Challenges and Contributions in Cooperative and Automated Vehicles

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I-CAVE

Integrated Cooperative Automated Vehicles

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i-CAVE

Design intrinsically safe and efficient Cooperative Dual Mode Automated Transport services for goods and people with a maximum level of comfort in urban type environments

i-CAVE Program objectives

i-CAVE: integrated Cooperative Automated Vehicles

- i-CAVE addresses current transportation challenges regarding land-use, throughput, and safety with an integrated approach to automated and cooperative driving.

- To this end, a Cooperative Dual Mode Transport system will be researched and designed, consisting of dual mode vehicles, which can be driven automatically and manually to allow for maximum flexibility.

- i-CAVE integrates the technological roadmaps for automated driving and for cooperative driving, thus accelerating the development of novel transportation systems addressing todays and future mobility demands.

- A living-lab demonstrator serves as a basis for a close-to-market transport system which can be commercialized by the transport industry.

i-CAVE Headlines

- Start: Mid 2016
- Excellent applied research
- Consortium of 4 univs & 20 partners/users
- Total program budget 6,4 MEuro
- STW funding near to 4 MEuro
- Research program duration 5 years
- 15 PhD students, 1 PDEng, 4,6 PostDocs + technicians

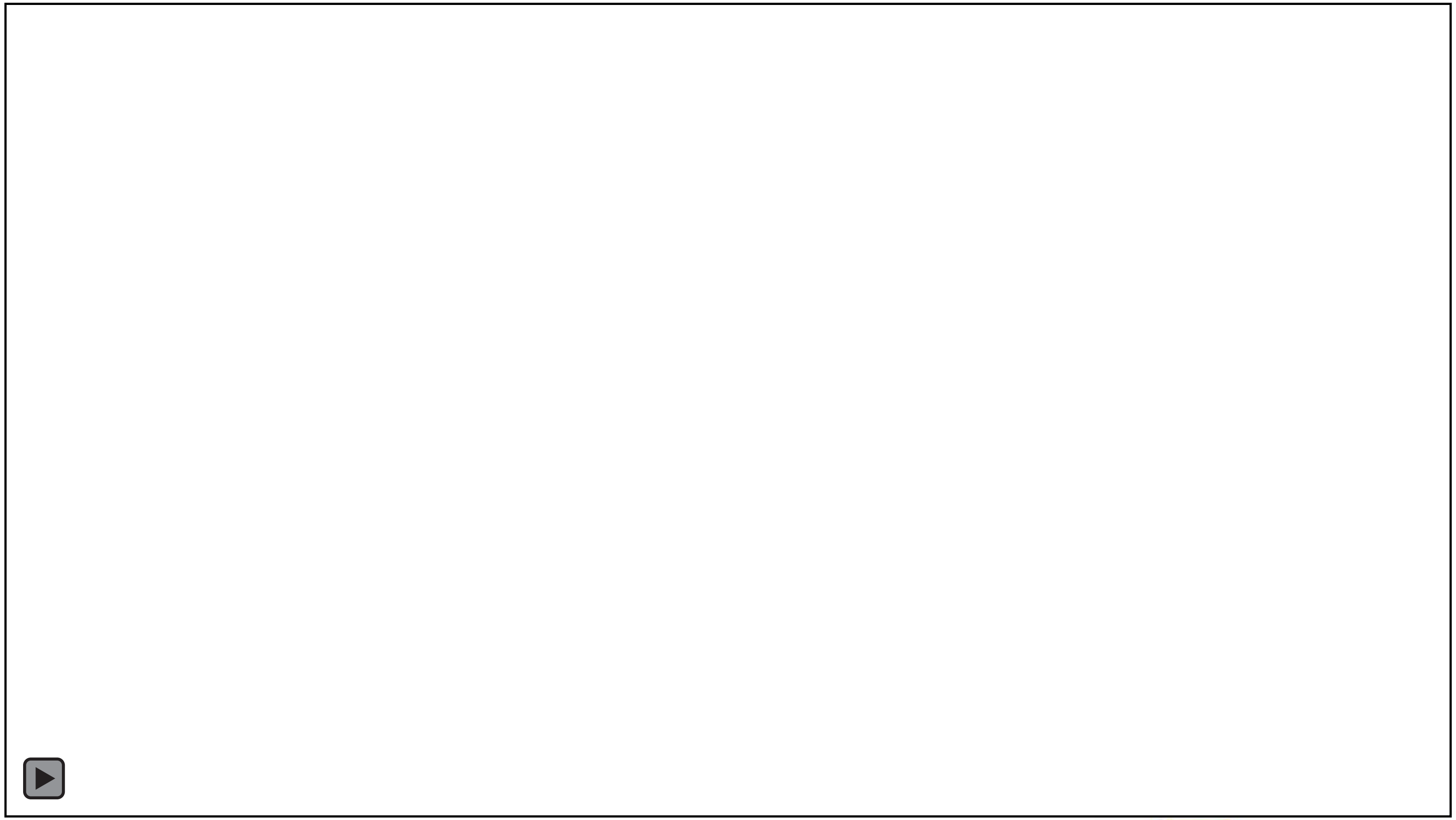
Where it all started

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	Throughput
***Human driver* monitors the driving environment**							
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	
***Automated driving system* ("system") monitors the driving environment**							
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	

Cooperation

Autonomous

Autonomous?



Cooperative driving (130km/h)

Jeroen Ploeg et al, TNO + TU/e

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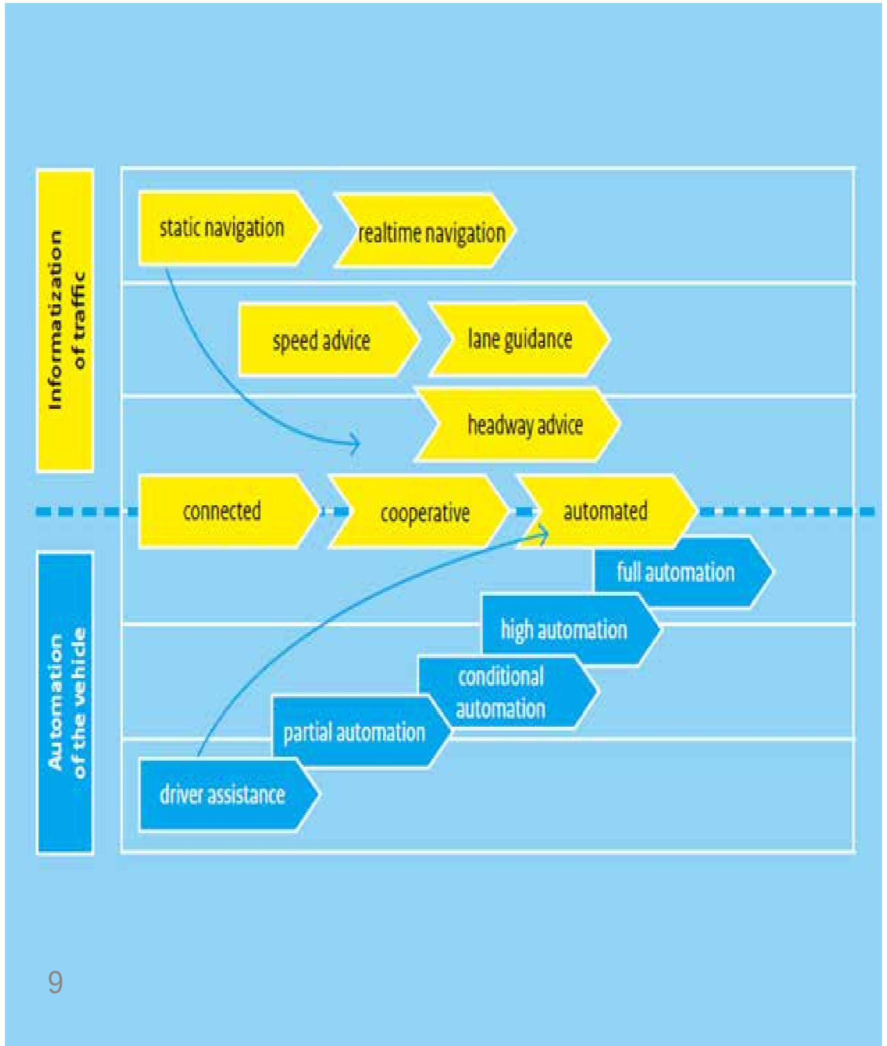
The near future and full potential of automated driving



