V2X Platooning Optimal Control

CE 295: Data Science for Energy, Fall 2021

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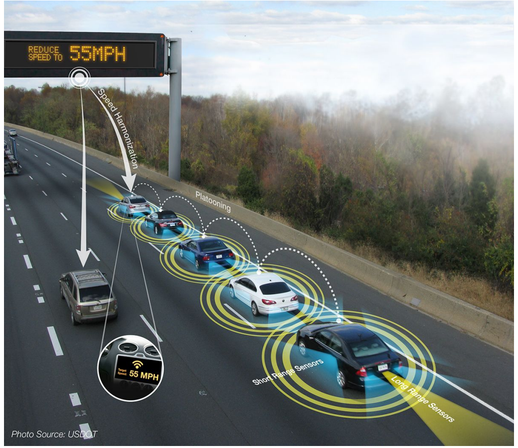
Introduction & Background

What is Vehicle Platooning?

- Vehicle fleet automation with integrated sensor array, active safety systems, and controllers to synchronize platoon acceleration and braking
- Vehicle-to-vehicle (V2V) communication [2]
- Vehicle-to-everything (V2X) communication [1]
- Emerging area of research in control and optimization: save time, money, energy
- Common scenarios this could apply to:
  - Trucks in highway driving
  - Cars in highway driving
  - **Cars in urban driving - our selection**



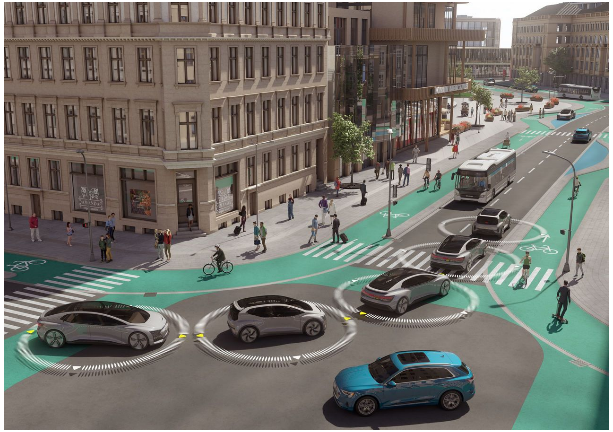
[1]

[2]

[1] "Platoon (automobile)" (5 Oct 2021). Wikipedia. Retrieved on 06 Nov 2021, 13:46, from https://en.wikipedia.org/wiki/Platoon_(automobile).
[2] Ashley, Steven (18 Nov 2014). "Robot truck platoons roll forward." BBC. Retrieved on 06 Nov 2021, 13:49, from https://www.bbc.com/future/article/20130409-robot-truck-platoons-roll-forward

Focus of the Study

- Cars platooning in an urban area
  - More obstacles and more powertrain varieties
- Focus on battery electric vehicle (BEV) platoons
- Optimal platoon trajectory
  - Given timed traffic lights and spacing in an urban area
  - Output: optimal trajectory for the car to save time *and* energy

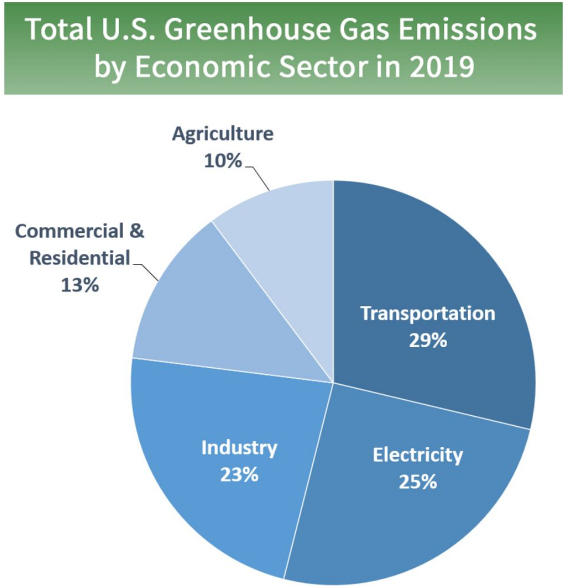


[3]

[3] Schneider, Tilman (16 Sept 2018). "Audi Study: No Congestion in the City of the Future." Audi MediaCenter. Retrieved on 06 Nov 2021, 13:52, from https://www.audi-mediacenter.com/en/press-releases/audi-study-no-congestion-in-the-city-of-the-future-10736.

