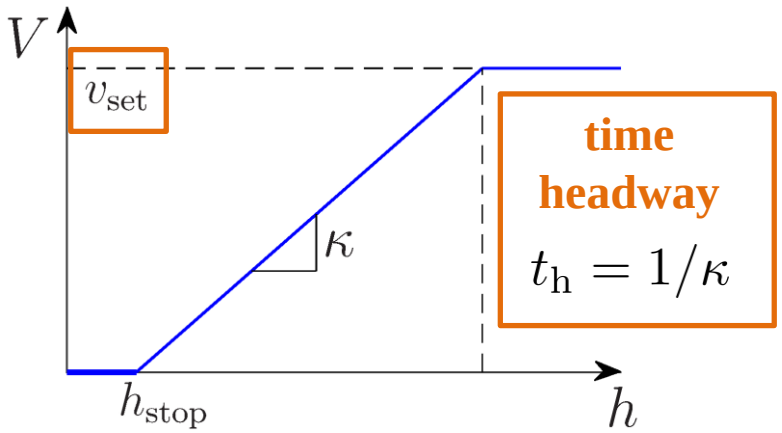
$$G_{02}(s) = T_{01}(s)T_{12}(s) + T_{02}(s)$$

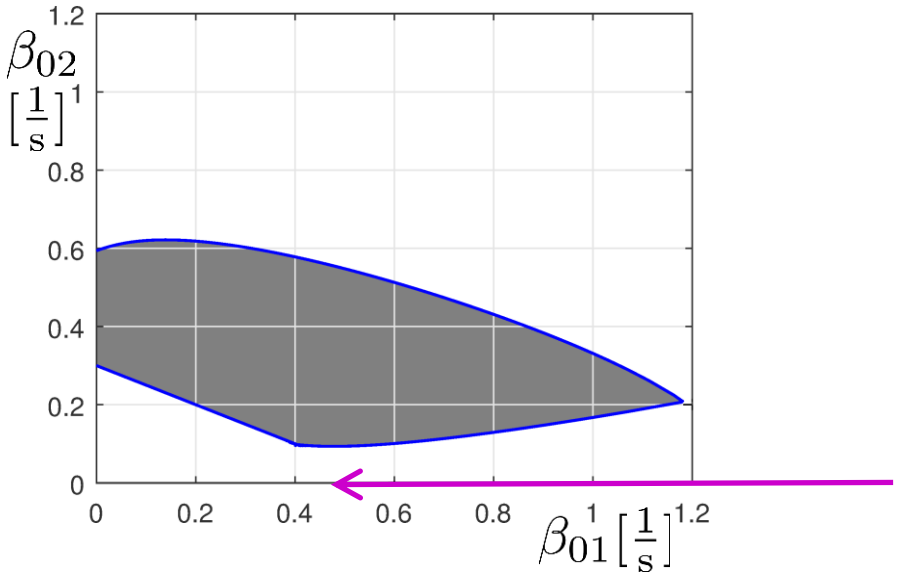
## CCC algorithm – going beyond the line of sight

$$u = \alpha\,(V(h) - v) + \beta_1(v_1 - v) + \boxed{\beta_2(v_2 - v)}$$

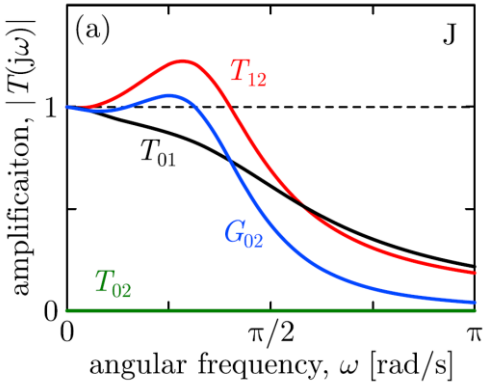
## Head-to-tail string stability

$$\boxed{|G_{02}(\mathrm{j}\omega)| < 1, \quad \forall \omega > 0}$$

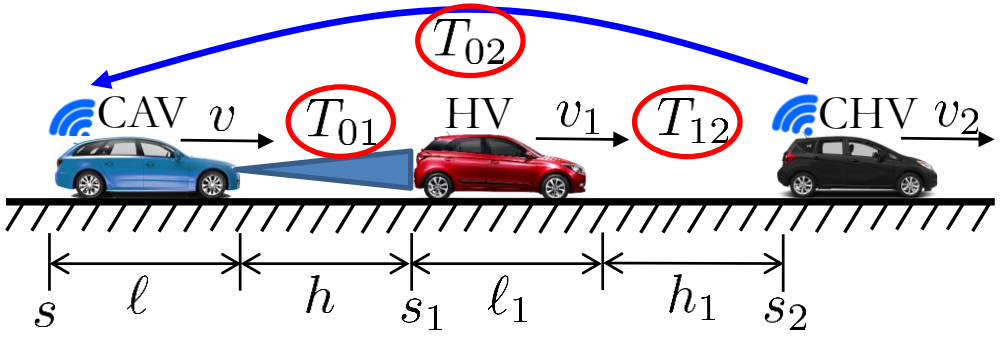



**Without connectivity**



# Connected Cruise Control (CCC)

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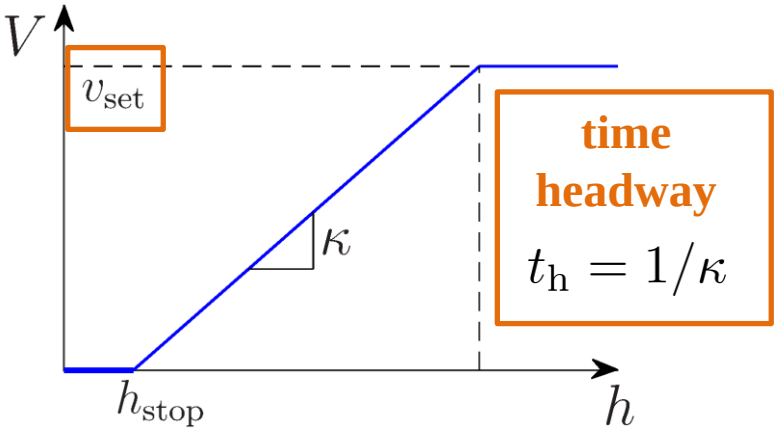
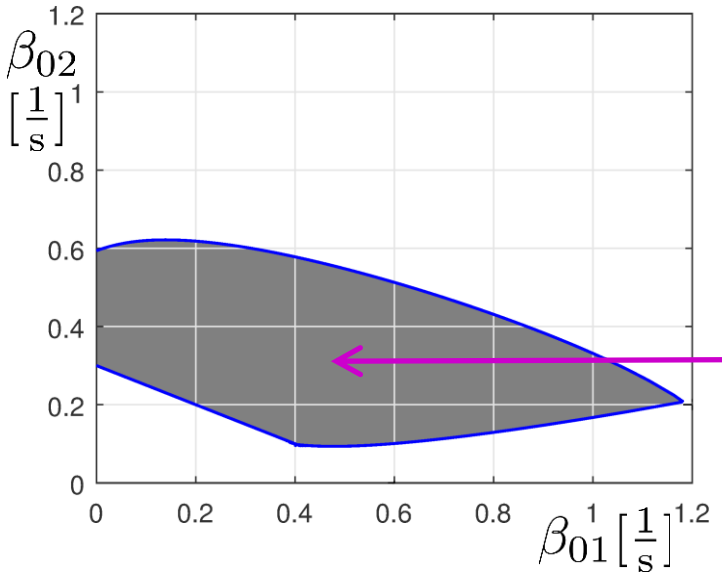
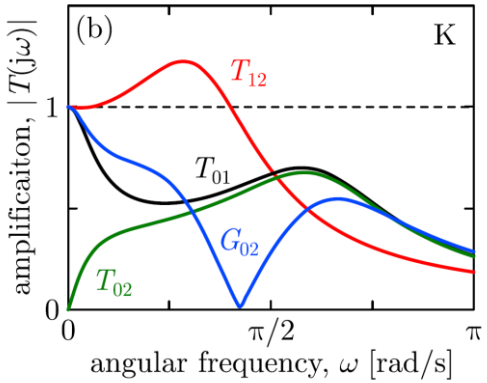
## Head-to-tail string stability

$$\boxed{|G_{02}(\mathrm{j}\omega)| < 1, \quad \forall \omega > 0}$$

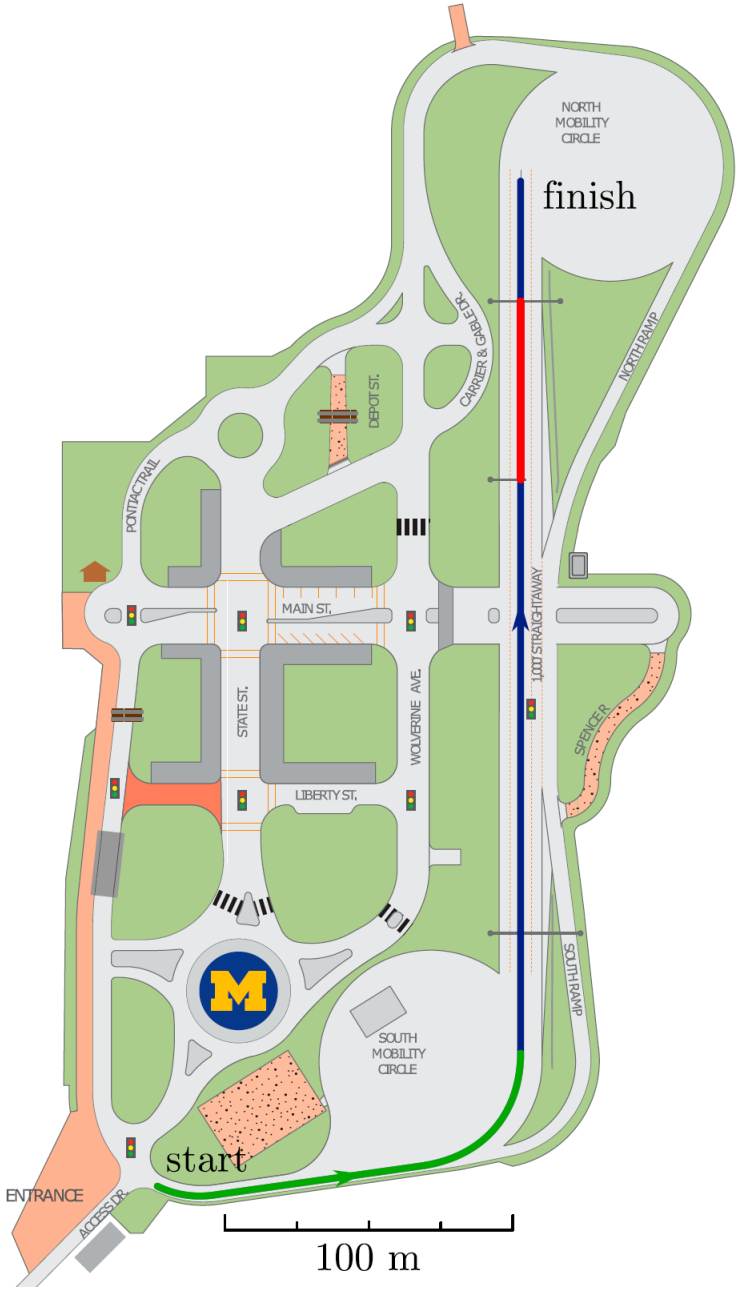



**With connectivity**



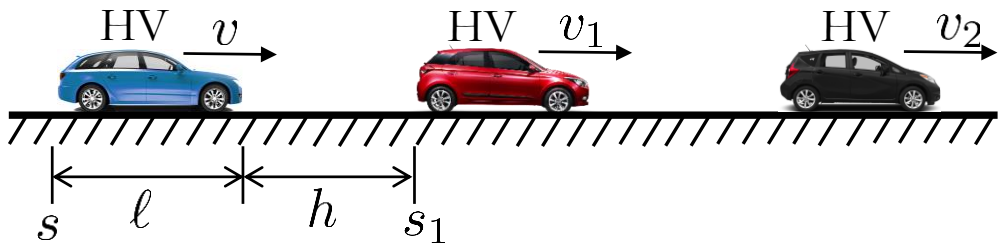
# Human Driver - Experiments

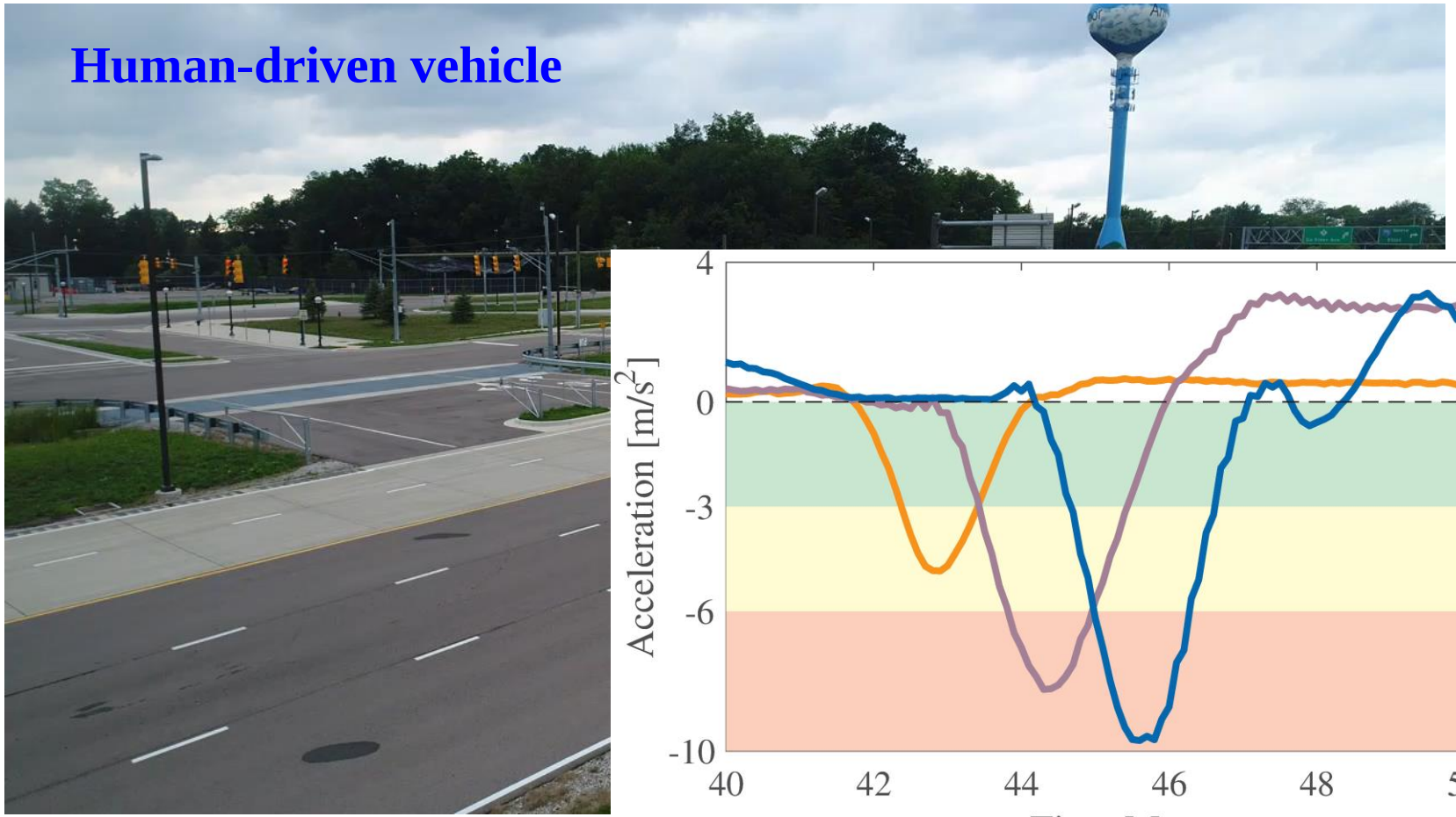



Acceleration

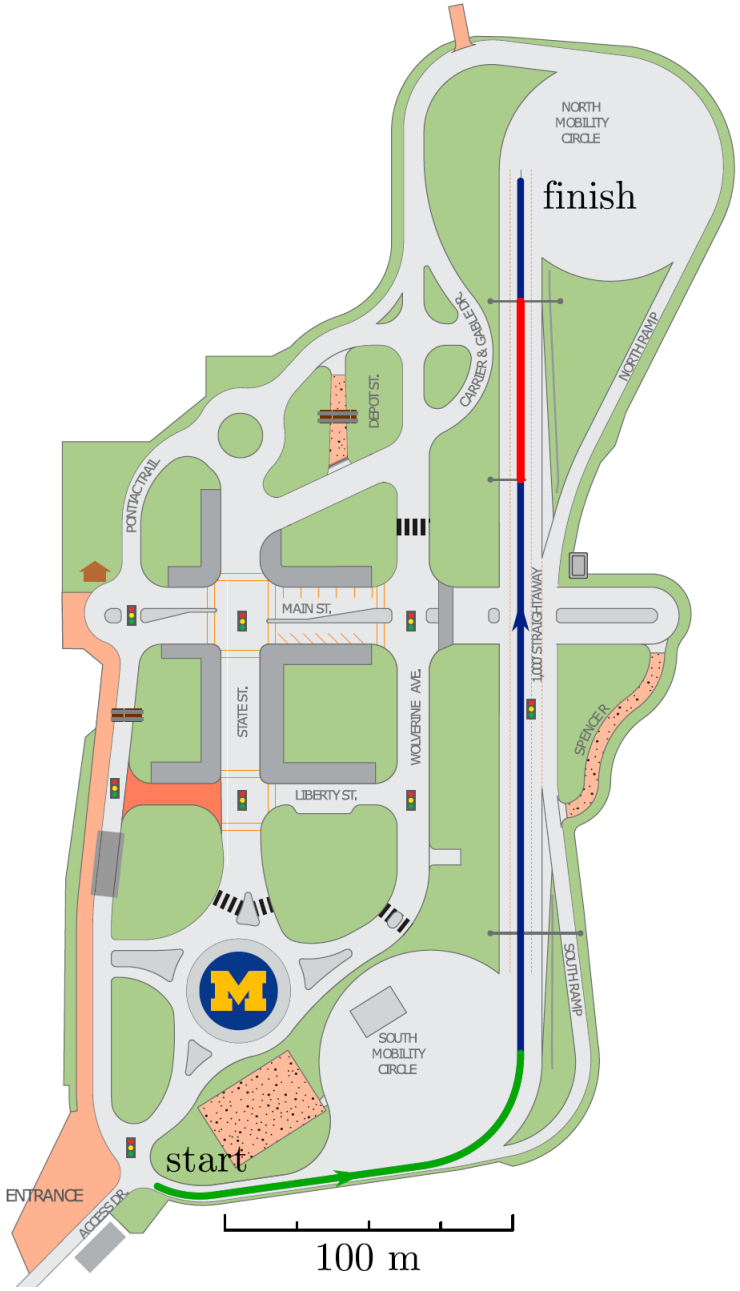
Constant Speed

Braking



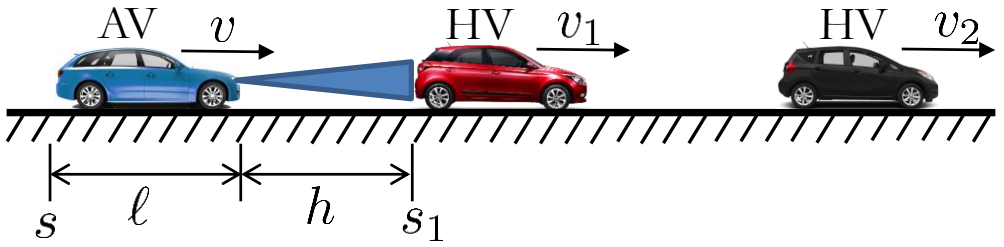
# Adaptive Cruise Control (ACC) - Experiments

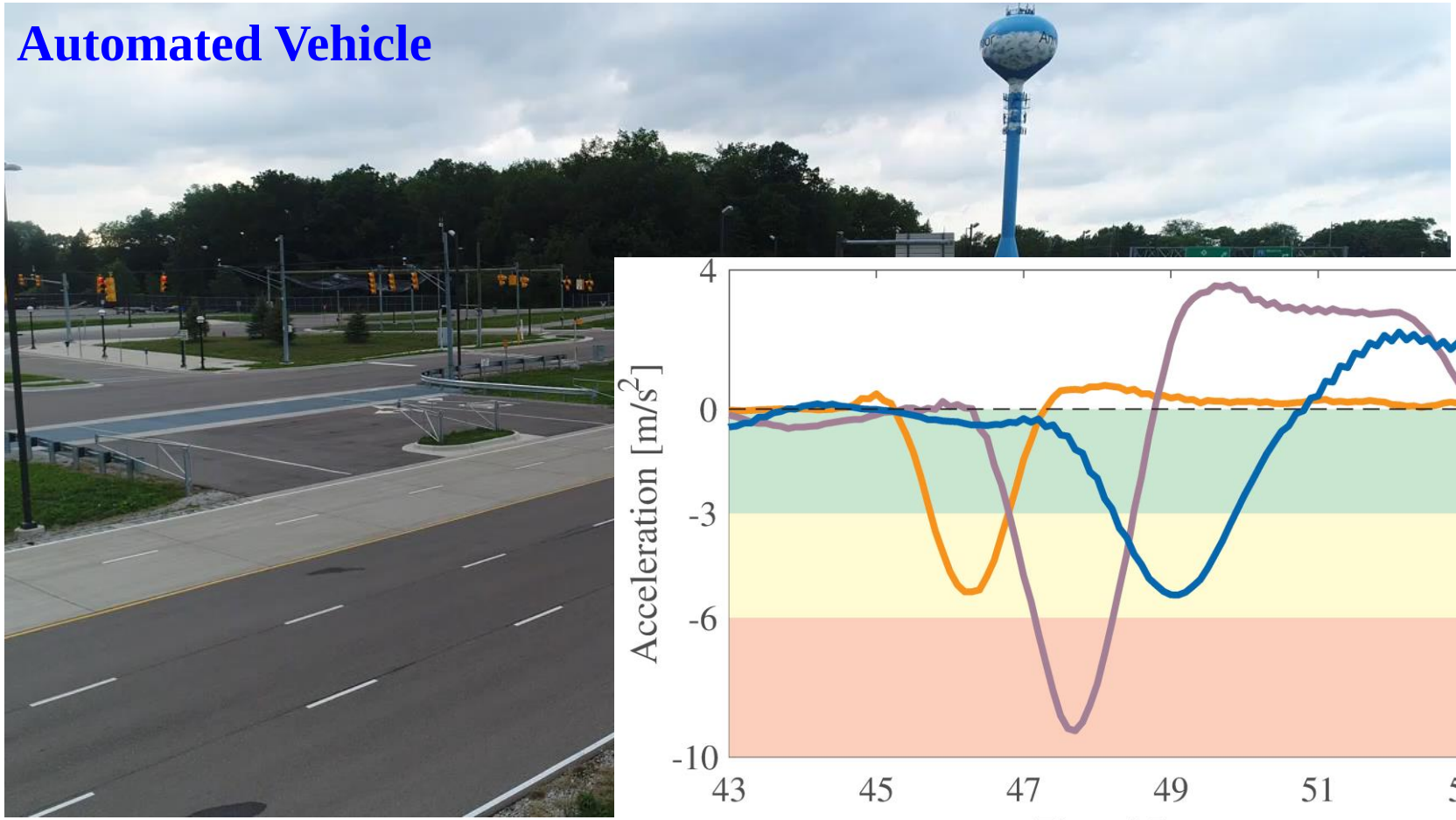



Acceleration

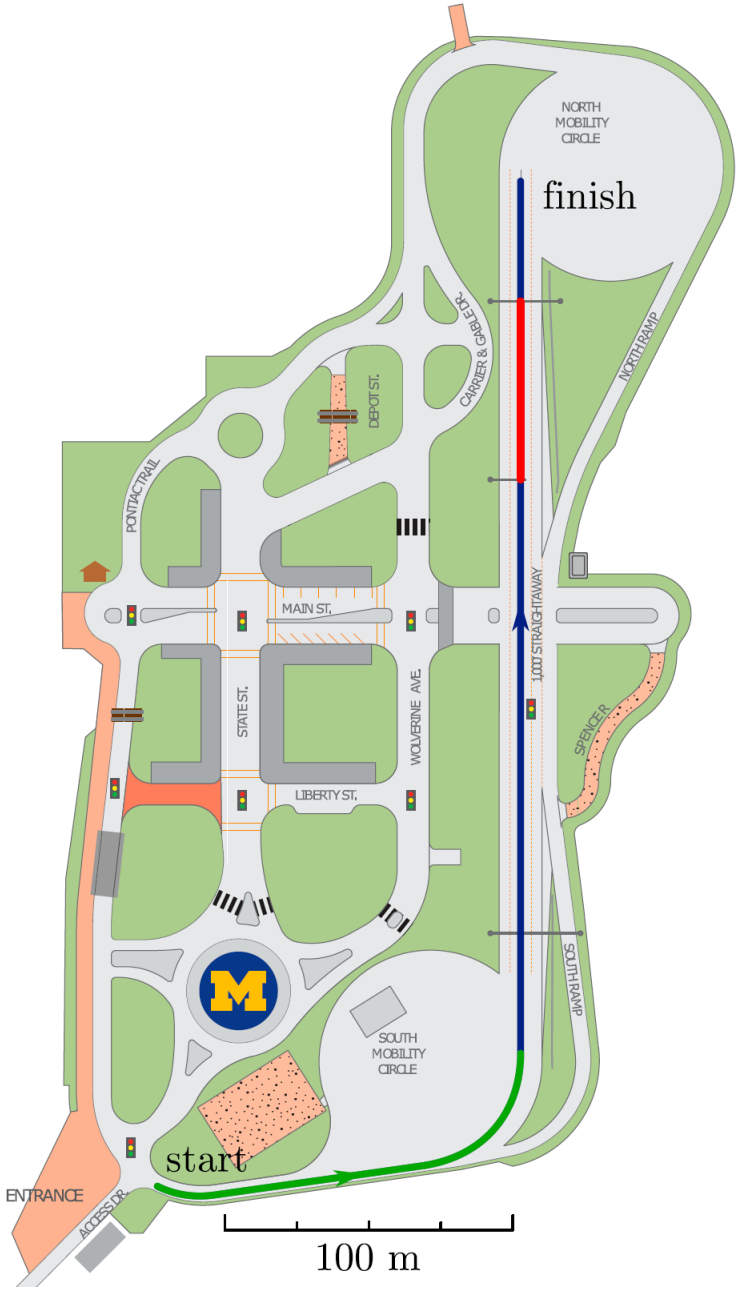
Constant Speed

Braking



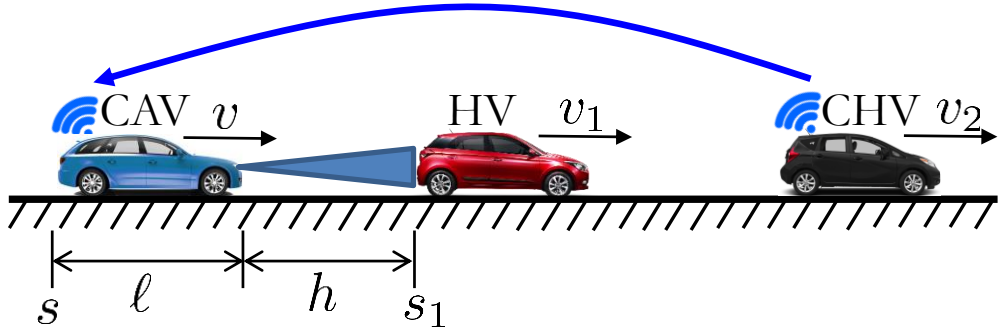
# Connected Cruise Control (CCC) - Experiments

