AVL Arastirma Ve Mühendislik Sanayi Ve Ticaret Limited Sirketi (Research and Engineering)

Cooperative Adaptive Cruise Control Implementation with MATLAB MPC Toolbox

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Autonomous Drive & Vehicle Controls

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Agenda

- AVL Introduction
- Cooperative Adaptive Cruise Control
  - Longitudinal Control Systems
  - MPC Formulation
  - Results
  - Conclusion & Future Directions

ENTERPRISE DEVELOPMENT AUTOMOTIVE

RESEARCH 10% of turnover in-house R&D

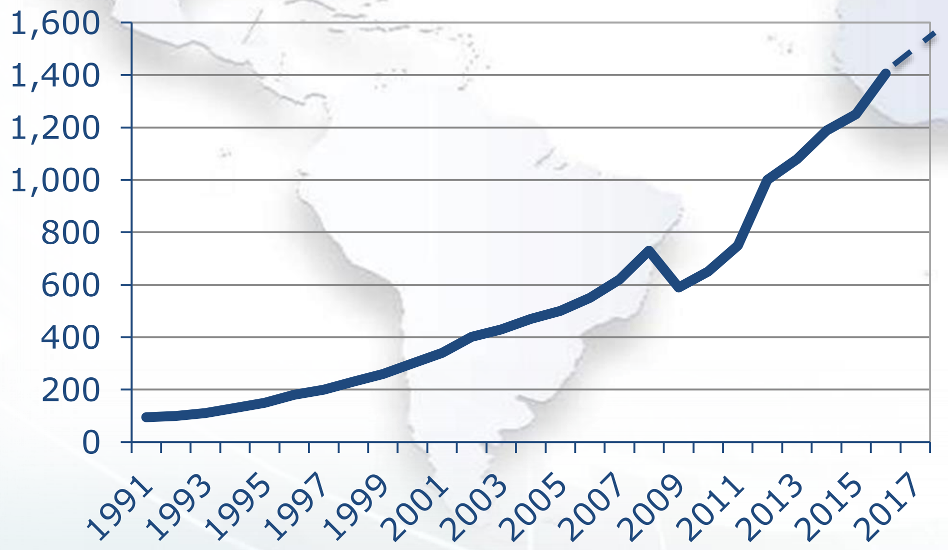
INNOVATION 1500 granted patents

STAFF
10000 employees

65% engineers and scientists

GLOBAL FOOTPRINT
30+ engineering locations
- **220+** test beds
- Global customer support network

GROWTH



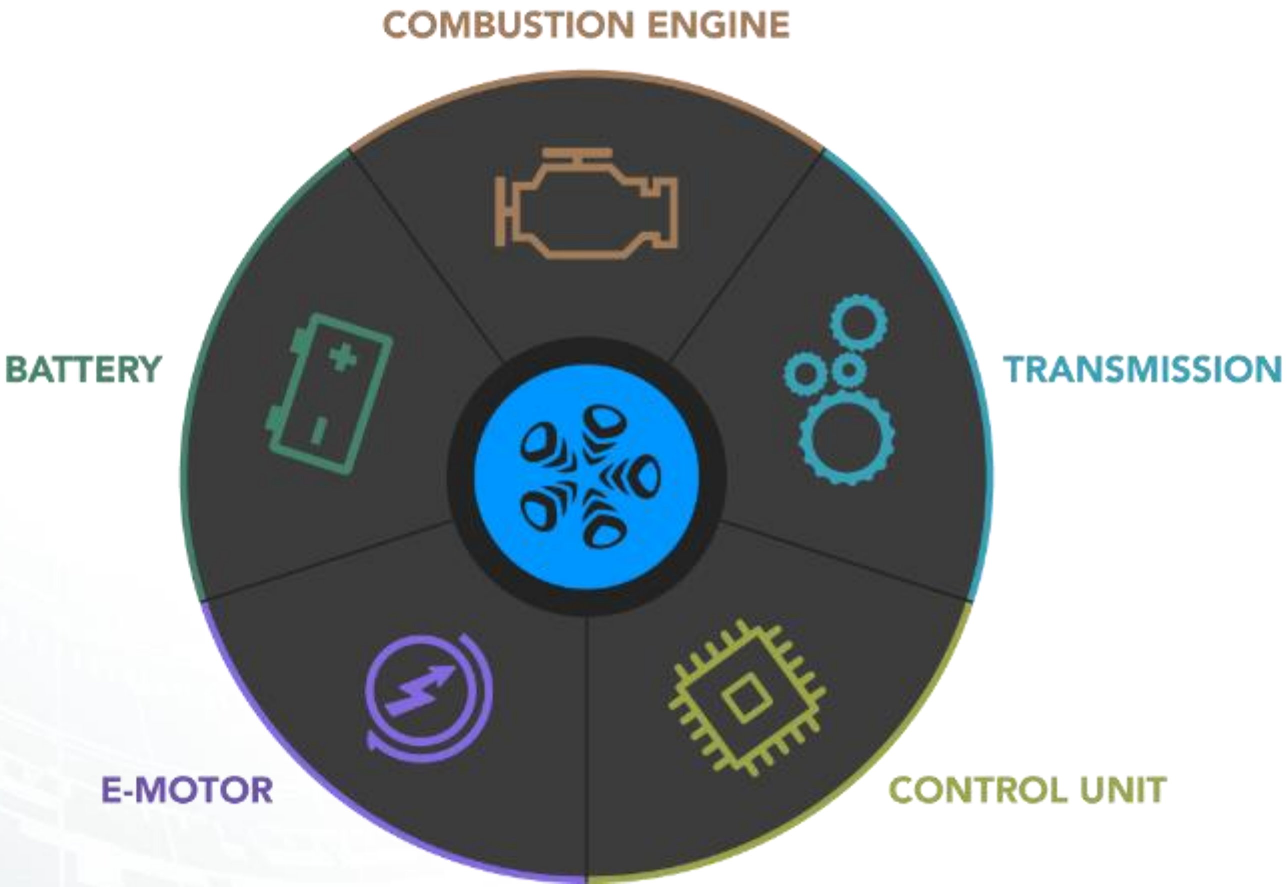
SALES
- 1995: 0.15 billion €
- 2015: 1.27 billion €
- 2017: 1.5 billion €

EXPERIENCE
65 years !