Why Does This Matter?

- Energy saved → reduced emissions!
    - Transportation is largest emissions sector
    - Electricity second - electric vehicles
    - Reducing carbon emissions benefits the planet and its occupants
- Time saved is a huge advantage for people…
    - Traveling to and from work → more free time or family time
    - Traveling to and from a destination → time saved in the vehicle
    - Transporting goods → quicker shipping time, can sell more



[4]

[4] "Sources of Greenhouse Gas Emissions" (2021). United States Environmental Protection Agency. Retrieved on 06 Nov 2021, 14:01, from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

Relevant Literature

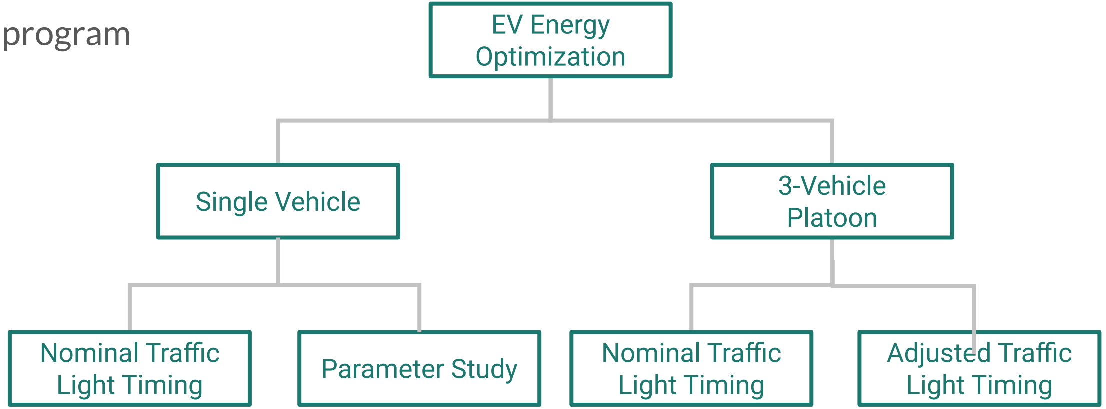
- Adaptive cruise control and cooperative adaptive cruise control can save energy [5]
- Platooning allows for closer headway → smaller drag, saves energy [6]
- Traffic lights in urban settings cause stops and delays, responsible for a large amount of emissions [7]
- Main conclusion: traffic lights increase emissions, cruise control + platooning decrease emissions
    - Can we combine the two for a more powerful energy savings effect?

[5] Wang, Z., Wu, G., \& Barth, M. J. (2018, November). A review on cooperative adaptive cruise control (CACC) systems: Architectures, controls, and applications. In 2018 21st International Conference on Intelligent Transportation Systems (ITSC) (pp. 2884-2891). IEEE.
[6] Ma, F., Yang, Y., Wang, J., Liu, Z., Li, J., Nie, J., ... \& Wu, L. (2019). Predictive energy-saving optimization based on nonlinear model predictive control for cooperative connected vehicles platoon with V2V communication. Energy, 189, 116120.
[7] C. Sun, J. Guanetti, F. Borrelli and S. J. Moura, "Optimal Eco-Driving Control of Connected and Autonomous Vehicles Through Signalized Intersections," in IEEE Internet of Things Journal, vol. 7, no. 5, pp. 3759-3773, May 2020, doi: 10.1109/JIOT.2020.2968120.

