Conflict analysis for decision making and control of connected automated vehicles

Gábor Orosz

University of Michigan, Ann Arbor

Motivation

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

Categorization (Michigan)

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

IAVSD

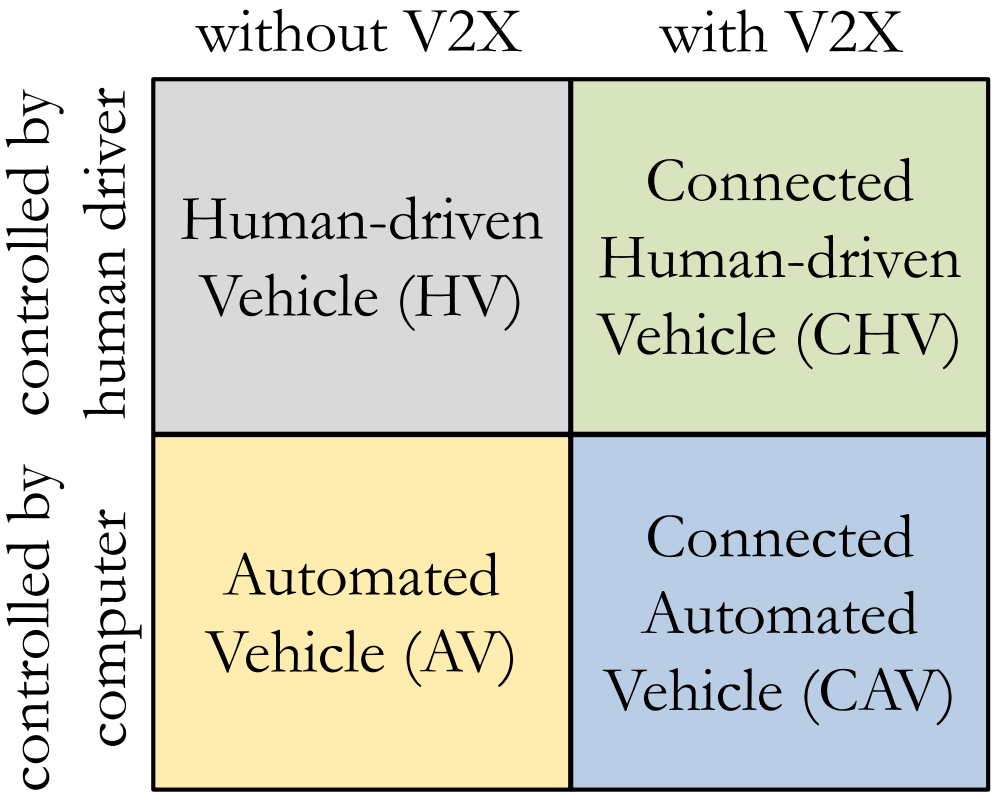
Taylor & Francis
Taylor & Francis Group

Check for updates

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

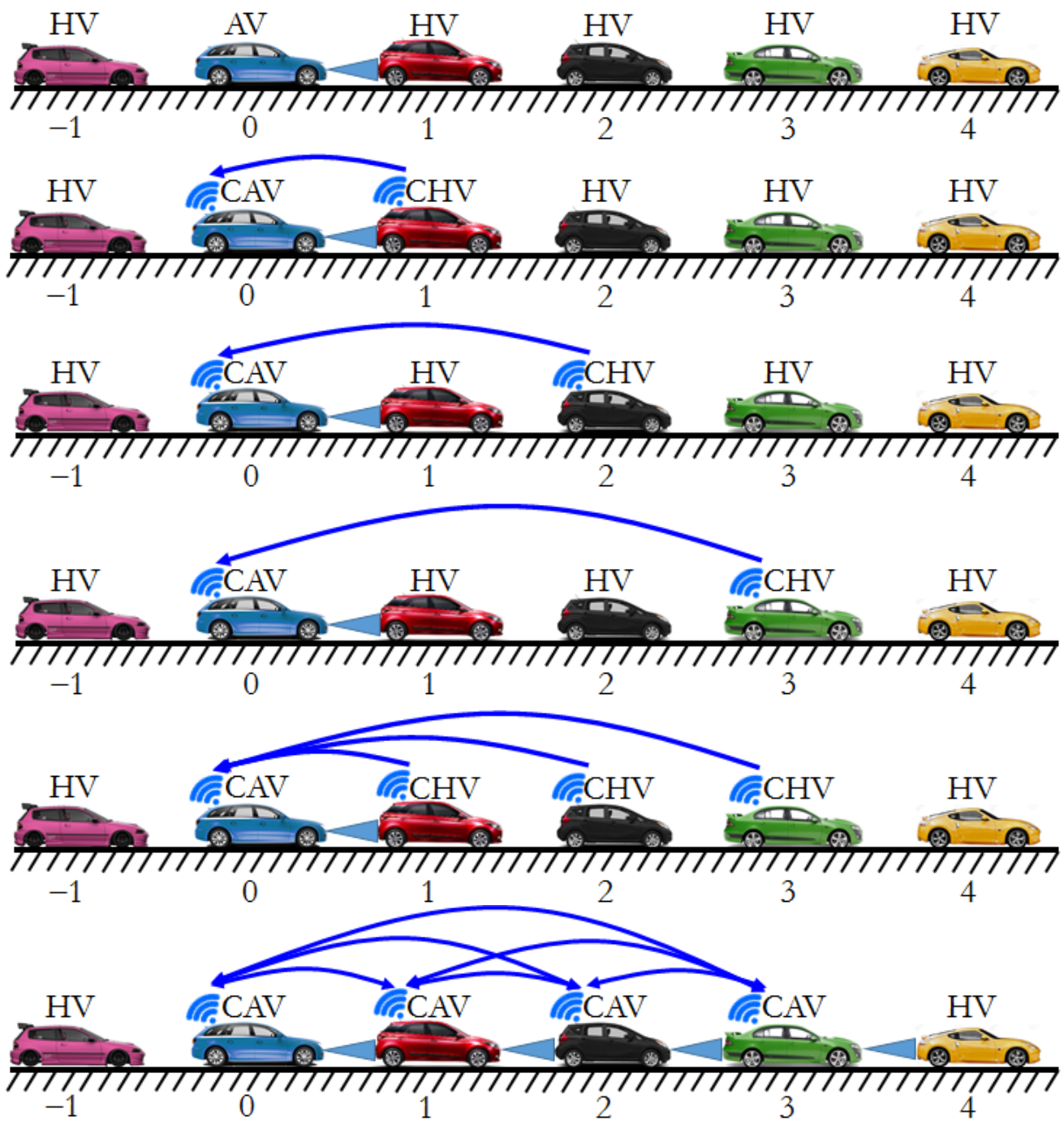


Mixed Traffic

Adaptive Cruise Control (ACC)

Connected Cruise Control (CCC)

Cooperative Adaptive Cruise Control (CACC)



Connected Cruise Control (theory)

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

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

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

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

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

Tamás G. Molnár, Wubing B. Qin, Tamás Insperger, 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

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 (practice)

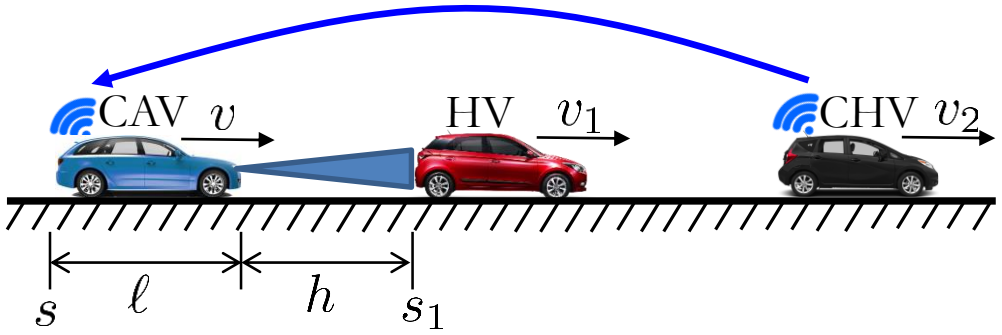
Transportation Research Part C 91 (2018) 335–352

Contents lists available at ScienceDirect

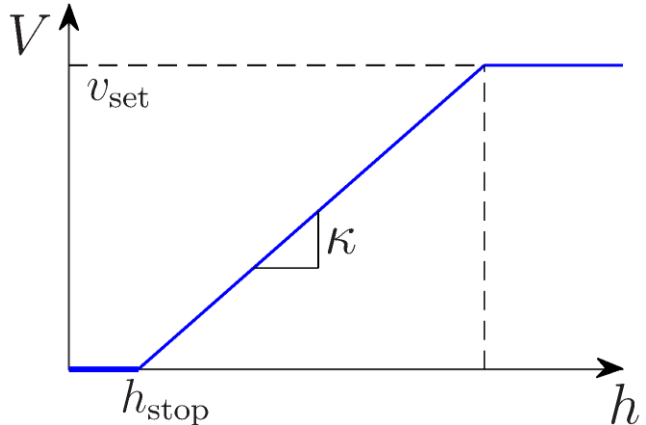
Transportation Research Part C

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

Experimental validation of connected automated vehicle design among human-driven vehicles



$$u = \alpha\left(V(h) - v\right) + \beta_1(v_1 - v) + \beta_2(v_2 - v)$$



Connected Cruise Control (practice)

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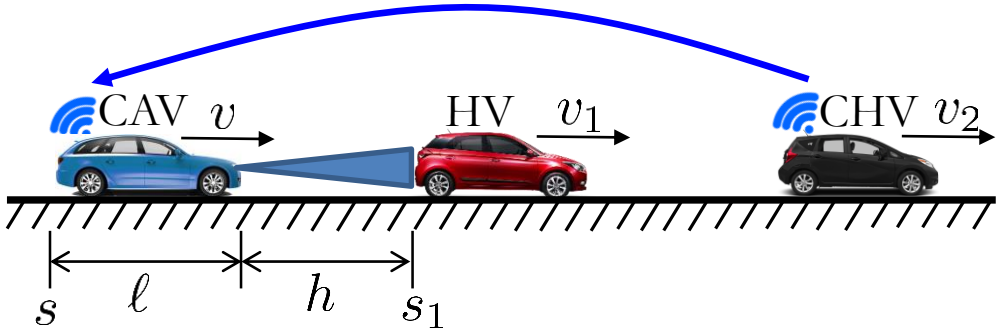

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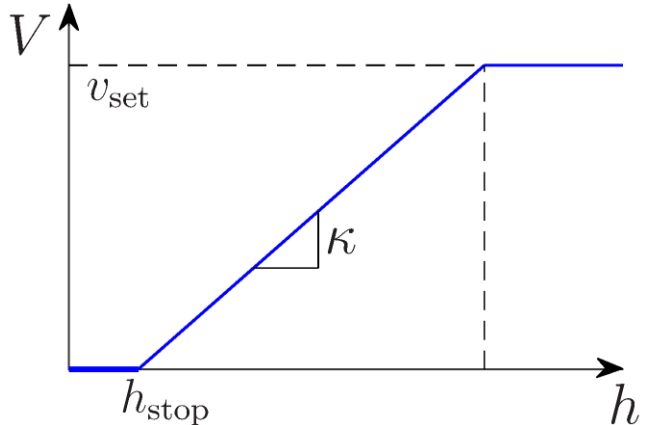

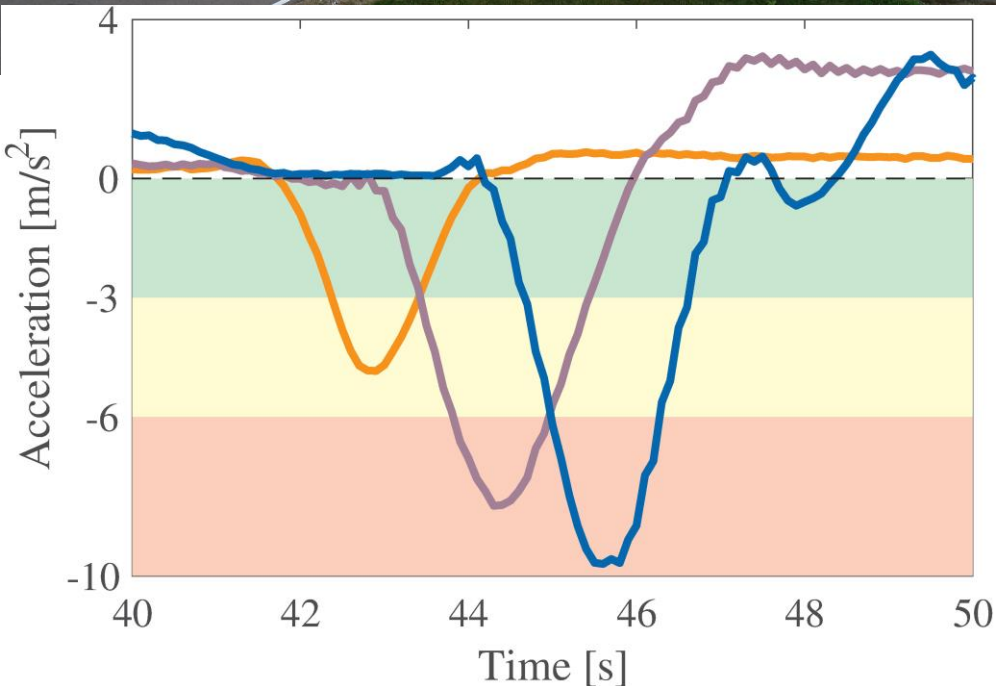

Connected Cruise Control (practice)