5 powertrain elements

ONE
PARTNER

5 ELEMENTS OF THE POWERTRAIN



AVL POWERTRAIN ENG – A GLOBAL NETWORK

+ another
9 Engineering
Offices

AVL TURKEY

2008
Founded

2015
Established R&D Center #1 in Sancaktepe

2016
Established R&D Center #2 in Sultanbeyli

2017
Recognised by TOBB as one of the Top 100 Fastest growing companies in Turkey

2018
R&D Center #2 expansion

Team of 200+ engineers, with mostly MSc and PhD degrees.

AVL TURKEY – A GLOBAL CENTER

AVL Turkey has two roles

Development Centre for Turkish Market

Global Engineering Centre for AVL Group

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Longitudinal Vehicle Control Systems

Cruise Control (CC) is a system that automatically controls the speed of a vehicle to maintain a **desired speed** set by the driver.

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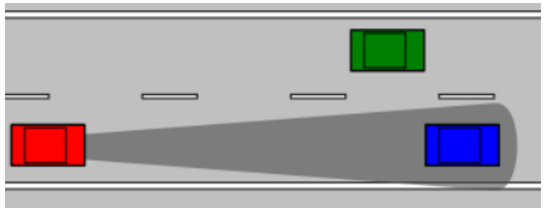
Adaptive cruise control (ACC) is an extension to **cruise control** system that automatically adjusts the vehicle speed to maintain a **safe distance** from the preceding vehicle.



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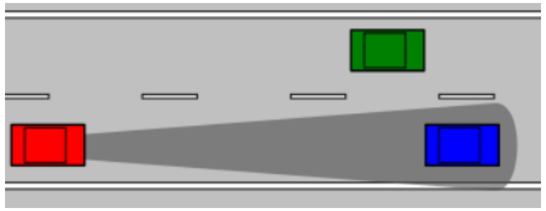
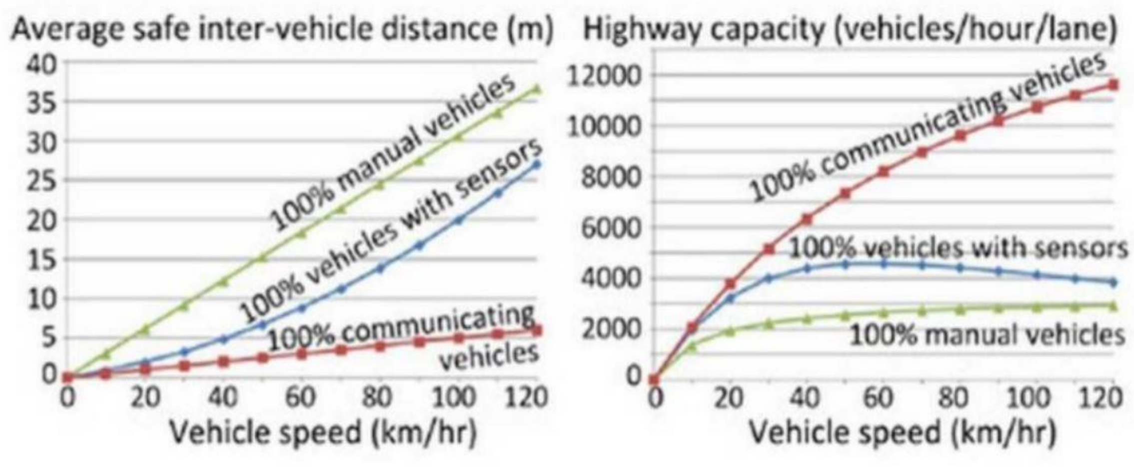


Cooperative Adaptive Cruise Control (CACC) is an extension to the **Adaptive cruise control** with the inclusion of communication with preceding vehicle.

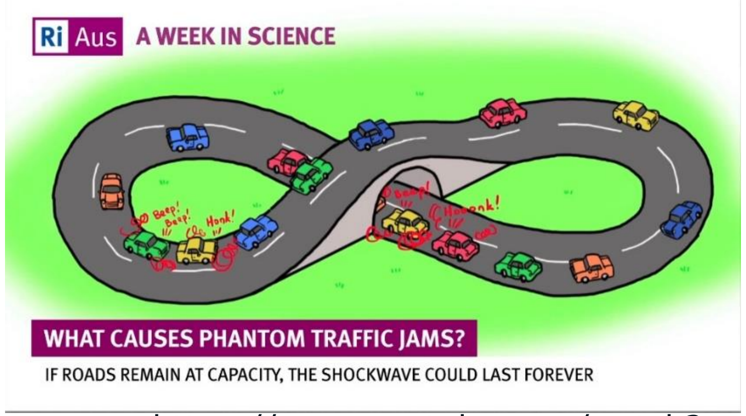
Improving Traffic Flows by Communication

- Inter-vehicle communication is advantageous in:
  - **Safety**: Decreases the average safe inter-vehicle distance, especially with increased speeds.
  - **Performance:** Increases the highway capacity due to this communication.



https://www.slideshare.net/Funk98/dedicated-roads-for-autonomous-vehicles

- **String instability:** A small braking action in one of the cars is magnified as following drivers react in succession, which can even cause the traffic to come to a complete stop.



https://www.youtube.com/watch?v=8ivycTcNvJQ

- **ACC** → not designed to increase traffic efficiency
  - Platoons based on ACC is not string stable.
- **CACC** → intends to maintain string stability of the vehicle platoons by using inter-vehicle communication.