Methods

Problem Structure

- Mixed-integer second order cone program (MISOCP)
- Modeling language: CVXPY
- Optimization solver: MOSEK
- Two cases
  - Single Vehicle
  - 3-Vehicle Platoon



Single Vehicle Optimal Control

- Longitudinal vehicle dynamics modeled
  - Nonlinear dynamics create need for second order cone constraints
- Traffic lights using the Big-M method
  - Creates need for a mixed-integer program

TABLE II: Drive Cycle Constraints

Constraint	*Value*	*Units*
Travel Distance	3000	m
Travel Time	380	sec
Velocity Lower Bound	0	m/s
Velocity Upper Bound	17.5	m/s
Acceleration Magnitude Bound	1.5	m/s^2
Jerk Magnitude Bound	1	m/s^3

$$z(t) = \begin{bmatrix} p(t) \\ v(t) \\ a(t) \\ E(t) \\ L_{i,bool} \end{bmatrix}, \quad u(t) = \begin{bmatrix} F(t) \\ F_{loss}(t) \\ I(t) \\ P_{mot}(t) \\ P_{batt}(t) \\ P_{loss}(t) \end{bmatrix}$$

$$p(L_{i,start}) \geq L_{i,pos} \quad \text{or} \quad p(L_{i,end}) \leq L_{i,pos}$$

Application of Big-M method $\Downarrow$

$$p(L_{i,start}) - L_{i,pos} \geq -M(1 - L_{i,bool})$$
$$p(L_{i,end}) - L_{i,pos} \leq M(L_{i,bool})$$

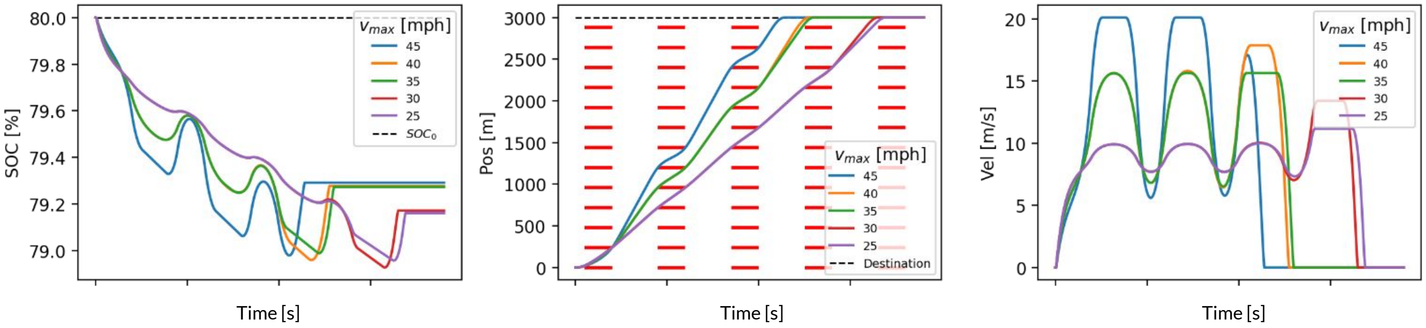
$$\min_{z(t),u(t)} \quad \int_{t_0}^{t_f} \frac{d}{dt} E(t)dt \tag{23a}$$

subject to

$$p(t) = p(t_0) + \int_{t_0}^{t} v(\tau)d\tau \tag{23b}$$
$$v(t) = v(t_0) + \int_{t_0}^{t} a(\tau)d\tau \tag{23c}$$
$$ma(t) = F(t) - F_{loss}(t) \tag{23d}$$
$$F(t) = \frac{1}{mR_{wheel}r_{final}\eta} T(t) \tag{23e}$$
$$F_{loss}(t) \geq C_{rr}mg + C_k v(t) + \frac{1}{2}\rho C_d A_f v(t)^2 \tag{23f}$$
$$P_{mot}(t) = P_{batt}(t) - P_{loss}(t) \tag{23g}$$
$$P_{batt}(t) = V_{oc}I(t) \tag{23h}$$
$$P_{loss}(t) \geq I(t)R_{int}^2 \tag{23i}$$
$$v_{min} \leq v(t) \leq v_{max} \tag{23j}$$
$$-a_{max} \leq a(t) \leq a_{max} \tag{23k}$$
$$-j_{max} \leq \frac{d}{dt}a(t) \leq j_{max} \tag{23l}$$
$$-P_{max} \leq P_{batt}(t) \leq P_{max} \tag{23m}$$
$$E(t) = E(t_0) + \int_{t_0}^{t} V_{oc}I(\tau)d\tau \tag{23n}$$
$$0.2 \leq SOC(t) \leq 0.8 \tag{23o}$$
$$p(L_{i,start}) - L_{i,pos} \geq -M(1 - L_{i,bool}) \tag{23p}$$
$$p(L_{i,end}) - L_{i,pos} \leq M(L_{i,bool}) \tag{23q}$$