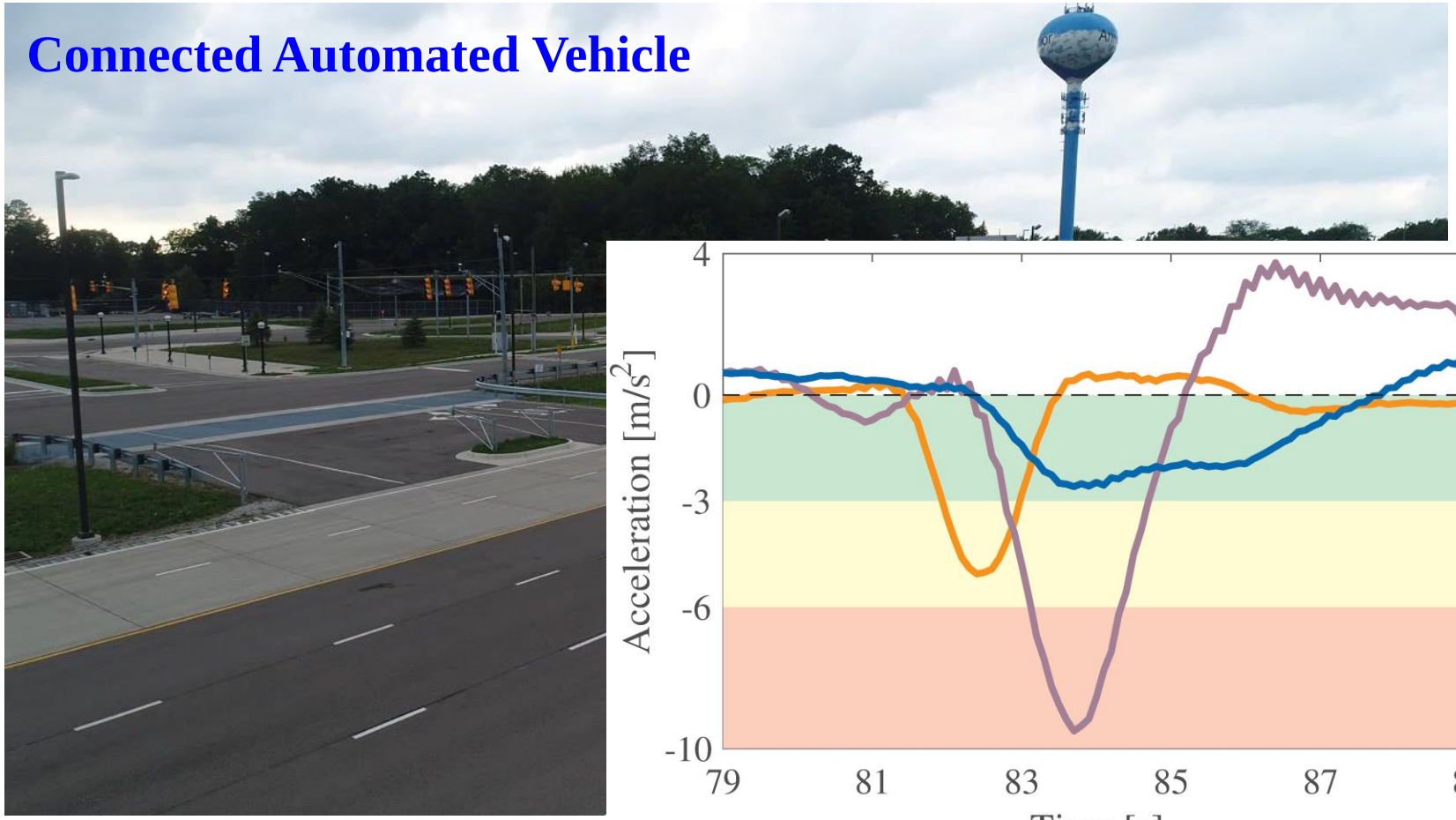



Acceleration

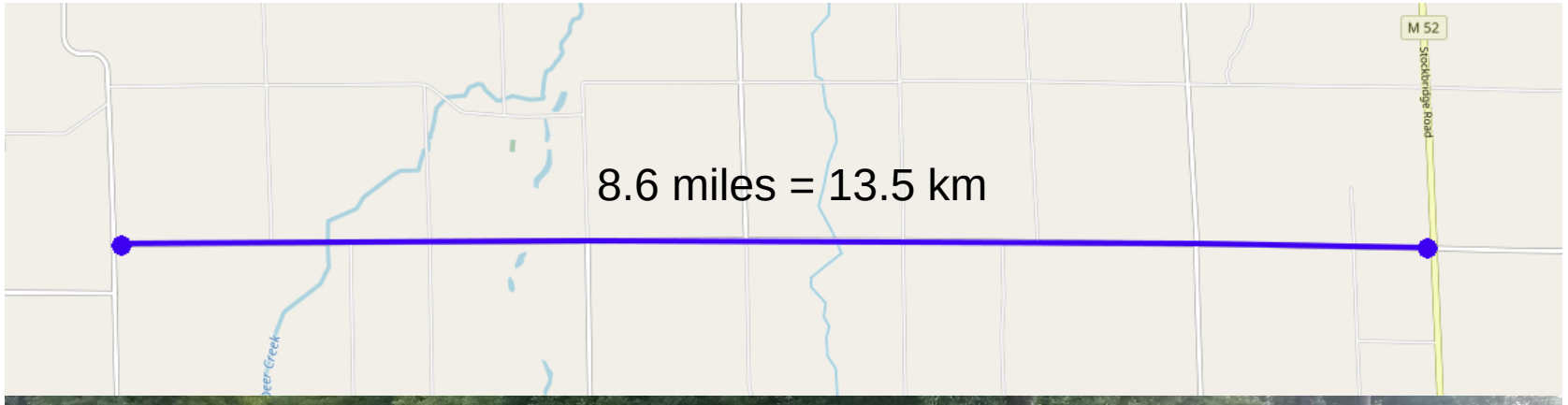
Constant Speed

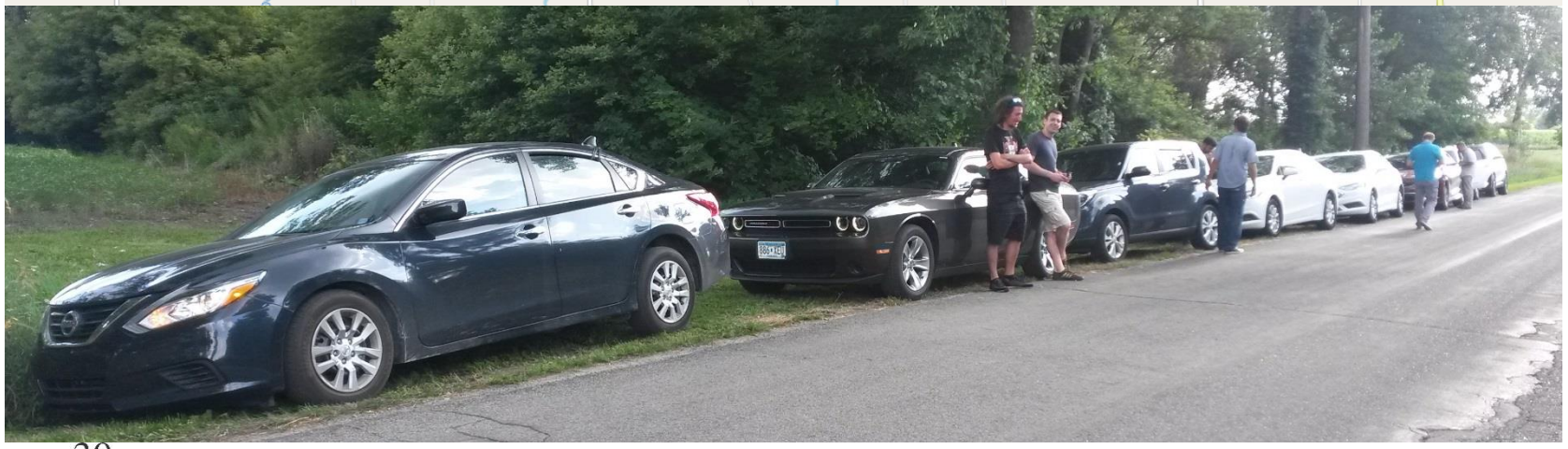
Braking

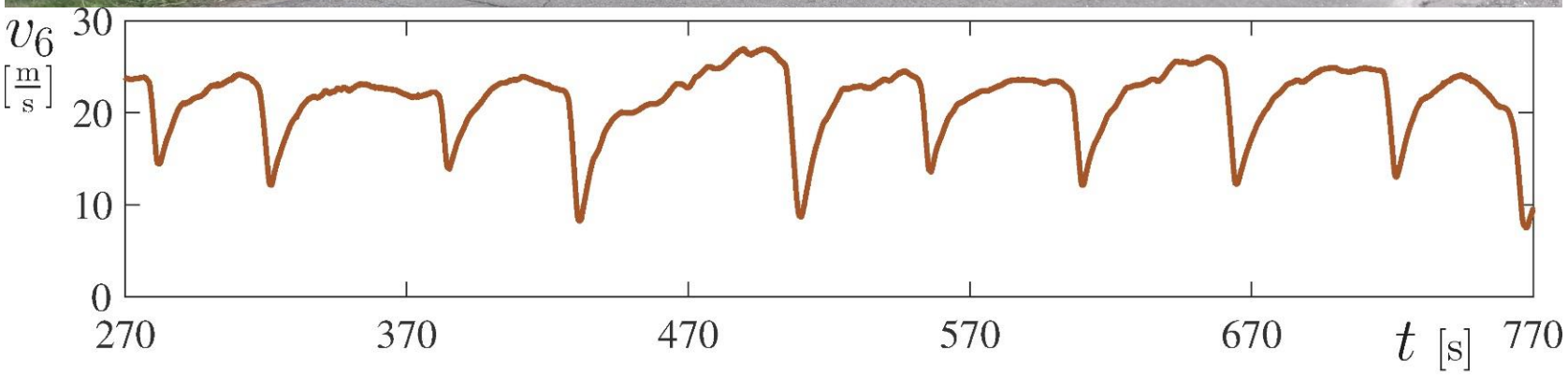


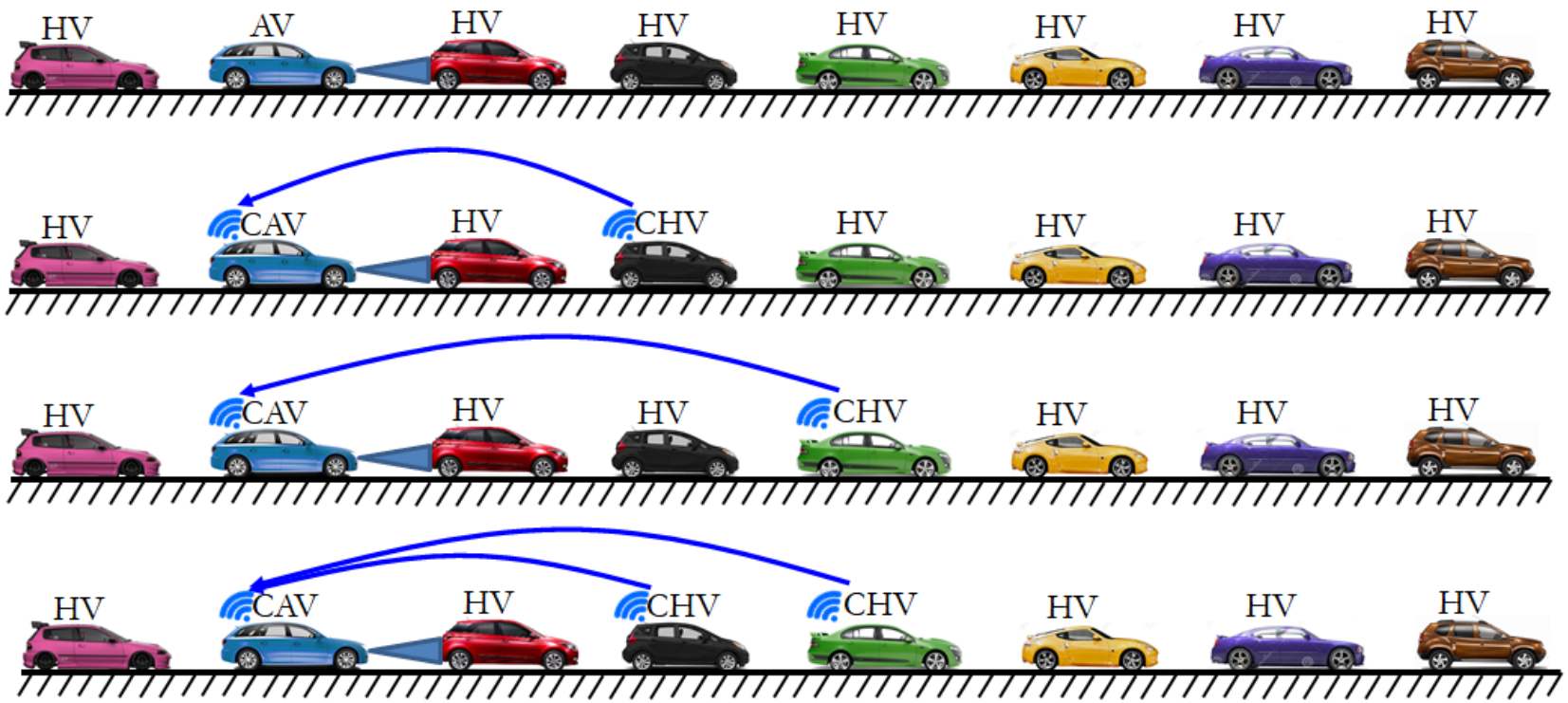
# Experiments in Mixed Traffic

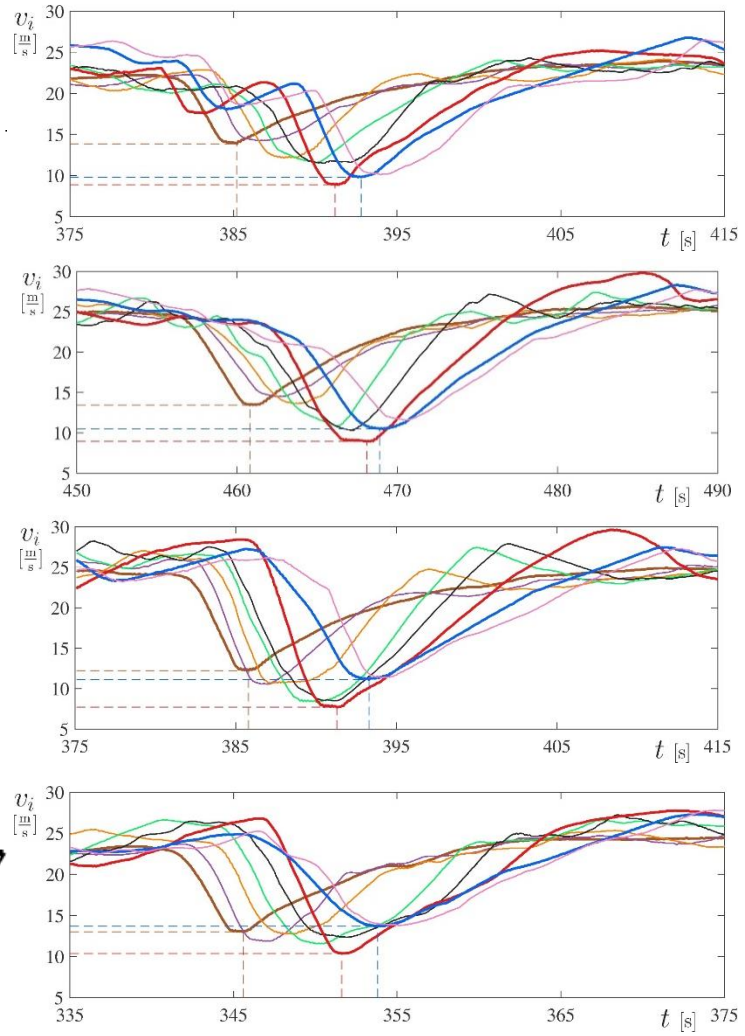




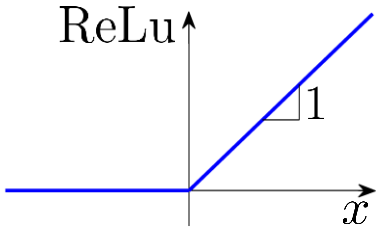
# Experiments in Mixed Traffic



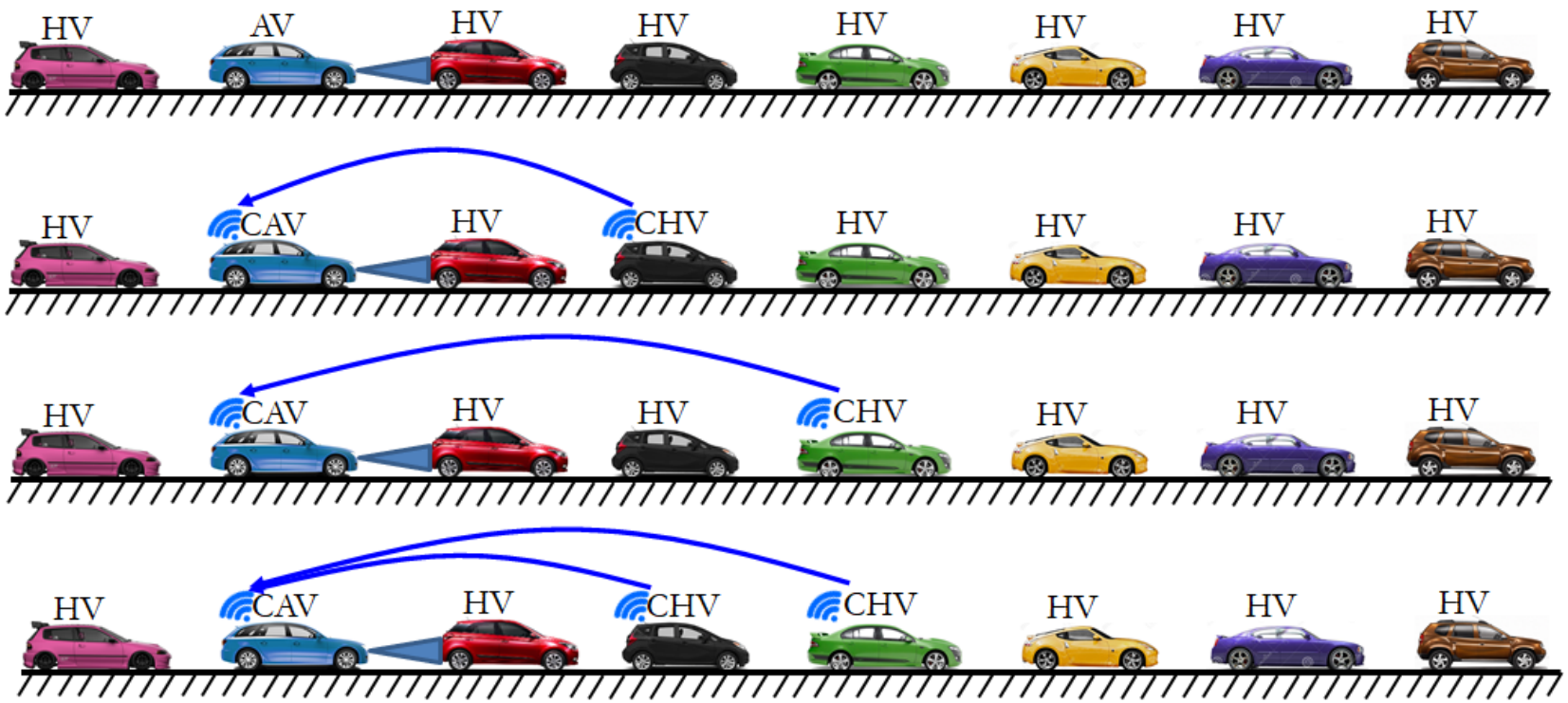



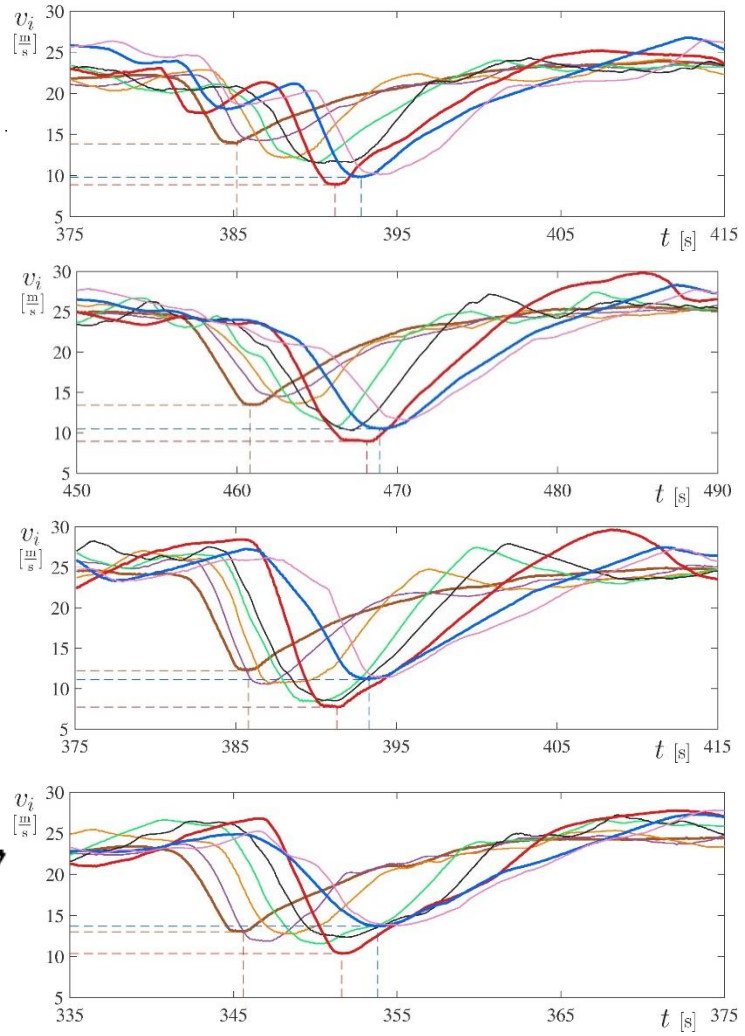

## Energy consumption (per unit mass)

$$w_i = \int_0^T \mathrm{ReLu}\big(\dot{v}_i(\theta)\big) v_i(\theta) \mathrm{d}\theta$$



# Experiments in Mixed Traffic




7% energy saving by connectivity

19% energy saving by connectivity

| | $w_{-1}$ [J/kg] | $w_0$ [J/kg] | $w_1$ [J/kg] | $w_2$ [J/kg] | $w_3$ [J/kg] | $w_4$ [J/kg] | $w_5$ [J/kg] | $w_6$ [J/kg] |
|---|---|---|---|---|---|---|---|---|
| Exp #1 | 86 | 93 | 100 | 79 | 77 | 72 | 66 | 63 |
| Exp #2 | 90 | 88 | 97 | 100 | 96 | 87 | 83 | 81 |
| Exp #3 | 83 | 84 | 100 | 94 | 91 | 81 | 77 | 73 |
| Exp #4 | 80 | 76 | 100 | 84 | 85 | 77 | 71 | 65 |

# Connectivity can Enhance the Benefits of Automation

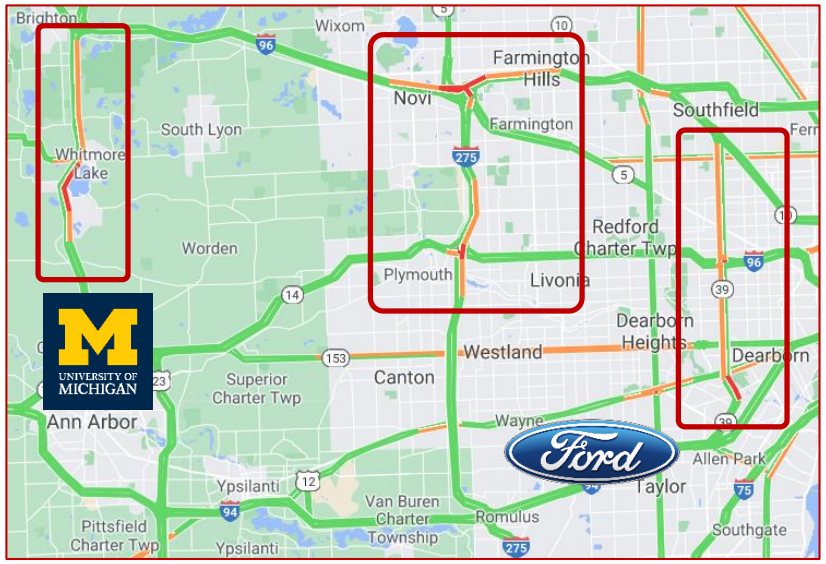
How can we
leverage connectivity
in large scale traffic?

# Connectivity can Enhance the Benefits of Automation

# Large Scale Transportation Systems with Lean Penetration of CAVs

Traffic jams cost time, fuel, money, increase pollution

V2X connectivity – can help!