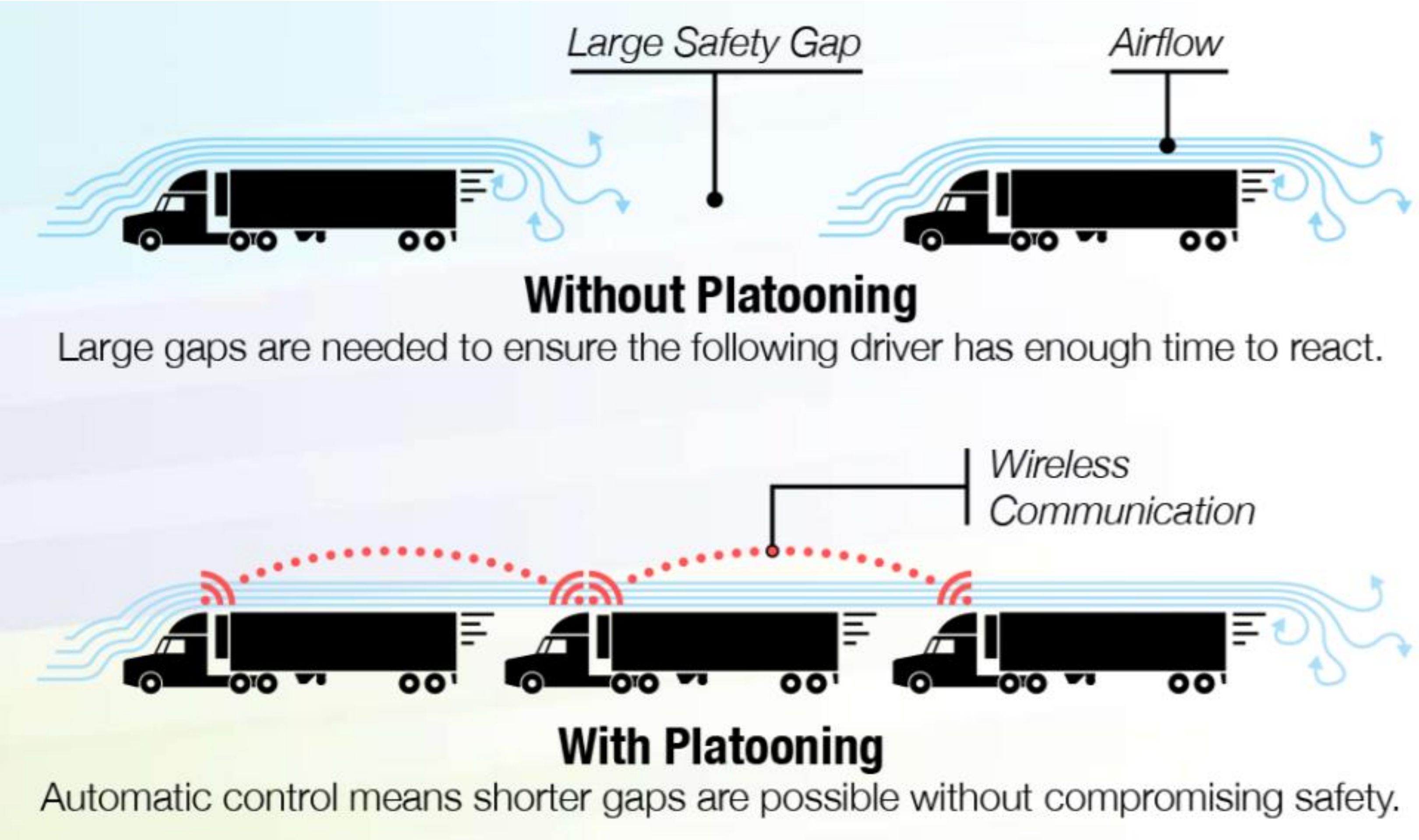
Potential Benefits of Vehicle Platooning

Less Congestion
Capacity improvements result in less delays and better travel time reliability.

Cost Savings
Typical fuel savings average 5-10% for all trucks when platooning.

Improved Safety
Automated control of braking and accelerating reduces crash frequency and severity.

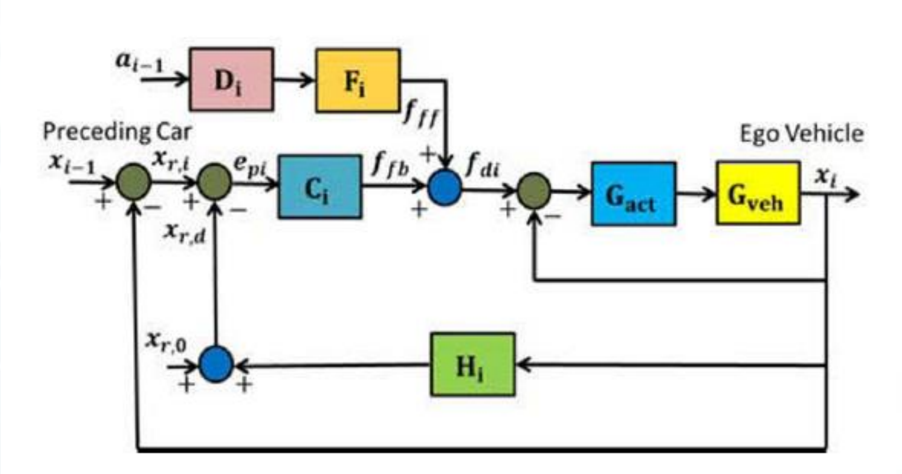
Enhanced Driver Comfort
Platooning technology takes much of the stress out of stop-and-go driving.