Single Vehicle Parameter Study Example

- Independent variable: Speed limit
- Dependent variable: Energy consumption
- Higher speed leads to a lower energy consumption*
  - *Savings eventually plateau likely due to higher aerodynamic drag at higher speeds

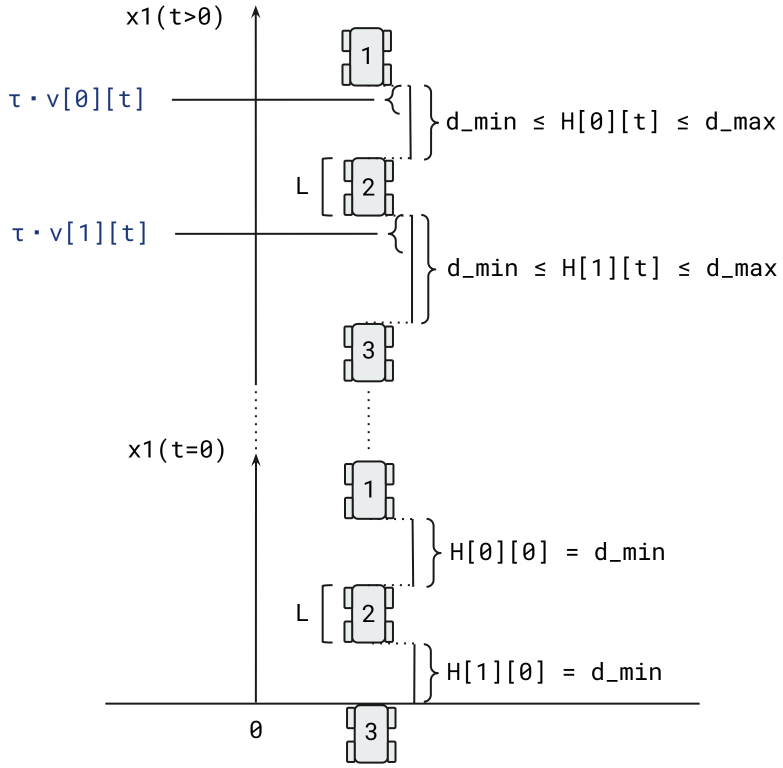


3-Vehicle Platoon Optimal Control

- Trajectory copying of the leading vehicle with constraints on:
    - Initial state, **`x1[veh][0]`**,
    - Following distance, **`H[veh][t]`**,
    - Reaction and actuation time delay, **τ**
- Assumes no vehicle overtaking and turning,
- Allows for 'breakaway' from the leading vehicles in light of red phase

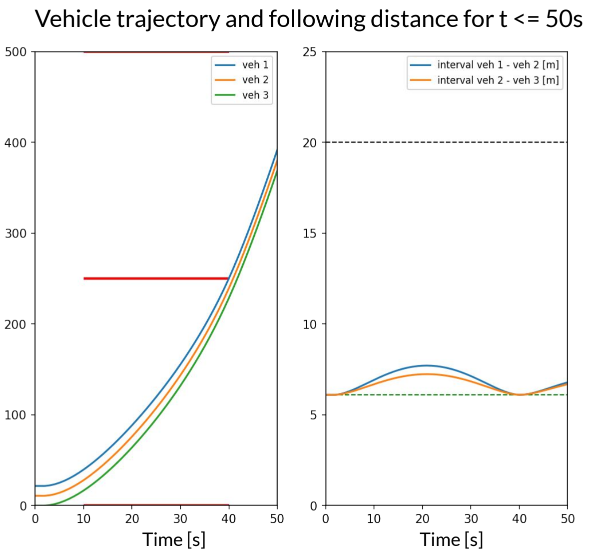
TABLE III: Vehicle Platooning Constraints