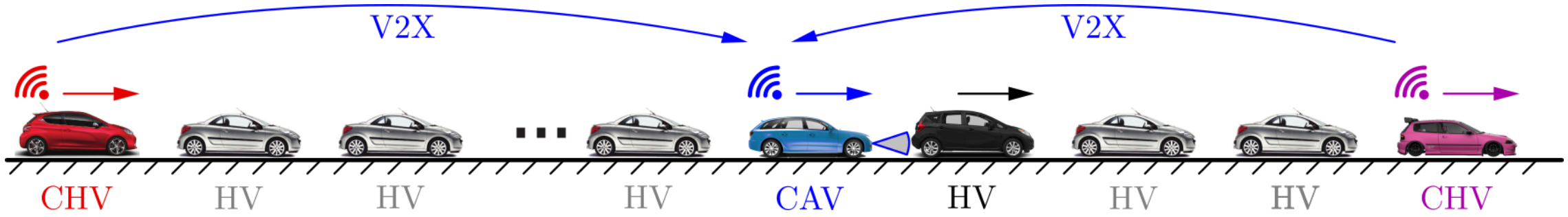
# Connectivity may Help to Improve Traffic Efficiency Even for Lean Penetration of Connectivity

**Connected Traffic Control (CTC)**

Measure effect on traffic behind

**Connected Cruise Control (CCC)**

Anticipate/predict traffic ahead



# Connectivity-based Traffic Predictions

Proceedings of Machine Learning Research vol 144:1–13, 2021 3rd Annual Conference on Learning for Dynamics and Control

## Traffic Forecasting using Vehicle-to-Vehicle Communication

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## Delayed Lagrangian continuum models for on-board traffic prediction

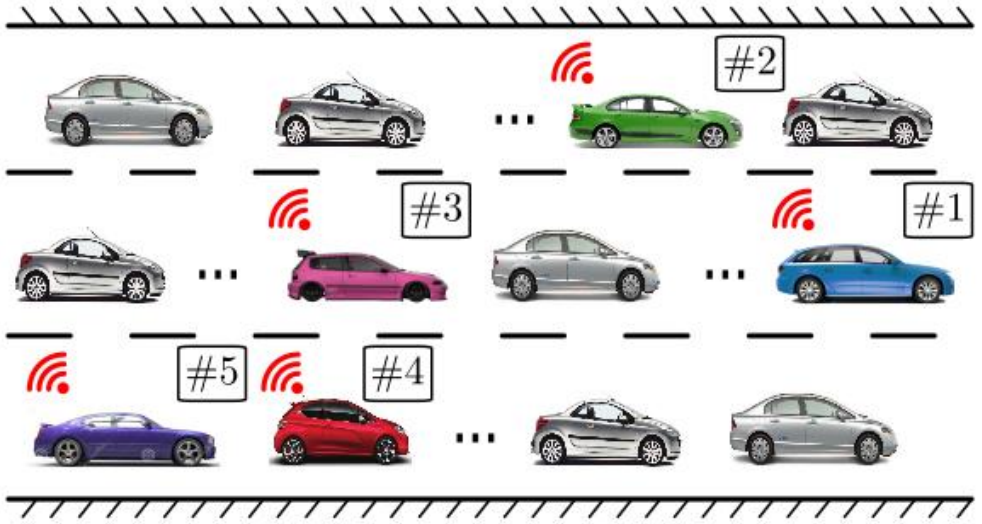
Tamás G. Molnár [a,*], Devesh Upadhyay [b], Michael Hopka [b], Michiel Van Nieuwstadt [b], Gábor Orosz [a,c]

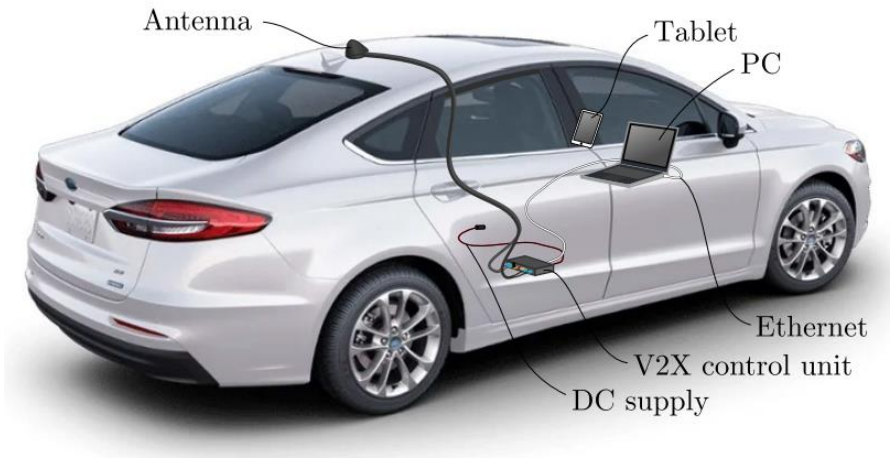
**2022 American Control Conference (ACC)**
**Atlanta, USA, June 8-10, 2022**

## On-Board Traffic Prediction for Connected Vehicles: Implementation and Experiments on Highways

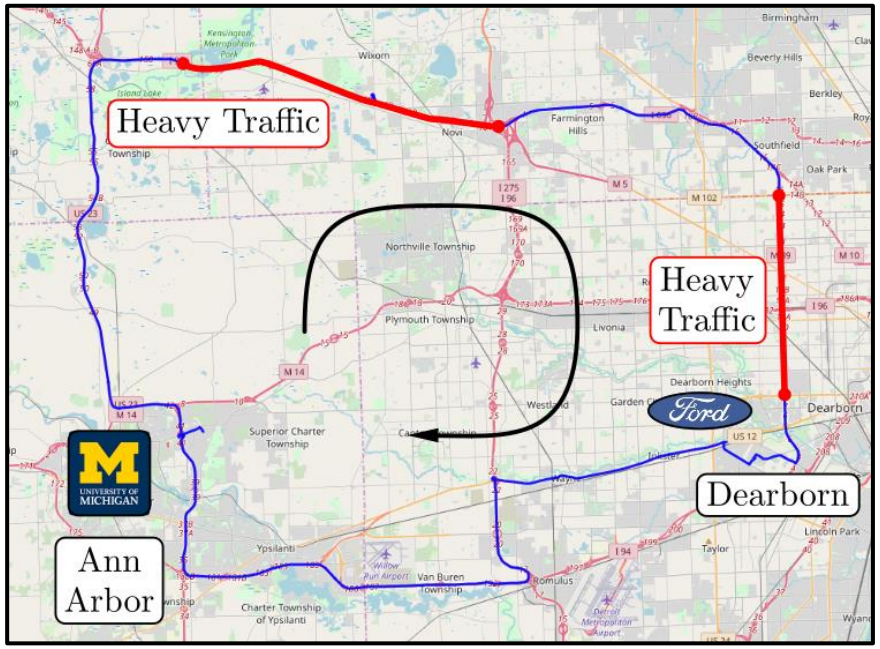
Tamás G. Molnár, Xunbi A. Ji, Sanghoon Oh, Dénes Takács,
Michael Hopka, Devesh Upadhyay, Michiel Van Nieuwstadt, and Gábor Orosz

# We Recorded Data in Real Traffic Conditions




Experiments with connected human-driven vehicles

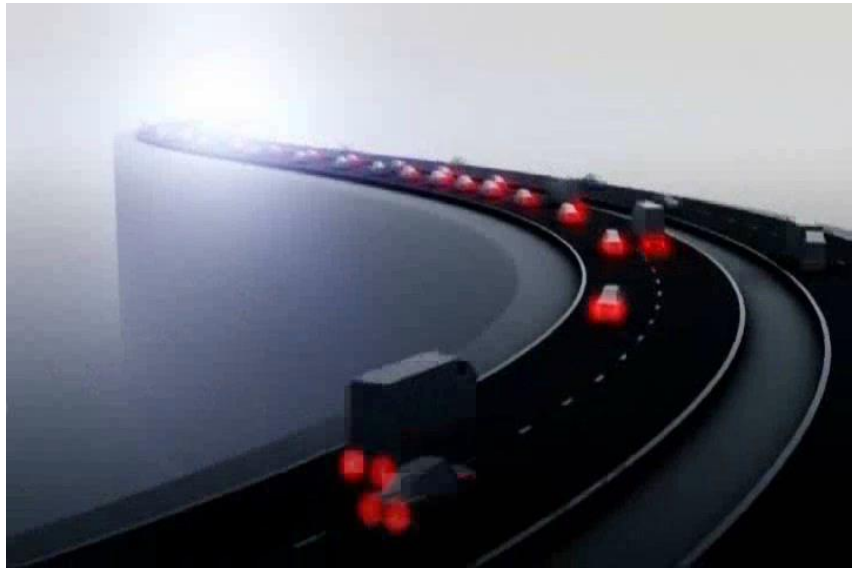



Natural driving no platooning, not necessarily same lane

Trajectory data in congestions

# GPS Trajectory Data Obtained via Connectivity

- Trajectories are similar, shifted copies of each other
- Congestion waves propagate in time and space (5-6 m/s)



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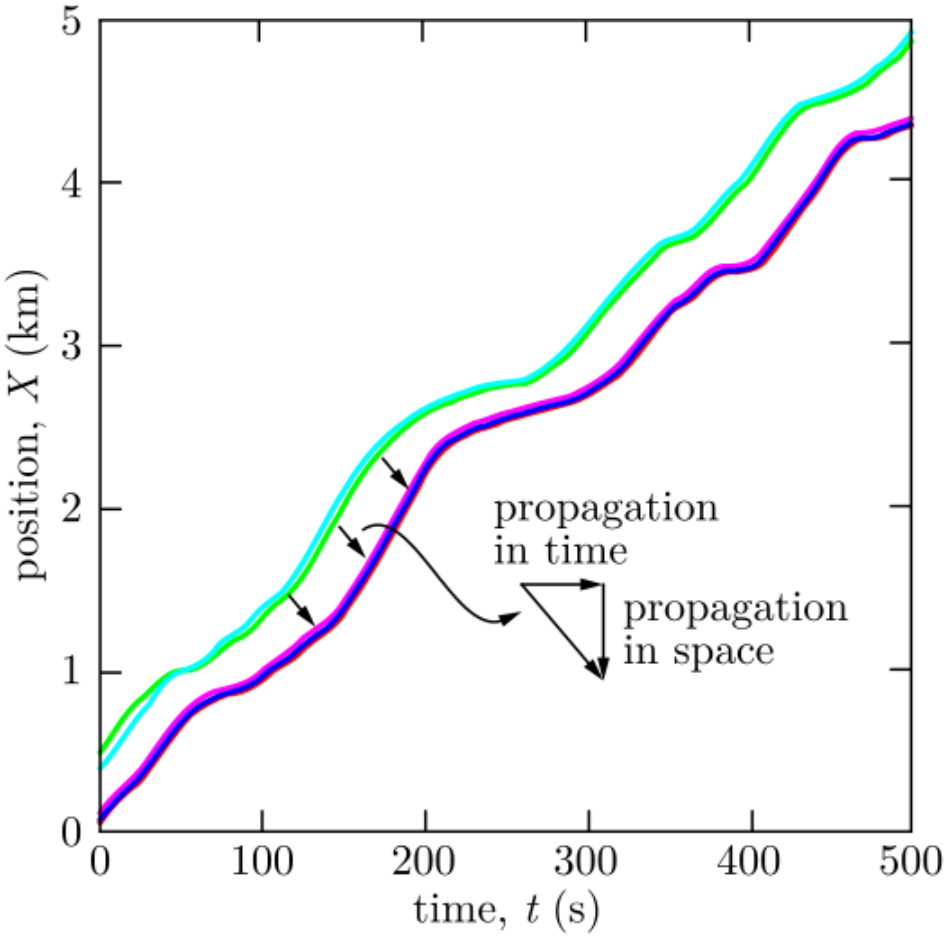
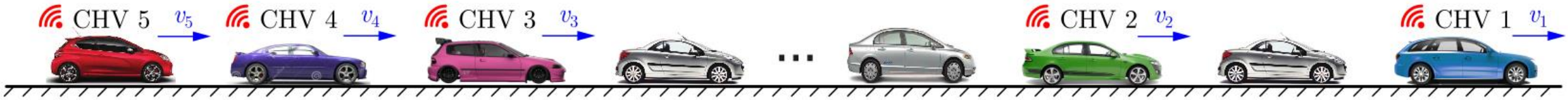


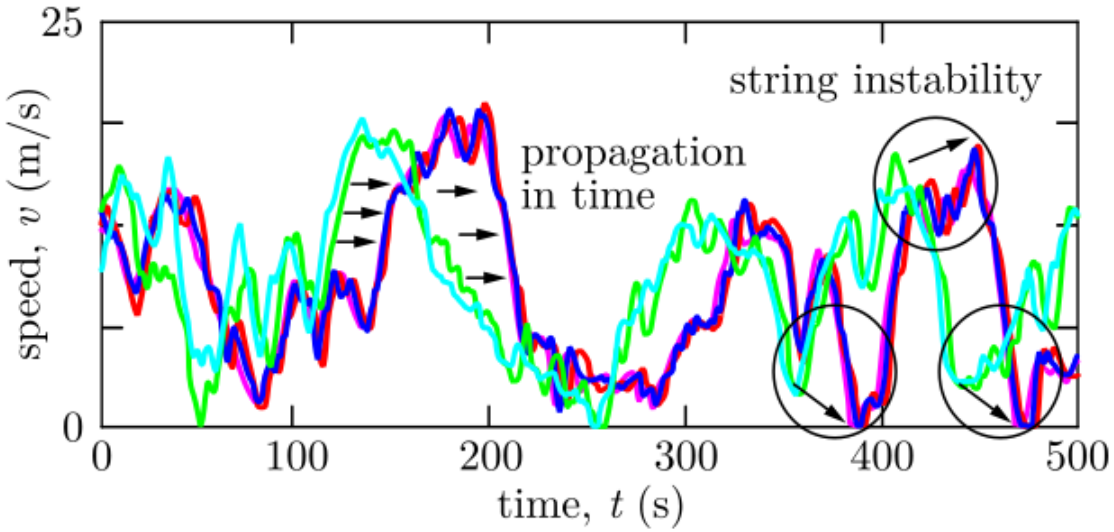



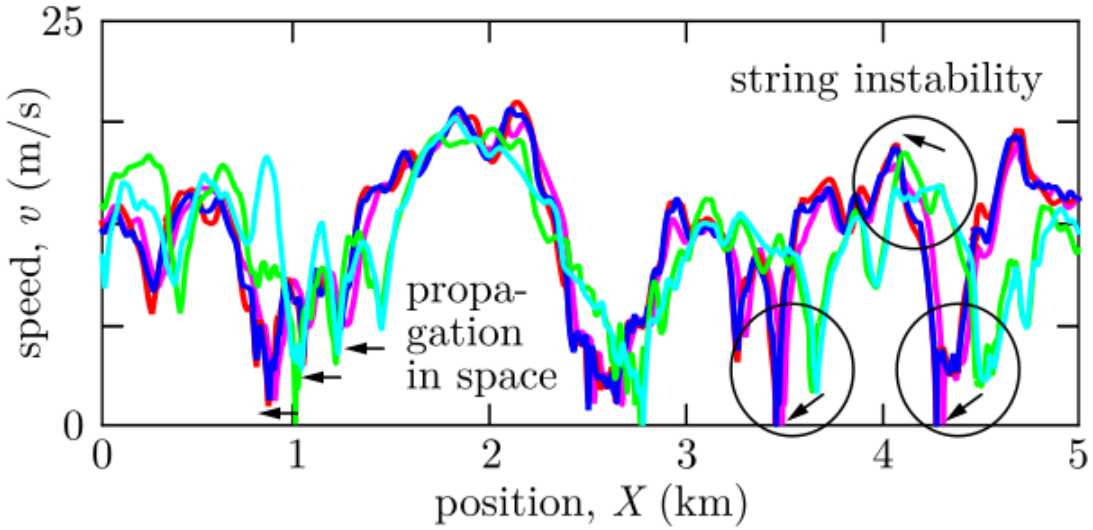
# V2X Data are Rich and Useful

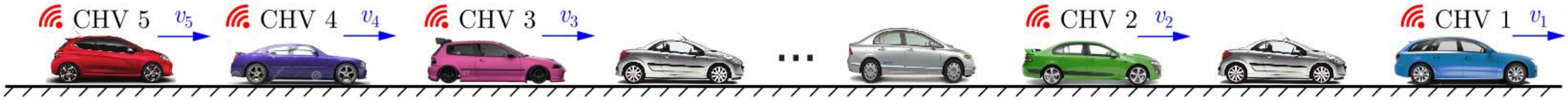
**Main features of V2X data:**

- Propagation of traffic in time
- Propagation of traffic in space
- String instability

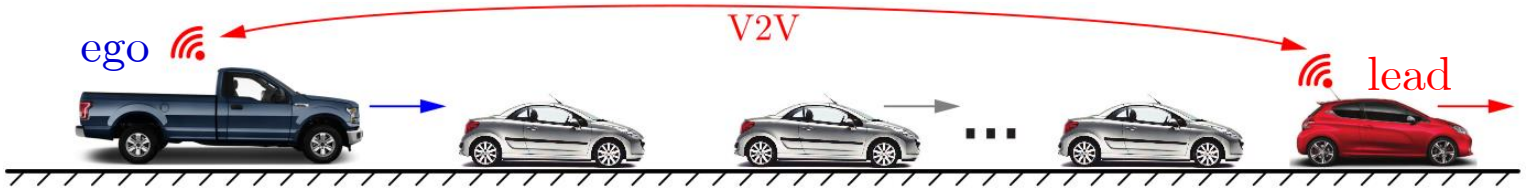
How to directly utilize V2X data for traffic prediction and control?



# Connectivity Enables Traffic Predictions

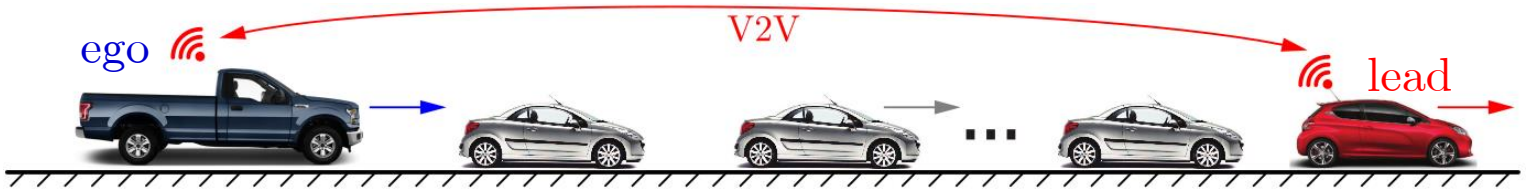



**Goal:** predict upcoming slowdowns

**Benefit:** optimized operation of our vehicle using prediction

**Method:** V2X-connectivity reveals what is ahead → tells what may happen to us later

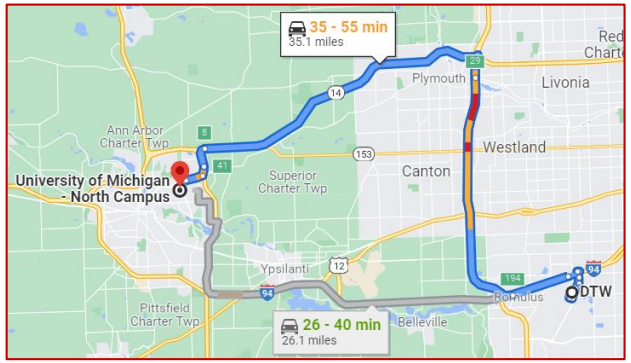
# Connectivity Enables Traffic Predictions

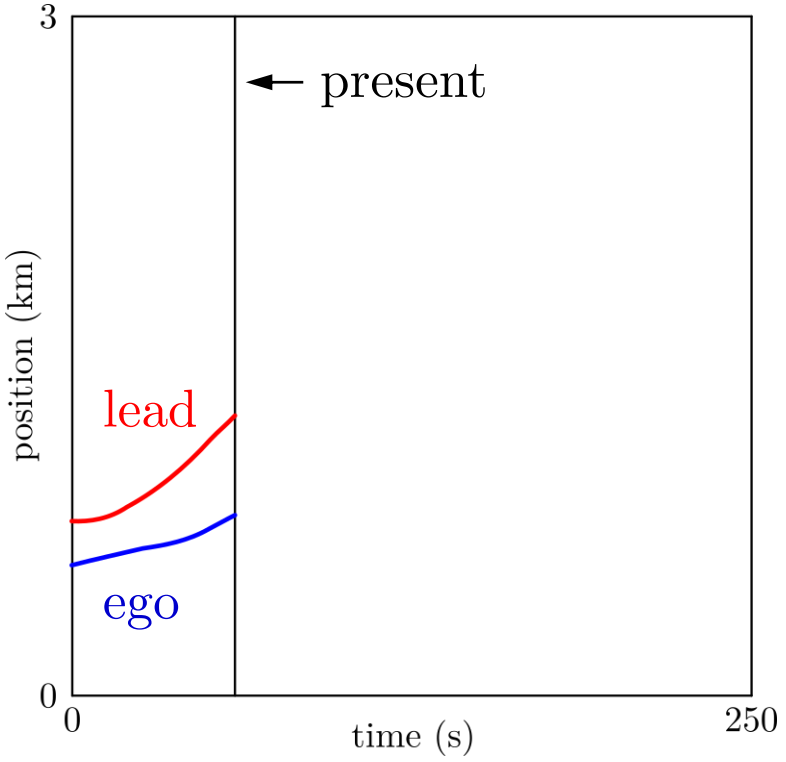


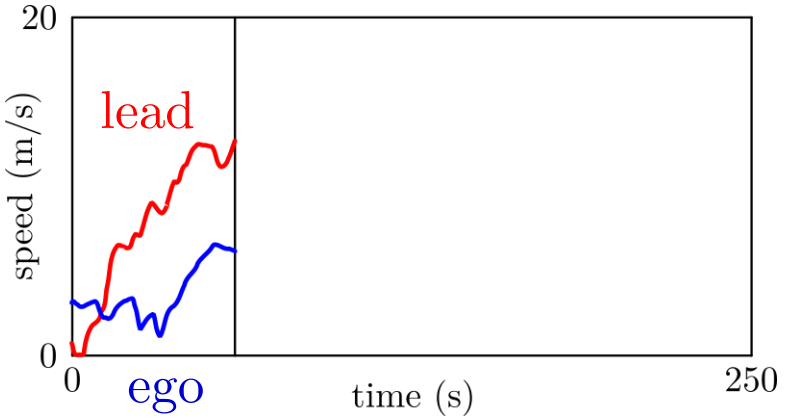

Predict the ego's future motion from lead's past data

**Connectivity-based prediction:** real-time
on-board
individualized

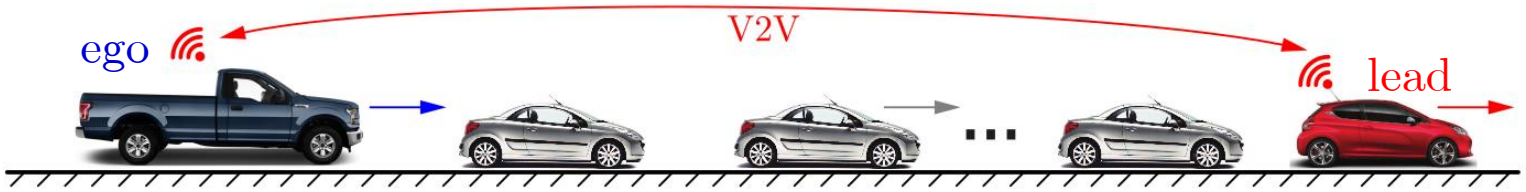
Different from routing apps
(location-based,
few minutes delay)



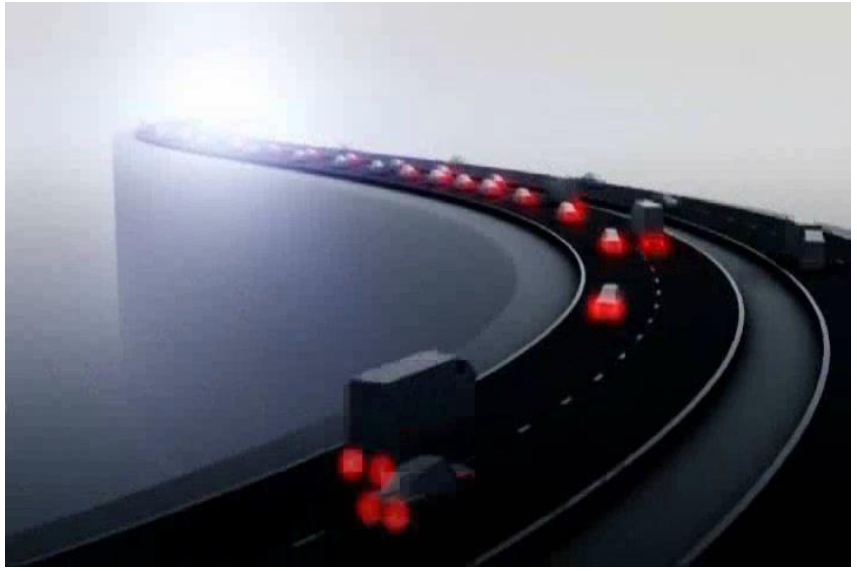



# Predictions Rely on Congestion Wave Propagation




- Congestion waves propagate backwards along the road
- Simplest prediction: copy and shift the lead's trajectory
- More sophisticated models improve the accuracy



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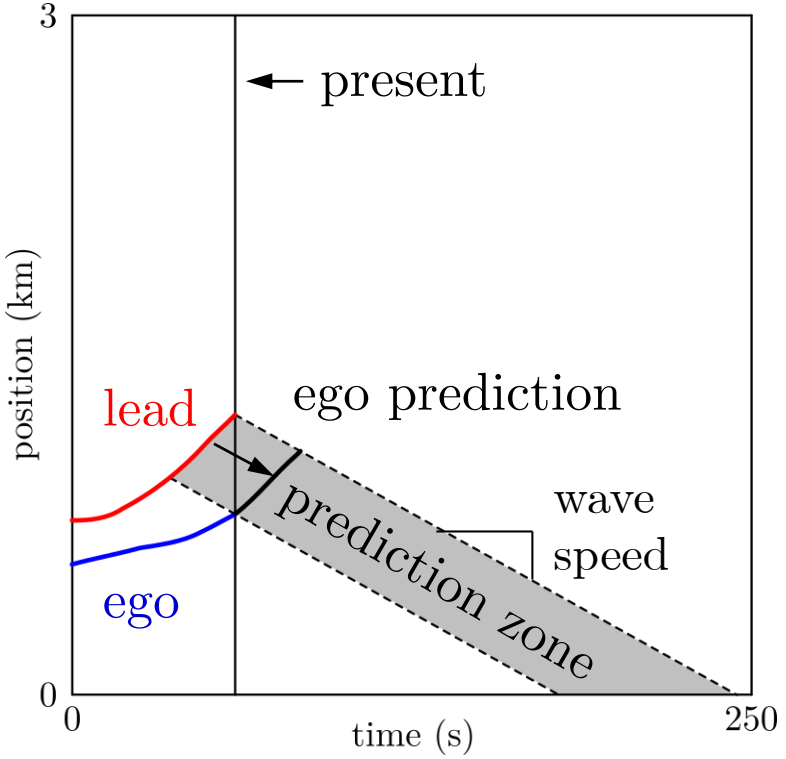
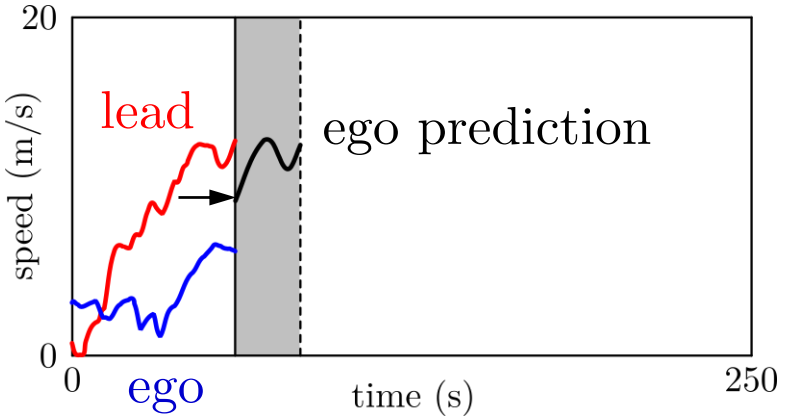
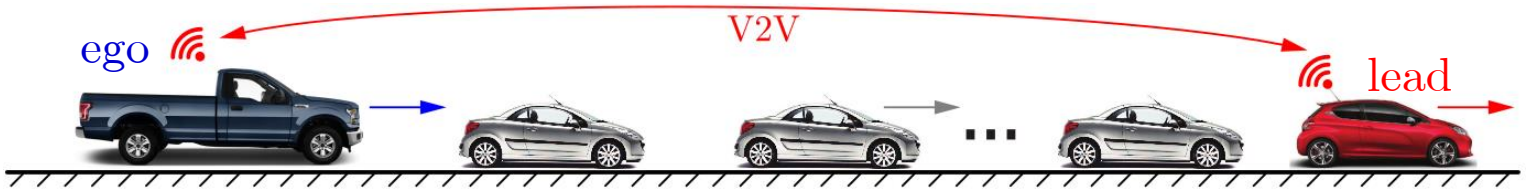
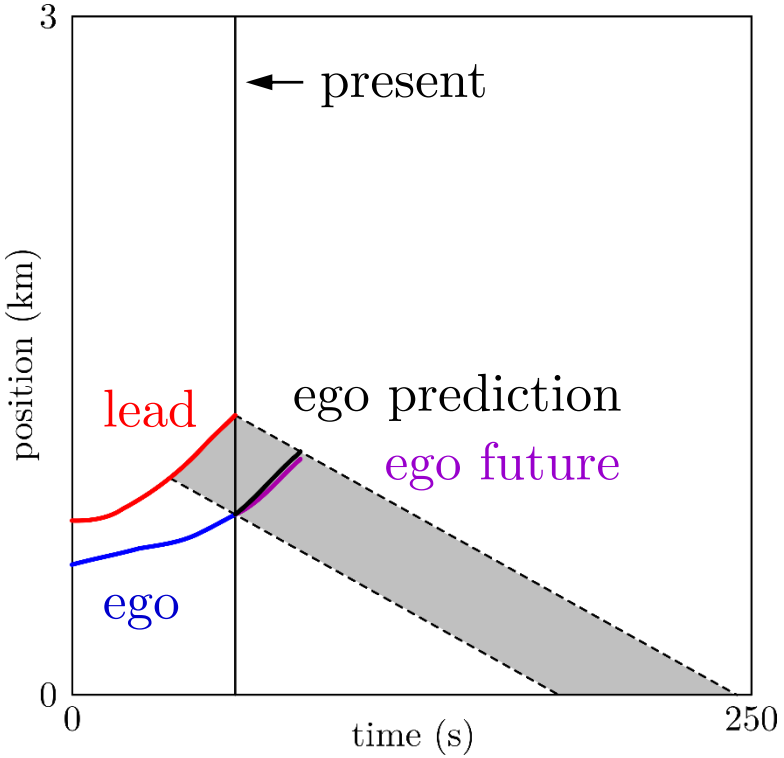