Control Methodologies for CACC

Conventional CACC controllers are designed based on a linear feedback controller (PD) with a feed-forward component.

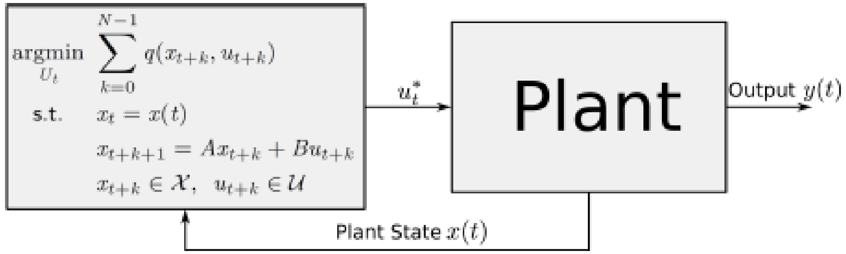
PD controller gains are usually chosen experimentally and the feed-forward controller is designed to ensure the string stability of the system.



Conventional CACC structure for platooning.

Recent studies show the advantages of using model based optimal control methods such as LQR and MPC.

MPC is favored because of its systematic way of handling constraints (since the road is a constrained environment) and its capabilities in satisfying multiple control objectives.



At each sample time:

- Measure /estimate current state $x(t)$
- Find the *optimal input sequence* for the entire planning window N: $U_t^* = \{u_t^*, u_{t+1}^*, \dots, u_{t+N-1}^*\}$
- Implement only the *first* control action u_t^*

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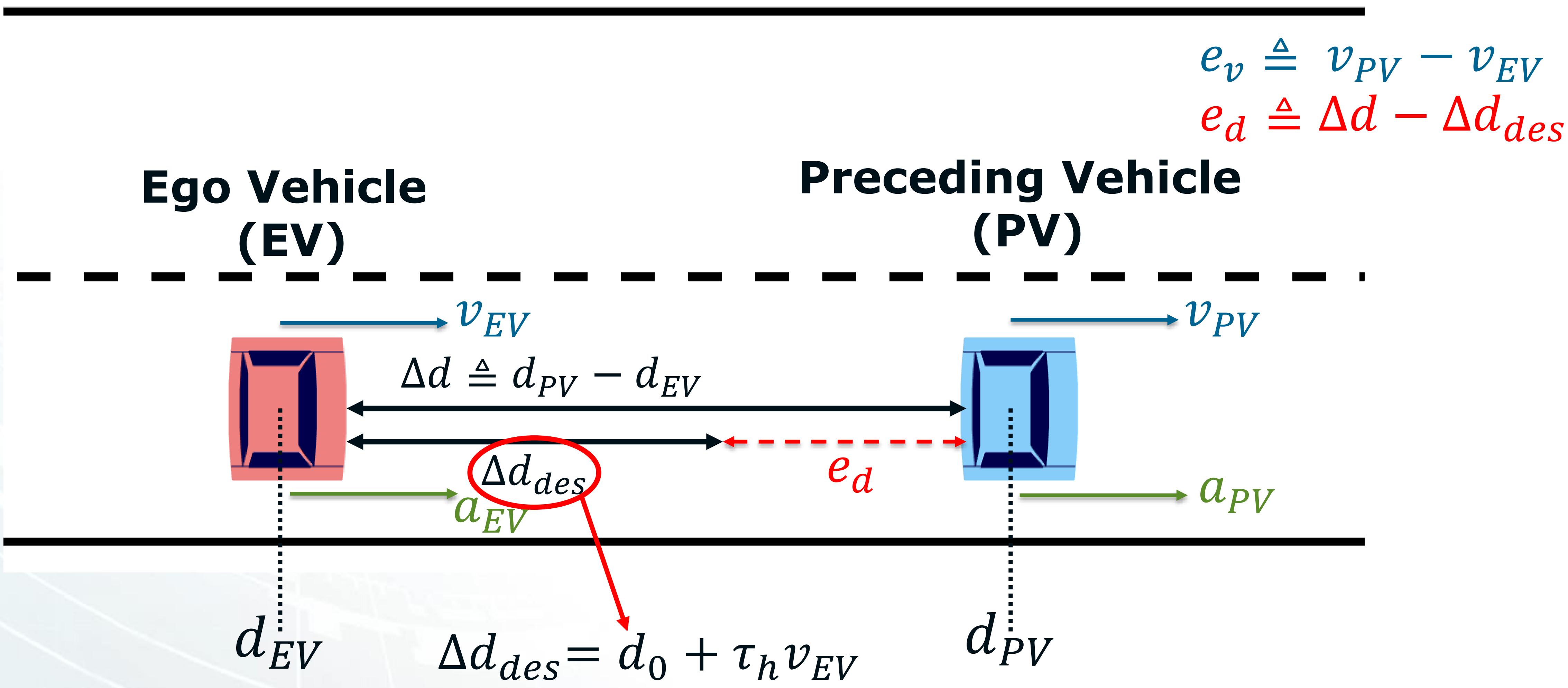
Modeling the car-following problem



ACC Prediction Model

- The prediction model includes the kinematic relations (i.e., distance and velocity) between the EV and PV.
- Add the actuator dynamics ($a_{ev}, \frac{K_a}{\tau_a}$) for better prediction performance.
- In order to limit the max-min velocities of EV, we can extend the state space with the velocity state of EV.

$$\begin{bmatrix} \dot{e}_d \\ \dot{e}_v \\ \dot{a}_{ev} \\ \dot{v}_{ev} \end{bmatrix} = \begin{bmatrix} 0 & 1 & -\tau_h & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & \left(\frac{-1}{\tau_a}\right) & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} e_d \\ e_v \\ a_{ev} \\ v_{ev} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \left(\frac{K_a}{\tau_a}\right) \\ 0 \end{bmatrix} a_{des,ev} + \cancel{\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} a_{pv}}$$

$$\dot{x}(t) = Ax(t) + Bu(t) + Fv(t)$$

Control input
(calculated by MPC)

set to zero for **conventional ACC** design
(no acceleration).