- The full potential of automated driving can only be reached by combining cooperative driving (V2x enabled) and automated driving to improve:
  - Vehicle and traffic efficiency
  - Safety
  - Comfort

Autonomous vs cooperative automated

Autonomous

Cooperative

action à reaction vs intention à *coordinated* reaction

Conclusion:

Autonomous vehicle priority on interacting with the environment (reactive)
Cooperative vehicle priority on understanding traffic behavior, taking coordinated action (pro-active)

Autonomous vs cooperative automated

- Action à reaction, creates over-reaction! (traffic jams, emergency braking)
  - Humans create traffic jams (time-delay, distraction, drowziness, ignorance, misunderstanding etc.) but, …
  - At the same time we have an extremely good capability to *anticipate* and *interact* on sudden situations

- Automated vehicles have limited capability of anticipation and interaction
  - Extreme perception and intelligence needed for prediction of behavior

i-CAVE Program: 7 Projects

1. Design highly accurate and scalable digital maps and video-based sensing and localization technologies
2. Control individual cooperative vehicles taking into account vehicle dynamics and tire behavior, including sufficient level of fail safety and fault tolerance
3. Manage (dispatch, route and reposition) a fleet of cooperative autonomous vehicles in an efficient and cooperative way
4. Obtain a sufficient fail-safe and fault tolerance system of V2V communication
5. Take into account human factor issues for drivers, passengers and other road users
6. Architecture and functional safety
7. Living lab demonstrator, applying on small electric cars (e.g. Twizy) as research platform

Integration is key

P1: Sensing, mapping and localizing

P2: Cooperative vehicle control

P3: Dynamic fleet management

P4: Communication

P5: Human factors

P6: Architecture and functional safety

P7: Demonstrator

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P1 - Sensing, Mapping, and Localization

How can we design highly reliable, accurate, and scalable digital video-based sensing, mapping, and localization technologies that support cooperative and automated driving?

Improve scalability of highly accurate 3D mapping and localization technology

- High definition map creation from crowdsourced data using pose-graph techniques
- Robust natural landmarks for vehicle localization

Reduce dependency on highly accurate 3D maps by improving real-time scene understanding capabilities of automated vehicles

- Improved real-time scene understanding via semantic-instance stixels.
- Geometric and topological scene understanding via deep graph neural network

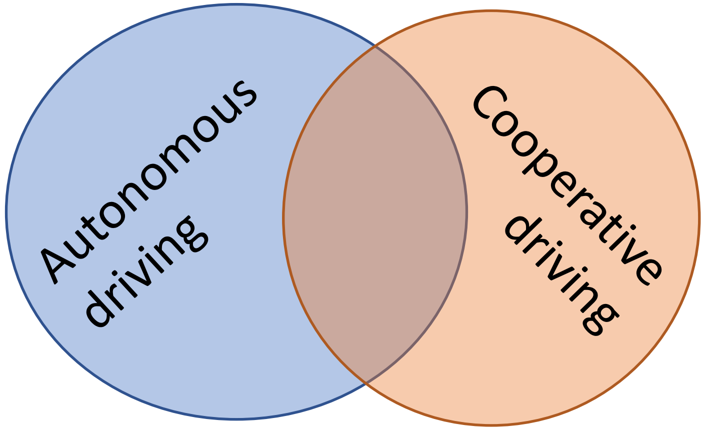
Twizy demonstrator platform (P7)

- A real-time perception framework for cooperative driving

P1- Sensing, Mapping, and Localization

P2- Cooperative vehicle control

How can we control individual cooperative vehicles taking into account vehicle dynamics, longitudinal and lateral string stability, and human behavior, including how to obtain a sufficient level of fail safety and fault tolerance?