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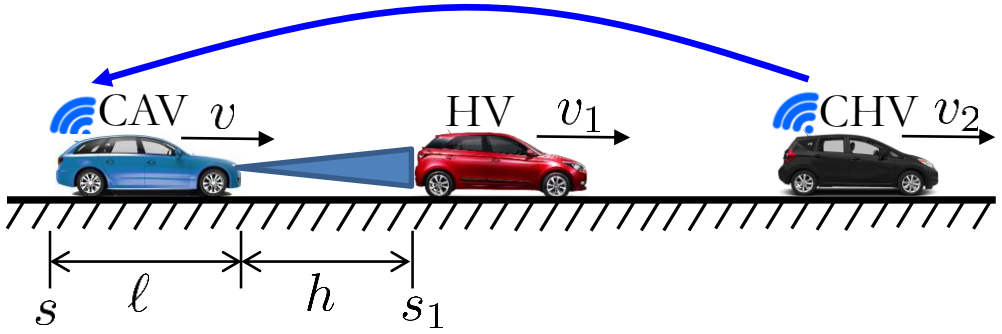

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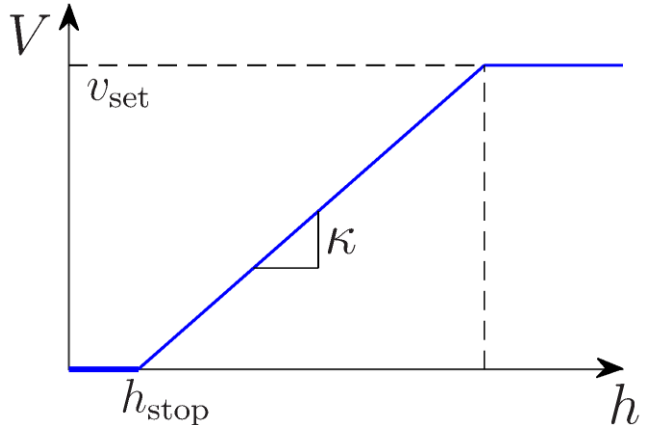

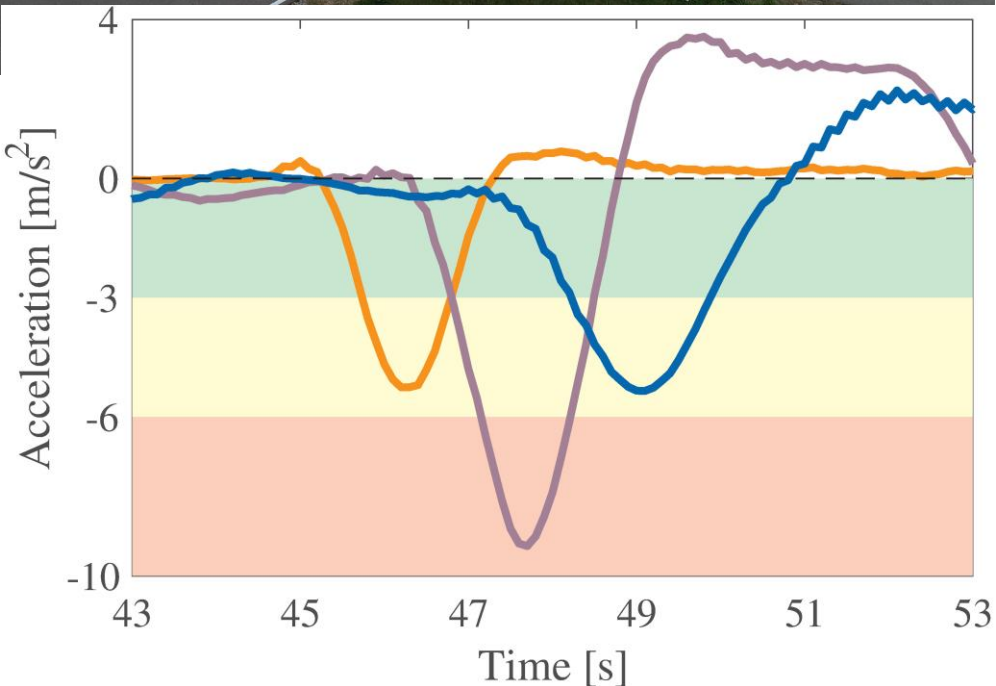

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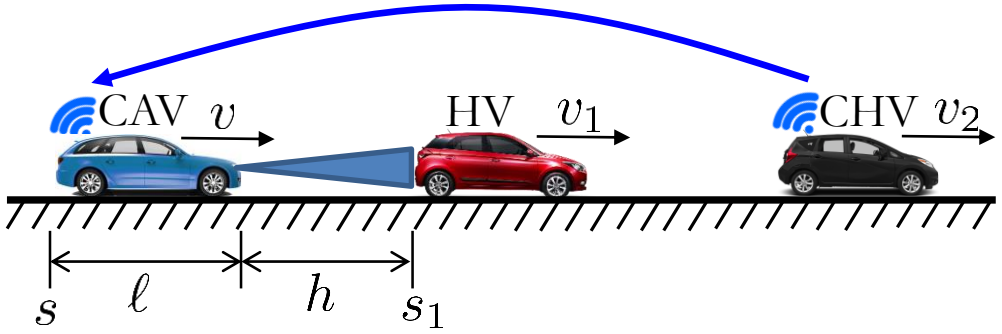

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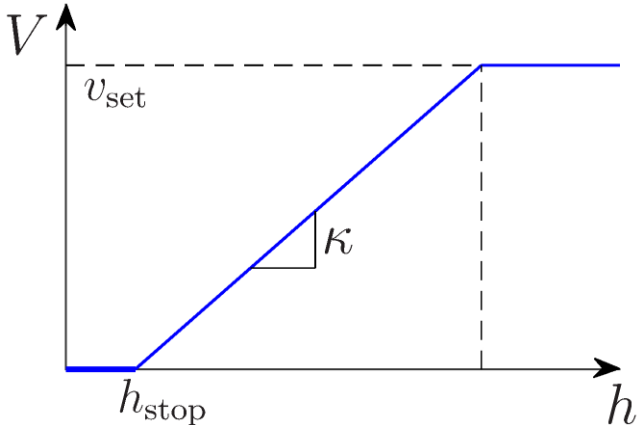
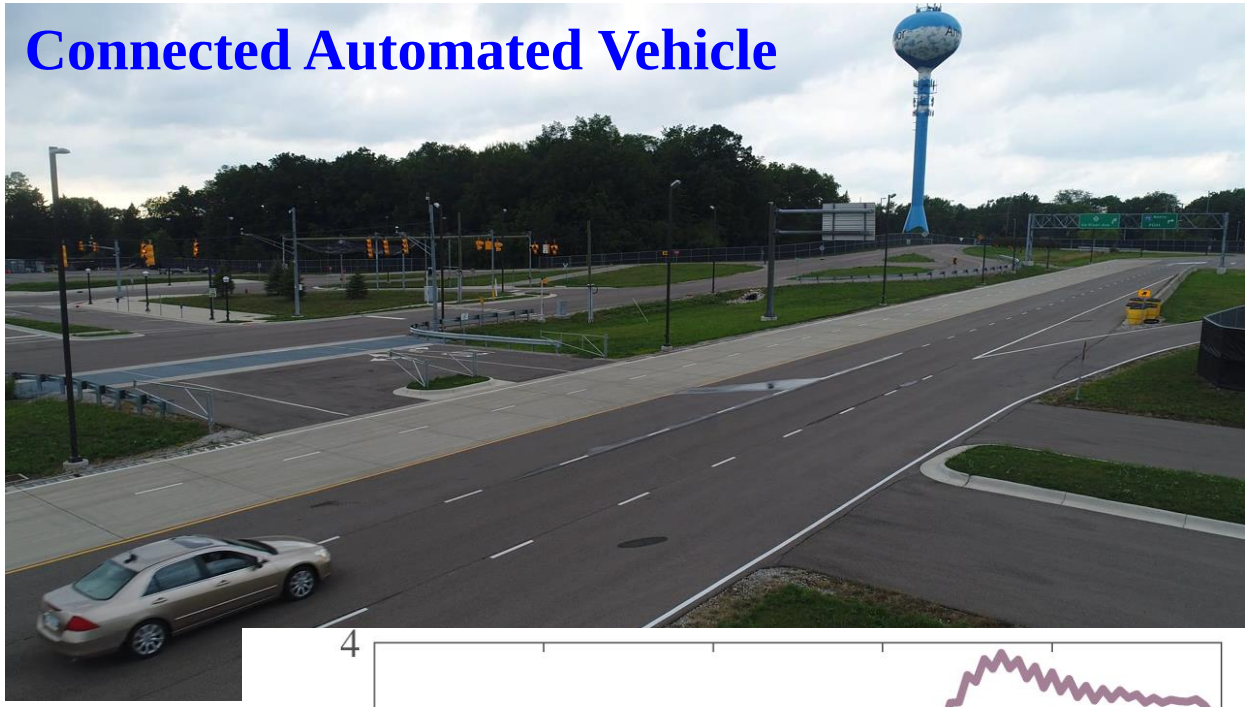
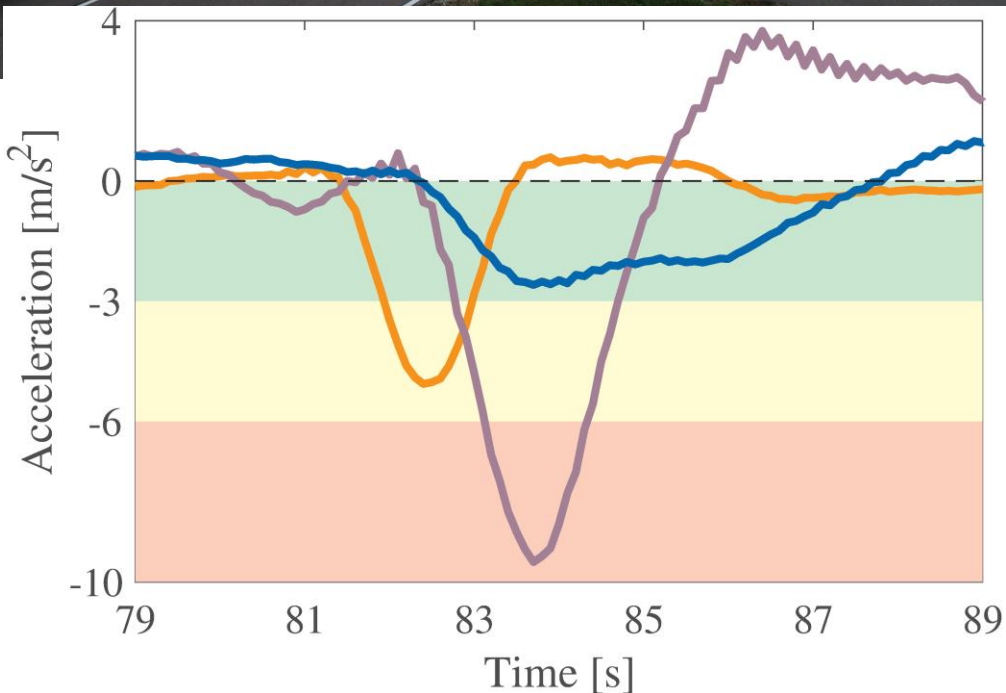
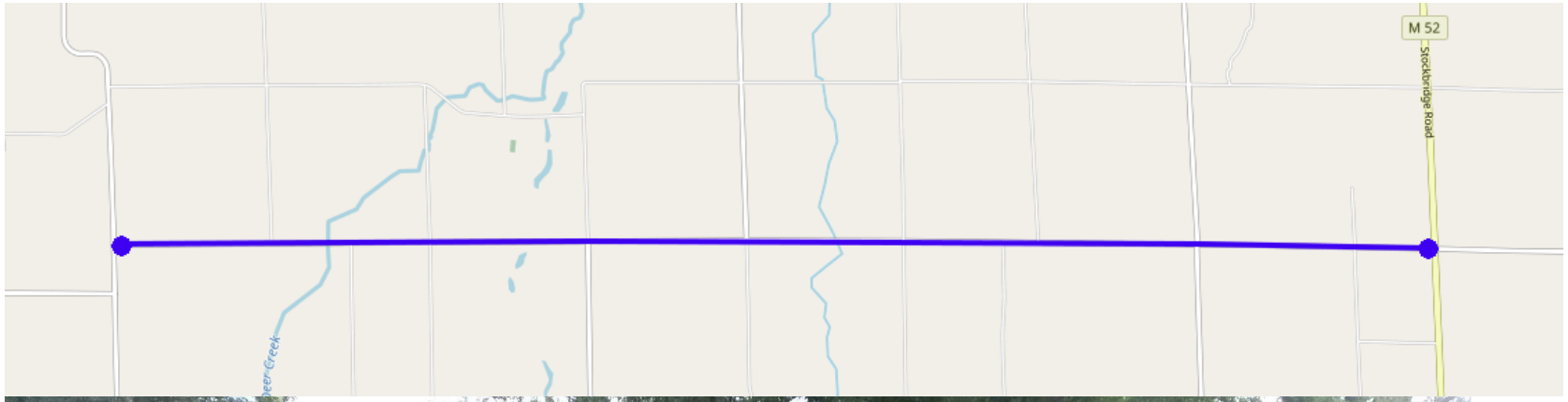
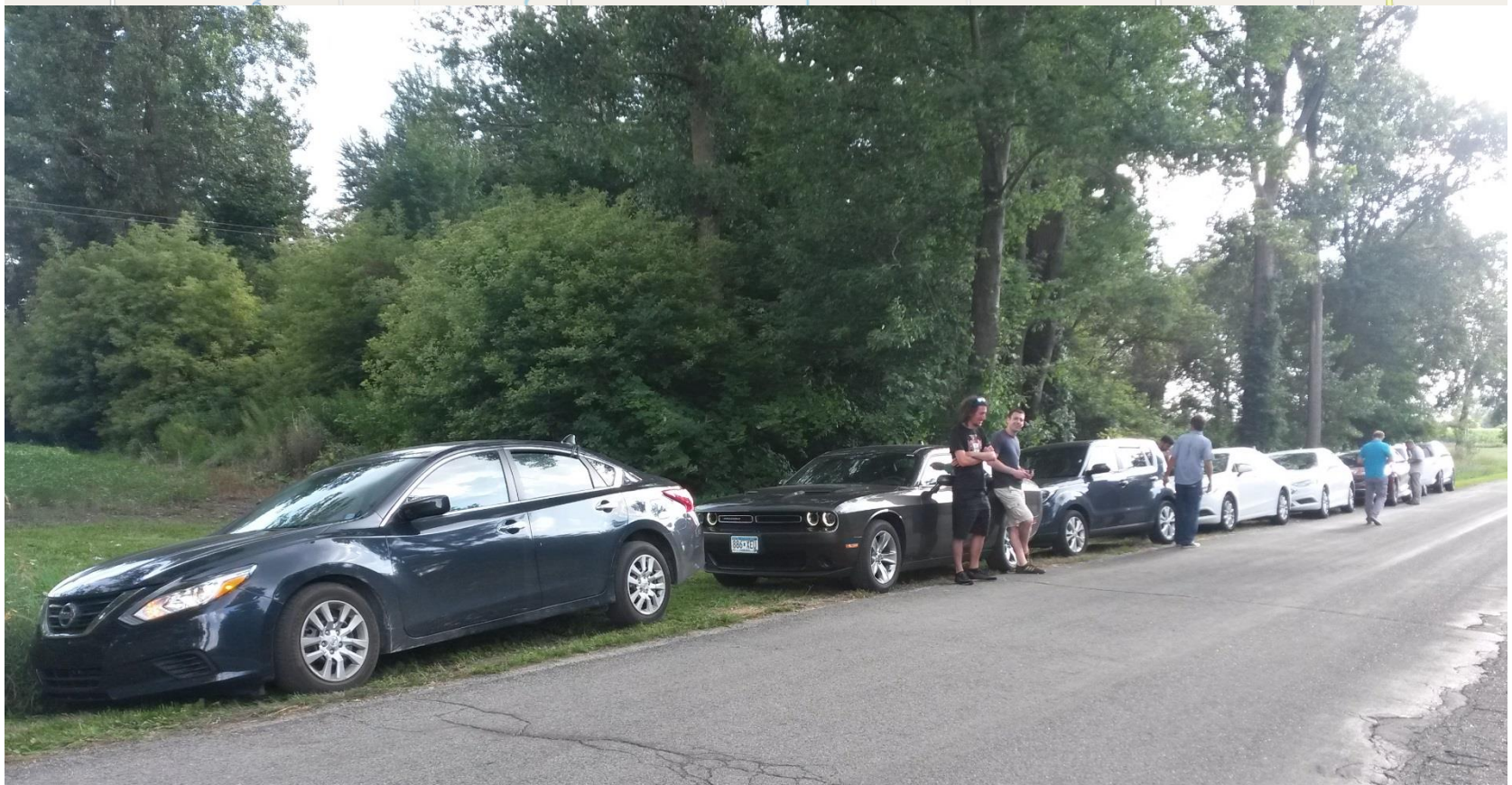