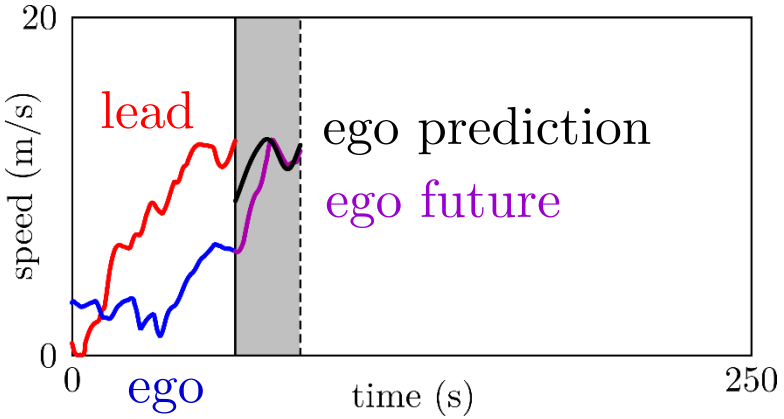



# Predictions are Obtained Over a Certain Horizon

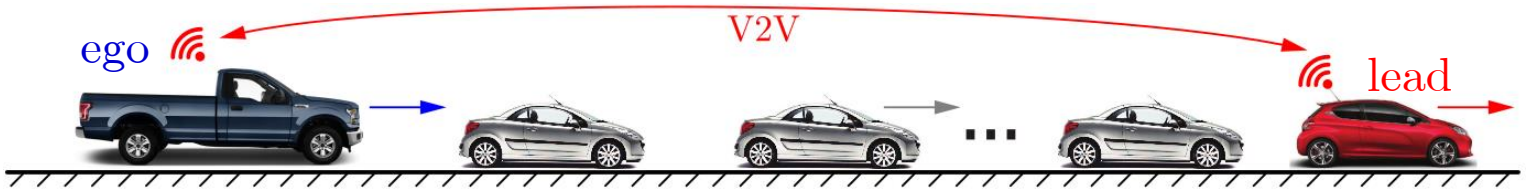



Prediction horizon depends on speed and distance



# Predictions can be Updated in Real Time

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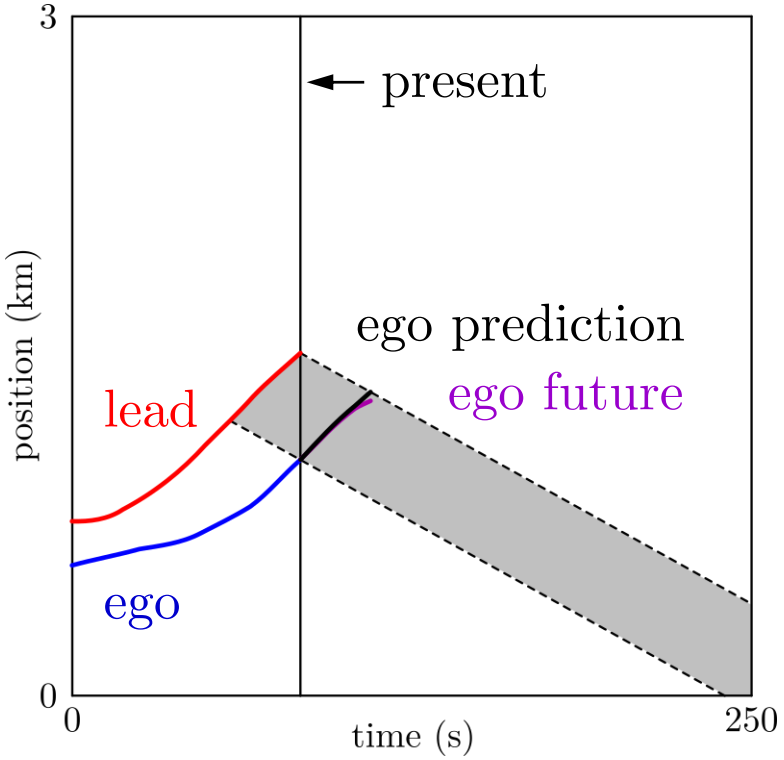
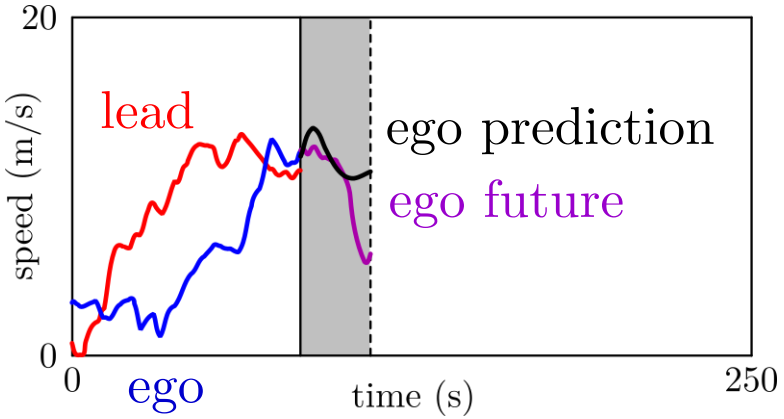
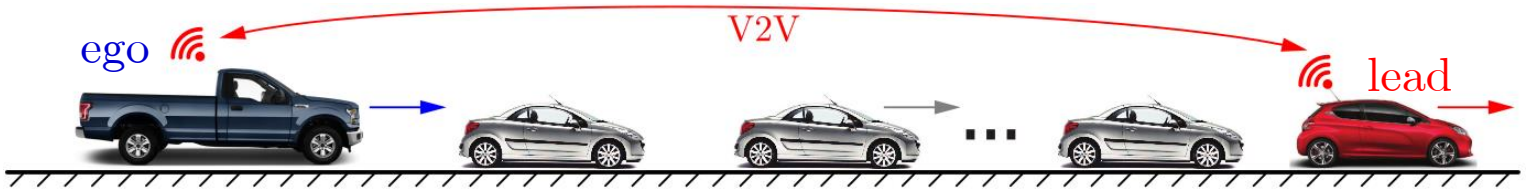
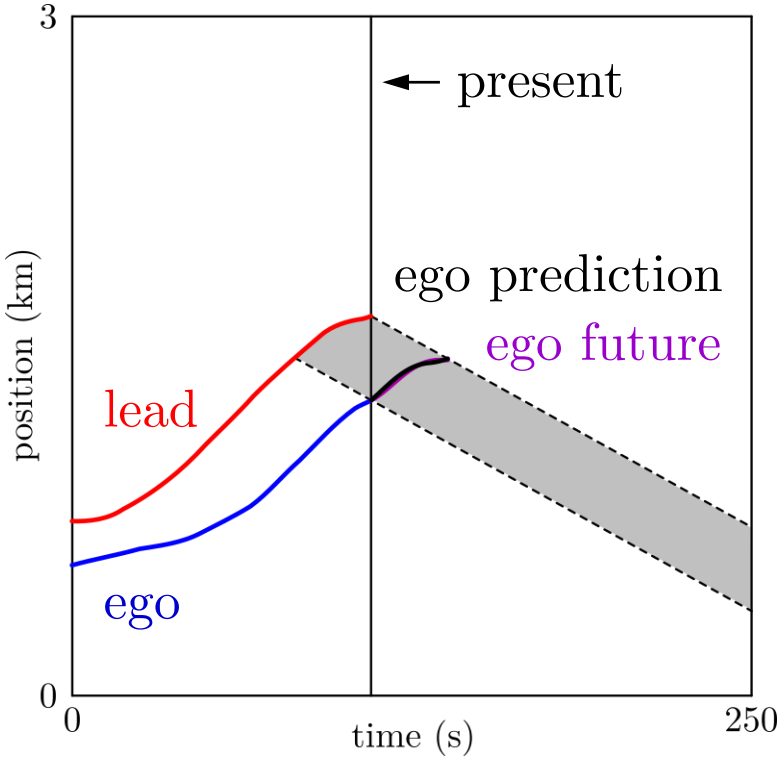


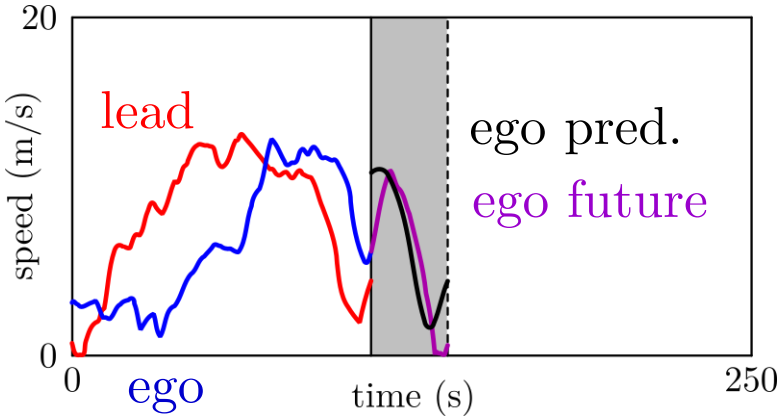



# Predictions can be Updated in Real Time

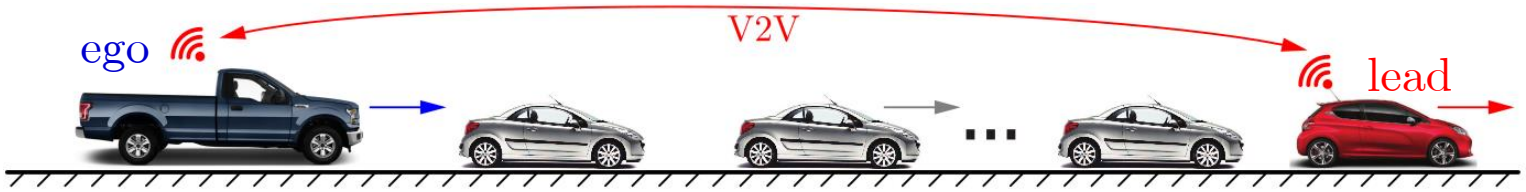



Prediction horizon depends on speed and distance

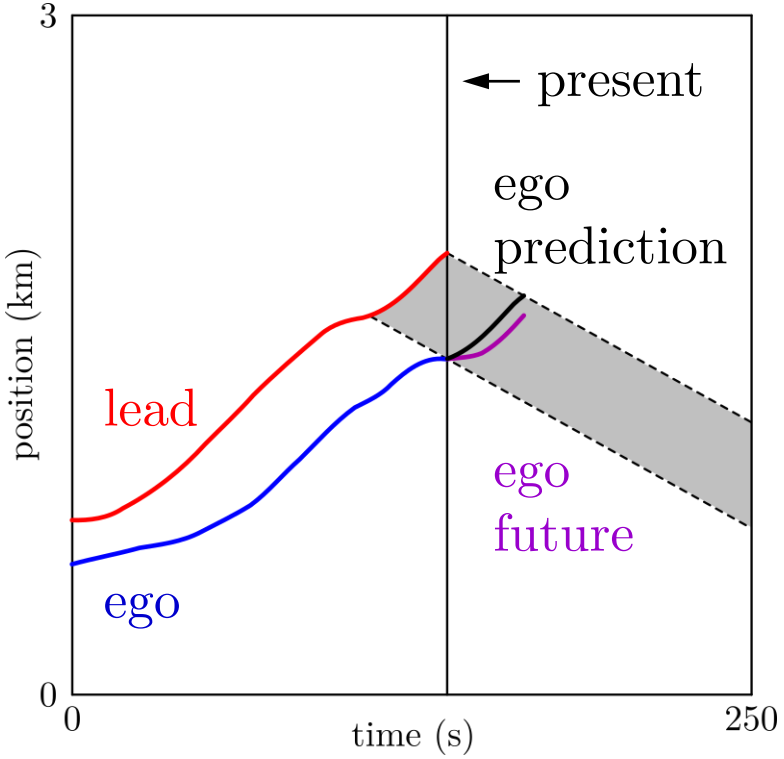


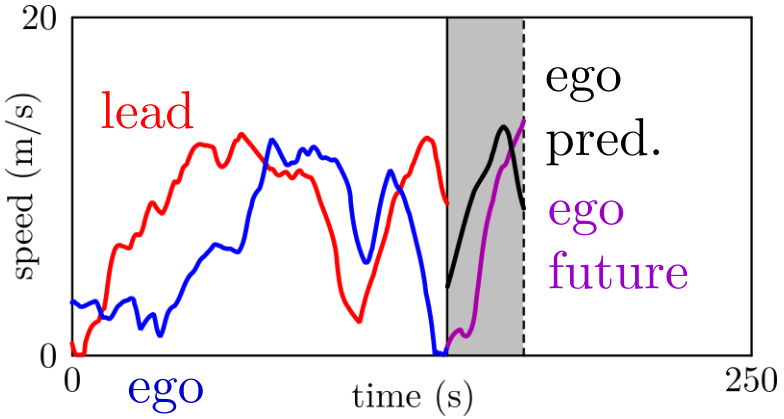



# Predictions can be Updated in Real Time

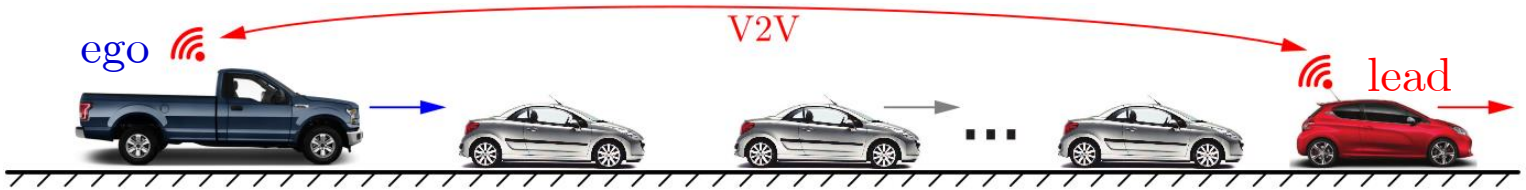



Prediction horizon depends on speed and distance

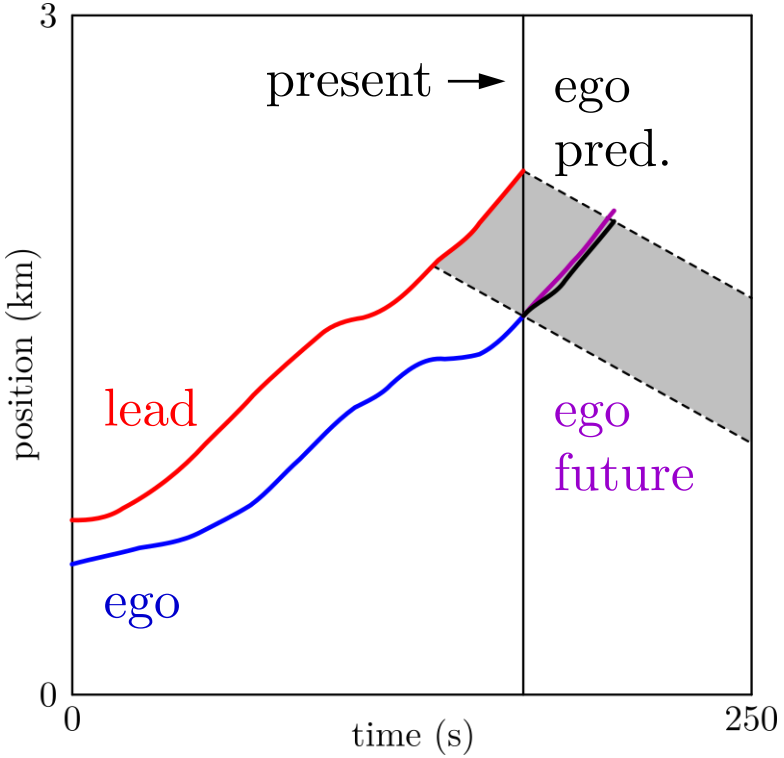


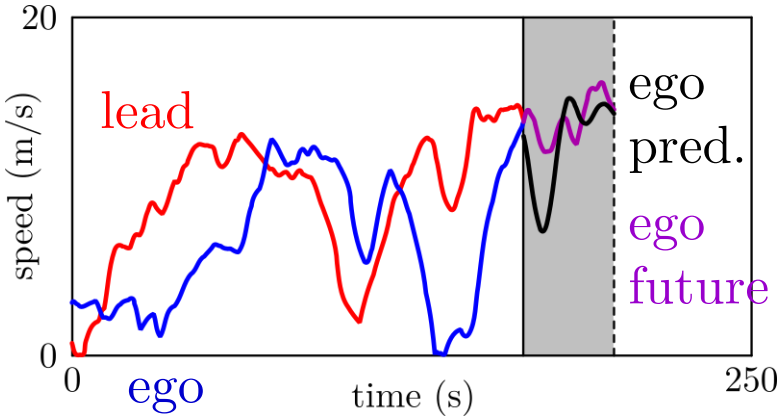



# Predictions can be Updated in Real Time

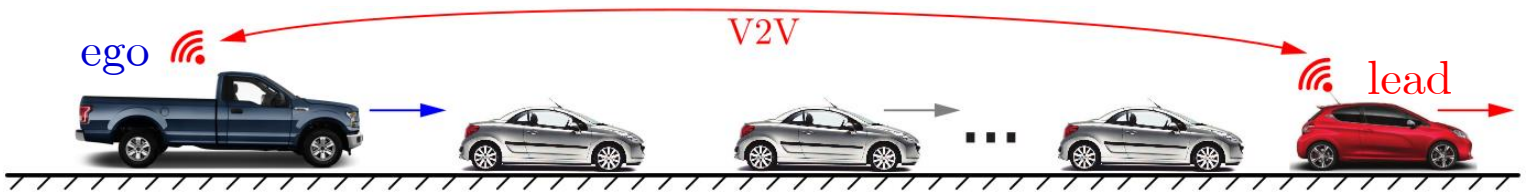



Prediction horizon depends on speed and distance

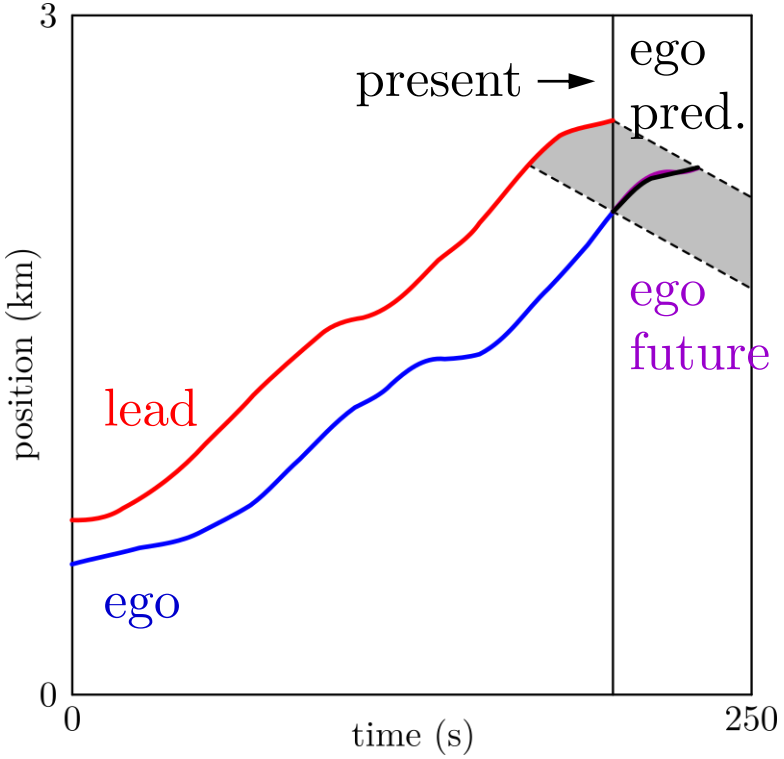


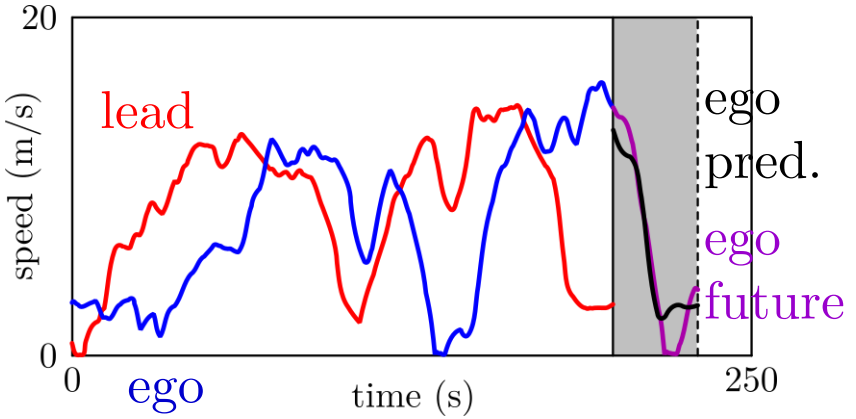



# Predictions can be Updated in Real Time

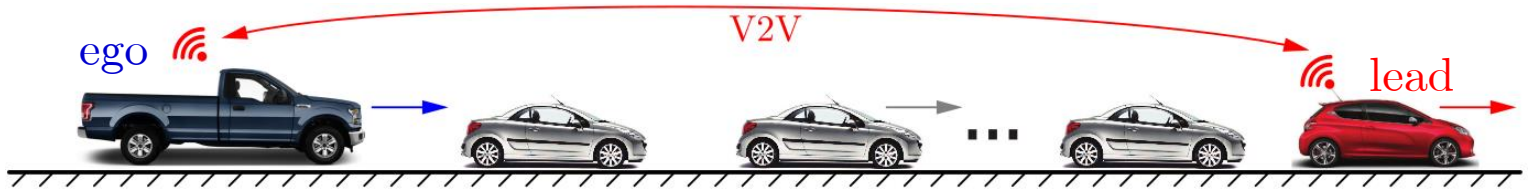


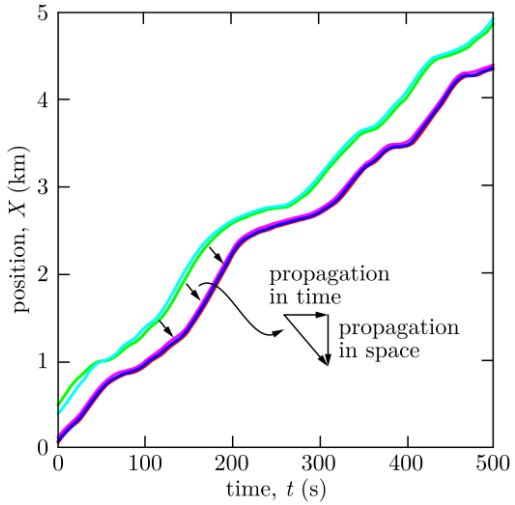

Prediction horizon depends on speed and distance



# Traffic Models are Needed for Predictions




**Car-following behavior:**

$$X(n,t) = X(n+1, t - t_{\mathrm{g}}) - d_{\mathrm{st}}$$
$$v(n,t) = v(n+1, t - t_{\mathrm{g}})$$

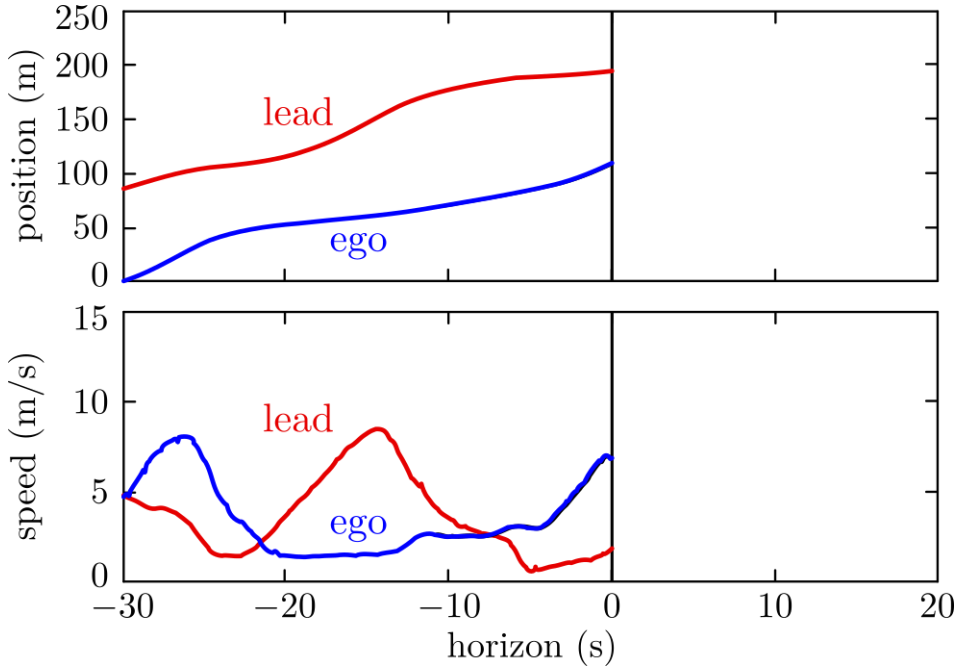
**Nominal traffic model:**

Input: position and speed of lead

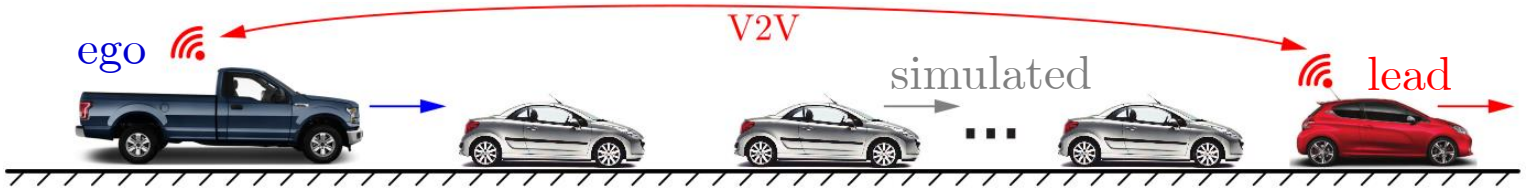
$$\mathbf{X}_{k+1} = \mathbf{A}\mathbf{X}_k + \mathbf{B}\mathbf{u}_k + \boldsymbol{\xi}, \quad \boldsymbol{\xi} \sim \mathcal{N}(0, \mathbf{Q})$$
$$\mathbf{y}_k = \mathbf{C}\mathbf{X}_k + \boldsymbol{\eta}, \quad \boldsymbol{\eta} \sim \mathcal{N}(0, \mathbf{R})$$