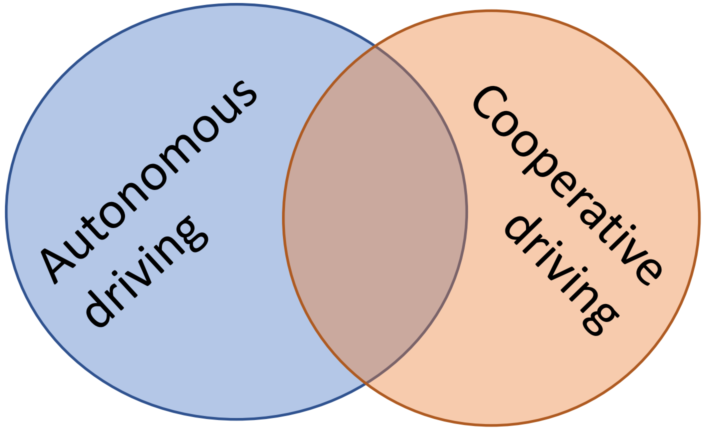


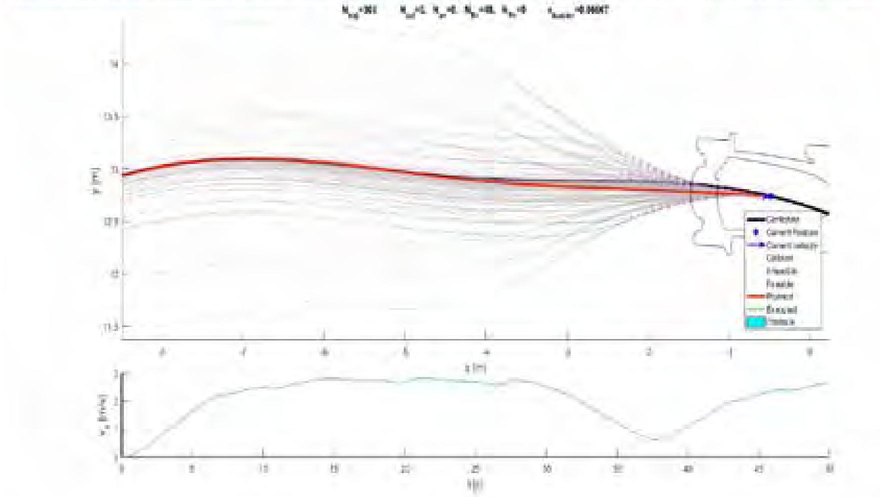
Cooperative path planning

- Using planned information of the preceding vehicle an optimal path can be planned
- B-spline planning approach

P2- Cooperative vehicle control

How can we control individual cooperative vehicles taking into account vehicle dynamics, longitudinal and lateral string stability, and human behavior, including how to obtain a sufficient level of fail safety and fault tolerance?





Cooperative path planning

- Using planned information of the preceding vehicle an optimal path can be planned
- B-spline planning approach