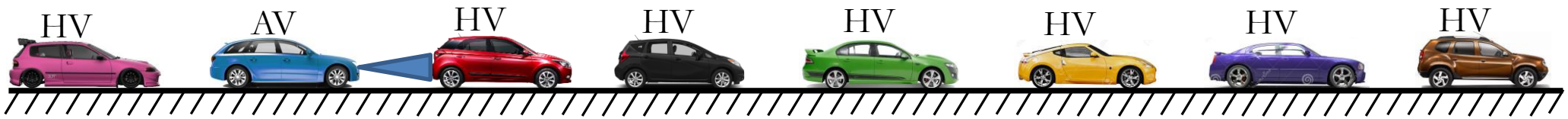
Connected Cruise Control (public road)

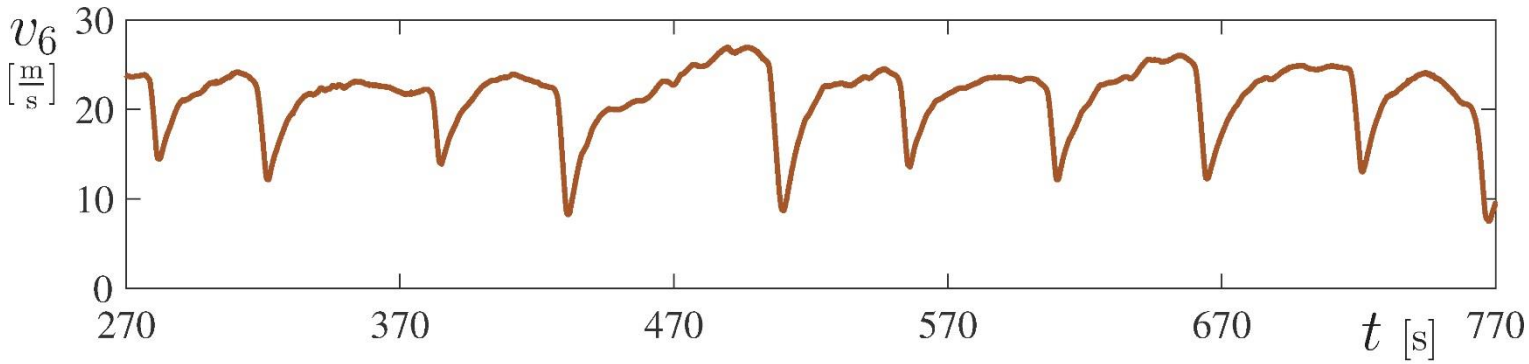


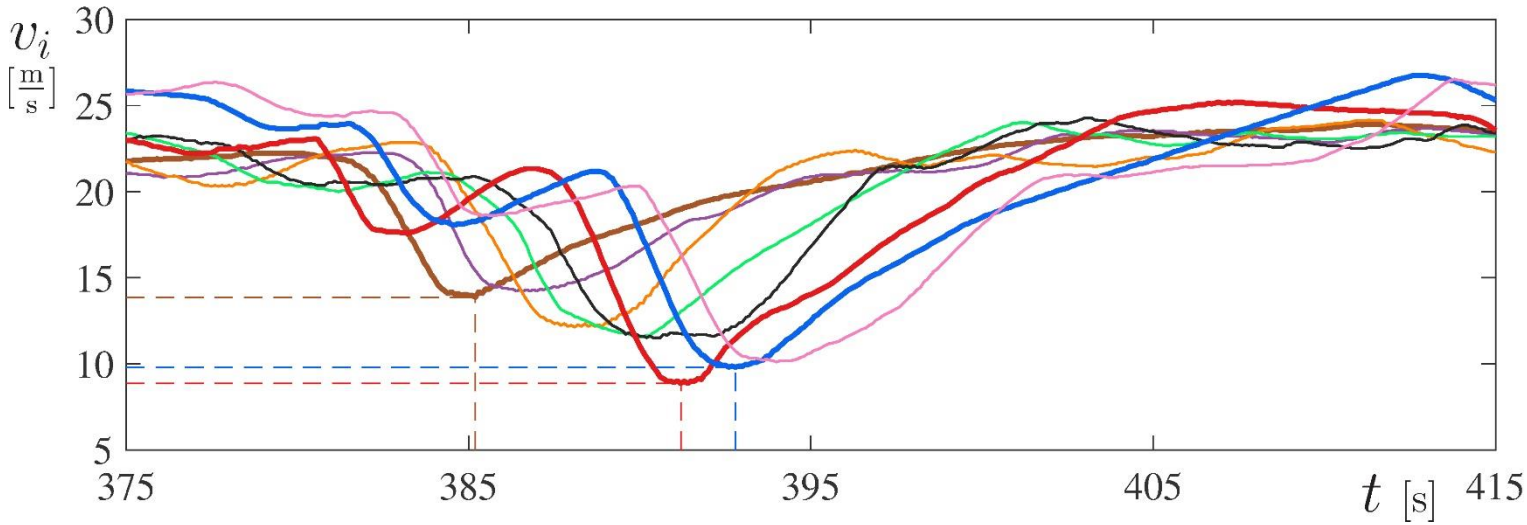


~~Connected~~ Cruise Control (public road)