Constraint	*Value*	*Units*
Number of Vehicles, N	3	Unitless
Reaction and Actuation Time Delay, τ	0.2	sec
Minimum Following Distance, d_{min}	40	ft
Maximum Following Distance, d_{max}	500	ft



Aerodynamic Drag

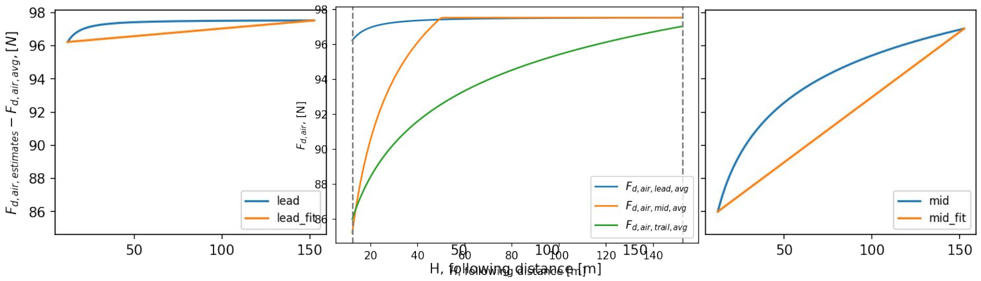
- `F_air(v,C_d(h))`→ non-convex in formulation (27) for each vehicle in the platoon,
- Using the velocity upper bound, we fixed the value of **`v_avg`** to estimate an average drag value and linearly fitted and adjusted for **h** (29)



$$F_{air_{k,i}}(h,v) = \frac{g(h_{k,i})}{2}\rho C_d v_{k,i}^2, \quad k = 0,1,\cdots,N, i = 0,1 \tag{27}$$

$$g(h_{k,i})(h) = \alpha h_{k,i}^{\beta} + c \tag{28}$$

$$F_{air,approx_{k,i}}(h,v) = \frac{1}{2}\rho C_d v_{k,i}^2 - b h_{k,i}, \quad k = 0,1,\cdots,N, i = 0,1 \tag{29}$$