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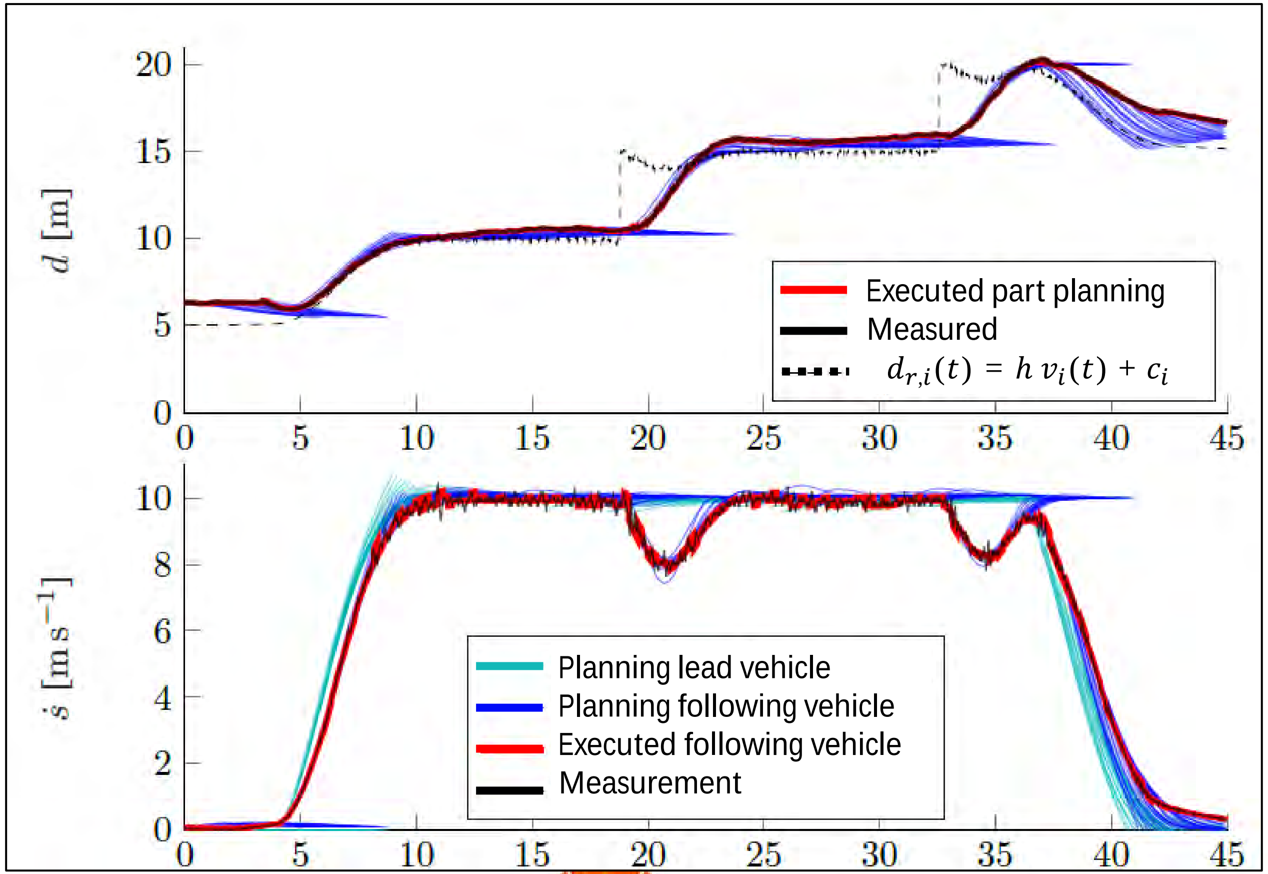
Experimental Implementation

- Implementation on two full-scale demonstrator setups.
- Cooperative vehicle following down to a time headway of 0.1



Cooperative trajectory planning for vehicle following

- Desired distance based on spacing policy:

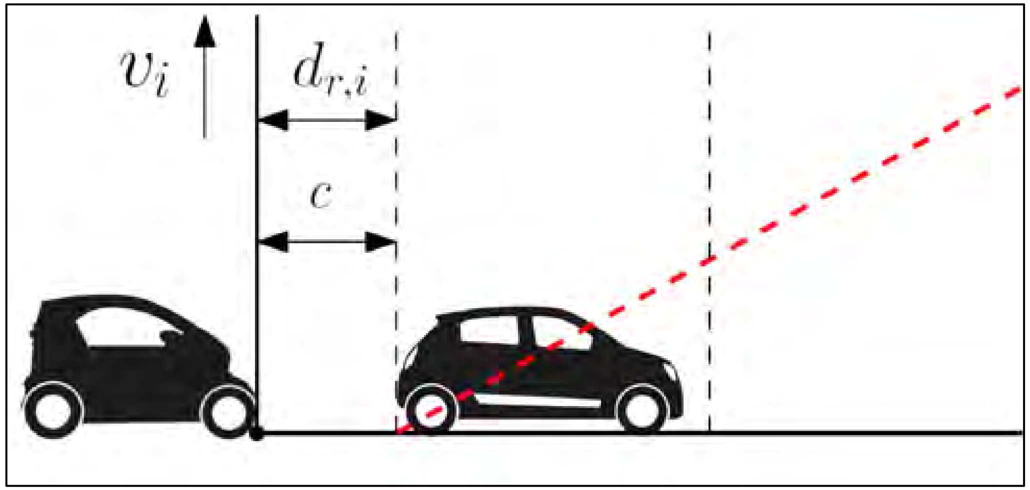
$$d_{r,i}(t) = h\, v_i(t) + c$$

Desired distance

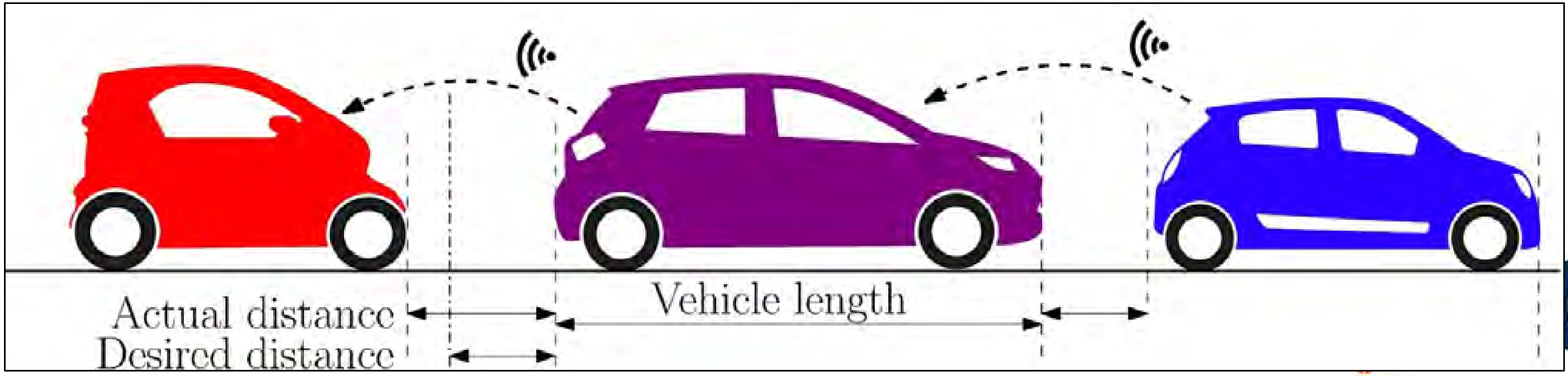
Headway time (seconds)