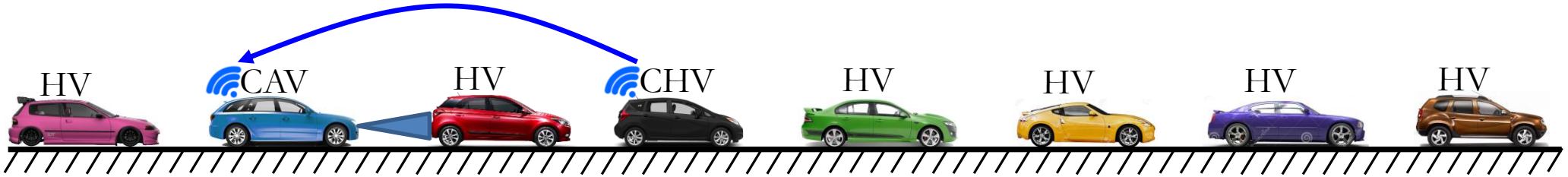
Adaptive

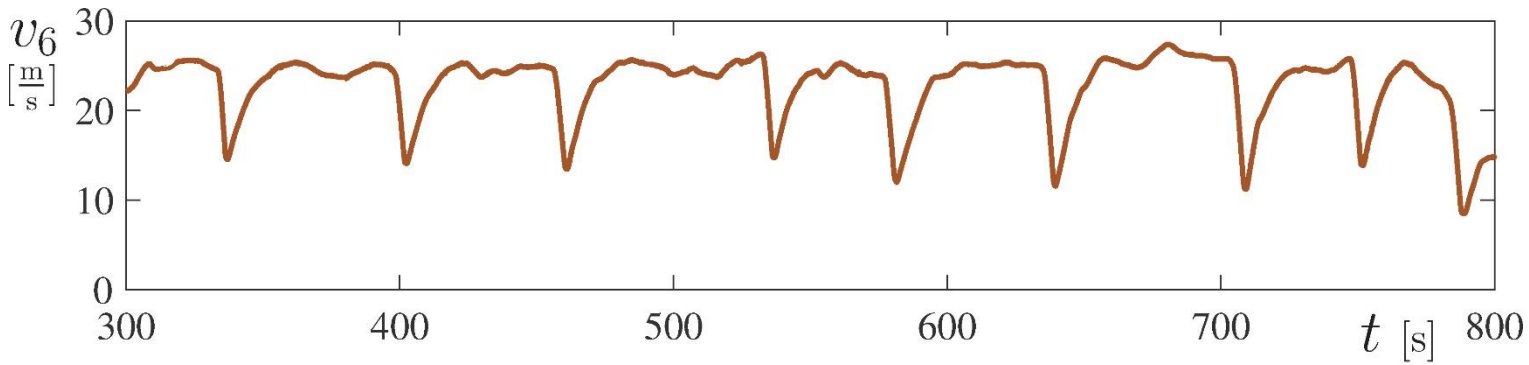


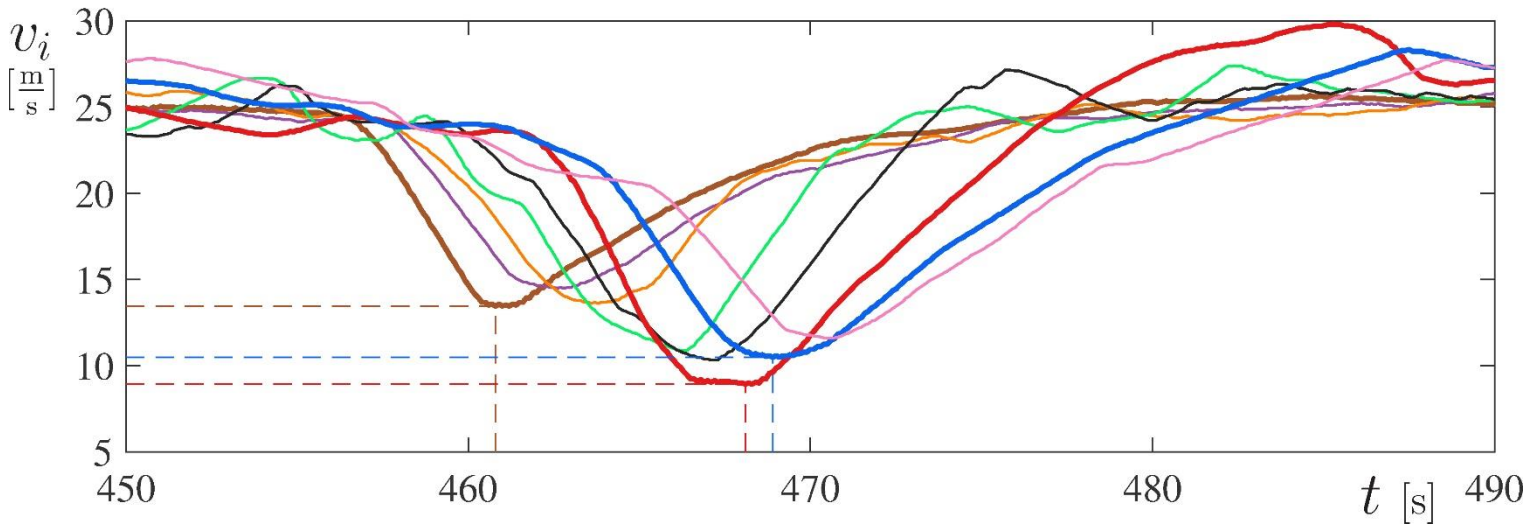




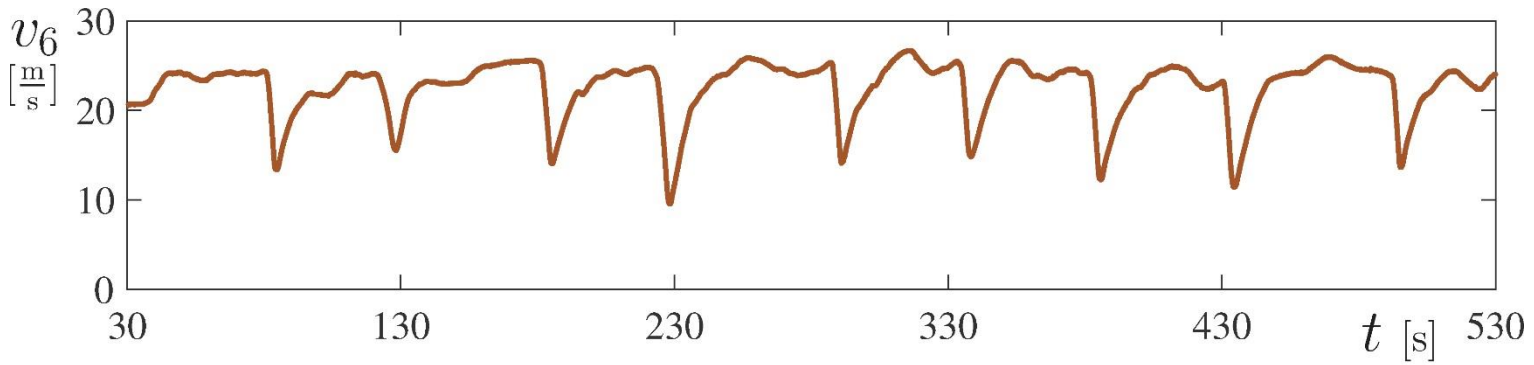
Connected Cruise Control (public road)

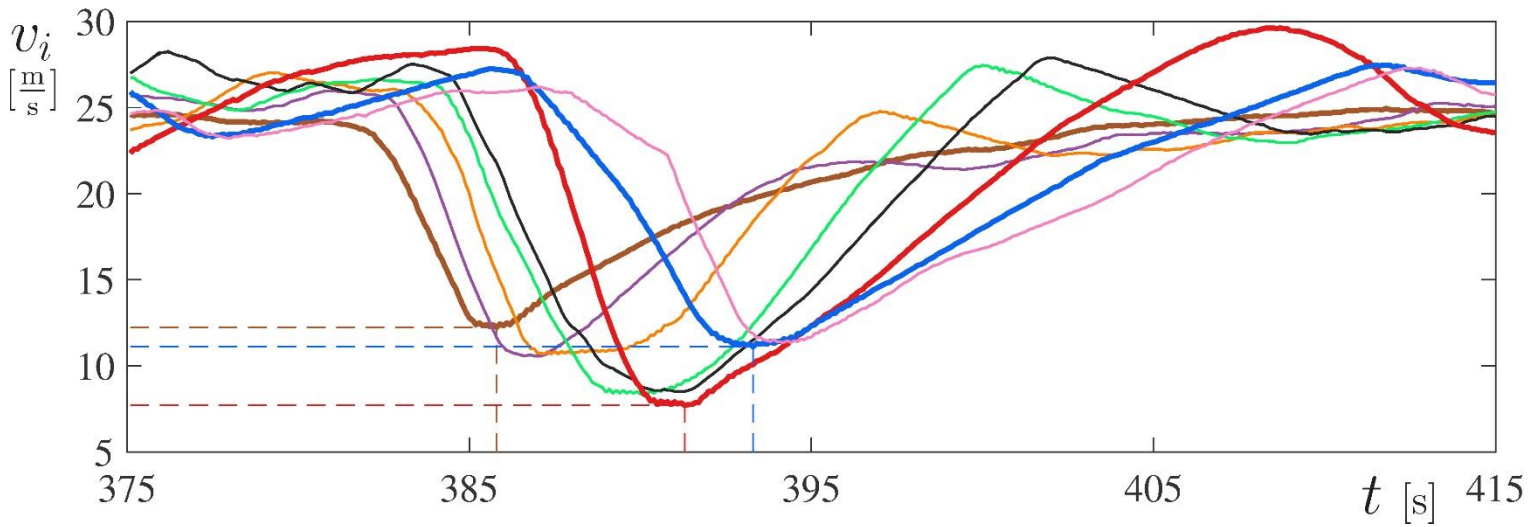




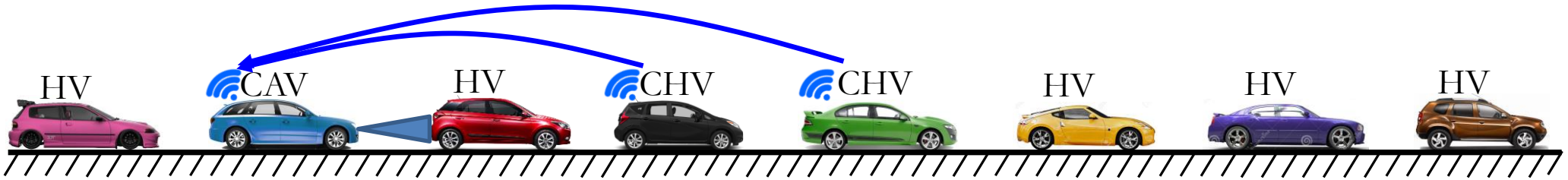


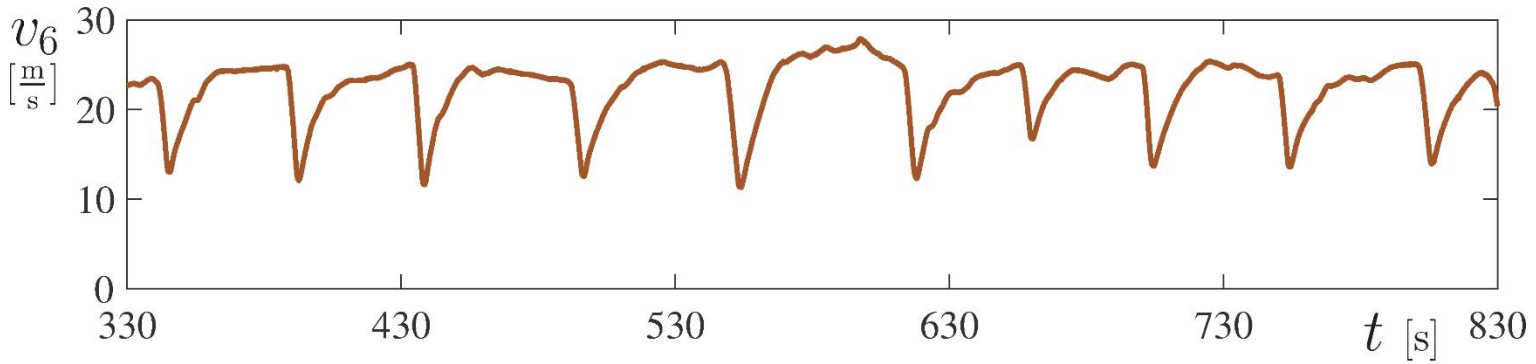
Connected Cruise Control (public road)

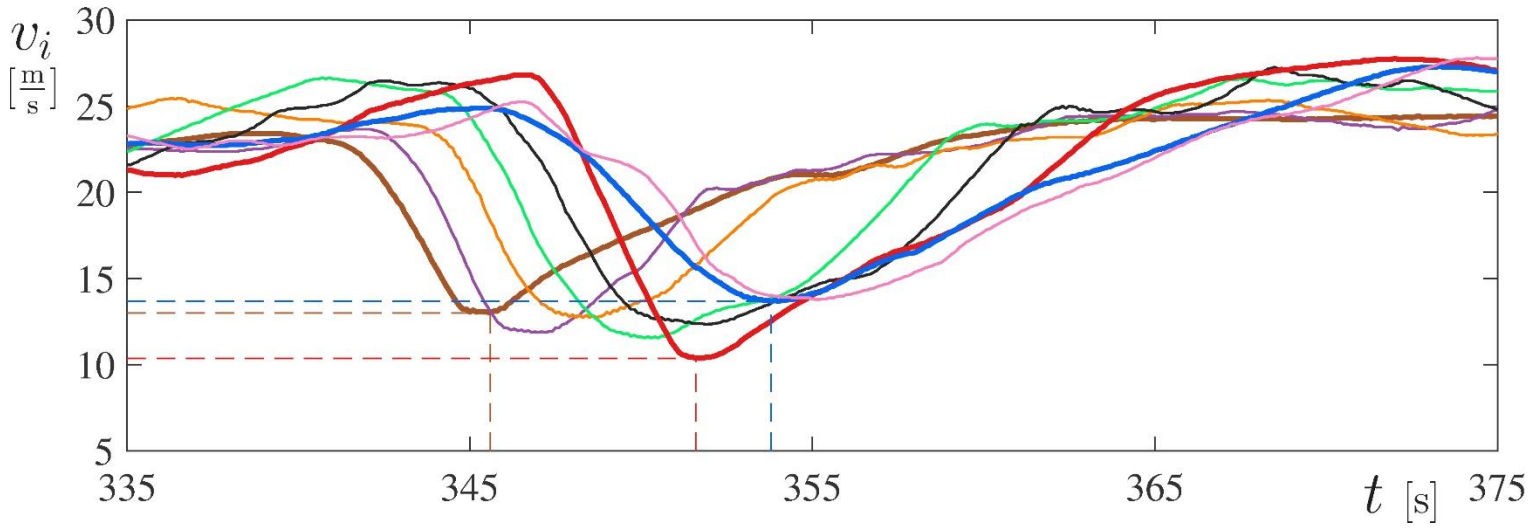




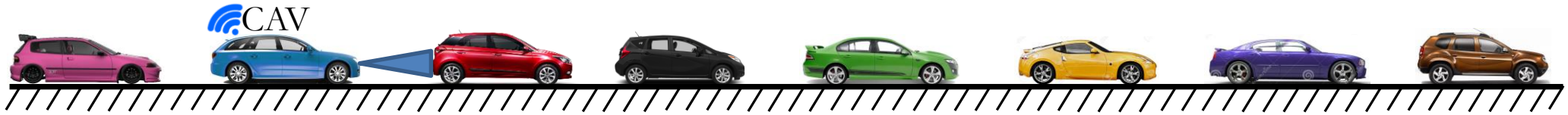
Connected Cruise Control (public road)





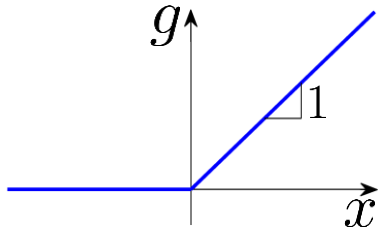


Energy Efficiency



Energy consumption (per unit mass)