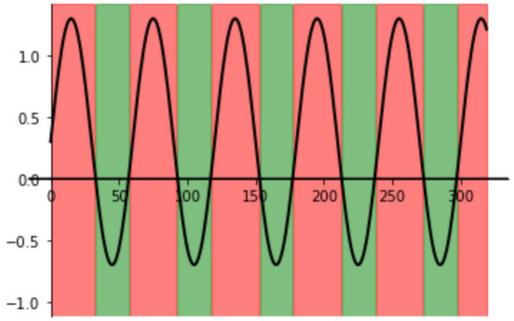
Results

Traffic Light Simulation

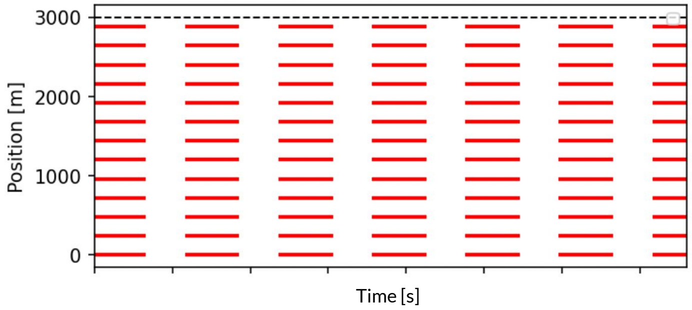
$$f(t) = sin(\omega t + \phi) + h$$

f(t) < 0: green light

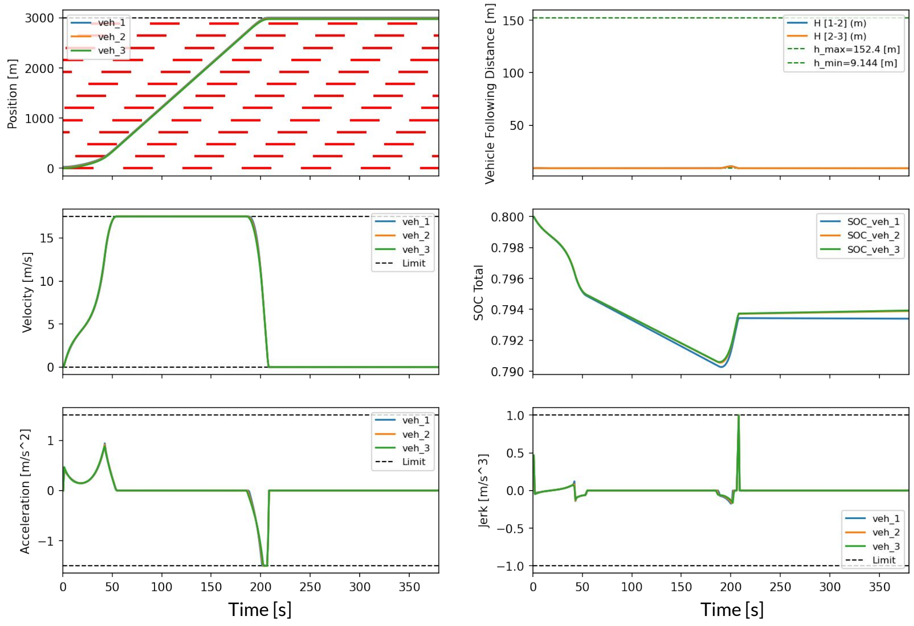
ω: traffic light cycle period
φ: phase shift
h: controls green-light duration