Velocity

Standstill distance

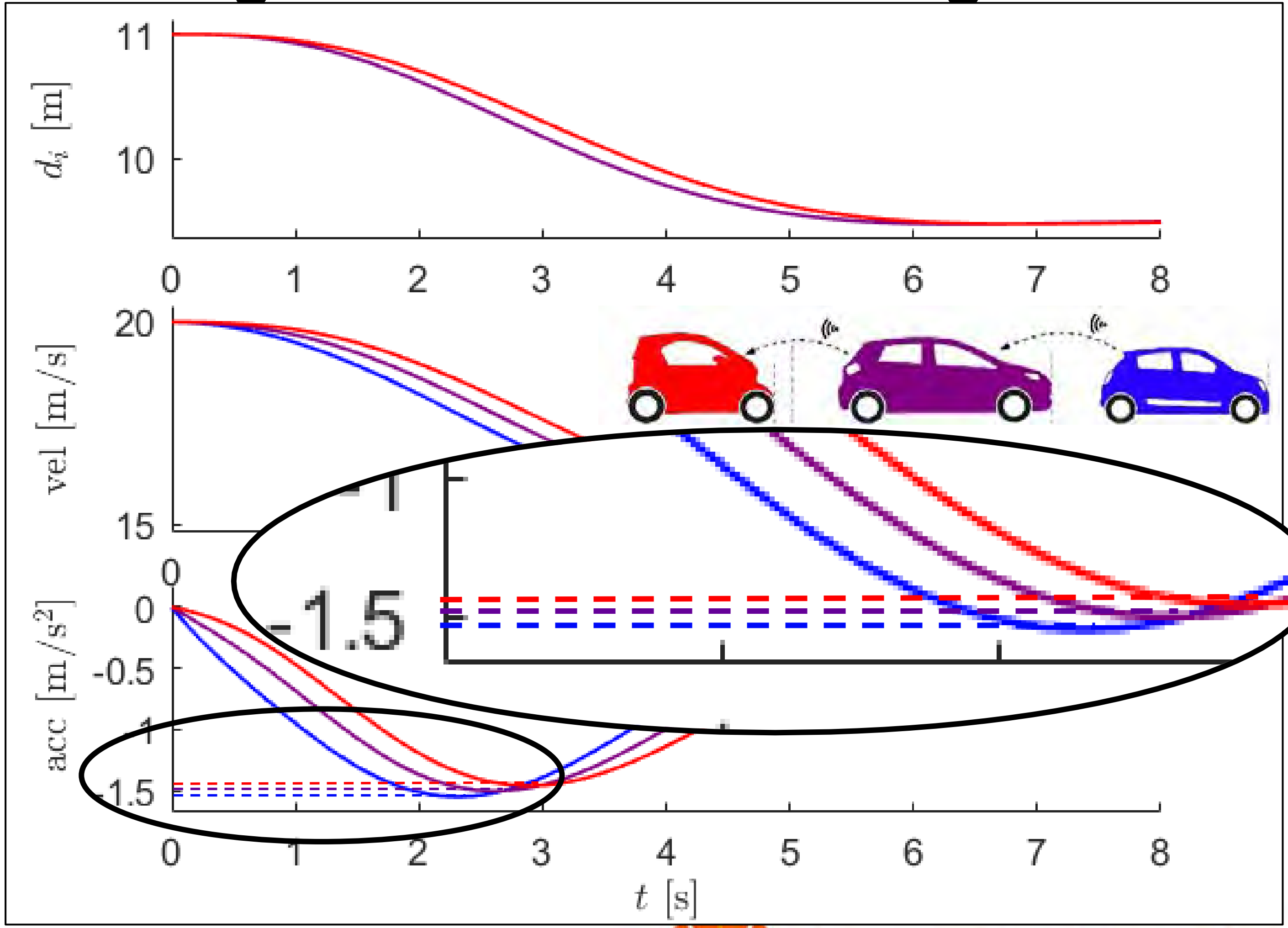


- Trajectory based on the communicated trajectory of the preceding vehicle



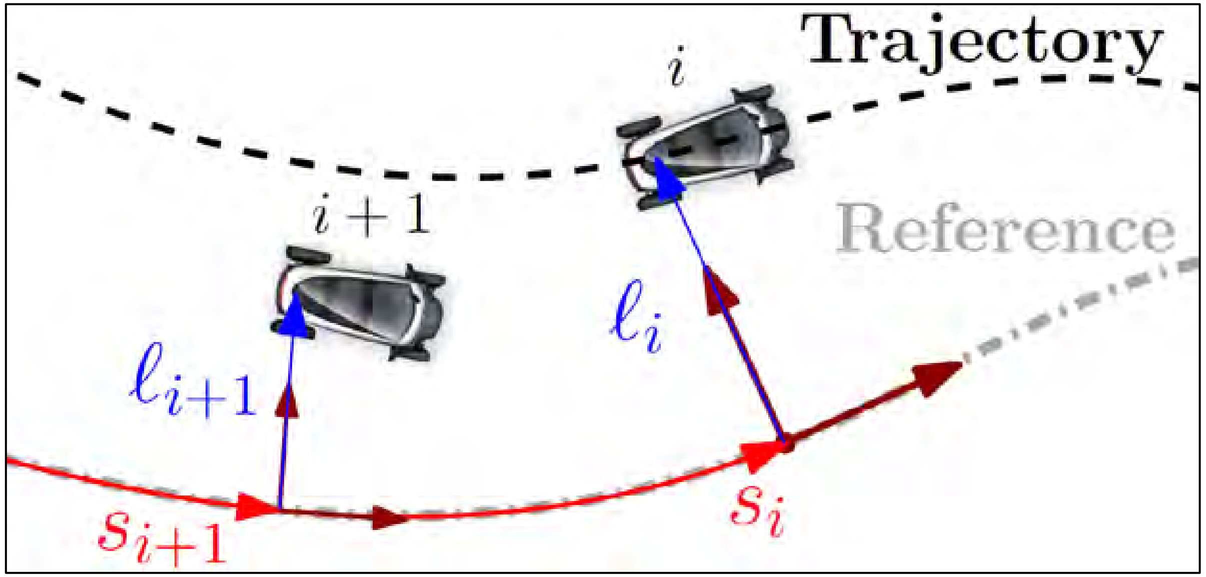
Cooperative trajectory planning for vehicle following

- Brake from 20m/s to 15 m/s
- All vehicles abide by the spacing policy:
  - $d_{r,i}(t) = h\, v_i(t) + c$