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



	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

7% energy saving by connectivity

19% energy saving by connectivity

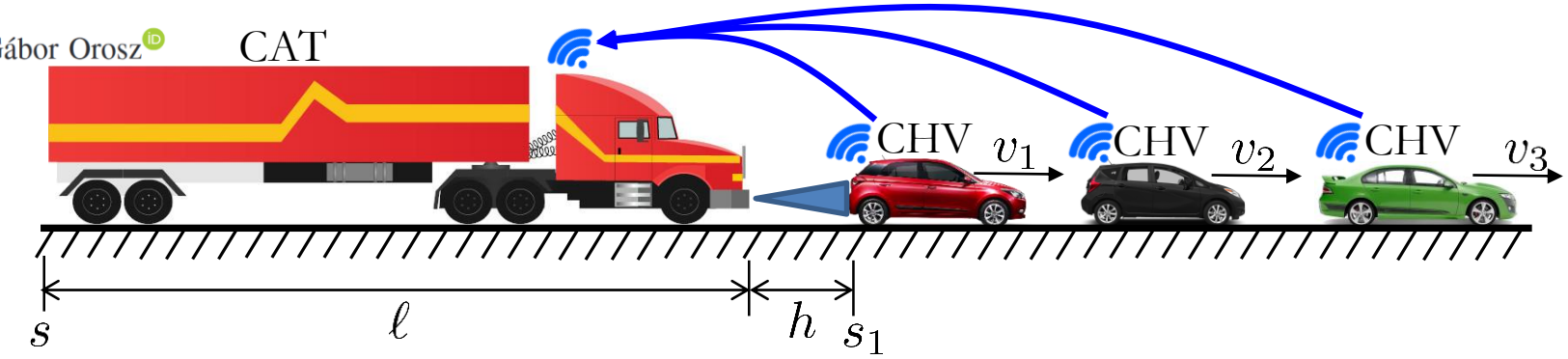
Energy Efficiency for Class-8 Trucks

Energy Efficiency of Class-8 Trucks

2474 IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 28, NO. 6, NOVEMBER 2020

Fuel Efficient Connected Cruise Control for Heavy-Duty Trucks in Real Traffic

Chaozhe R. He, Jin I. Ge, and Gábor Orosz



Independent of the control design:

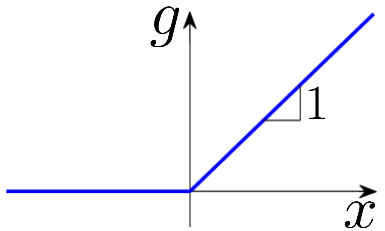
Theorem:

$$\alpha_1(J) \le w \le \alpha_2(J)$$

class $\mathcal{K}$ functions

where

$$w = \int_0^T g\big(\dot v(\theta)\big) v(\theta) \mathrm{d}\theta$$

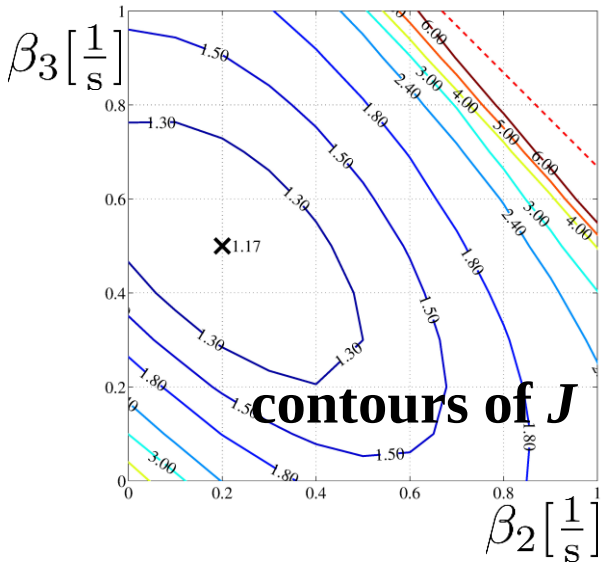


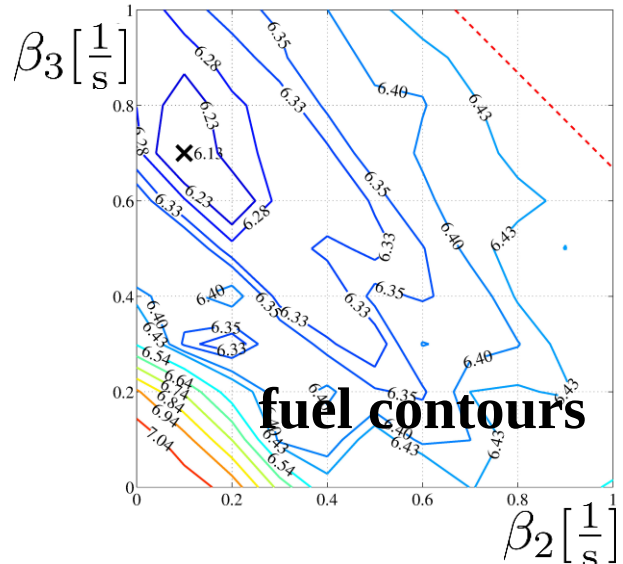
$$J = \sum_{k=0}^{M} \omega_k^2 D_k^2 \qquad \omega_k = k\frac{2\pi}{T}$$

Fourier components

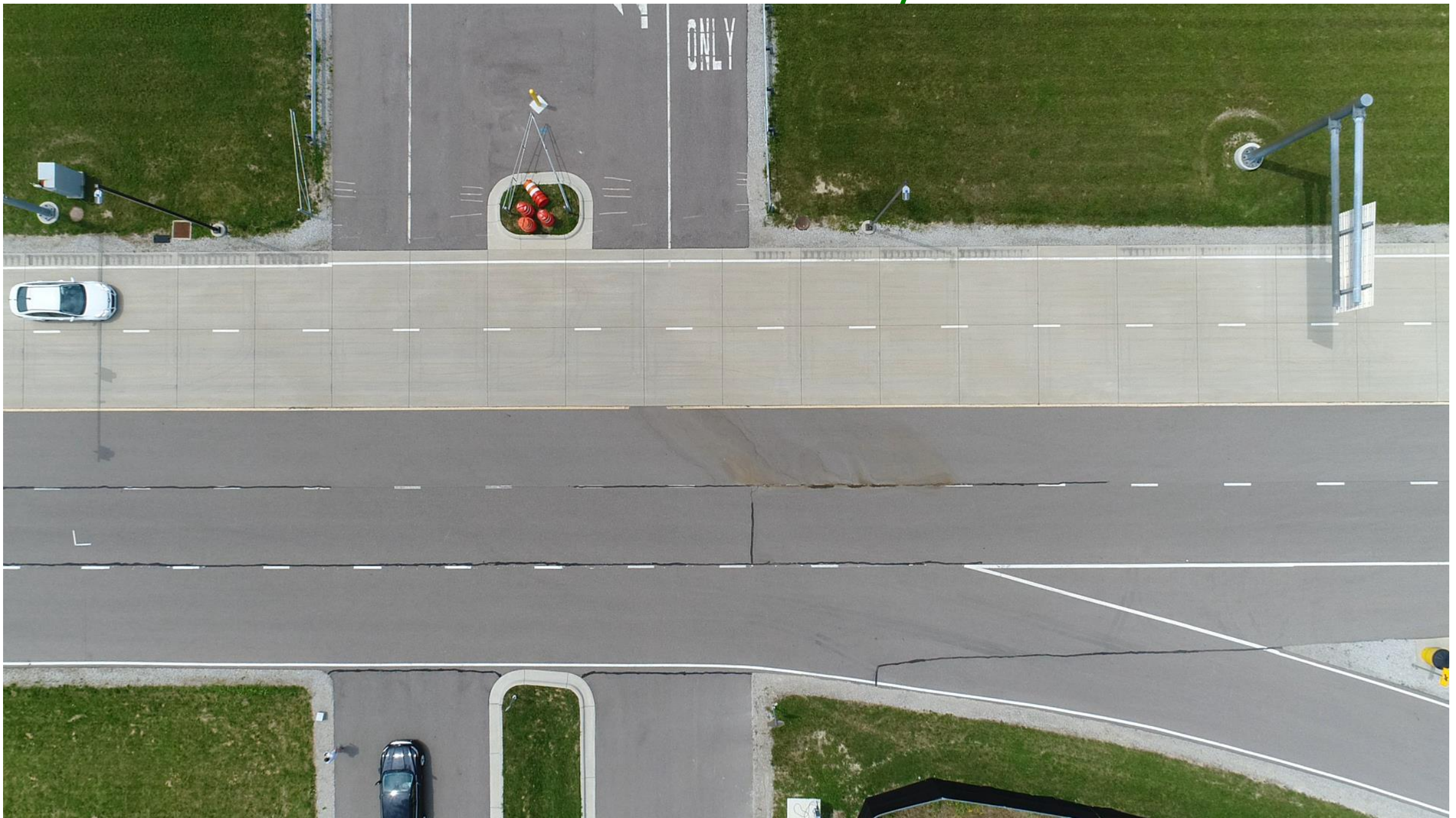
Applying this to the controller

$$u = \alpha\,(V(h) - v) + \beta_1(v_1 - v) + \beta_2(v_2 - v) + \beta_3(v_3 - v)$$





What about safety?



Verifying / Synthetizing Safe Controllers

Barrier functions

- based on Lyapunov approach

- provide sufficient conditions on user defined safety region

Formal methods

- based on linear temporal logic $\wedge$ (and), $\vee$ (or), $\rightarrow$ (implies)
  $\Box$ (always), $\Diamond$ (eventually), $\Box\Diamond$

- discretizes time and quantizes state space and utilizes games

- give exact results but suffer from curse of dimensionality

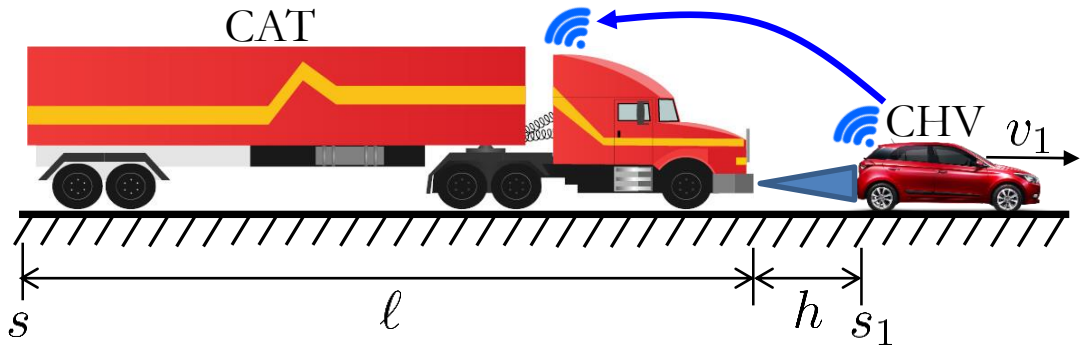
Reachability calculations

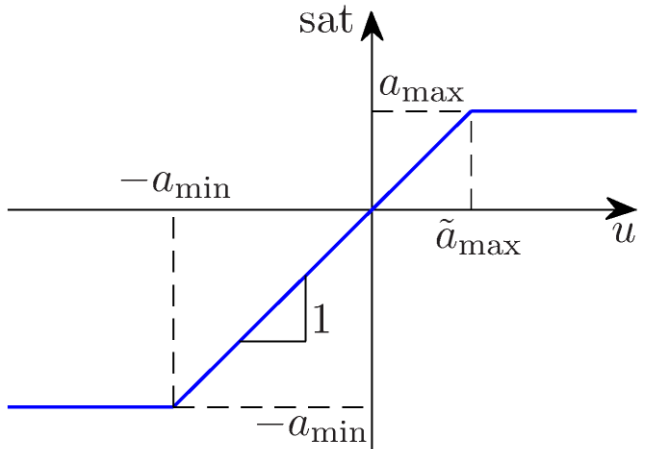
- based on Hamilton-Jacobi PDEs

- utilizes differential games

- give exact results but suffer from curse of dimensionality

Barrier functions





Longitudinal dynamics

$$\dot{h} = v_1 - v$$

$$\dot{v} = \mathrm{sat}(u)$$

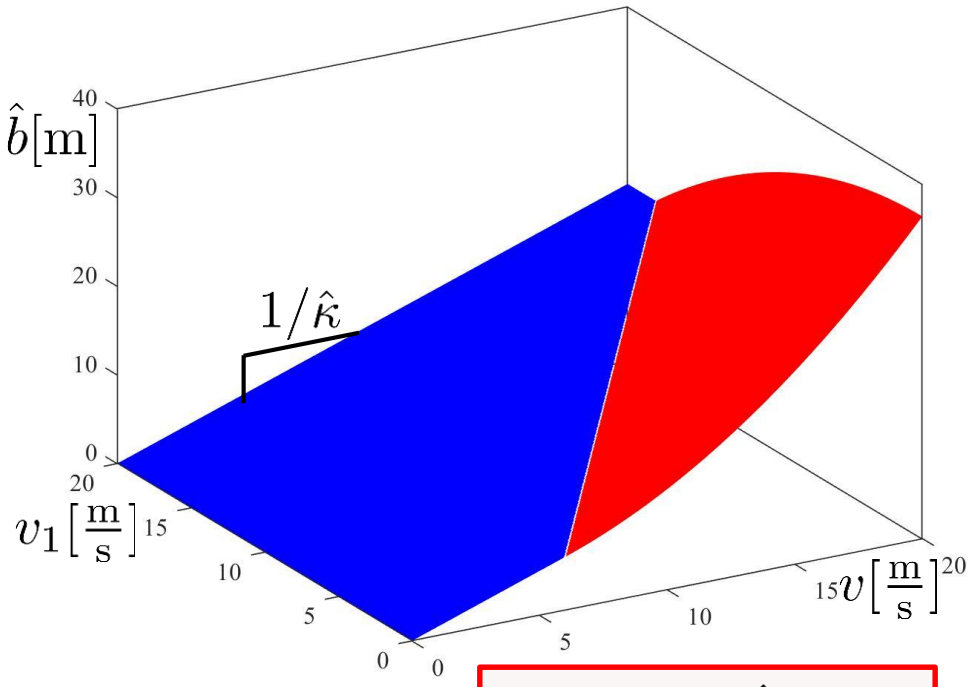
$$\dot{v}_1 = a_1 \quad \longleftarrow \quad -a_{1,\min} < a_1 < a_{1,\max}$$

Safety $\Leftrightarrow$ Invariant set in state space $x = \begin{bmatrix} h & v & v_1 \end{bmatrix}^{\mathrm{T}}$

$$\mathcal{S} = \{x \in \mathbb{R}^n : b(x) \geq 0\}$$

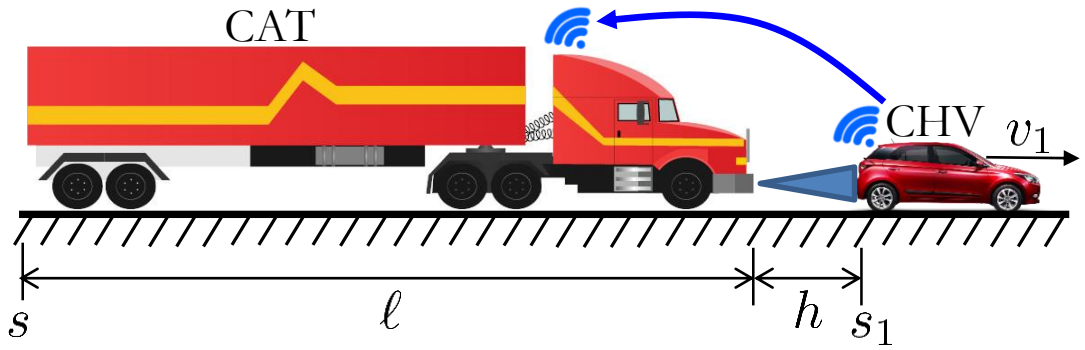
Theorem $\mathcal{S}$ is invariant is $\exists\ \eta > 0$ s.t.