State: position and speed of vehicles between lead and ego

Output: position and speed of ego



# First We Estimate the Present State of Traffic



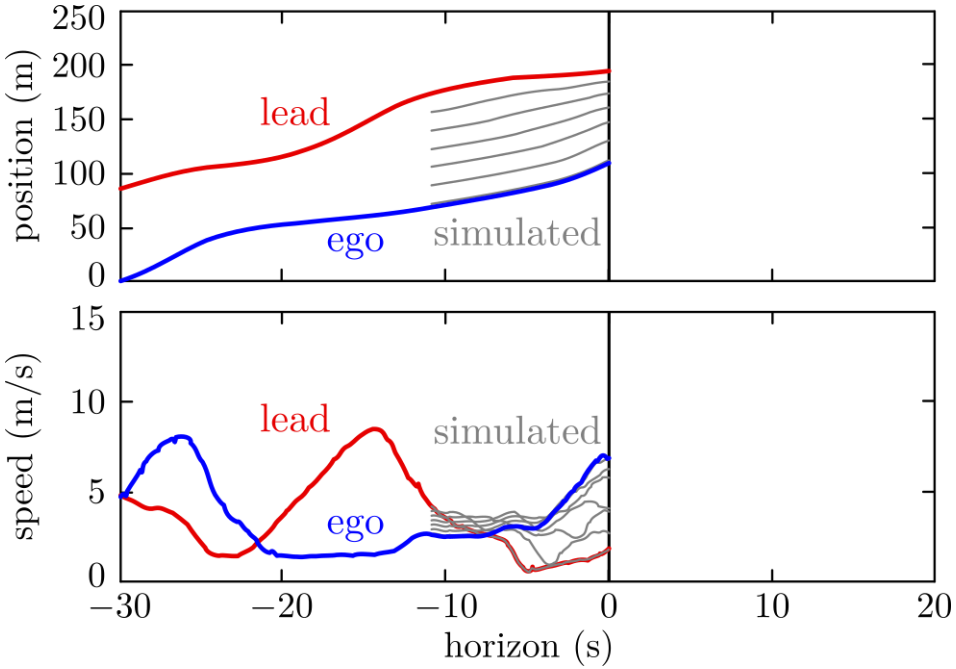

- Simulate traffic between lead and ego over the past, up to present
- Use **traffic memory** to correct the model with **Kalman filter**

Predict

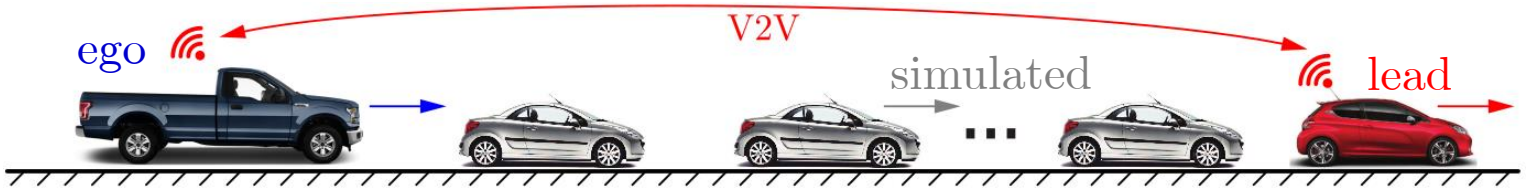
$$\hat{\mathbf{X}}_{k|k-1} = \mathbf{A}\hat{\mathbf{X}}_{k-1|k-1} + \mathbf{B}\mathbf{u}_{k-1}$$
$$\mathbf{P}_{k|k-1} = \mathbf{A}\mathbf{P}_{k-1|k-1}\mathbf{A}^{\top} + \mathbf{Q}$$

Correct

$$\mathbf{M}_k = \mathbf{P}_{k|k-1}\mathbf{C}^{\top}(\mathbf{C}\mathbf{P}_{k|k-1}\mathbf{C}^{\top} + \mathbf{R})^{-1}$$
$$\hat{\mathbf{X}}_{k|k} = \hat{\mathbf{X}}_{k|k-1} + \mathbf{M}_k(\mathbf{y}_k^{\mathrm{m}} - \mathbf{C}\hat{\mathbf{X}}_{k|k-1})$$
$$\mathbf{P}_{k|k} = (\mathbf{I} - \mathbf{M}_k\mathbf{C})\mathbf{P}_{k|k-1}$$



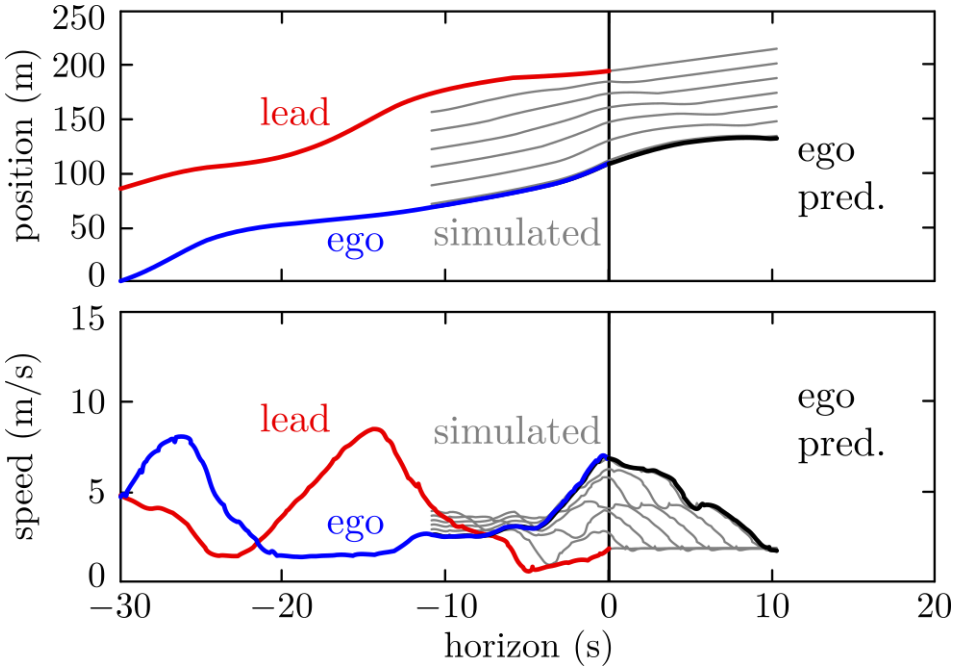
# Then We Predict The Future



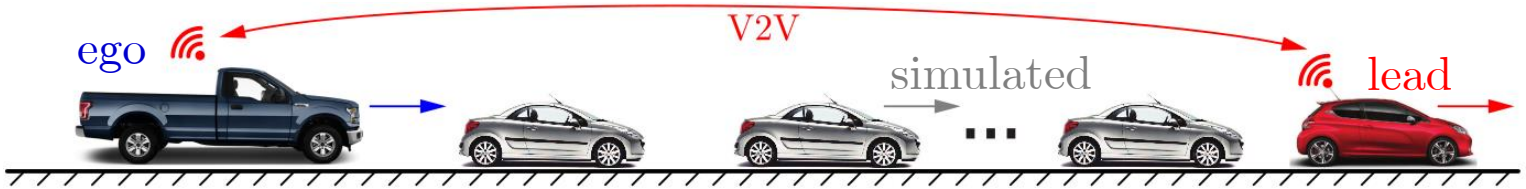

- Simulate traffic between lead and ego into the future
- Use nominal model, no correction

Predict

$$\hat{\mathbf{X}}_{k|k-1} = \mathbf{A}\hat{\mathbf{X}}_{k-1|k-1} + \mathbf{B}\mathbf{u}_{k-1}$$
$$\mathbf{P}_{k|k-1} = \mathbf{A}\mathbf{P}_{k-1|k-1}\mathbf{A}^{\top} + \mathbf{Q}$$



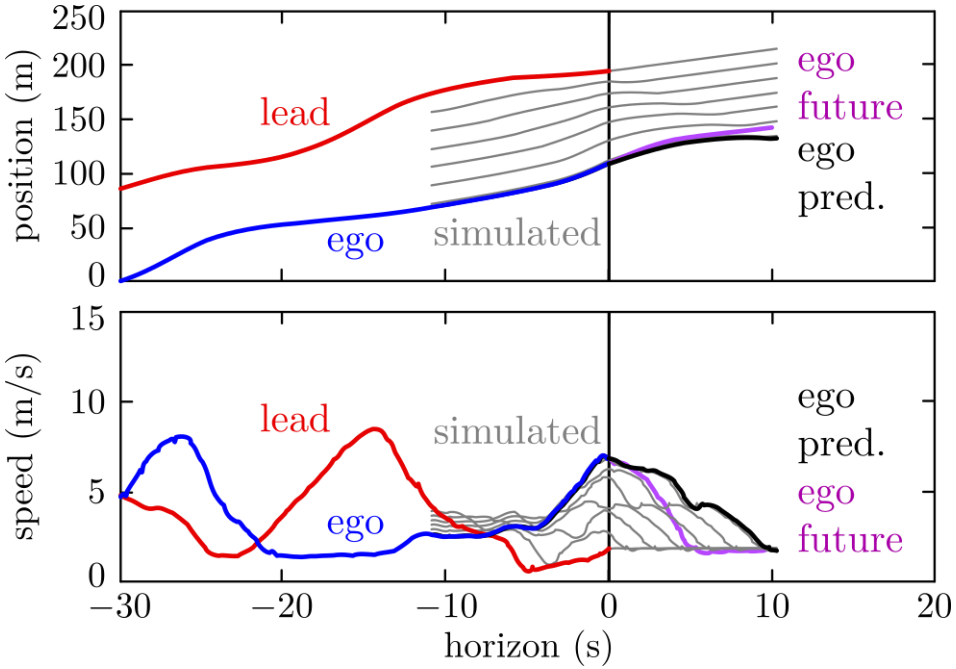
# Predictions Match the Collected Data



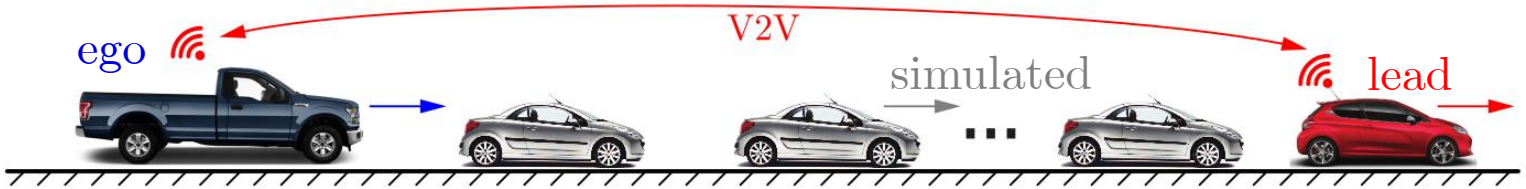

- Simulate traffic between lead and ego into the future
- Use nominal model, no correction

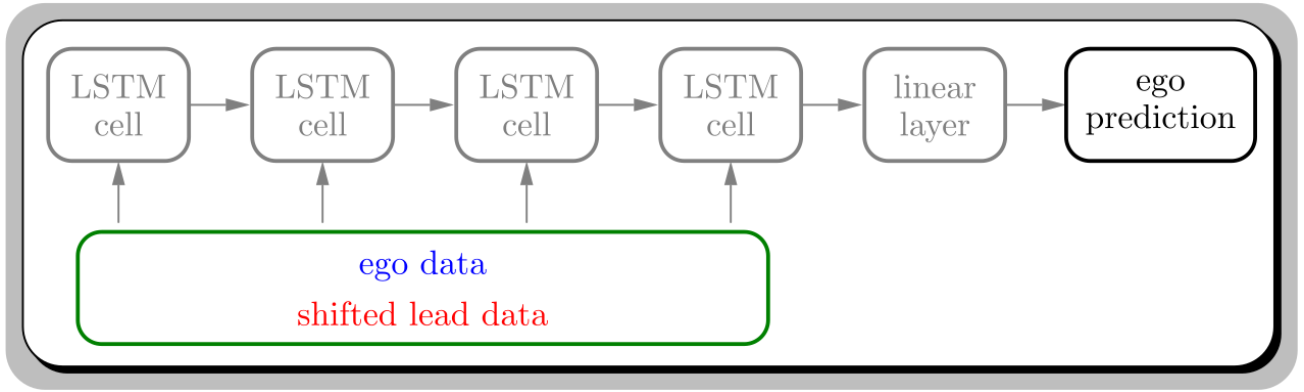
Predict

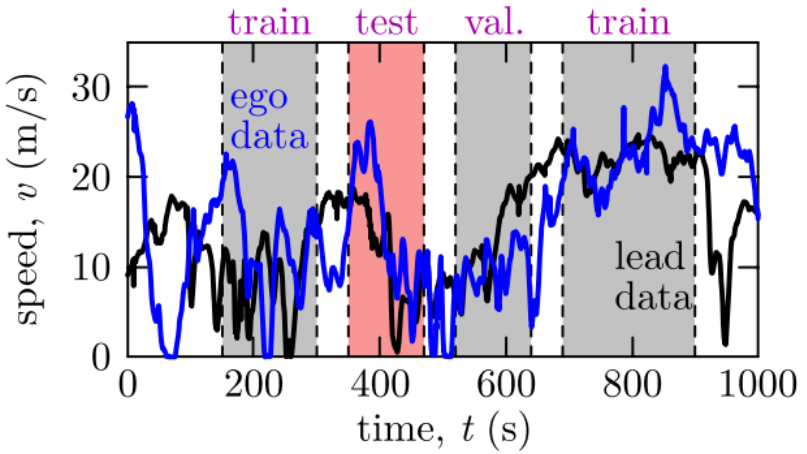
$$\hat{\mathbf{X}}_{k|k-1} = \mathbf{A}\hat{\mathbf{X}}_{k-1|k-1} + \mathbf{B}\mathbf{u}_{k-1}$$
$$\mathbf{P}_{k|k-1} = \mathbf{A}\mathbf{P}_{k-1|k-1}\mathbf{A}^{\top} + \mathbf{Q}$$

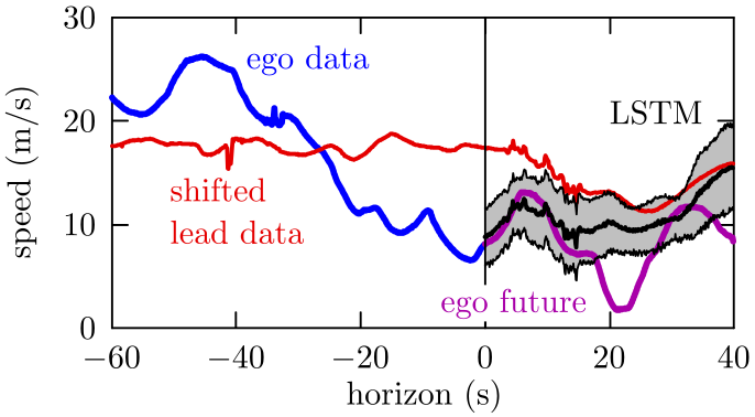


# Similar Accuracy is Achieved when using LSTM

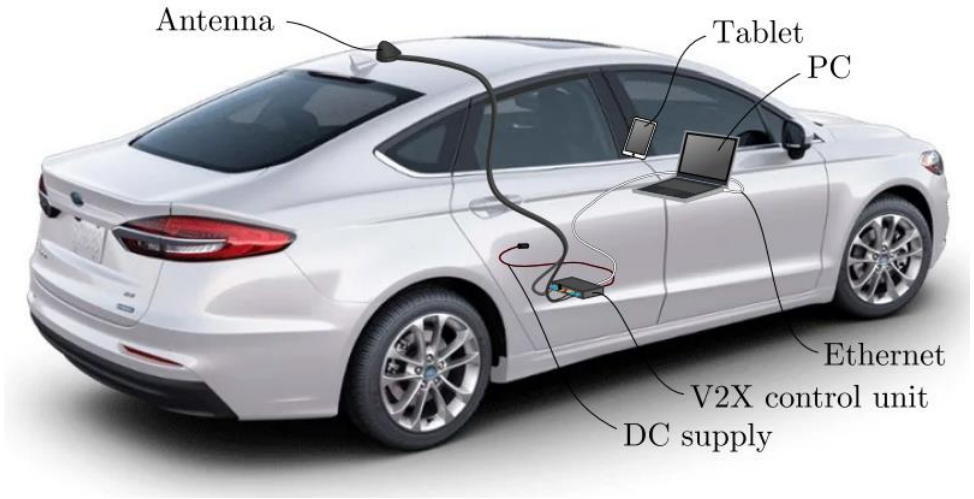


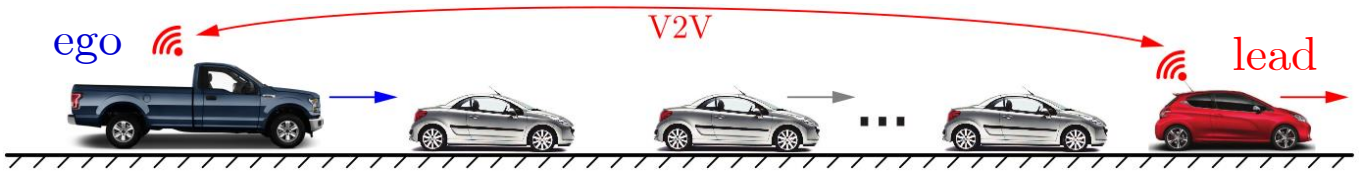



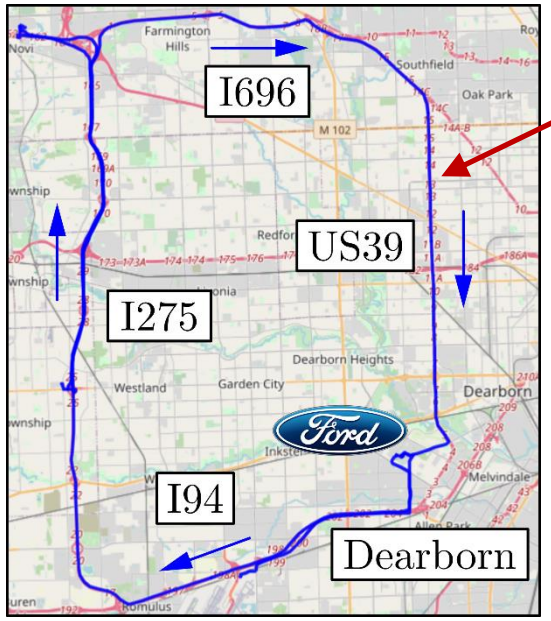



# The Method was Tested in Real Traffic



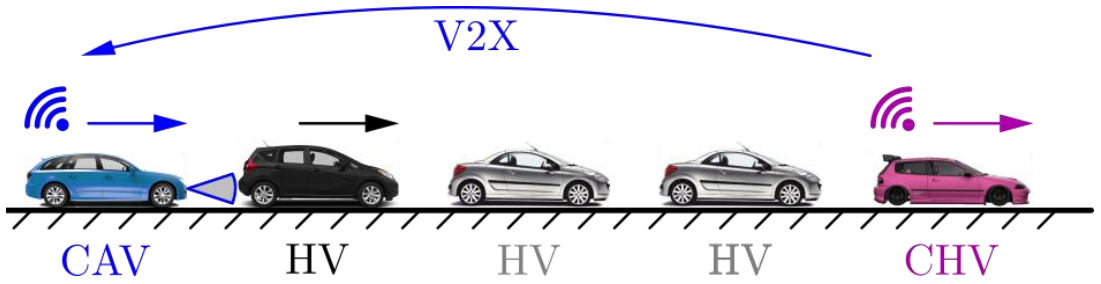



# The Method was Tested in Real Traffic

# Predictions Obtained via Connectivity can be Used to Control CAVs

## Connected Cruise Control (CCC)



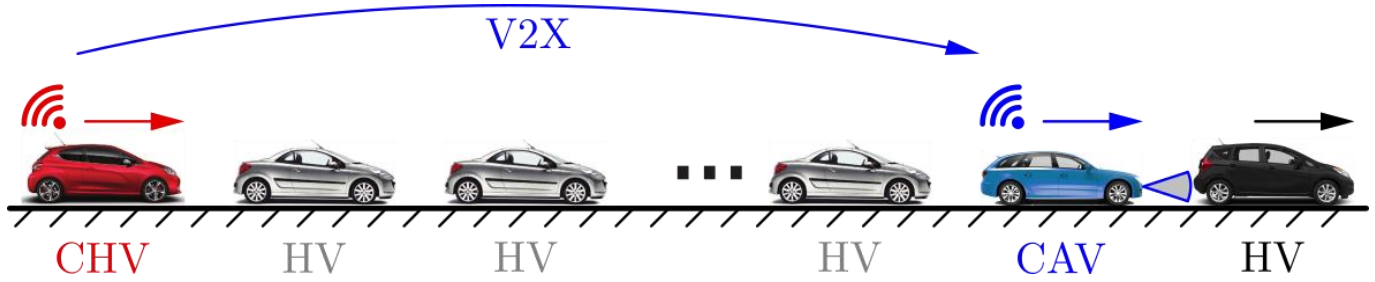



# Energy-efficient Reactive and Predictive Connected Cruise Control

Minghao Shen, *Student Member, IEEE,* Robert Austin Dollar, *Member, IEEE* Tamas G. Molnar, *Member, IEEE,* Chaozhe R. He, *Member, IEEE,* Ardalan Vahidi, *Senior Member, IEEE,* Gábor Orosz *Senior Member, IEEE*

# Connectivity can Enable Traffic Control via CAVs

## Connected Traffic Control (CTC)




**Virtual Rings on Highways: Traffic Control by Connected Automated Vehicles**

**Tamás G. Molnár, Michael Hopka, Devesh Upadhyay, Michiel Van Nieuwstadt, and Gábor Orosz**

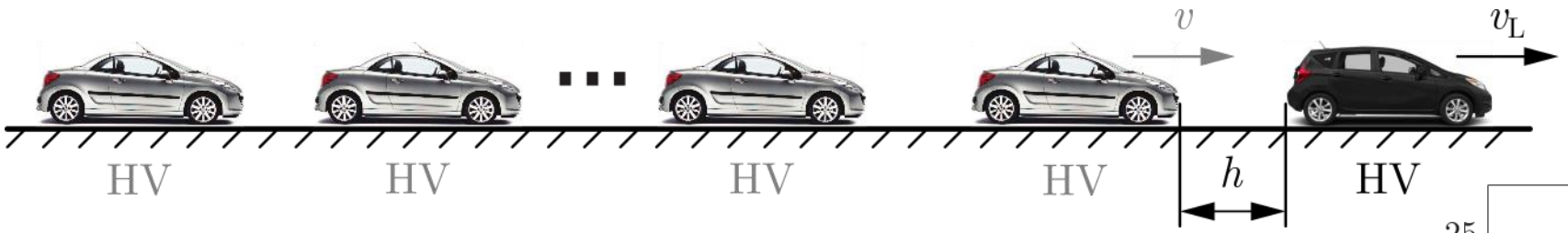
Check for updates

IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS

Connected Cruise and Traffic Control for Pairs of Connected Automated Vehicles

Sicong Guo, Gábor Orosz, *Senior Member, IEEE*, and Tamas G. Molnar, *Member, IEEE*

# String Unstable Human Drivers Cause Traffic Jams

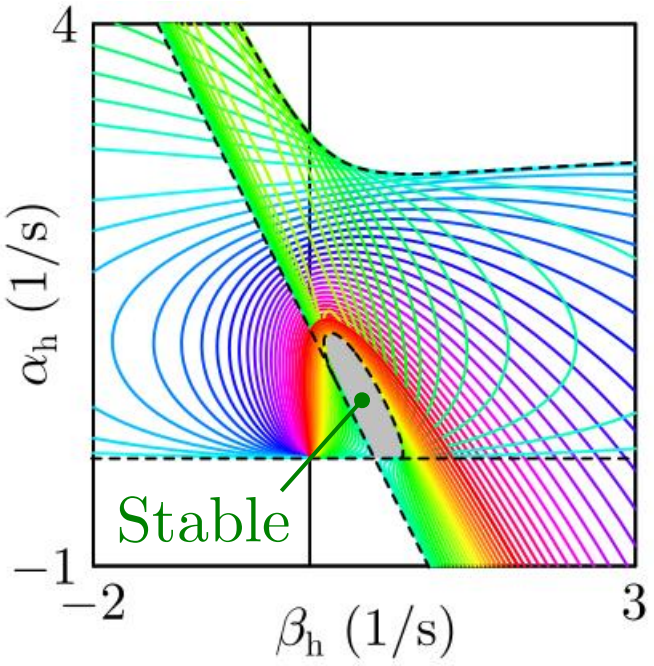


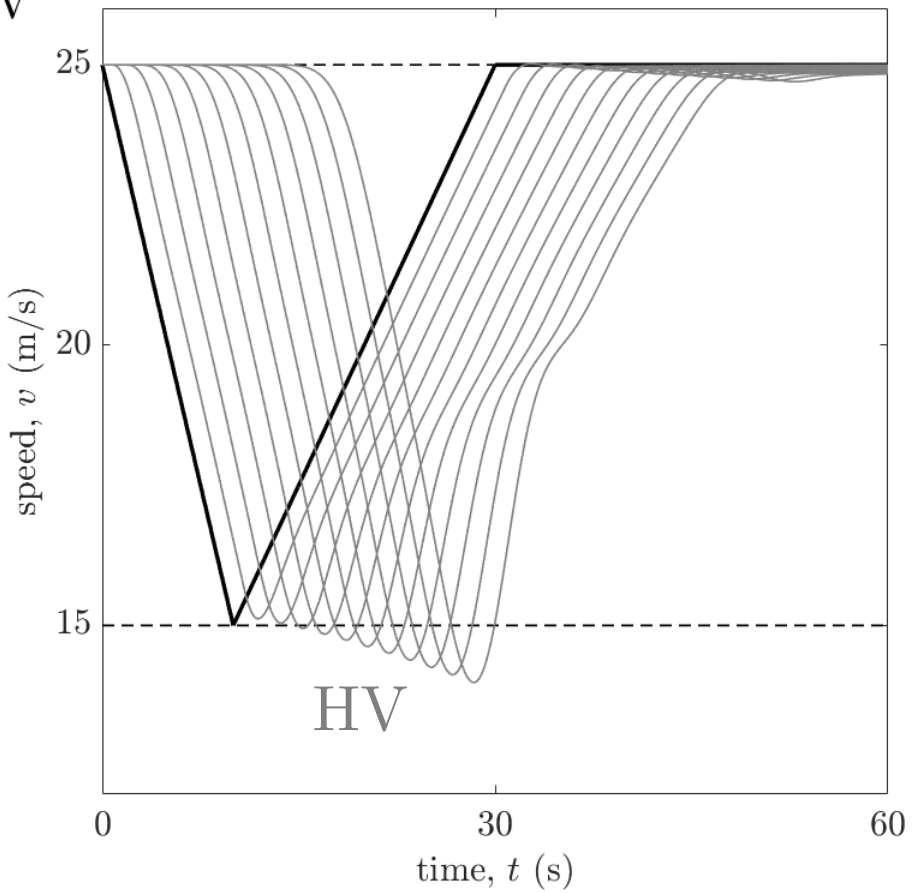

$$u_{\mathrm{HV}} = \alpha_{\mathrm{h}}(V_{\mathrm{h}}(h) - v) + \beta_{\mathrm{h}}(v_{\mathrm{L}} - v)$$

$$\dot{h}(t) = v_{\mathrm{L}}(t) - v(t)$$

$$\dot{v}(t) = u(t - \tau)$$

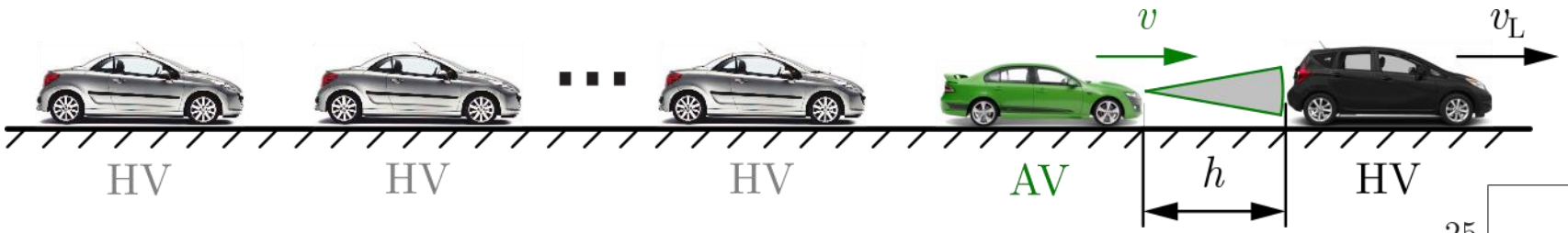
Undesired human response causes instability