CACC Prediction Model

Augment ACC model with **preceding vehicle** actuator dynamics.

$$\begin{bmatrix} \dot{e}_d(t) \\ \dot{e}_v(t) \\ \dot{a}_{ev}(t) \\ \dot{v}_{ev}(t) \\ \dot{a}_{pv}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & -\tau_h & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & \left(\frac{-1}{\tau_a}\right) & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \left(\frac{-1}{\tau_a}\right) \end{bmatrix} \begin{bmatrix} e_d(t) \\ e_v(t) \\ a_{ev}(t) \\ v_{ev}(t) \\ a_{pv}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \left(\frac{K_a}{\tau_a}\right) \\ 0 \\ 0 \end{bmatrix} a_{des,ev}(t) + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \left(\frac{K_a}{\tau_a}\right) \end{bmatrix} a_{des,pv}(t)$$

Control input
(calculated by MPC)

Measured disturbance
(PV transmits)

Control Objectives in Car Following

Tracking capability, fuel economy, driver desired response, safety and environmental issues, as well as limitations from vehicles and traffic flow—all these objectives shape the behavior of the system.

Objective A

1. When the preceding vehicle is at steady state, the tracking errors should converge to small values.
2. When the preceding vehicle accelerates, the inter-vehicle states should satisfy a driver permissible tracking range as much as possible to avoid frequent preceding vehicles' cut-in from adjacent lanes.
3. When the preceding vehicle decelerates, rear-end collision must be avoided.

Objective B

1. Satisfy driver desired distance characteristic.
2. Satisfy driver longitudinal ride comfort.

Objective Function

- The tracking capability is usually specified in terms of speed error (e_v) and distance error (e_d).

- It is more reasonable to employ the 2-norm of tracking errors to quantify the **objective A.1-2**

$$J_{A1} = \sum_{i=0}^{N+1} (w_d e_d(k+i|k)^2 + w_v e_v(k+i|k)^2)$$

- Satisfying the desired longitudinal ride comfort is specified by penalizing the desired longitudinal acceleration and its derivative (jerk) **objective B.2**

$$J_{B2} = \sum_{i=0}^{N} (w_u u(k+i|k)^2 + w_{du}(u(k+i|k) - u(k+i-1|k))^2)$$

w: weight
k: time index
i: prediction index
u: control input

Constraint Formulation

Model Constraints (hard-equality)

$$x(i+1|k) = A_d x(i|k) + B_d u(i|k) + F_d v(i|k), \mathrm{i} = 0 \ldots \mathrm{N}$$

$x(0|k) \triangleq \mathrm{x(k)}$ $\rightarrow$ initial condition

Actuator Constraints (hard - inequality)

$$u_{min} \leq u(i|k) \leq u_{max}$$

$$\Delta u_{min} \leq u(i|k) - u(i-1|k) \leq \Delta u_{max}$$

$u_{min} = -2.5\ m/s^2$

$u_{max} = 3.0\ m/s^2$

$\Delta u_{max} = \pm 5.0\ m/s^3$

Longitudinal Velocity Constraint (soft-inequality)

$$v_{EV}(i|k) \leq v_{max} + \epsilon$$

$v_{max} = 35\ m/s$

Safety Following Constraint (soft-inequality)

$$e_d(i|k) + \left(d_0 + \tau_h v_{ev}(i|k)\right) + \epsilon \geq \max(-TTC.e_v, d_{s0})$$

$TTC = 2\ s$

$d_{s0} = 5\ m$

Constrained Finite Time Optimal Control Problem

$$U_t^*(x(t)) := \operatorname*{argmin}_{U_t} \boxed{\sum_{k=0}^{N-1} q(x_{t+k}, u_{t+k})} \rightarrow \text{Objective Function}$$

subj. to	$x_t = x(t)$	measurement
	$x_{t+k+1} = Ax_{t+k} + Bu_{t+k}$	system model
	$x_{t+k} \in \mathcal{X}$	state constraints
	$u_{t+k} \in \mathcal{U}$	input constraints
	$U_t = \{u_t, u_{t+1}, \ldots, u_{t+N-1}\}$	optimization variables

At each sample time:

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Simulation Environment

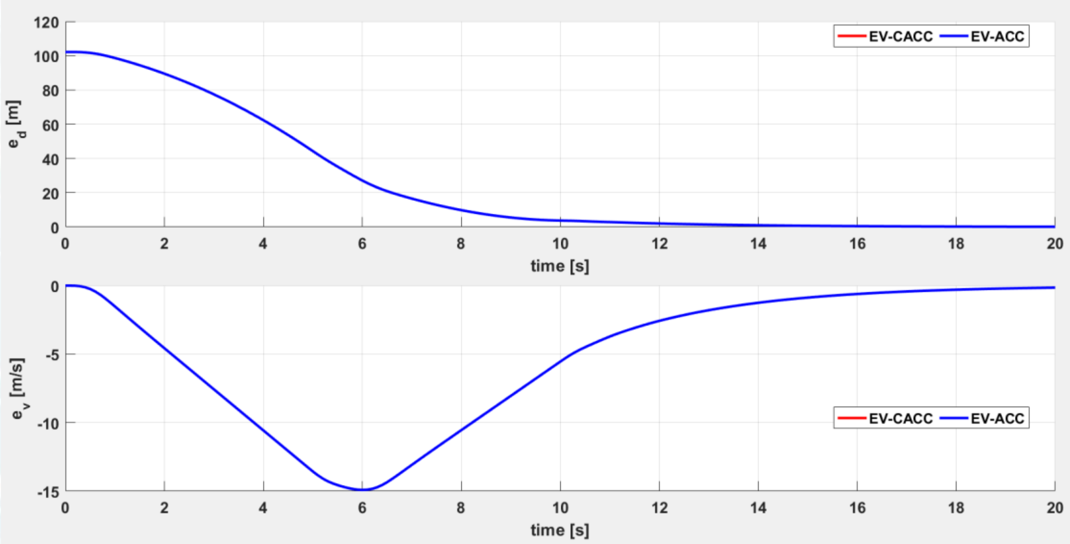
- We used Matlab & Simulink for the simulation.
- MPC is formulated by utilizing Matlab MPC Toolbox.