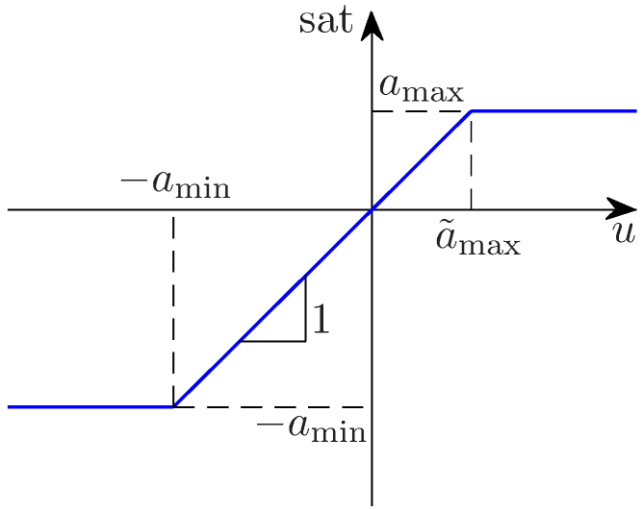
$$\sup_u \left[\dot{b}(x) + \eta b(x)\right] \geq 0, \quad \forall x \in \mathcal{S}$$



$$b(x) = h - \hat{b}(v, v_1)$$

Barrier functions





Longitudinal dynamics

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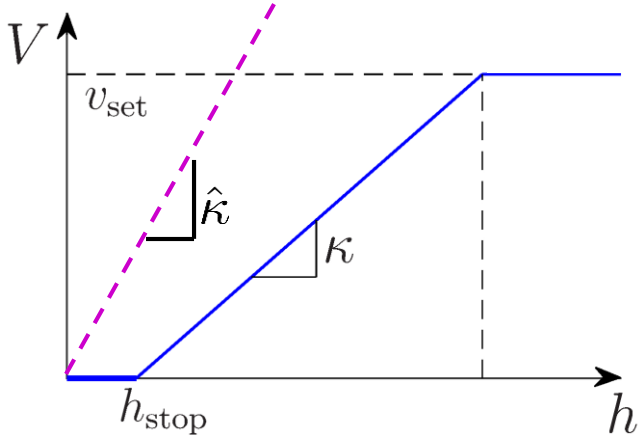
$$\dot{v} = \mathrm{sat}(u)$$

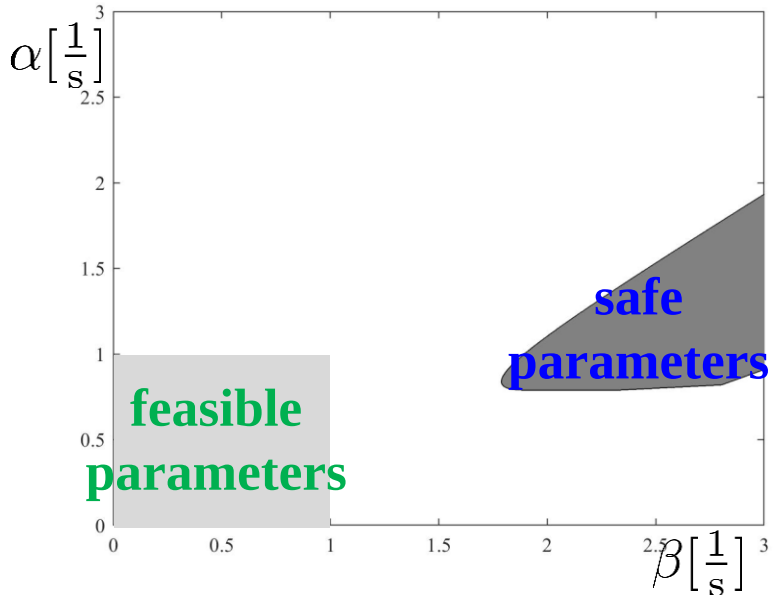
$$\dot{v}_1 = a_1 \quad \leftarrow \quad -a_{1,\min} < a_1 < a_{1,\max}$$

Nominal controller

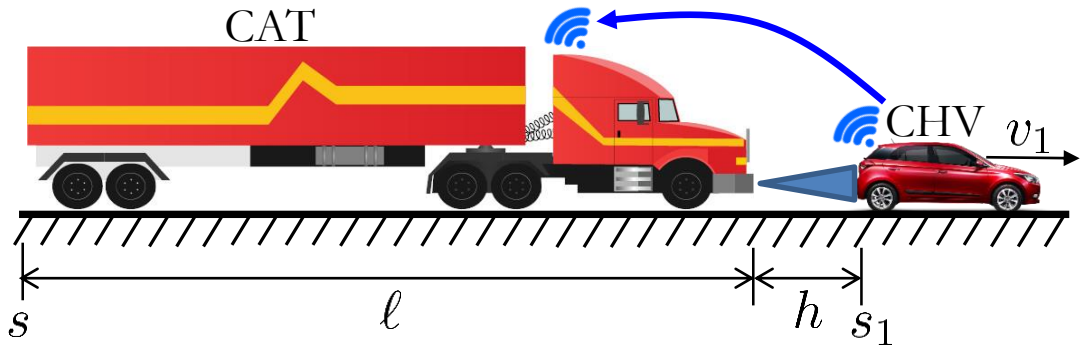
$$u = \alpha\,(V(h) - v) + \beta(v_1 - v)$$

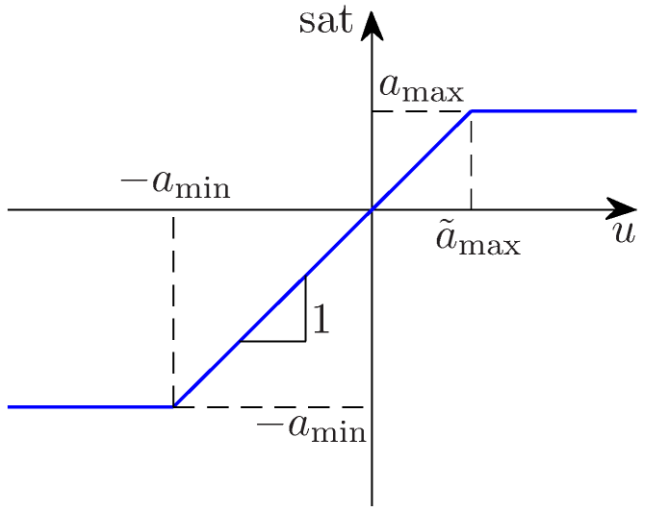


Safety chart



Barrier functions





Longitudinal dynamics

$$\dot{h} = v_1 - v$$

$$\dot{v} = \mathrm{sat}(u)$$

$$\dot{v}_1 = a_1 \quad \longleftarrow \quad -a_{1,\min} < a_1 < a_{1,\max}$$

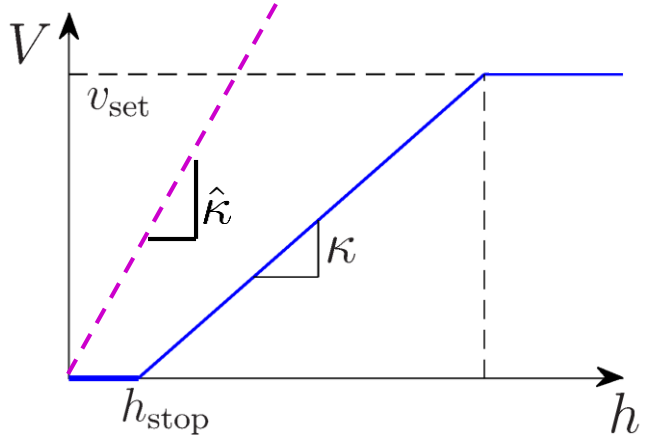
Intervening control $\min\{u, \hat{u}\}$

$$\hat{u} = \left(\frac{\partial \hat{b}}{\partial v}\right)^{-1} \left(v_1 - v - \frac{\partial \hat{b}}{\partial v_1} a_1 + \eta(h - \hat{b})\right)$$

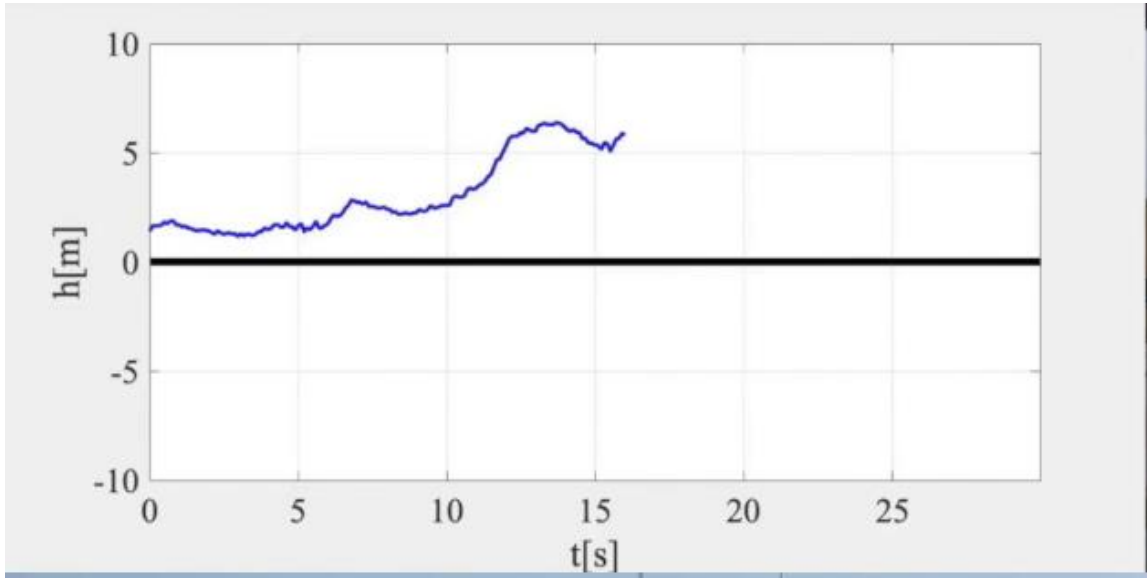
via connectivity

Nominal controller

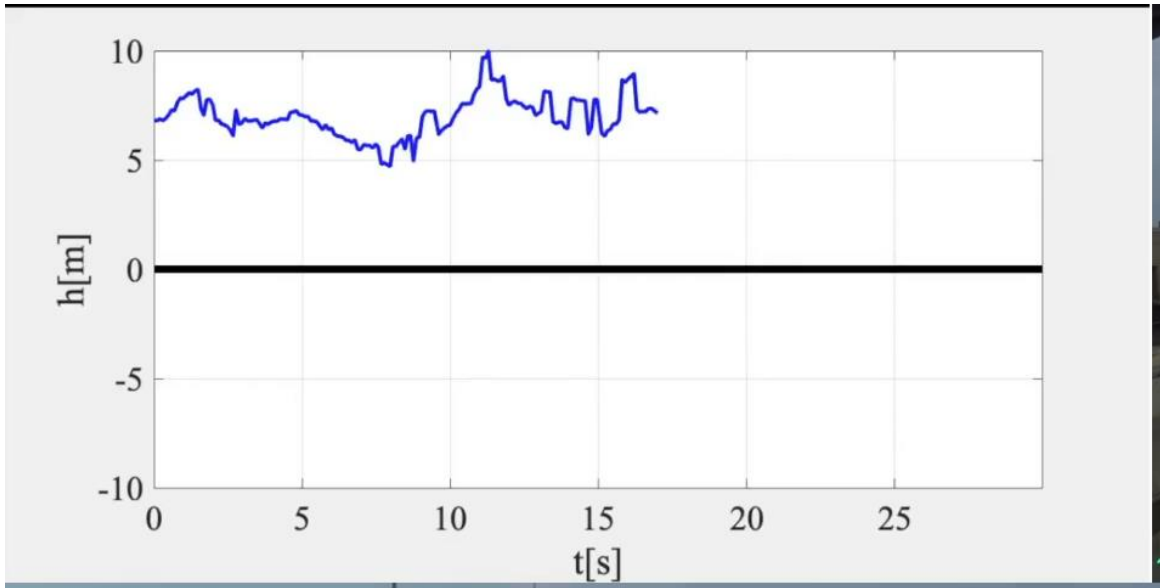
$$u = \alpha\left(V(h) - v\right) + \beta(v_1 - v)$$