# Smooth Driving Mitigates Congestion

## Adaptive Cruise Control (ACC)

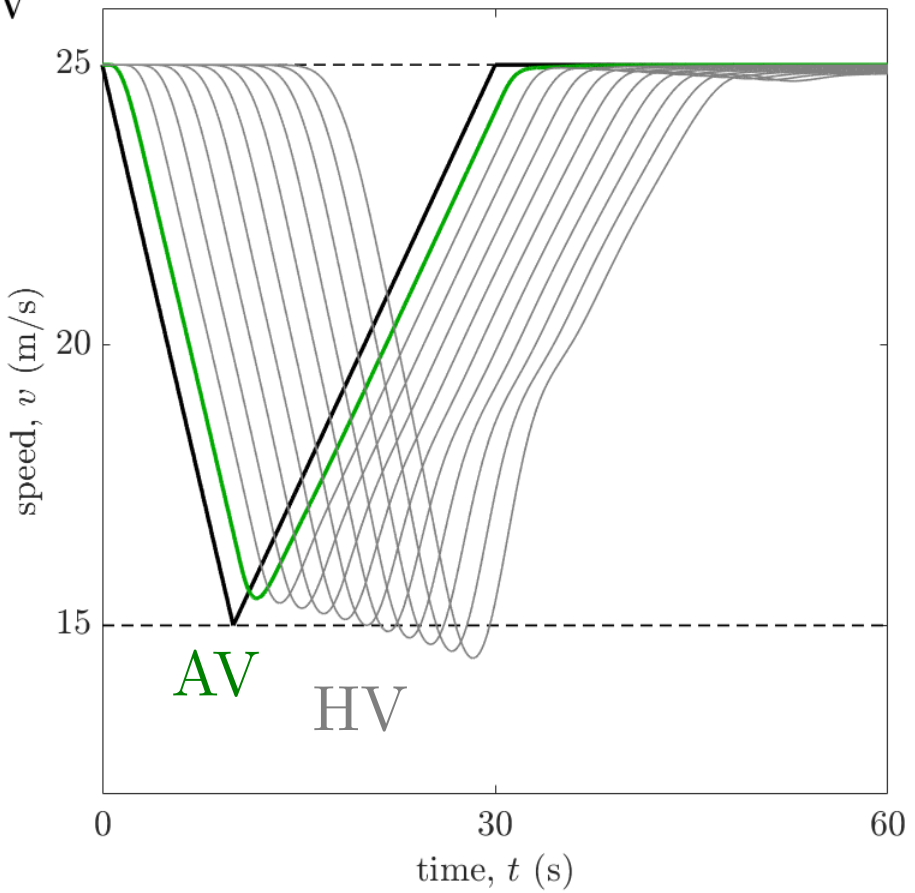



$$u_{\mathrm{HV}} = \alpha_{\mathrm{h}}(V_{\mathrm{h}}(h) - v) + \beta_{\mathrm{h}}(v_{\mathrm{L}} - v)$$

$$u_{\mathrm{AV}} = \alpha(V(h) - v) + \beta(v_{\mathrm{L}} - v)$$

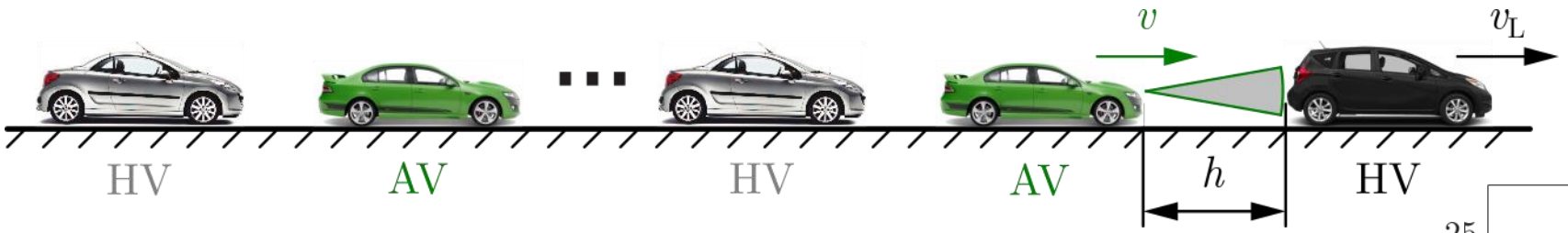
Automated vehicles can drive smoother…

…but may be outnumbered by unstable drivers



# Traffic Control Require High Penetration of Automation

**Adaptive Cruise Control (ACC)**

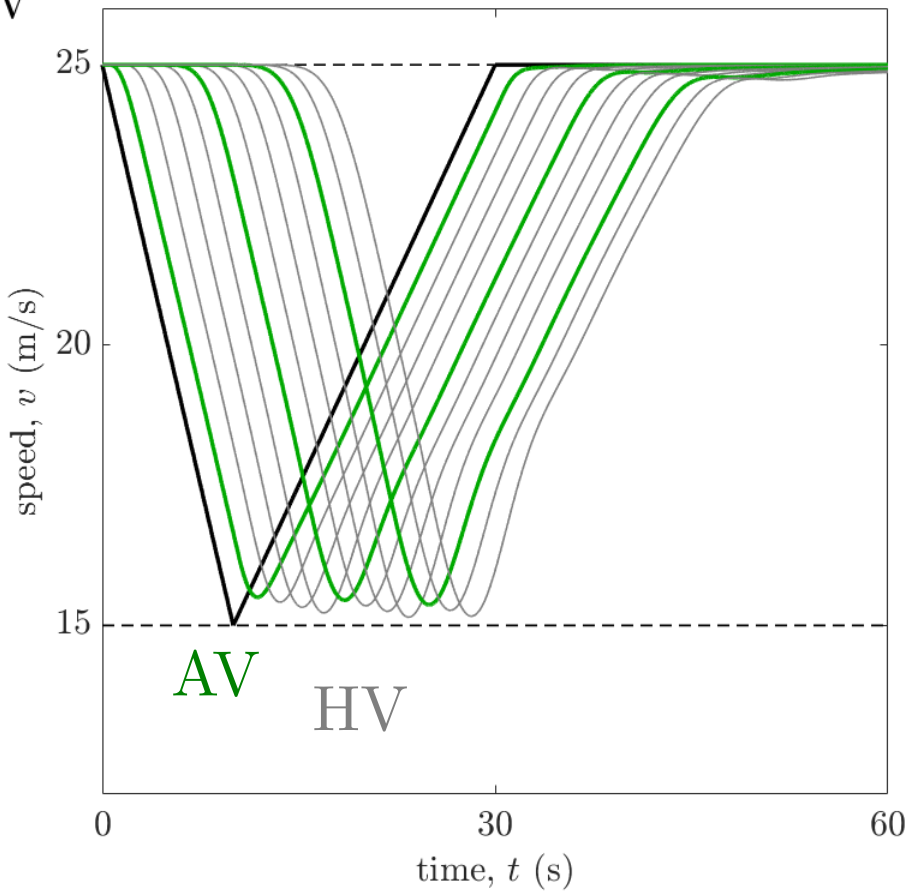



$$u_{\mathrm{HV}} = \alpha_{\mathrm{h}}(V_{\mathrm{h}}(h) - v) + \beta_{\mathrm{h}}(v_{\mathrm{L}} - v)$$

$$u_{\mathrm{AV}} = \alpha(V(h) - v) + \beta(v_{\mathrm{L}} - v)$$

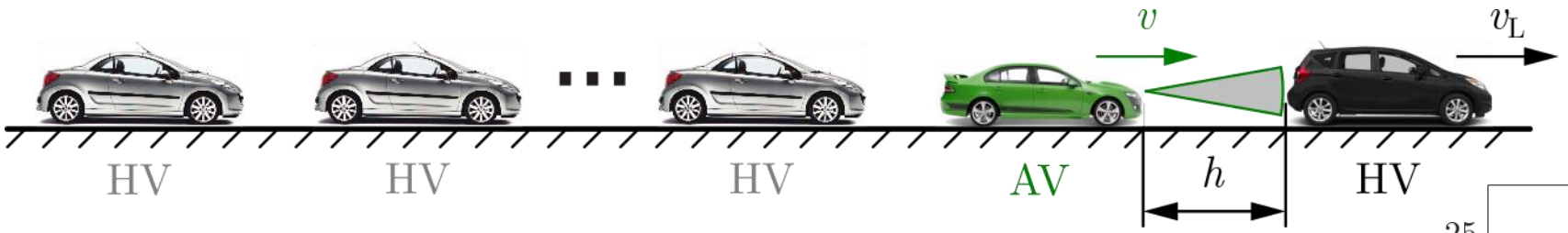
Large penetration of automation
is needed to mitigate congestions

Can connectivity help?



# Smooth Driving Mitigates Congestion

## Adaptive Cruise Control (ACC)

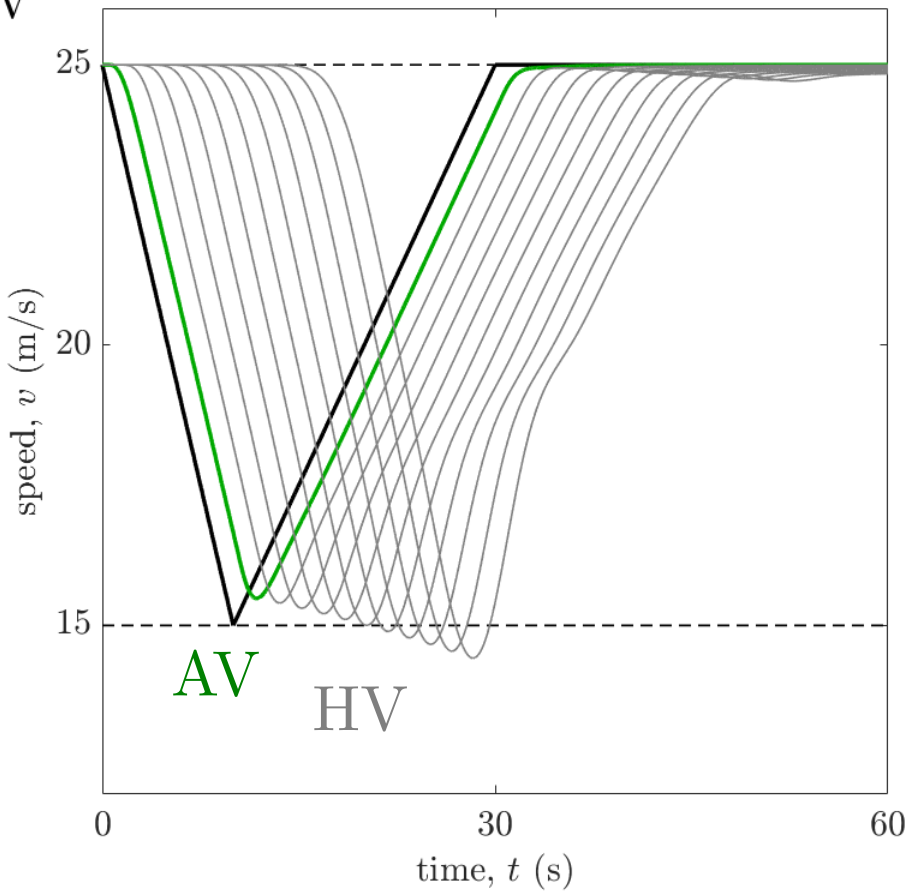



$$u_{\mathrm{HV}} = \alpha_{\mathrm{h}}(V_{\mathrm{h}}(h) - v) + \beta_{\mathrm{h}}(v_{\mathrm{L}} - v)$$

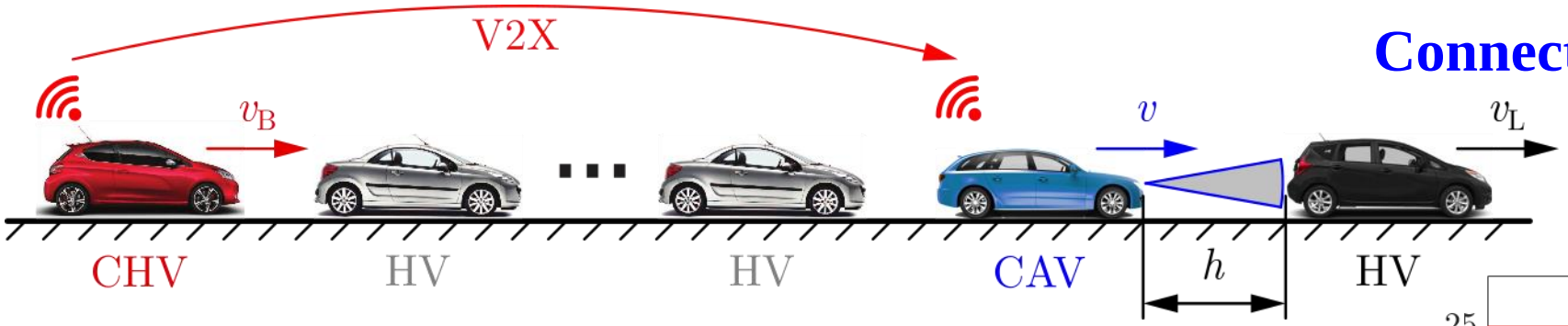
$$u_{\mathrm{AV}} = \alpha(V(h) - v) + \beta(v_{\mathrm{L}} - v)$$

Automated vehicles can drive smoother…

…but may be outnumbered by unstable drivers



# Even Low Penetration of Connectivity is Beneficial

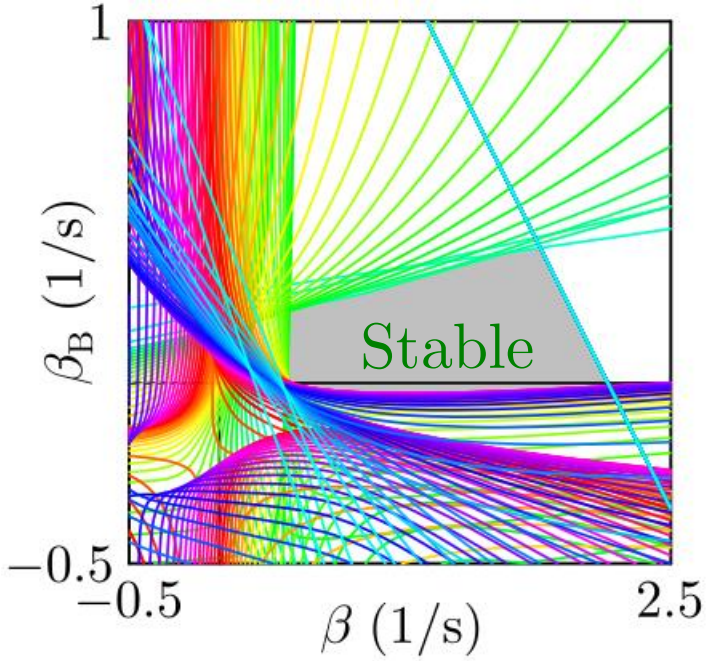


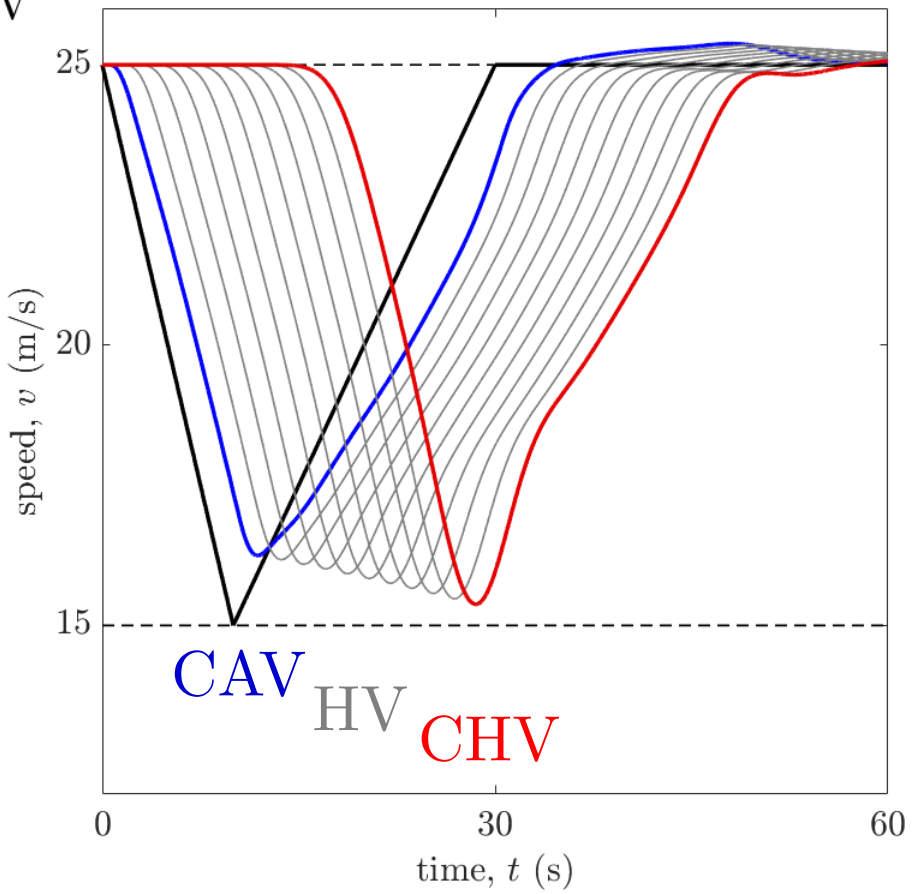

**Connected Traffic Control (CTC)**

$$u_{\mathrm{CAV}} = \alpha(V(h) - v) + \beta(v_{\mathrm{L}} - v) + \beta_{\mathrm{B}}(v_{\mathrm{B}} - v)$$

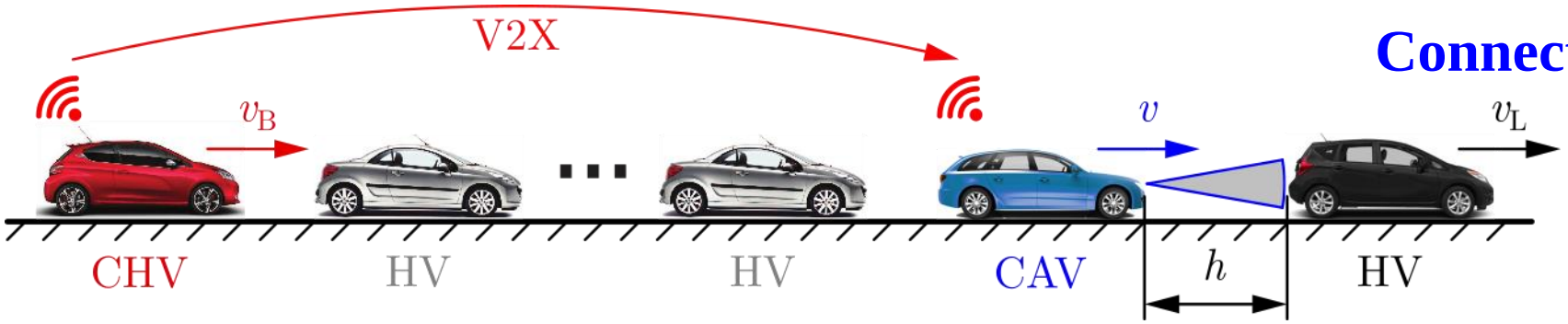
Connectivity helps to smoothen traffic

Stability may be achievable, degree of instability decreases



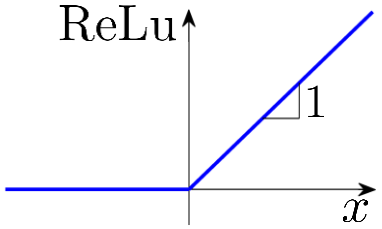
# Even Low Penetration of Connectivity is Beneficial




## Connected Traffic Control (CTC)

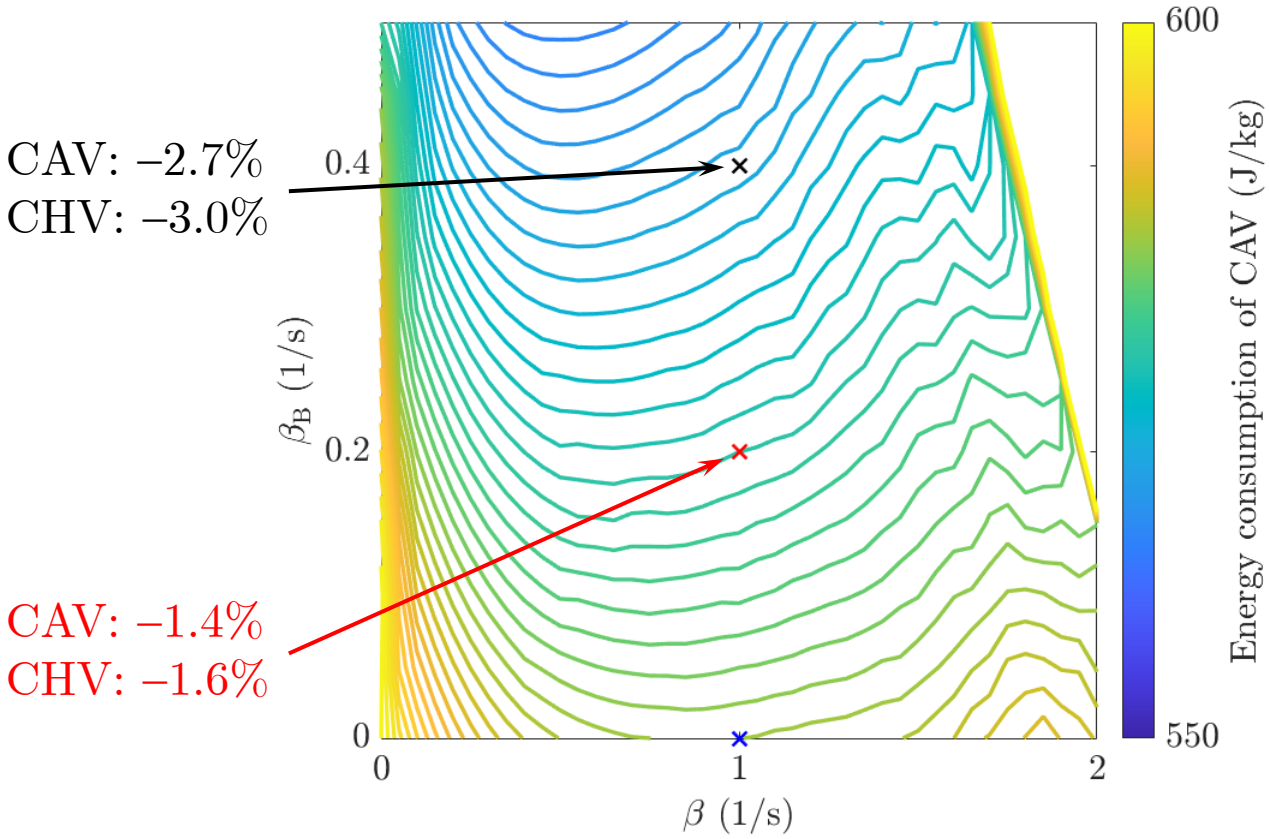
## Energy consumption (per unit mass)

$$w_i = \int_0^T \mathrm{ReLu}\big(\dot{v}_i(\theta)\big) v_i(\theta) \mathrm{d}\theta$$