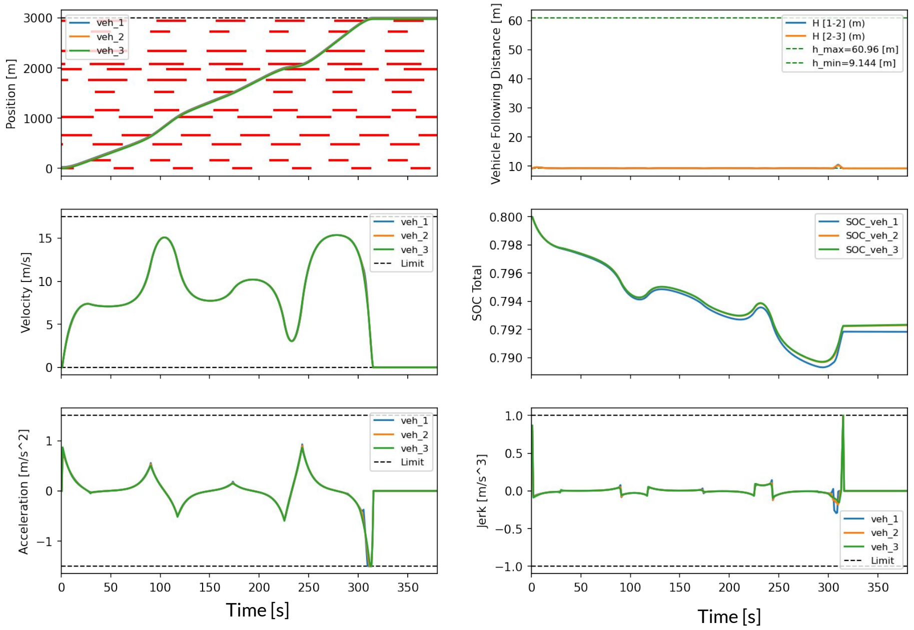
T = 60s
ω = 2π/T
φ = 0
h = 0.3



Uniform phase shift



Random parameters



Results: Traffic Light Simulation Parameter Study

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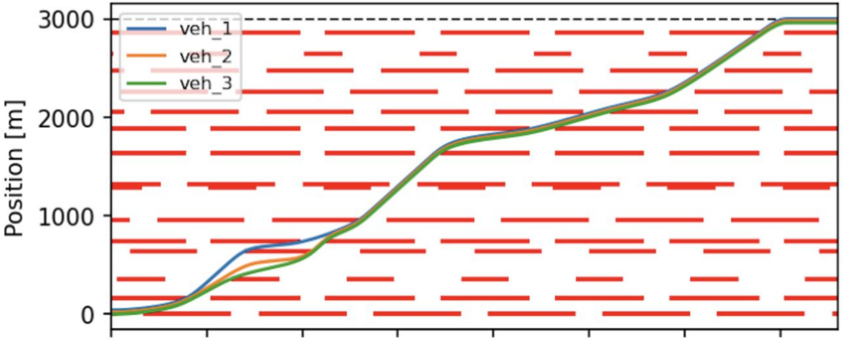
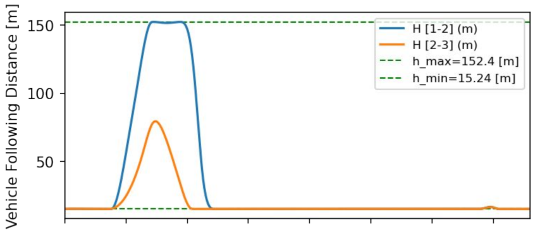
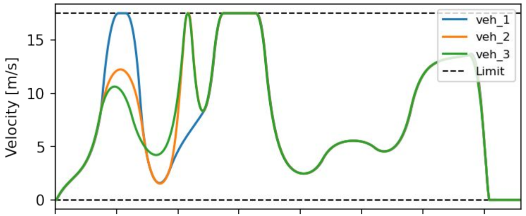
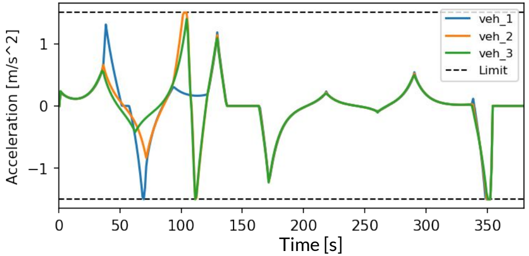
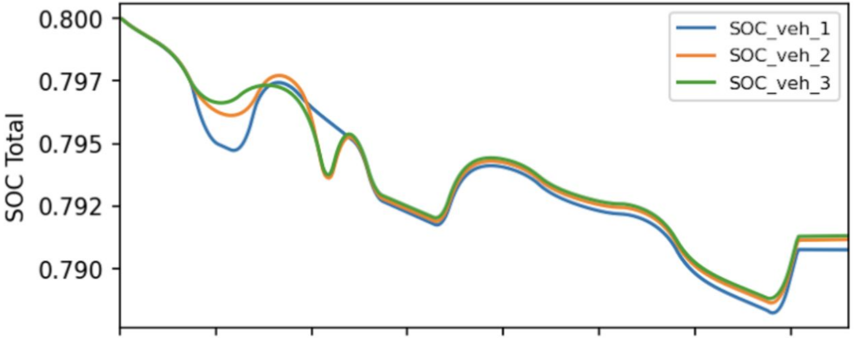
Random parameters + following distance