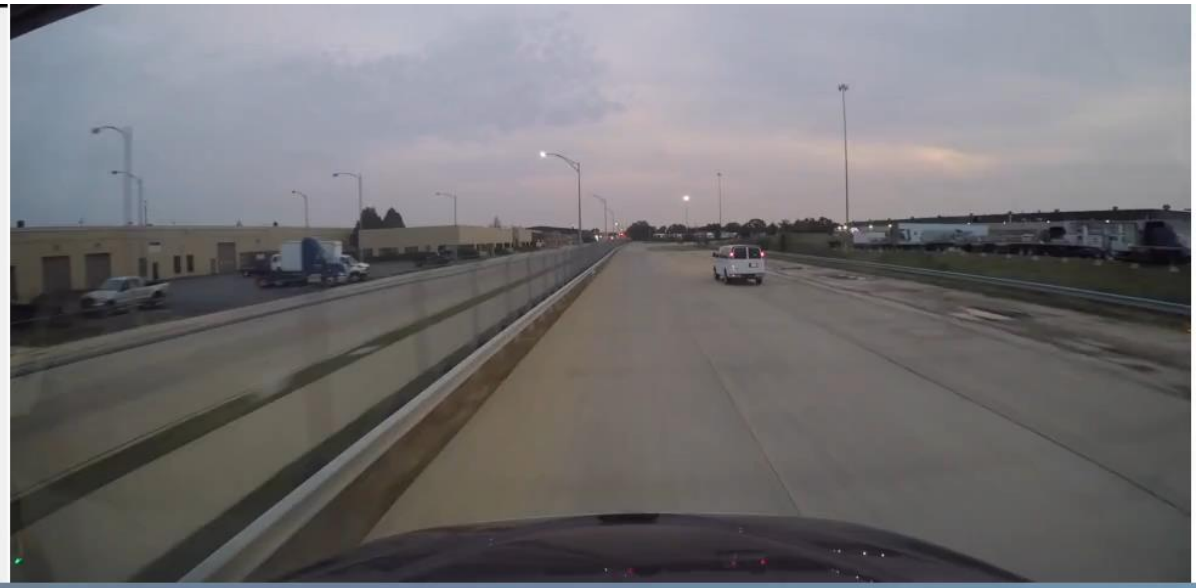


Without barrier function



With barrier function

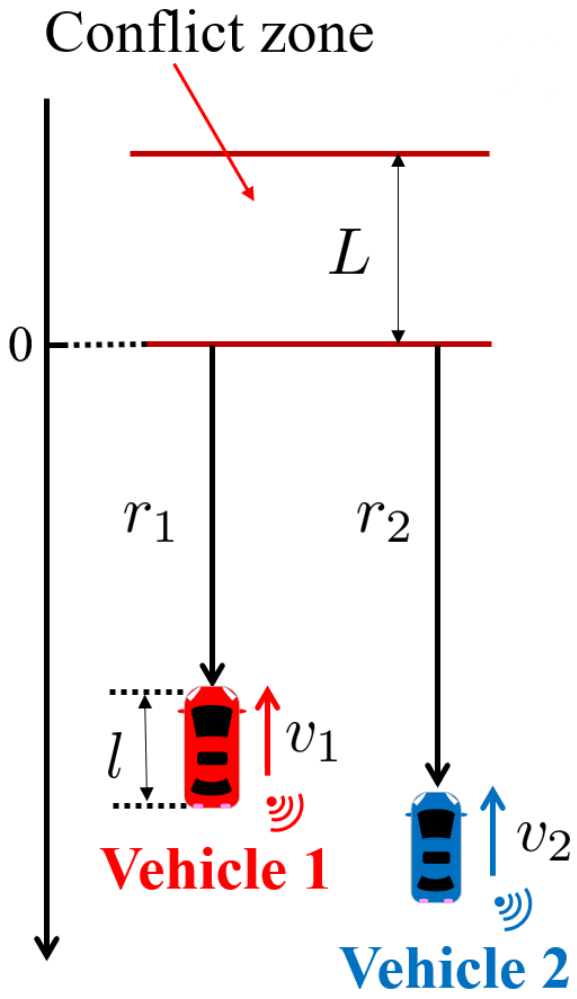




Is there any way to resolve conflicts earlier?

Is there any way to resolve conflicts?

Conflicts Analysis



Longitudinal dynamics

$$\begin{aligned}\dot{r}_1 &= -v_1,\\ \dot{v}_1 &= \mathrm{sat}(u_1),\\ \dot{r}_2 &= -v_2,\\ \dot{v}_2 &= \mathrm{sat}(u_2),\end{aligned}$$

Conflict

$$C := \{\exists t, r_1(t) \in [-s, 0] \wedge r_2(t) \in [-s, 0]\} \qquad s = L + l$$

Vehicle 2 merges ahead

$$P := \{\exists t, r_1(t) = 0 \wedge r_2(t) < -s\}$$

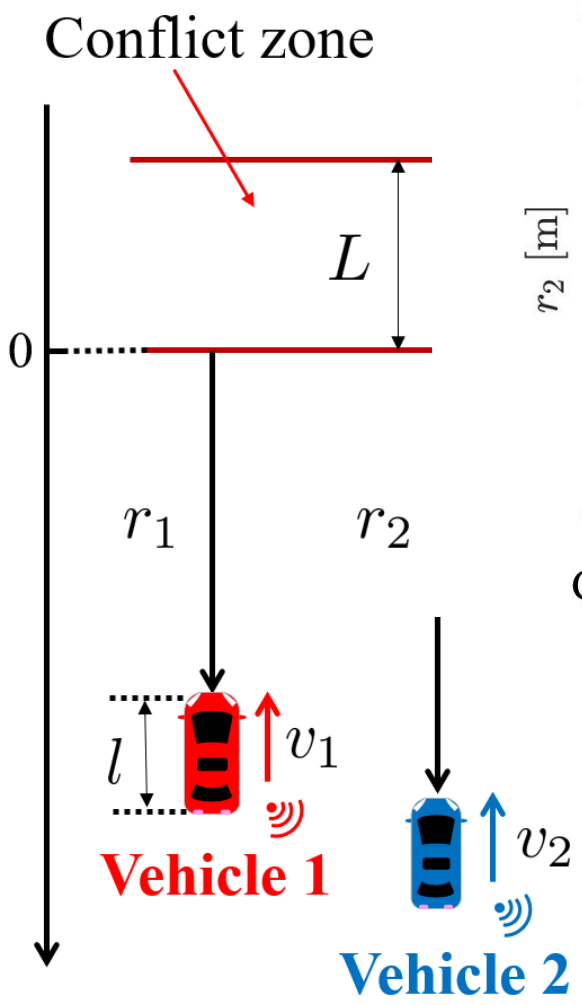
Vehicle 2 merges behind

$$Q := \{\exists t, r_1(t) = -s \wedge r_2(t) > 0\}$$

Theorem

$$P \vee Q \iff \neg C$$

Conflicts Analysis



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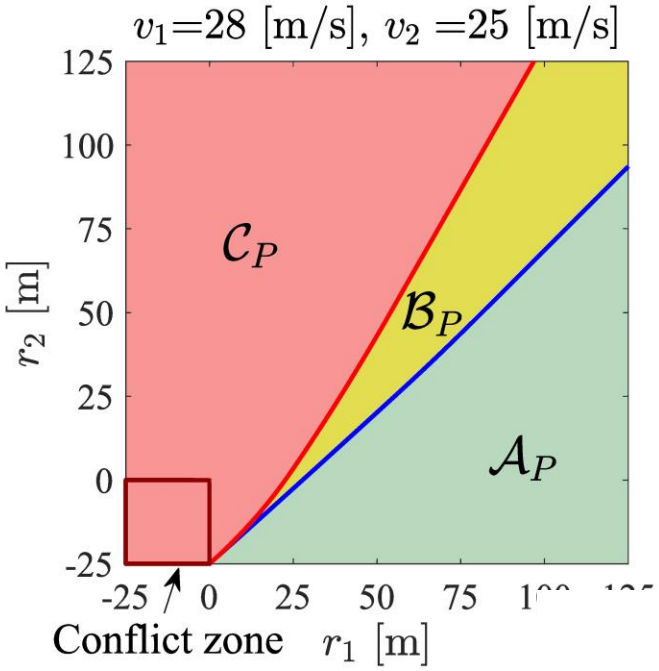
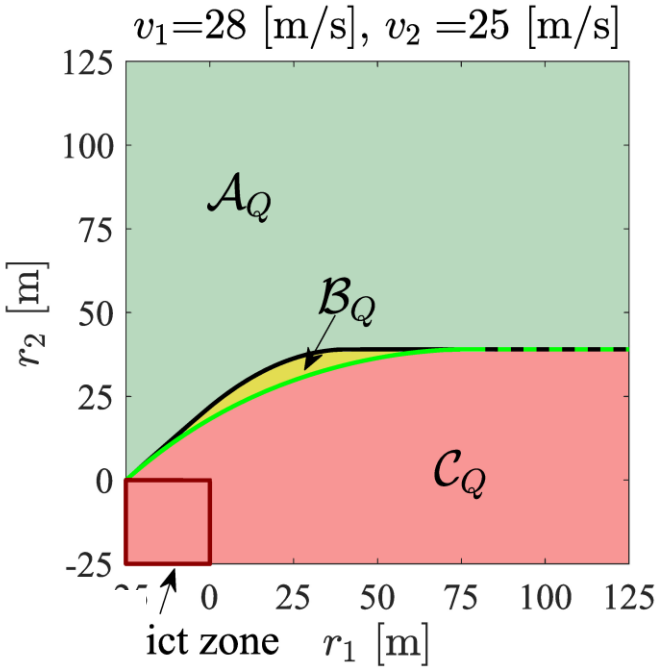
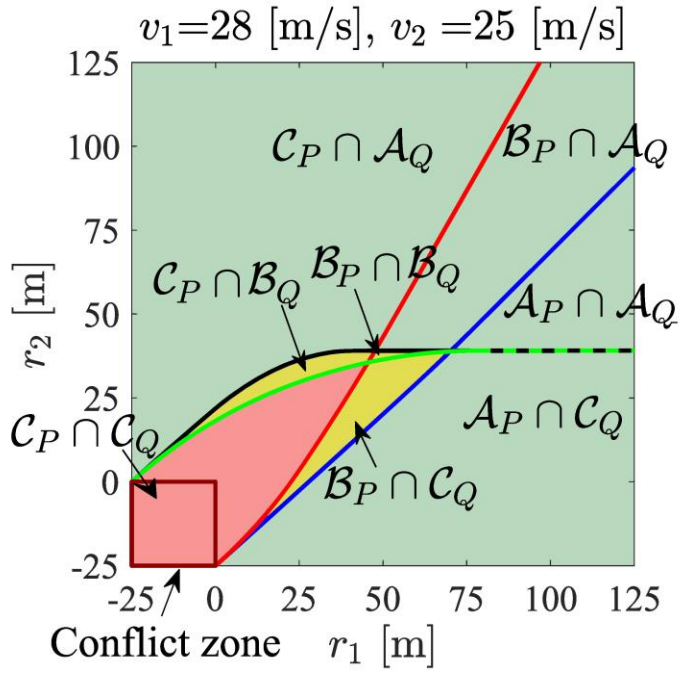