Energy is saved

Beneficial both for CHV and CAV



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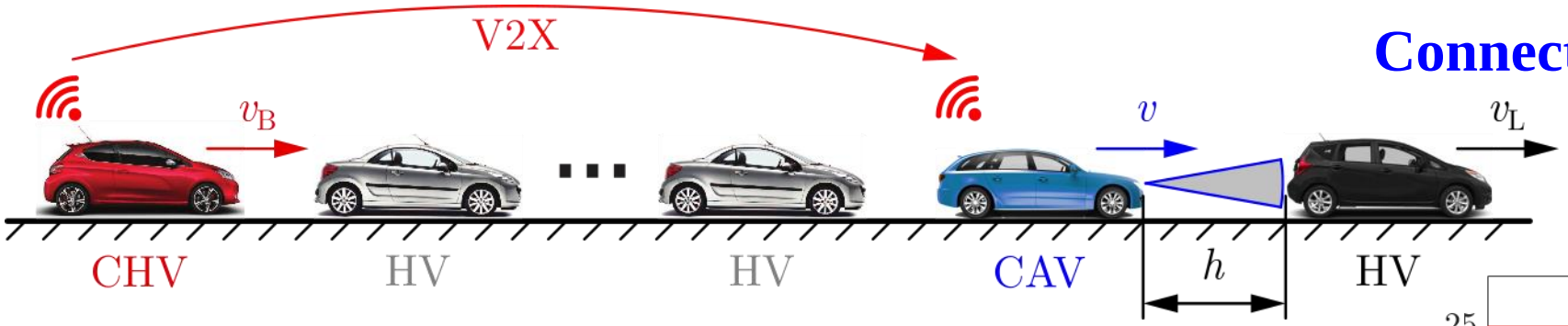
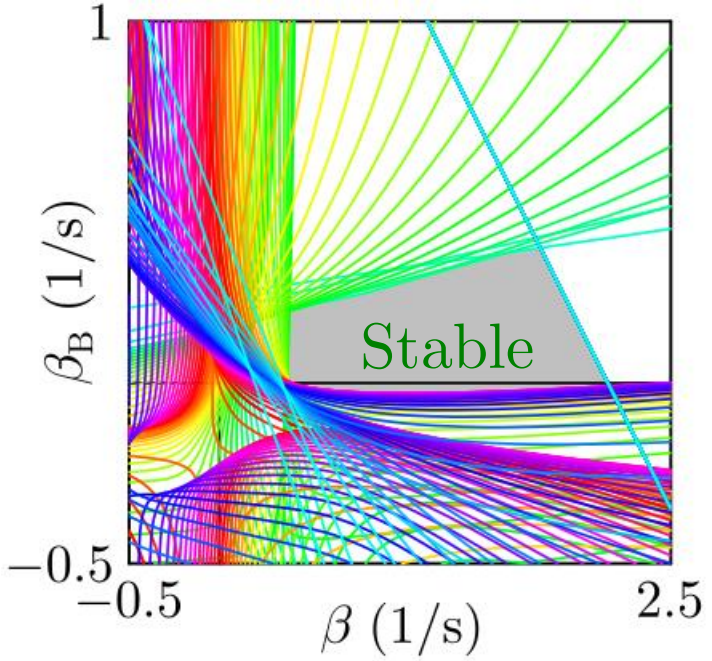


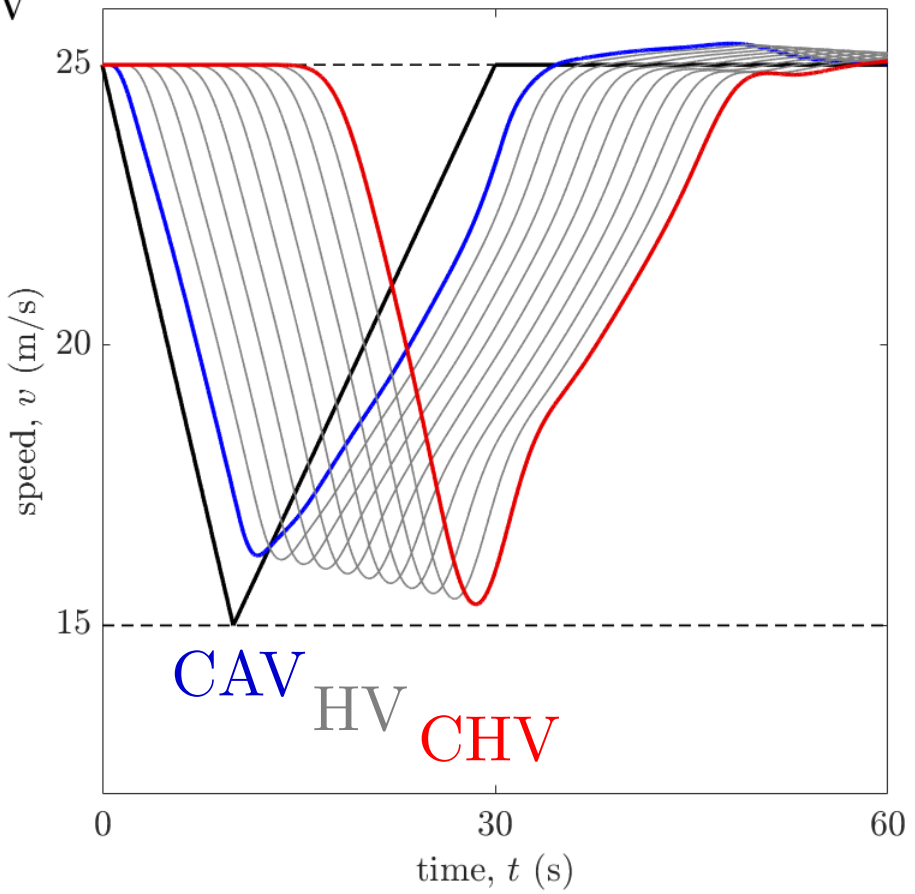

**Connected Traffic Control (CTC)**

$$u_{\mathrm{CAV}} = \alpha(V(h) - v) + \beta(v_{\mathrm{L}} - v) + \beta_{\mathrm{B}}(v_{\mathrm{B}} - v)$$

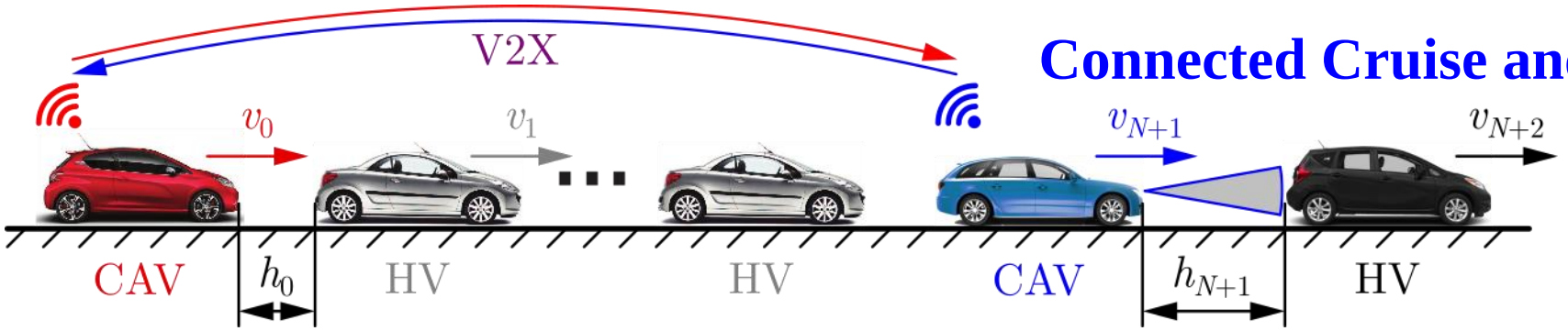
Connectivity helps to smoothen traffic

Stability may be achievable, degree of instability decreases



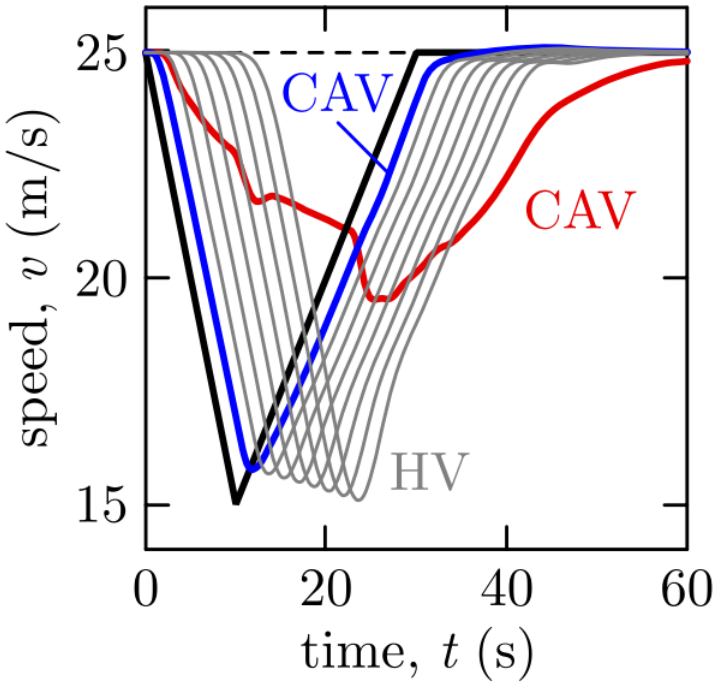
# What about Combining CCC and CTC → Cooper Pairs in Traffic




**Connected Cruise and Traffic Control (CCTC)**

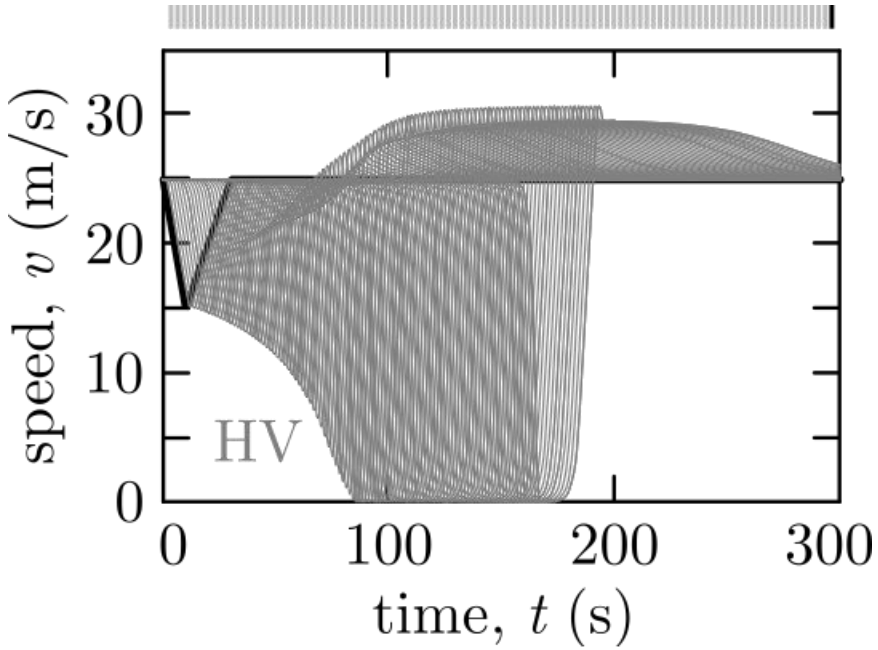
$$u_0 = \alpha_0\big(V_0(h_0) - v_0\big) + \beta_0(v_1 - v_0) + \beta_{0,N+1}(v_{N+1} - v_0)$$

$$u_{N+1} = \alpha_{N+1}\big(V_{N+1}(h_{N+1}) - v_{N+1}\big) + \beta_{N+1}(v_{N+2} - v_{N+1}) + \beta_{N+1,0}(v_0 - v_{N+1})$$



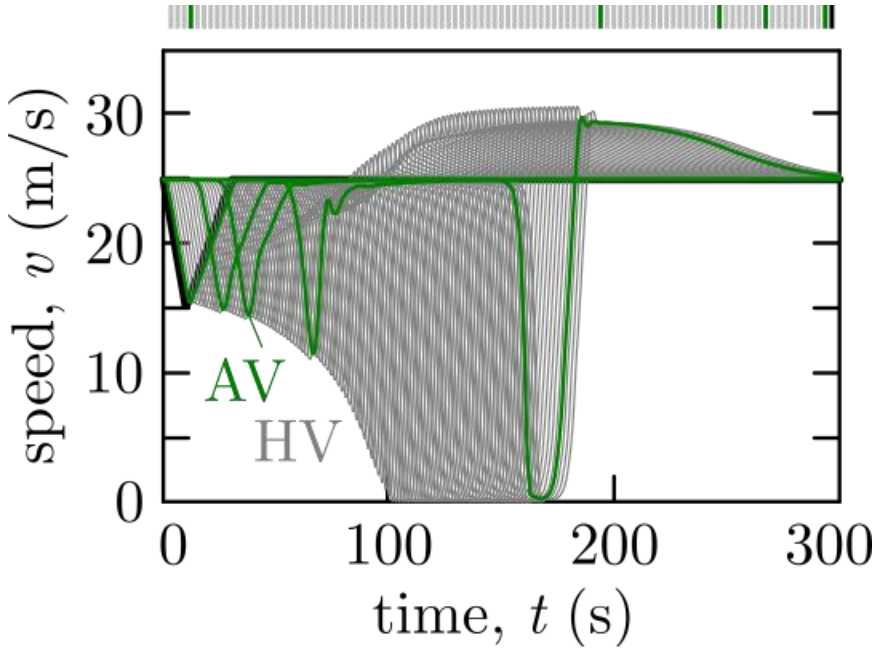
# Human Drivers are String Unstable

100% HV



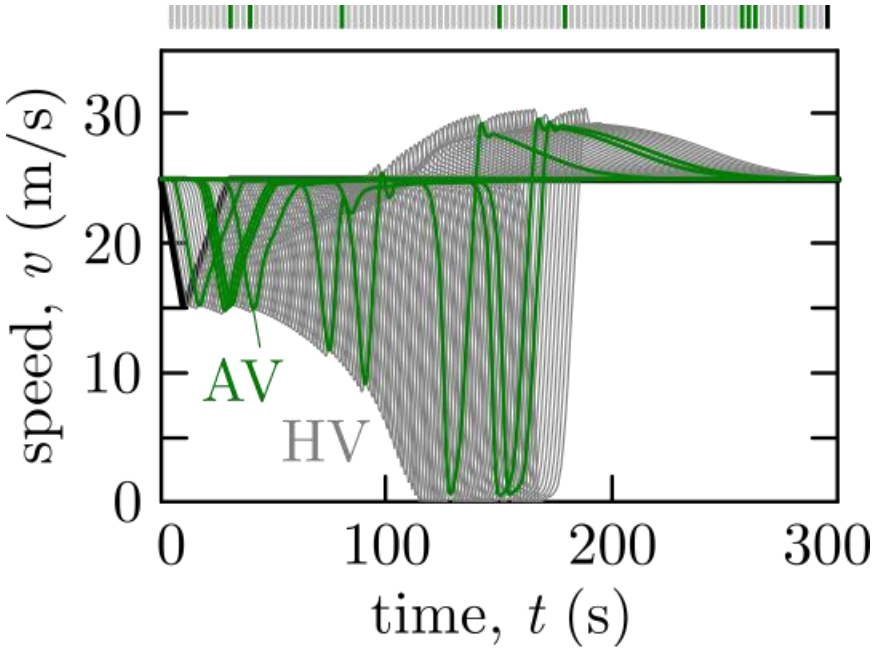
# Large Penetration of AVs can Smoothen Traffic

5% AV



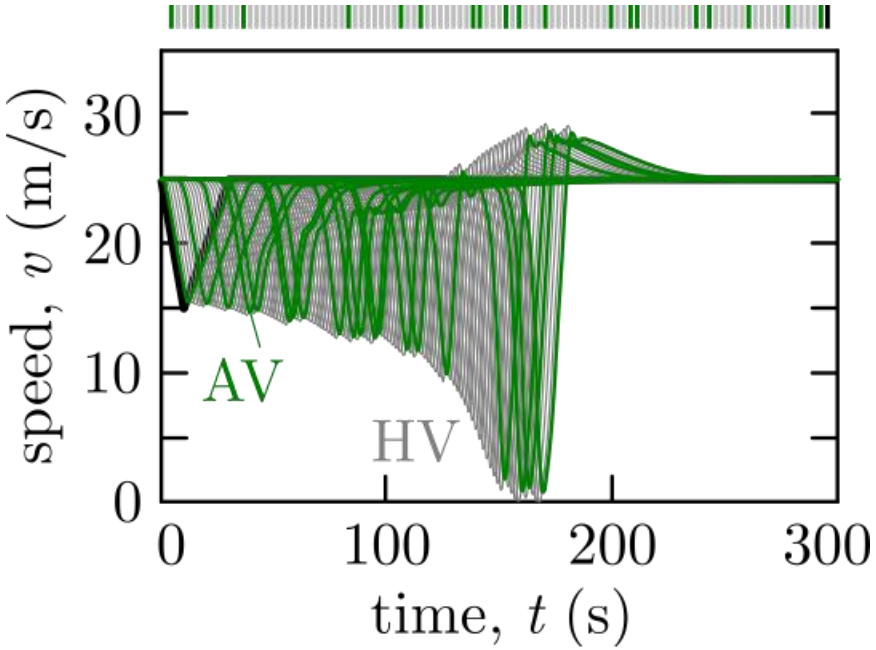
# Large Penetration of AVs can Smoothen Traffic

10% AV



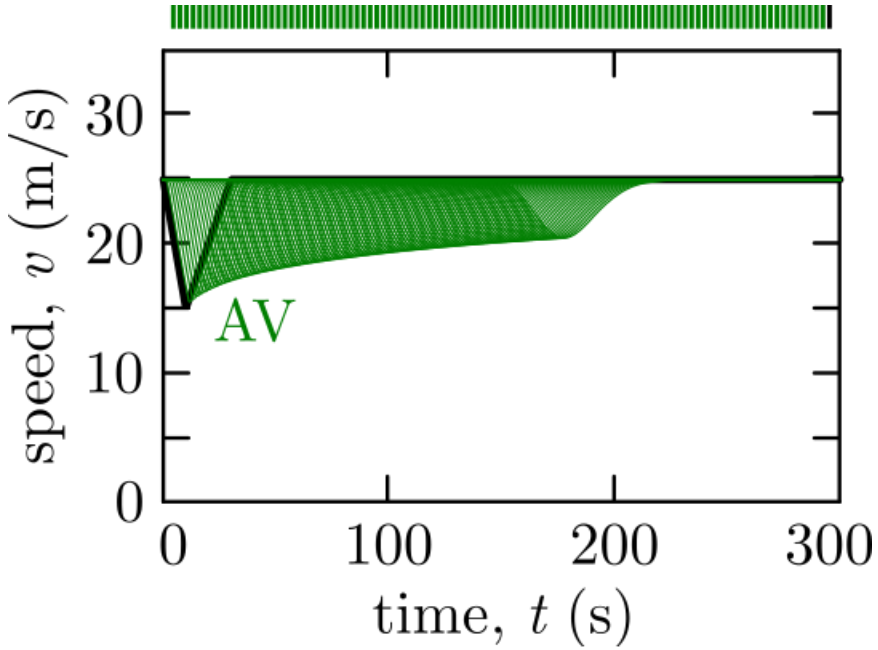
# Large Penetration of AVs can Smoothen Traffic