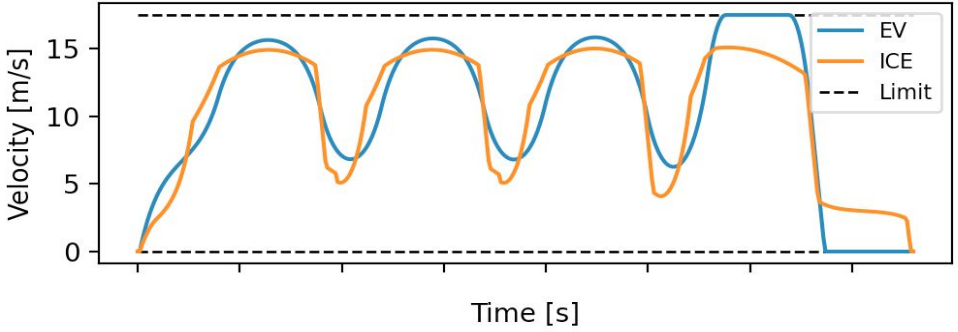




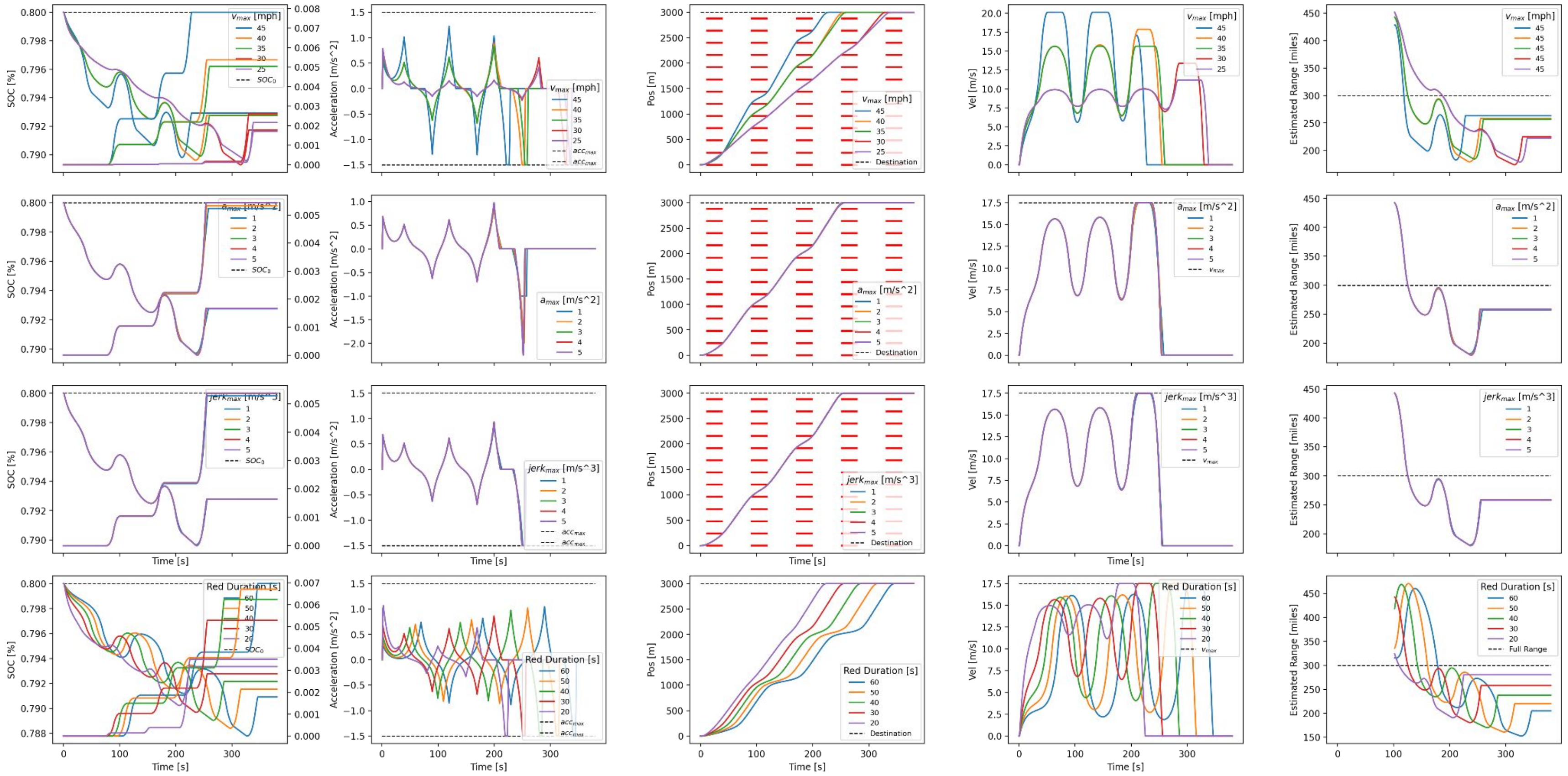
Future Work

Future Work

- ICE, PHEV powertrains
- Add traffic lights as a decision variable with constraints
  - Anticipation of the length and position of platoons
- Partial knowledge of traffic light parameters
- Background traffic (non-V2X)



Thank You!



Results: Single Vehicle (BEV) Parameter Study