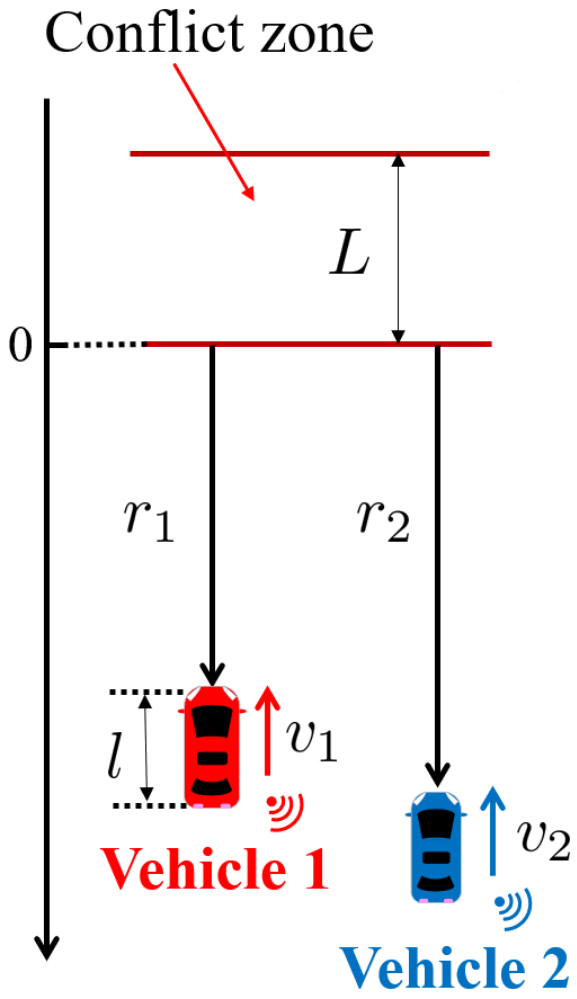
Vehicle 2 merges behind



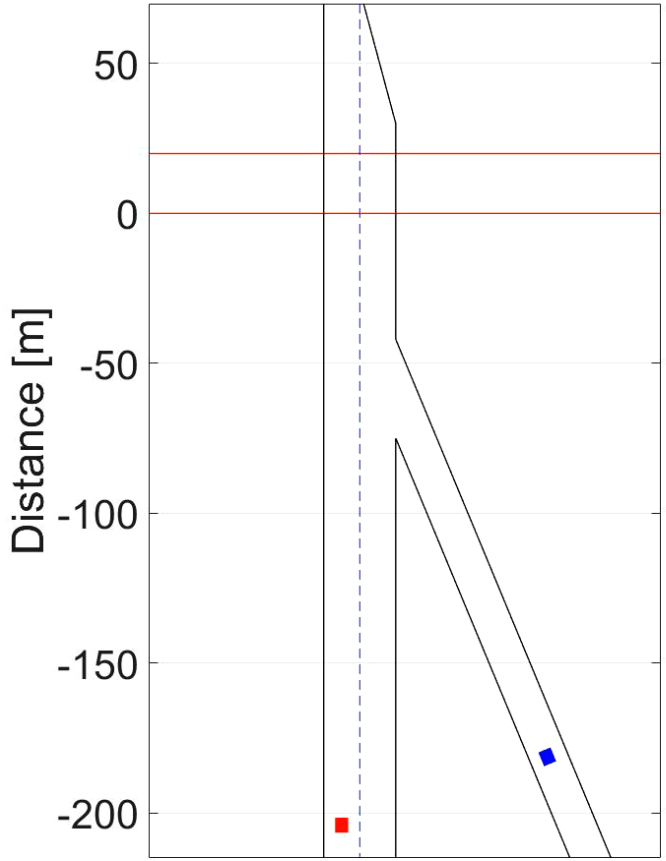
Conflict Chart

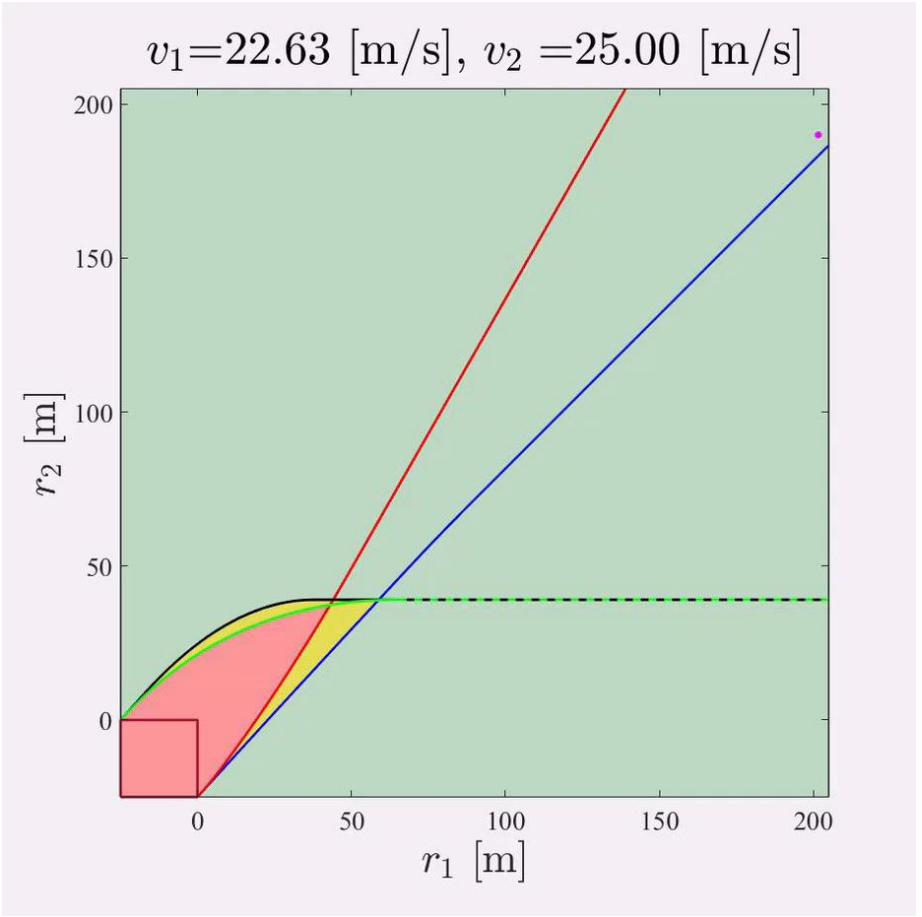


Connectivity Enabled Decision Making

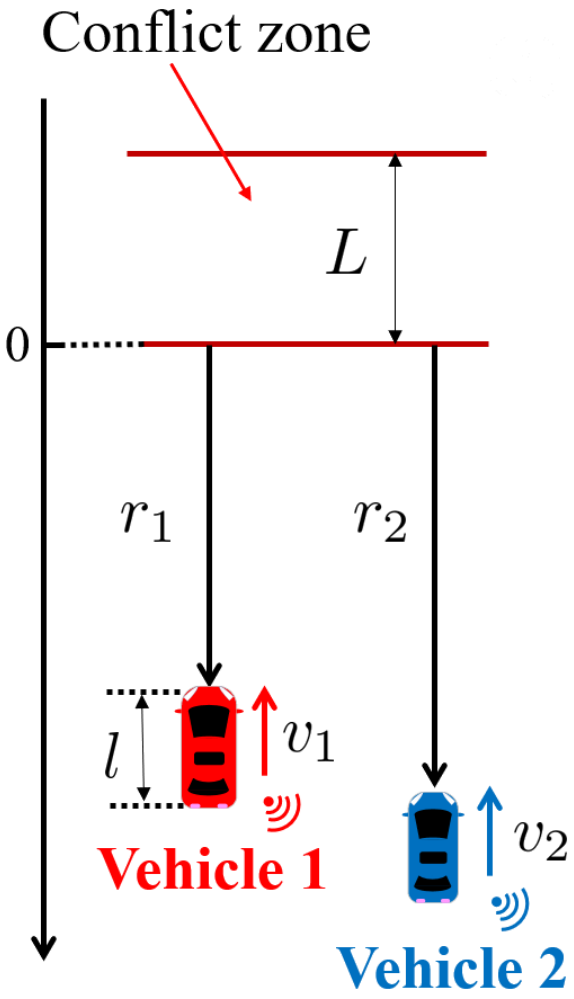


Vehicle 2 merges behind

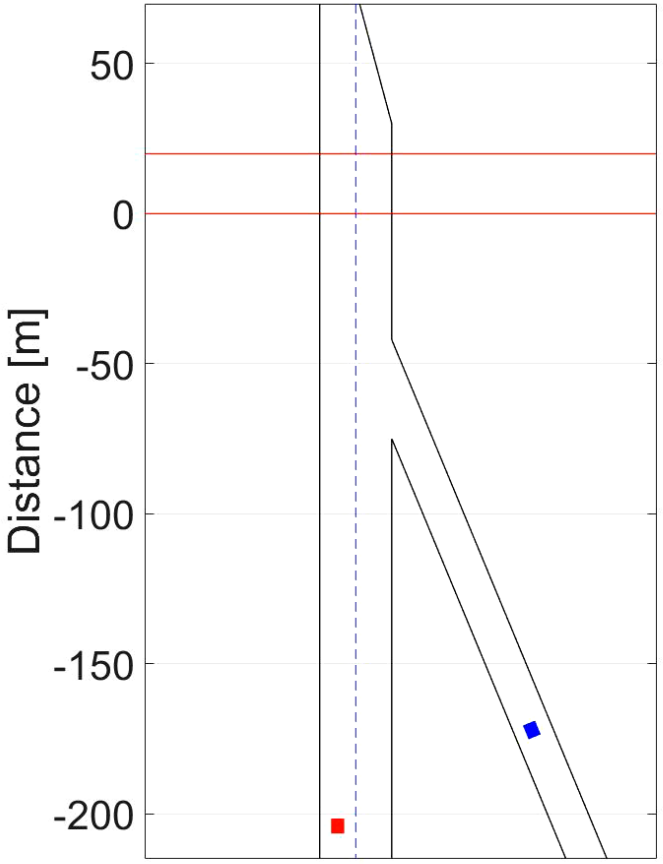


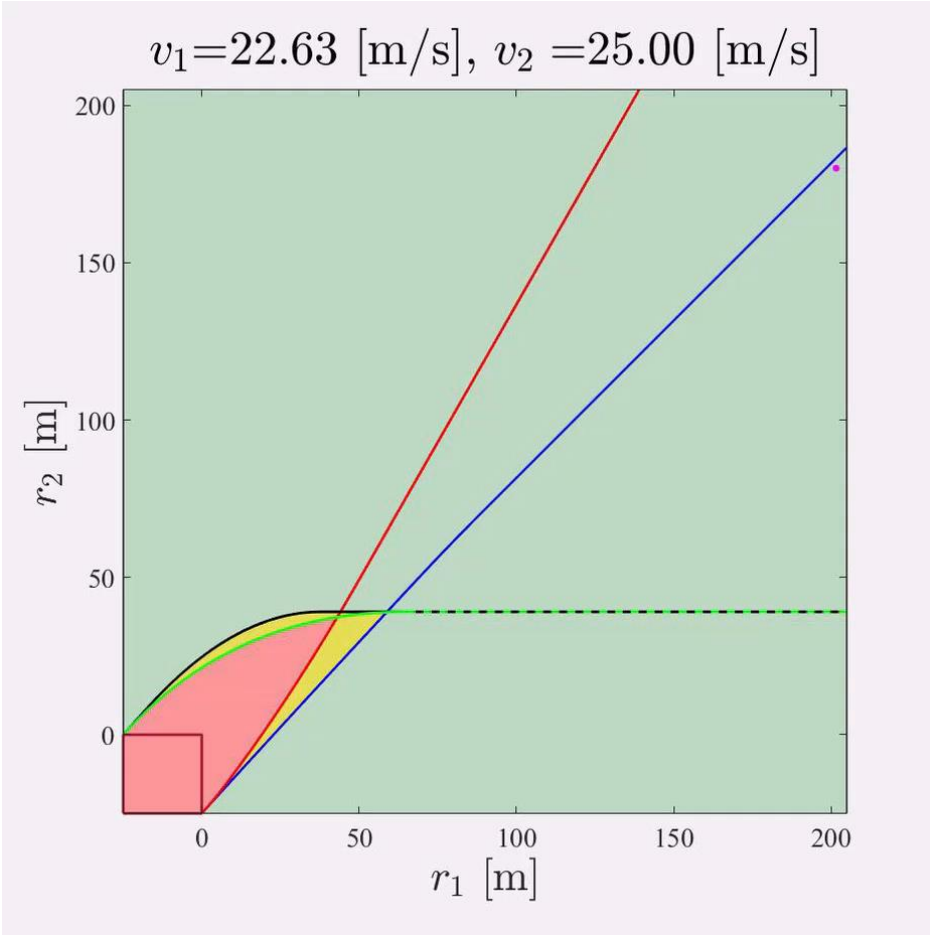


Connectivity Enabled Decision Making



Vehicle 2 merges ahead





Conclusions

- High level **societal goals** can be turned into **control objectives for CAVs**
- **Connectivity may help** CAVs to achieve better **performance and efficiency**
- **Safety** may be ensured using **barrier functions** and **conflict analysis**

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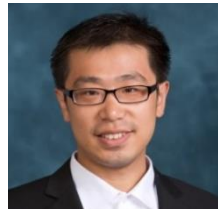
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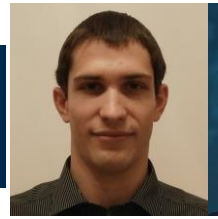
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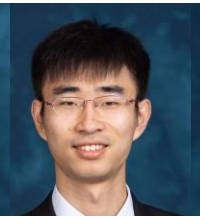
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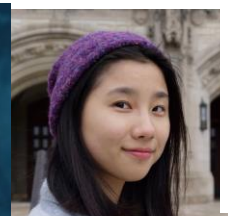
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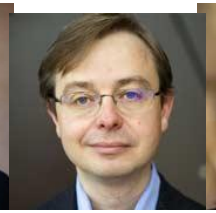
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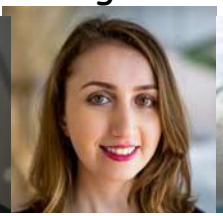
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