20% AV

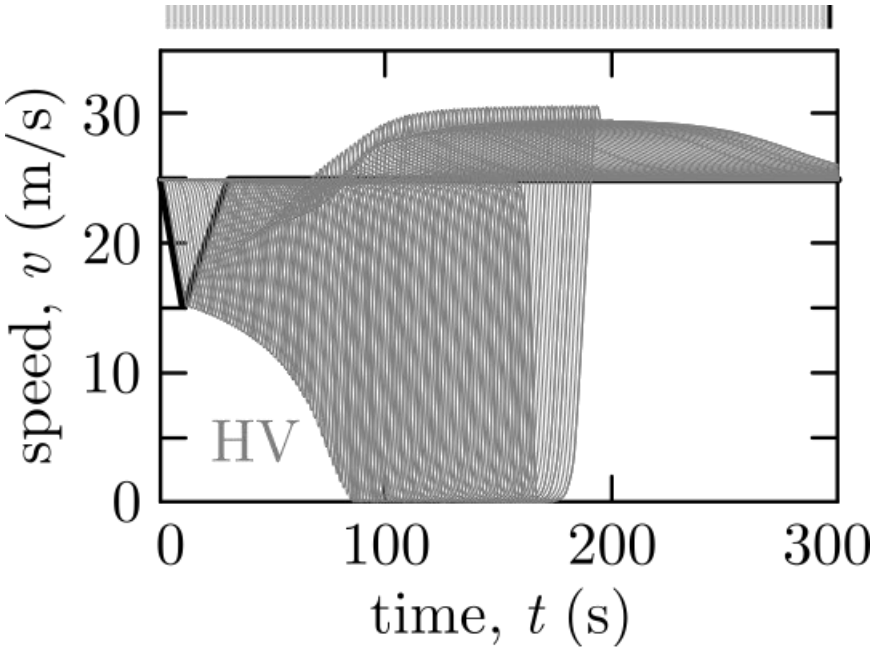


# Large Penetration of AVs can Smoothen Traffic

100% AV

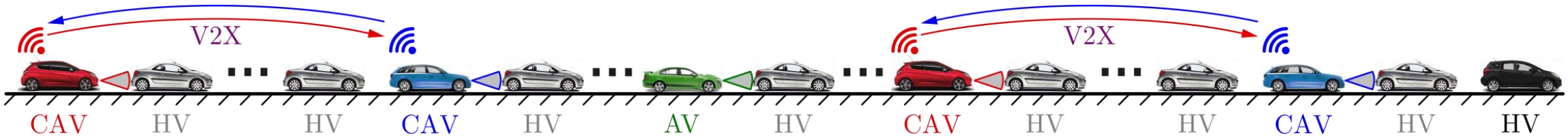


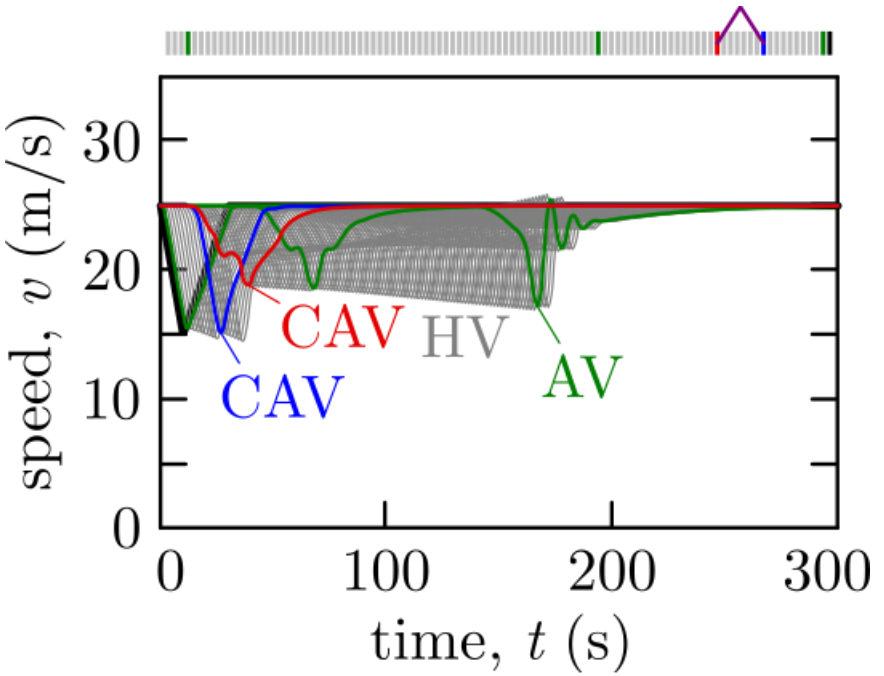
# Human Drivers are String Unstable



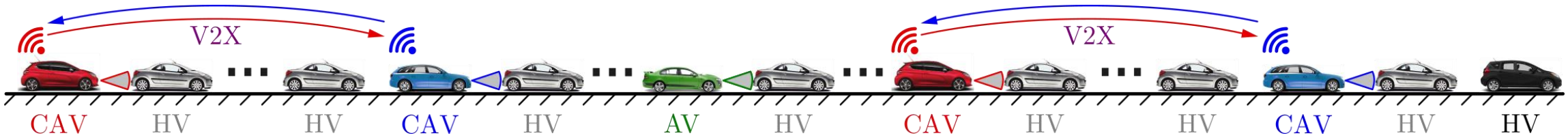

100% HV

# Low Penetration of CAV can Smoothen Traffic



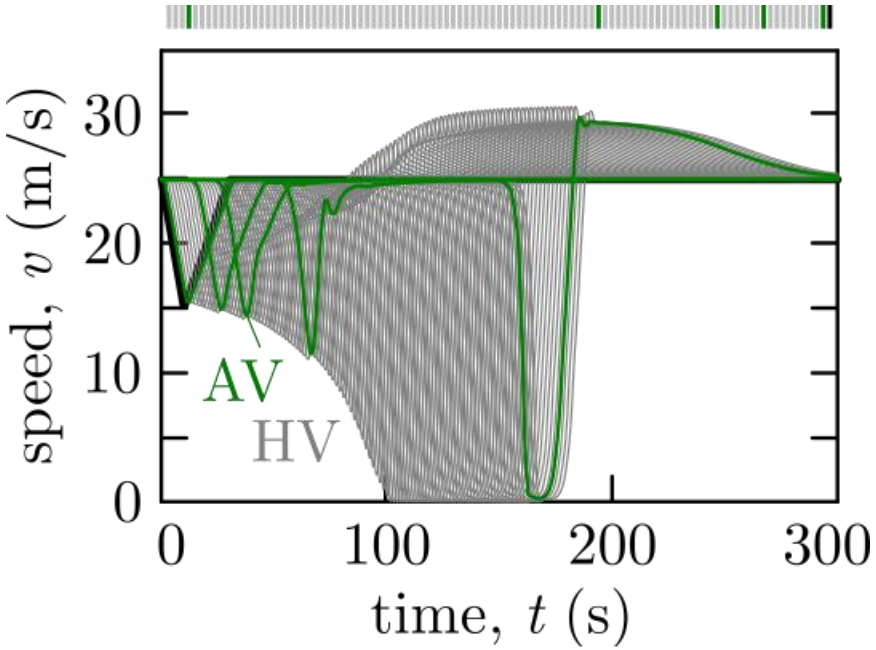



# Low Penetration of CAV can Smoothen Traffic



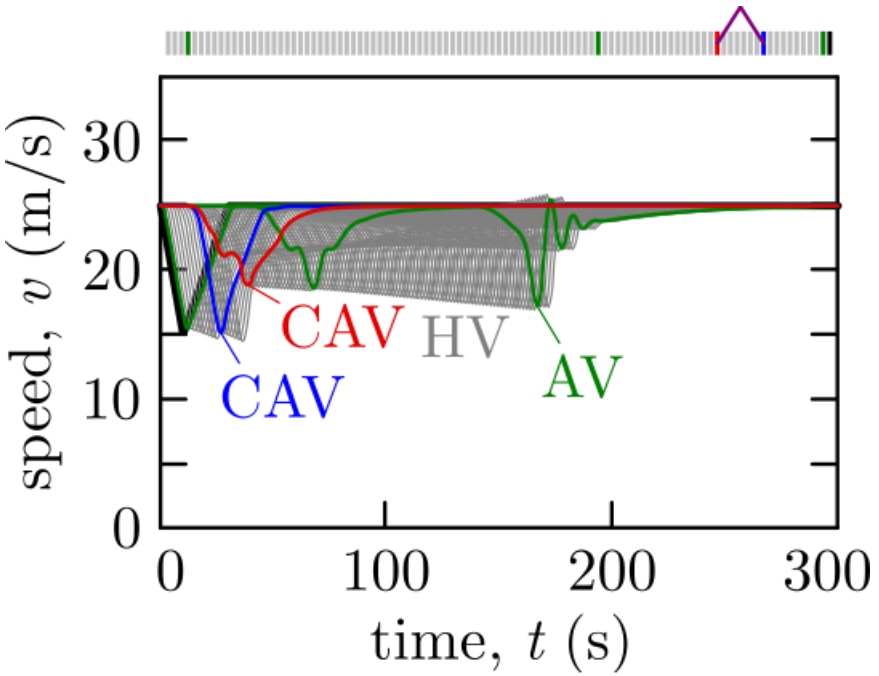

## Without Connectivity

5% AV

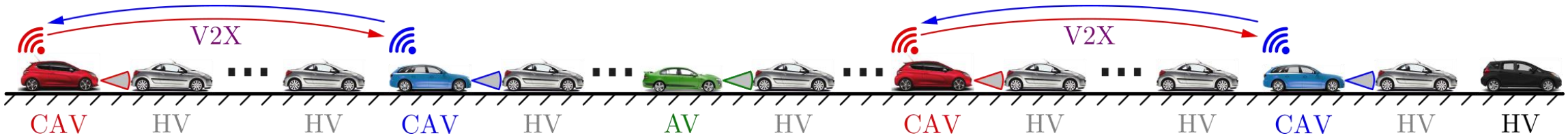



## With Connectivity

5% CAV



# Low Penetration of CAV can Smoothen Traffic

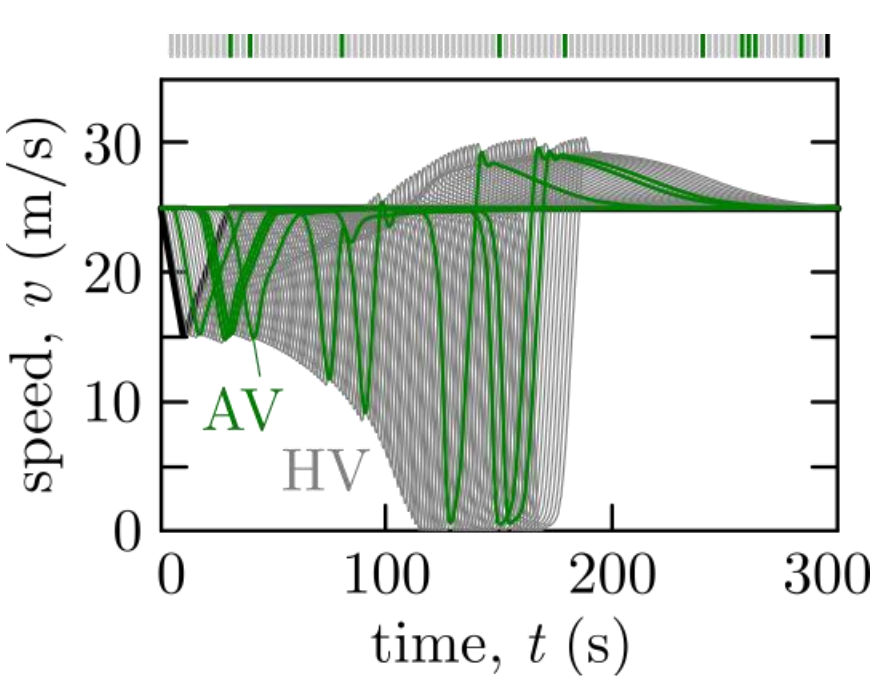


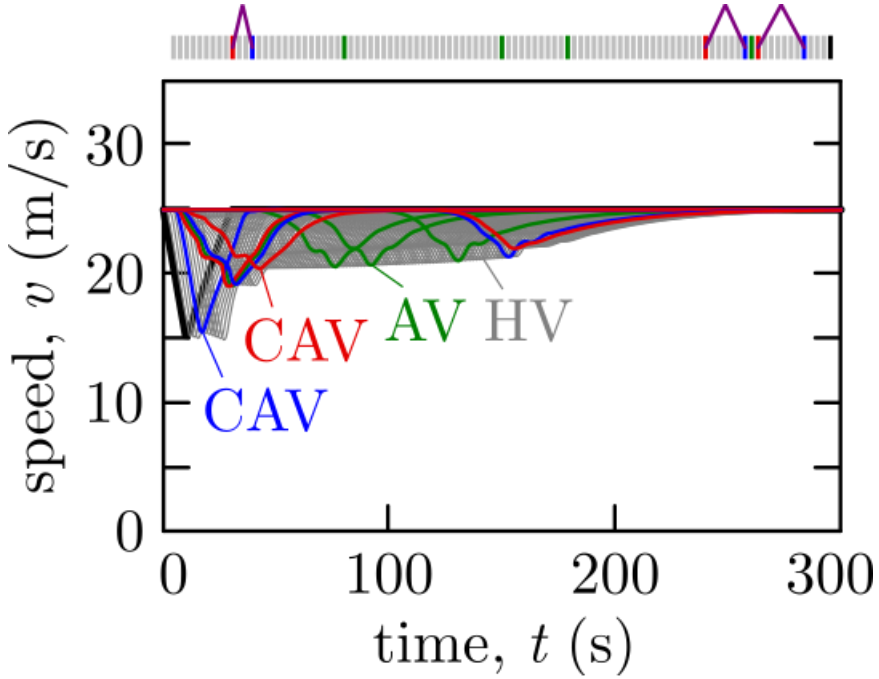

Without Connectivity

With Connectivity

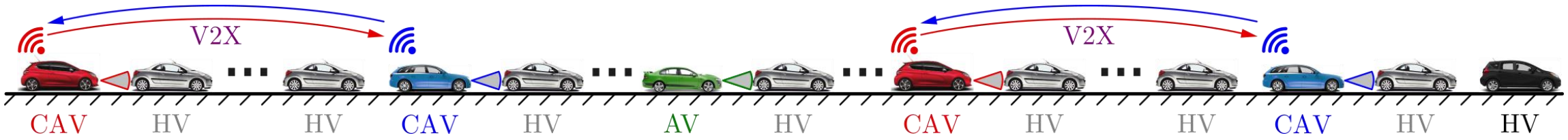
10% AV

10% CAV



# Low Penetration of CAV can Smoothen Traffic

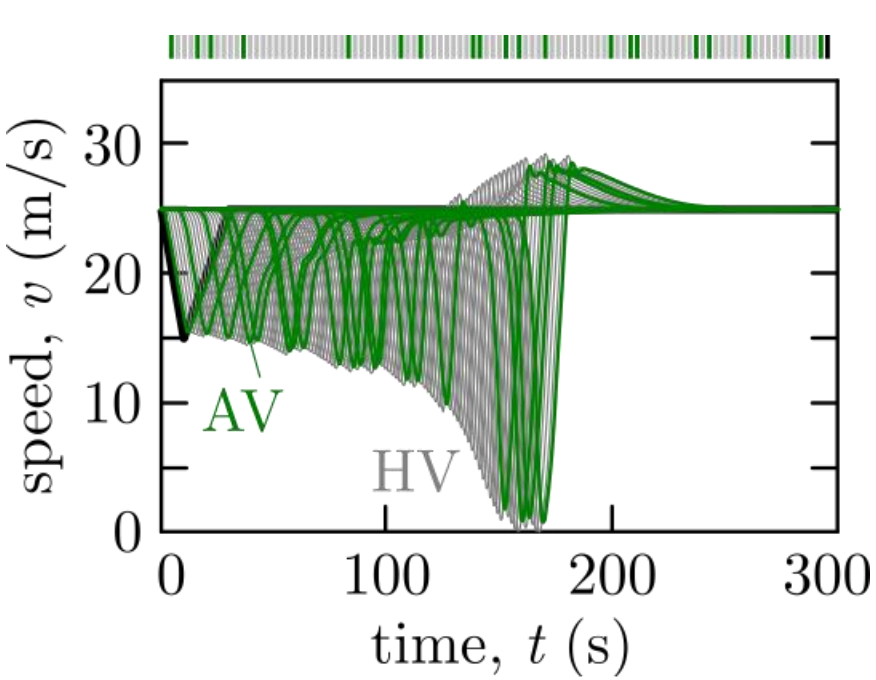


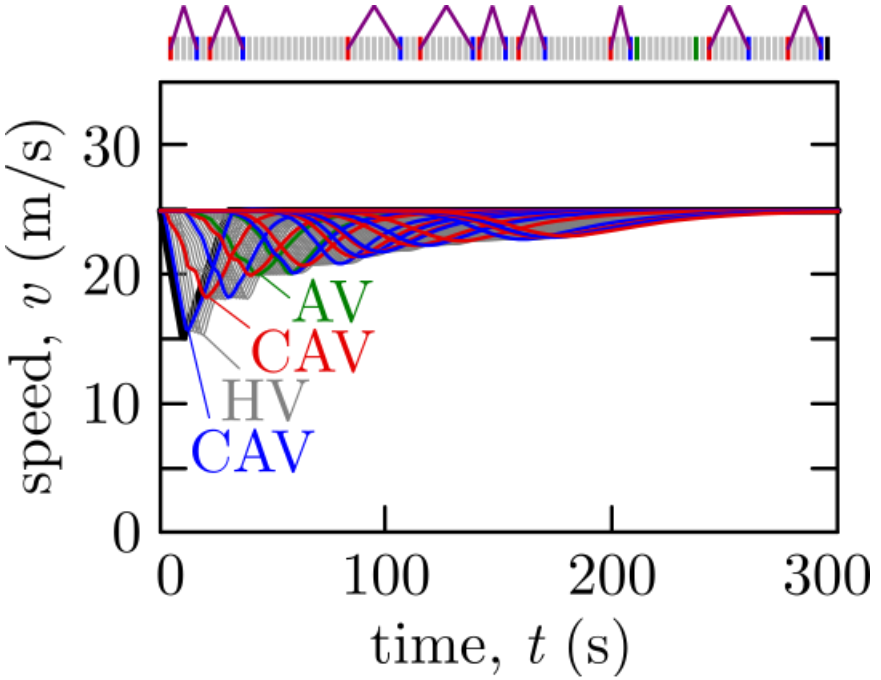

Without Connectivity

With Connectivity

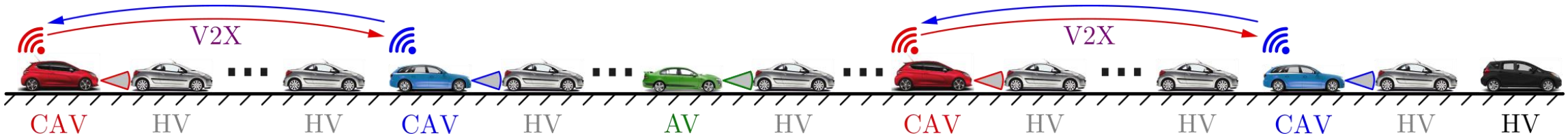
20% AV

20% CAV



# Low Penetration of CAV can Smoothen Traffic

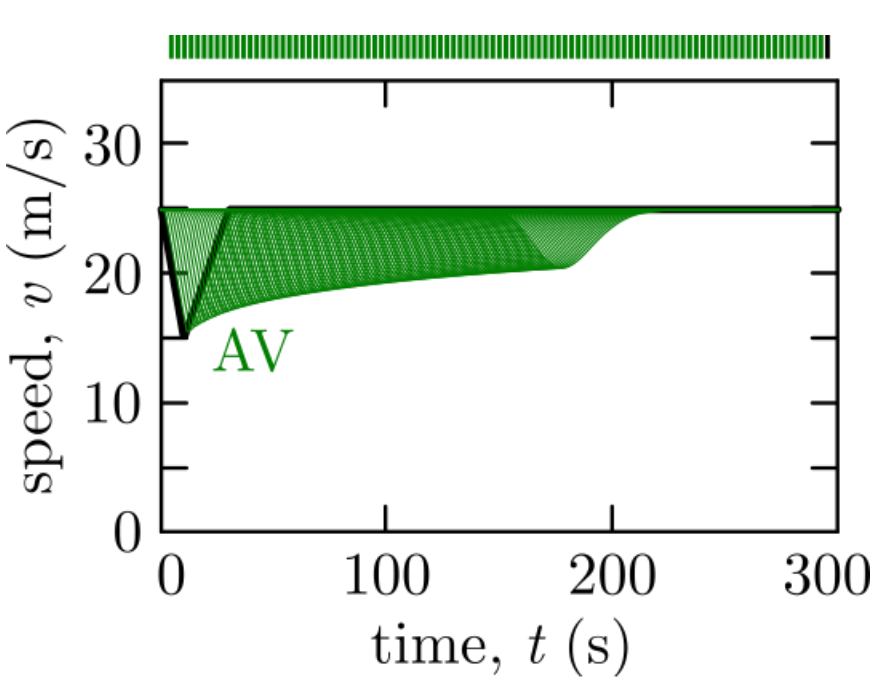


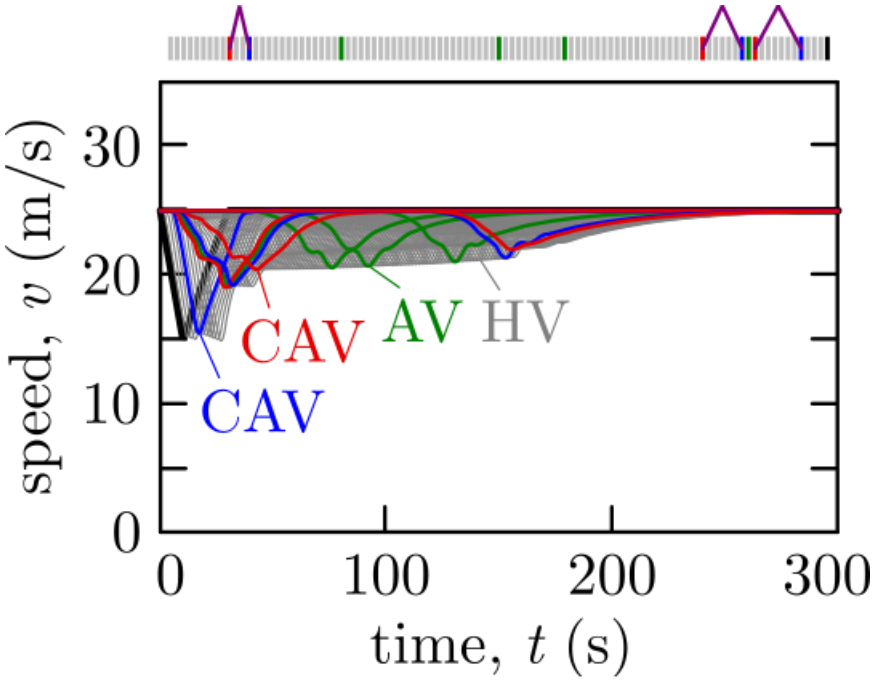

Without Connectivity

With Connectivity

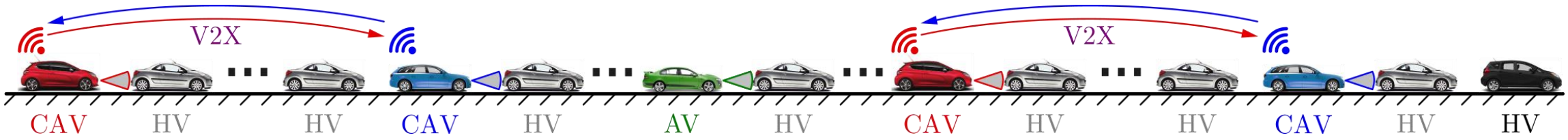
100% AV

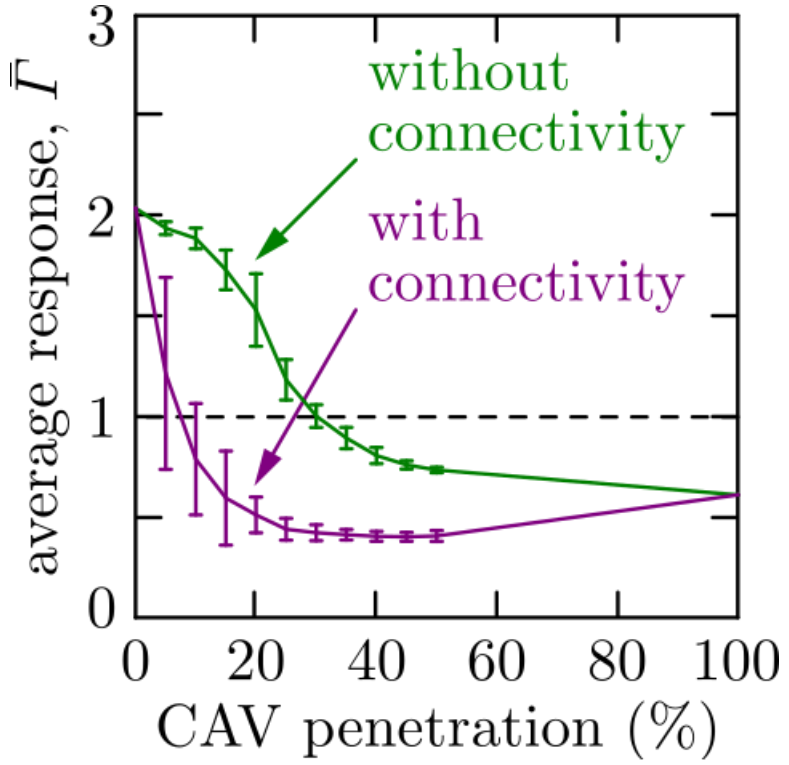
10% CAV



# Low Penetration of CAV can Smoothen Traffic



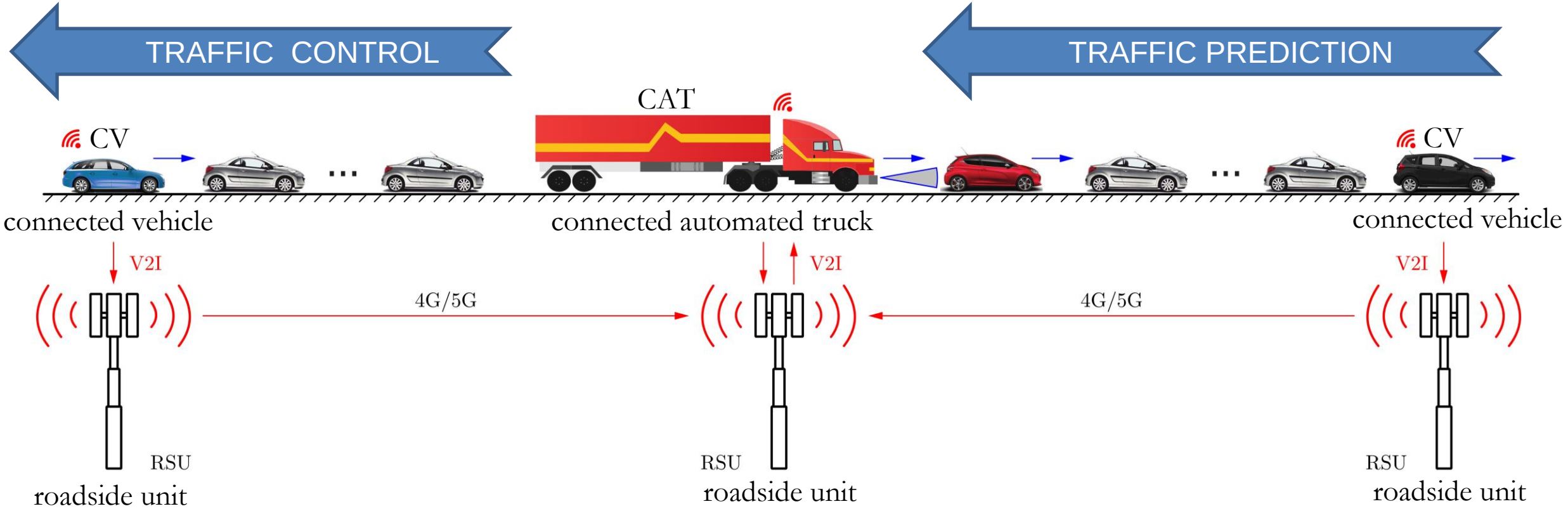




$$\Gamma_i = \frac{\max_{t\geq 0} |v_i(t) - v_i(0)|}{\max_{t\geq 0} |v_{\rm L}(t) - v_{\rm L}(0)|}$$

$$\bar{\Gamma} = \frac{1}{100} \sum_{i=0}^{99} \Gamma_i$$

Connectivity can really make a difference!

# Bridging the Connectivity Gap with Infrastructure




CCAT
CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

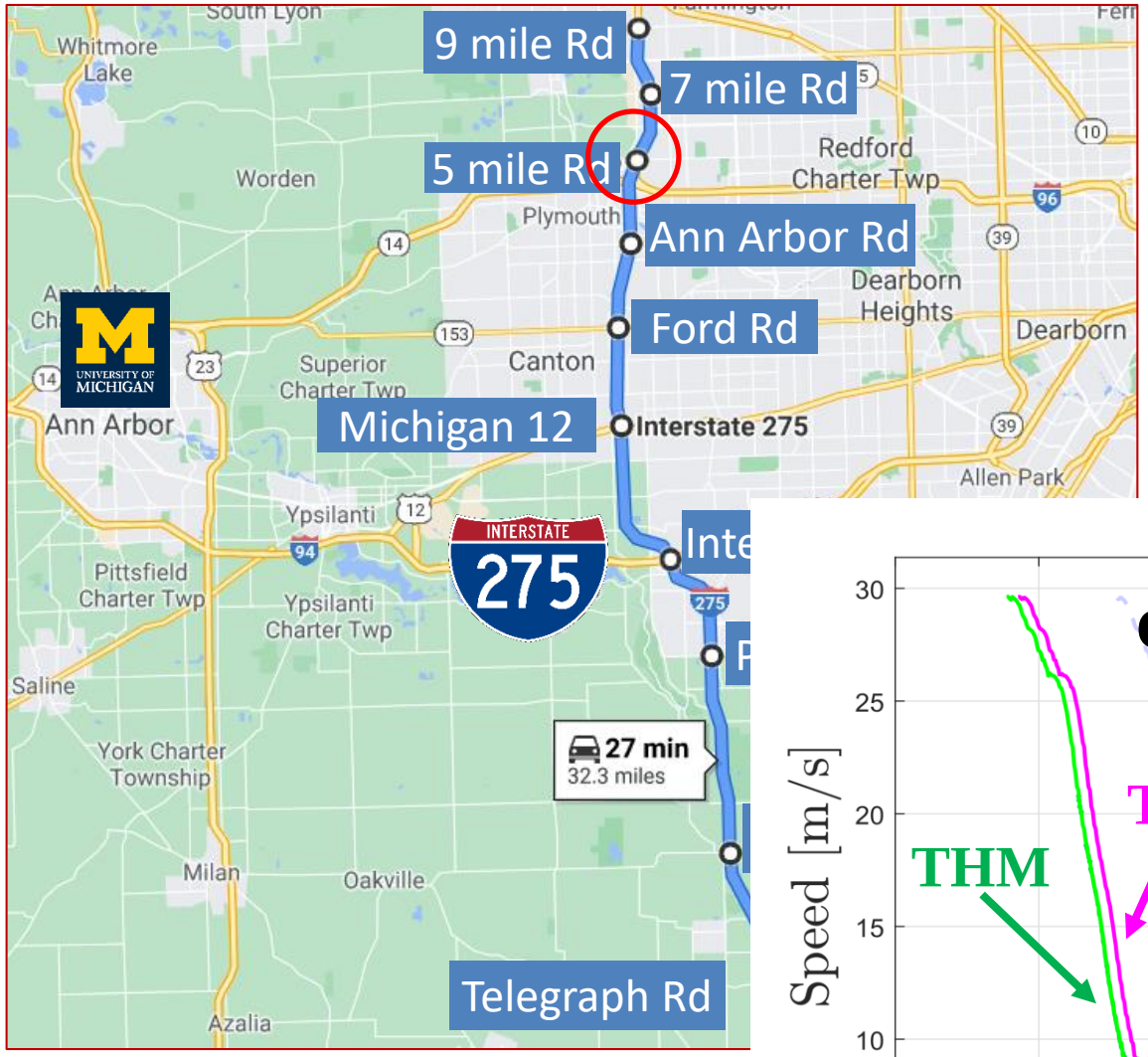
MDOT
Michigan Department of Transportation

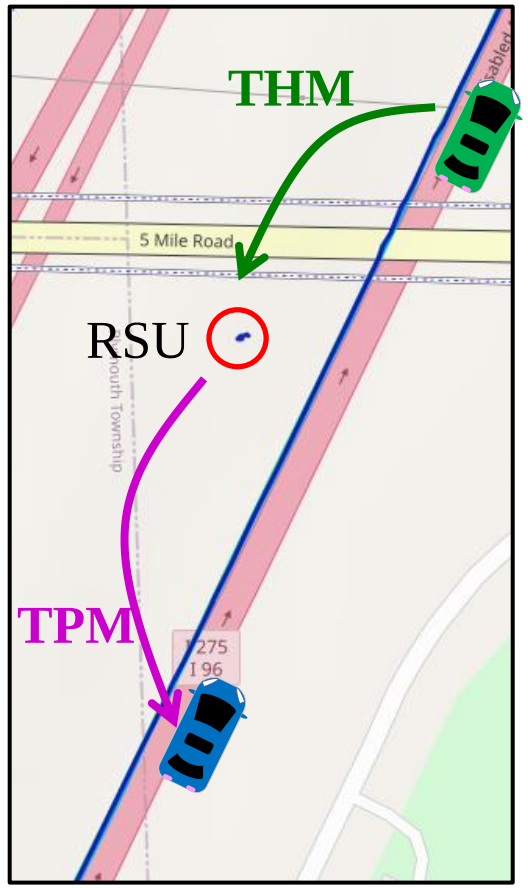
NAVISTAR®

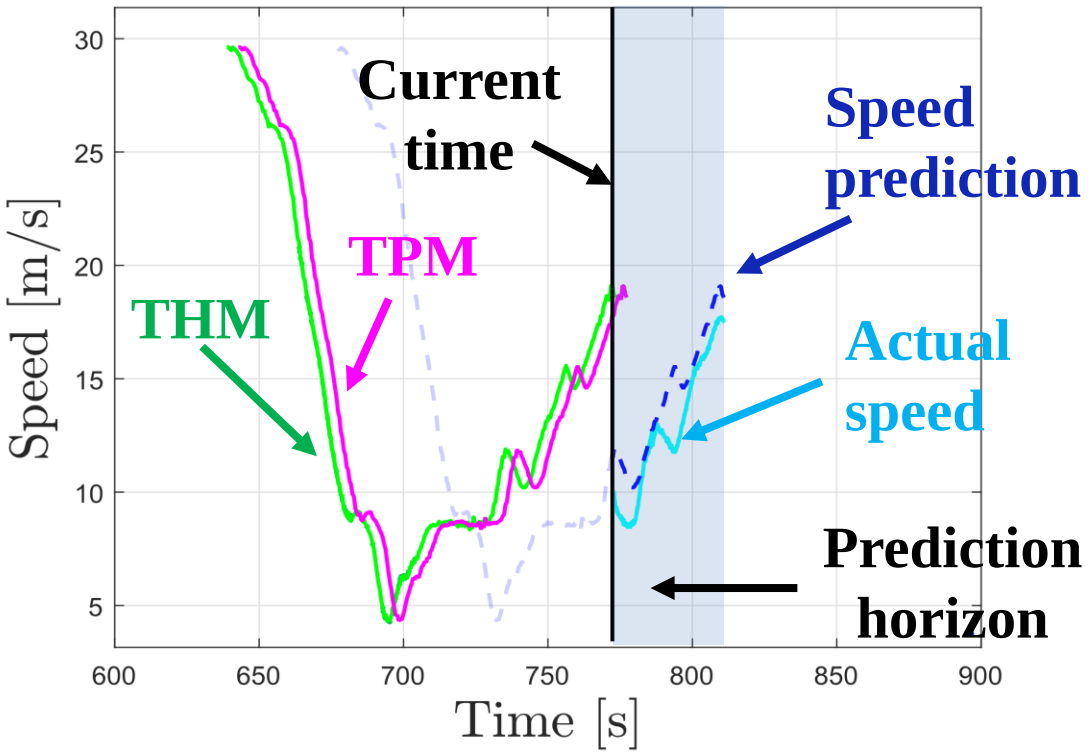
commsignia

Ford

# Bridging the Connectivity Gap with Infrastructure





# Because Traffic has a Memory

Questions ?