- For the simulating the vehicle (the plant), we integrated
  - A low-level control algorithm which produces required traction torque for front wheel (a front driven wheel) from the difference between desired acceleration (calculated by controller) and current acceleration.
  - Wheel dynamics – a second order rotational dynamics
  - Pacejka tire model for generating the longitudinal tire forces
  - Other forces acting on vehicle mass such as aerodynamic, rolling resistance and gravitational forces
  - Longitudinal vehicle dynamics
  - Actuator dynamics
  - Communication dynamics (modeled as a time delay of 0.1 sec.)

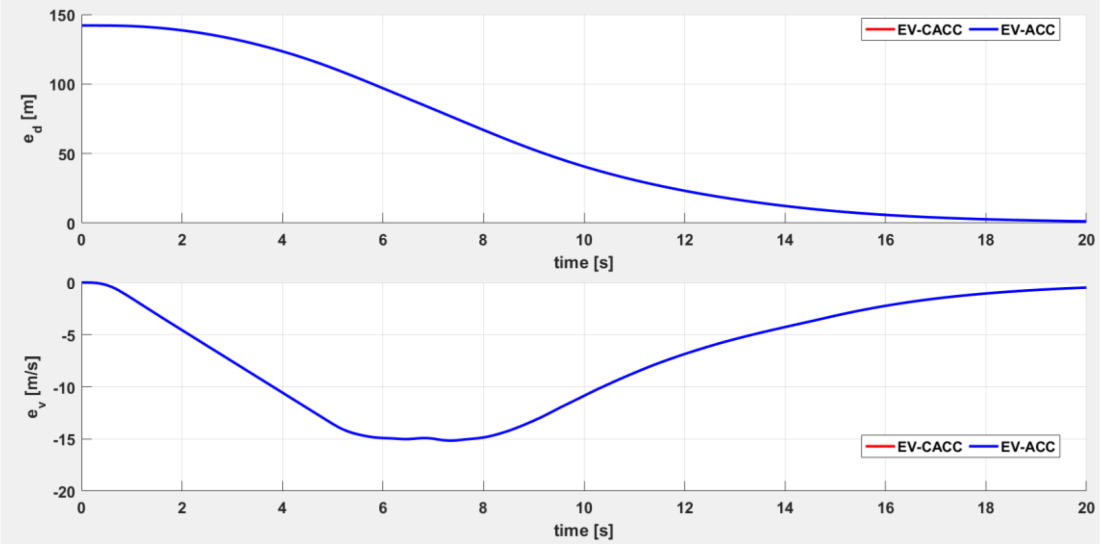
Simulation #1 -> Constant velocity catch up

$d_{EV}(0) = 0\ m,$ $\quad d_{PV}(0) = 150\ m$
$v_{EV}(0) = 20\ m/s$ $\quad v_{PV}(0) = 20\ m/s$
$v_{EV,max} = 35\ m/s$

Case 1 : constant time gap policy $\tau_h = 2.0\ s\ , d_0 = 5.0\ m$



Case 2 : constant spacing policy $\tau_h = 0.0\ s, d_0 = 5.0\ m$



No difference between **ACC** and **CACC** performance in both cases since $a_{pv} = 0$

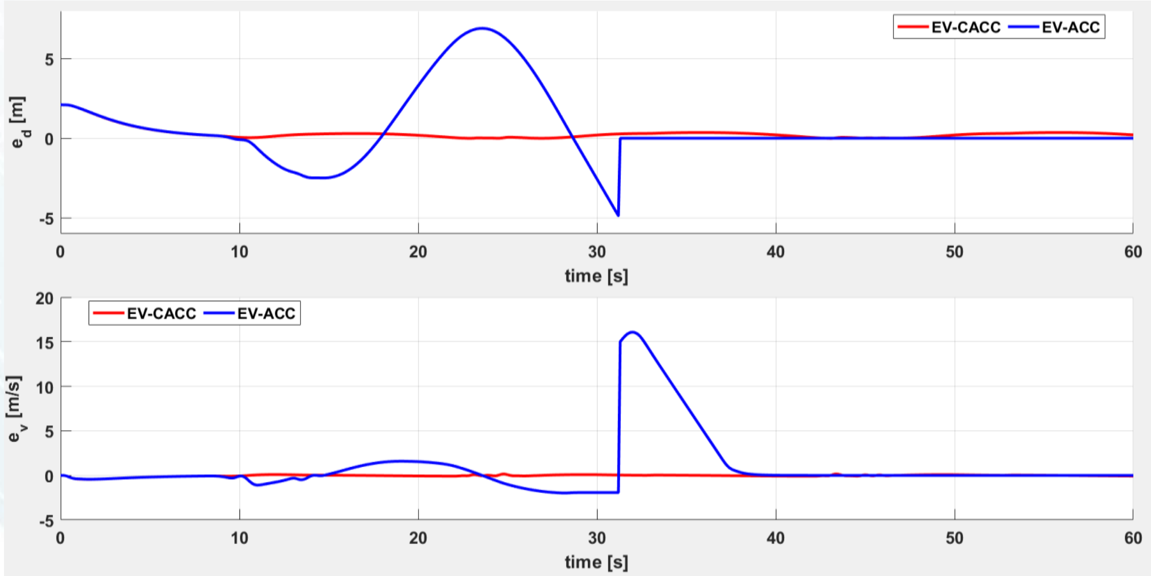
Simulation #2 PV sinusoidal velocity behavior

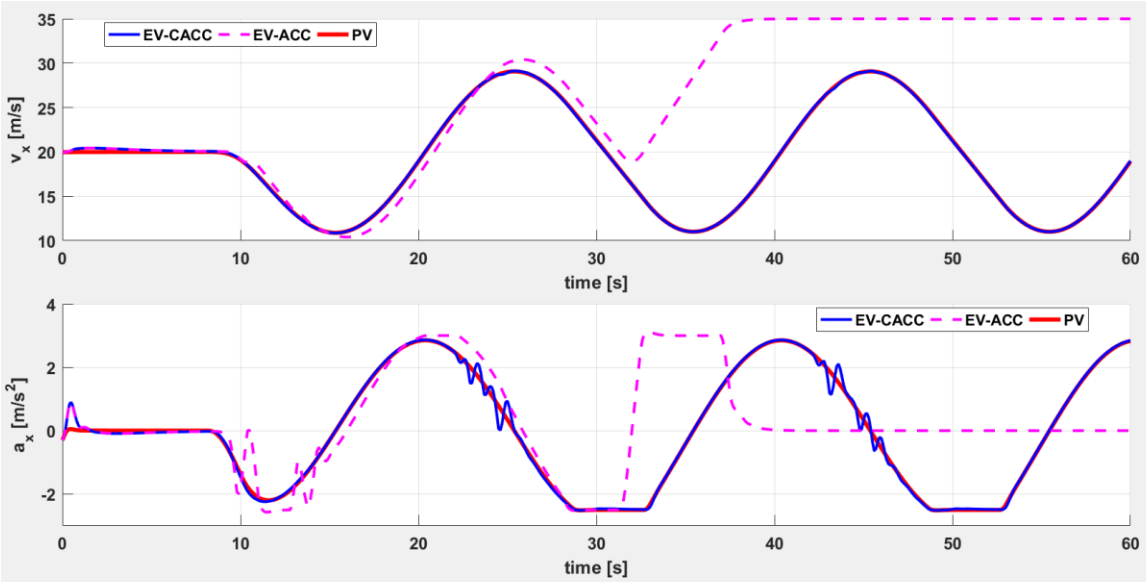
$$d_{ev}(0) = 0\ m,\quad v_{ev}(0) = 20\ m/s,\quad v_{ev,max} = 35\ m/s$$

$$d_{pv}(0) = 10\ m,\quad v_{pv}(0) = 20\ m/s$$

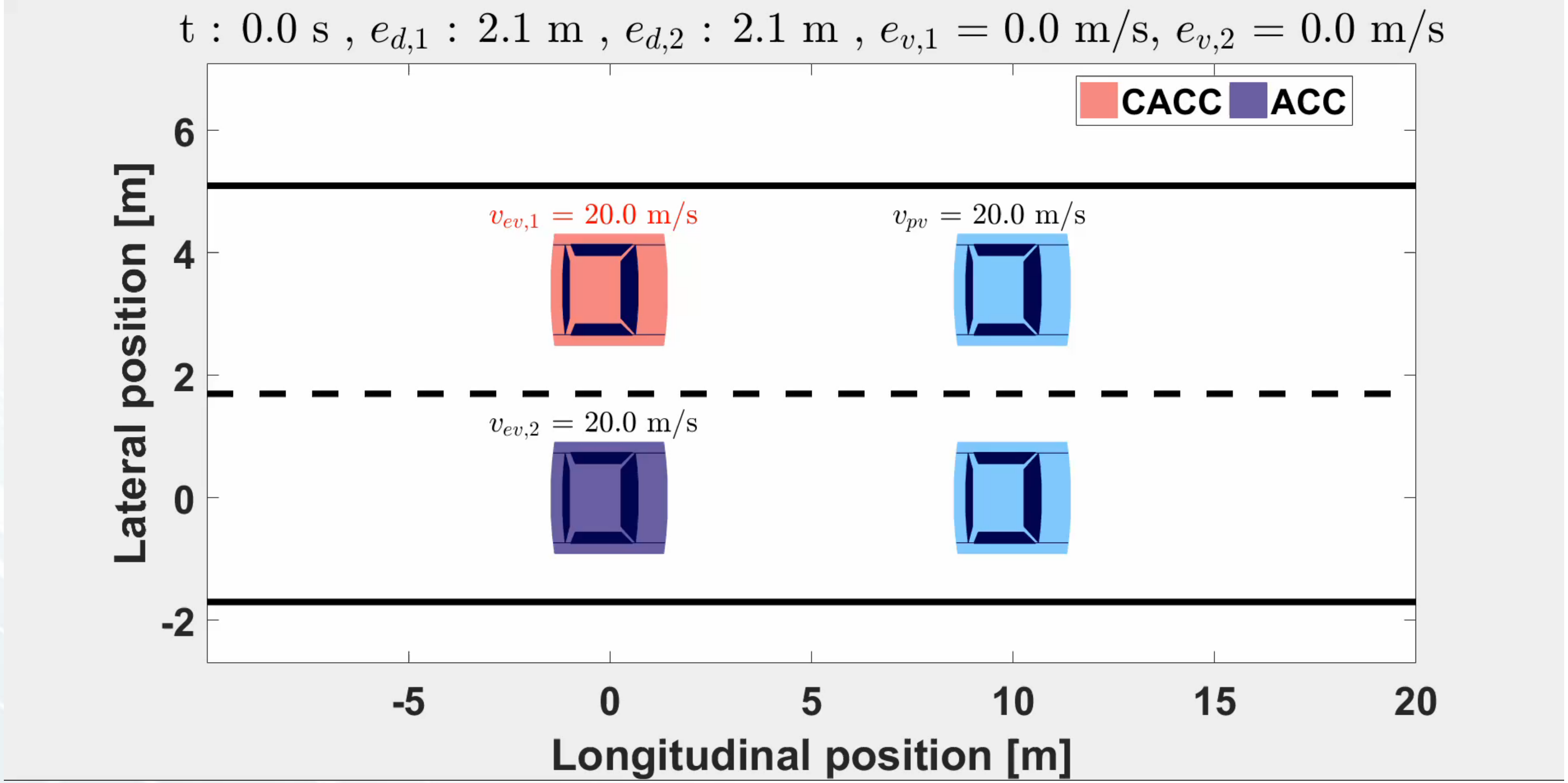
$$f_{sine,pv} = 0.05\ Hz,\quad v_{sine,pv} = 10\ m/s$$

Case 2 : constant spacing policy $\tau_h = 0.0\ s, d_0 = 5.0\ m$



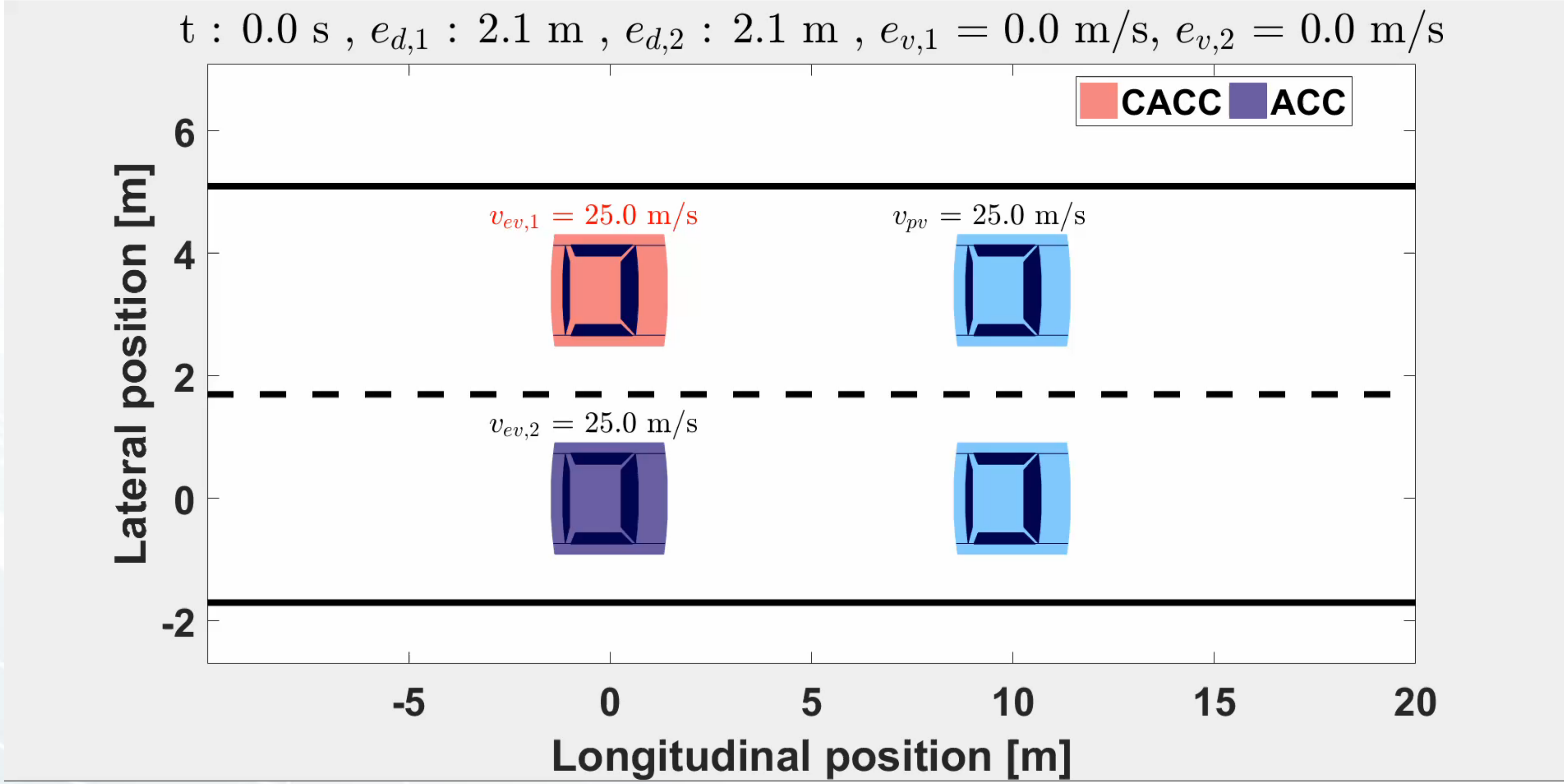


Video: PV sinusoidal velocity behavior



Video: CACC vs ACC

Simulation #3 -> PV full brake & full throttle (constant spacing policy)



Conclusion & Future Directions

- In this work, a CACC system is designed by using model predictive control framework in MATLAB.

- Linear MPC is formulated and the resulting optimization problem is QP. Therefore, the proposed controller could be easily implemented in embedded systems.

- The proposed controller is validated in simulations with a more realistic vehicle model (as plant) in different highway scenarios.

- The results show the effectiveness of the proposed method with good tracking capabilities under different driving characteristics.

Thank You

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