  - $h = 0.3s, \quad c = 5m$
- Lower acceleration for vehicles further up the platoon à String-Stability



Framework for Autonomous and Cooperative driving

- Frame attached to reference path trajectory in coordinates:
  - ℓ *lateral distance to center line*
  - s *curvilinear distance along centerline*

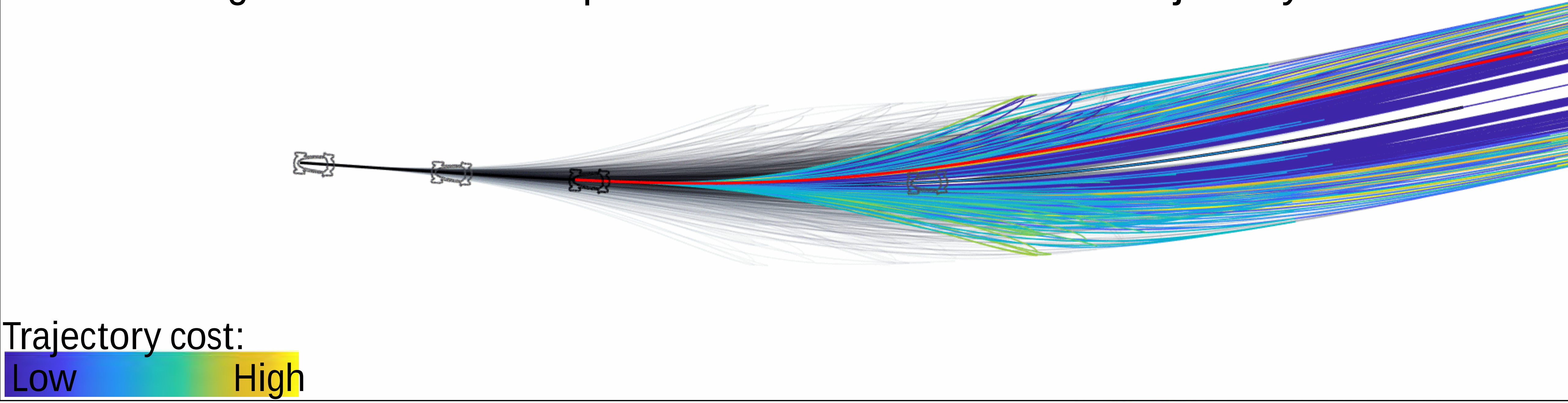


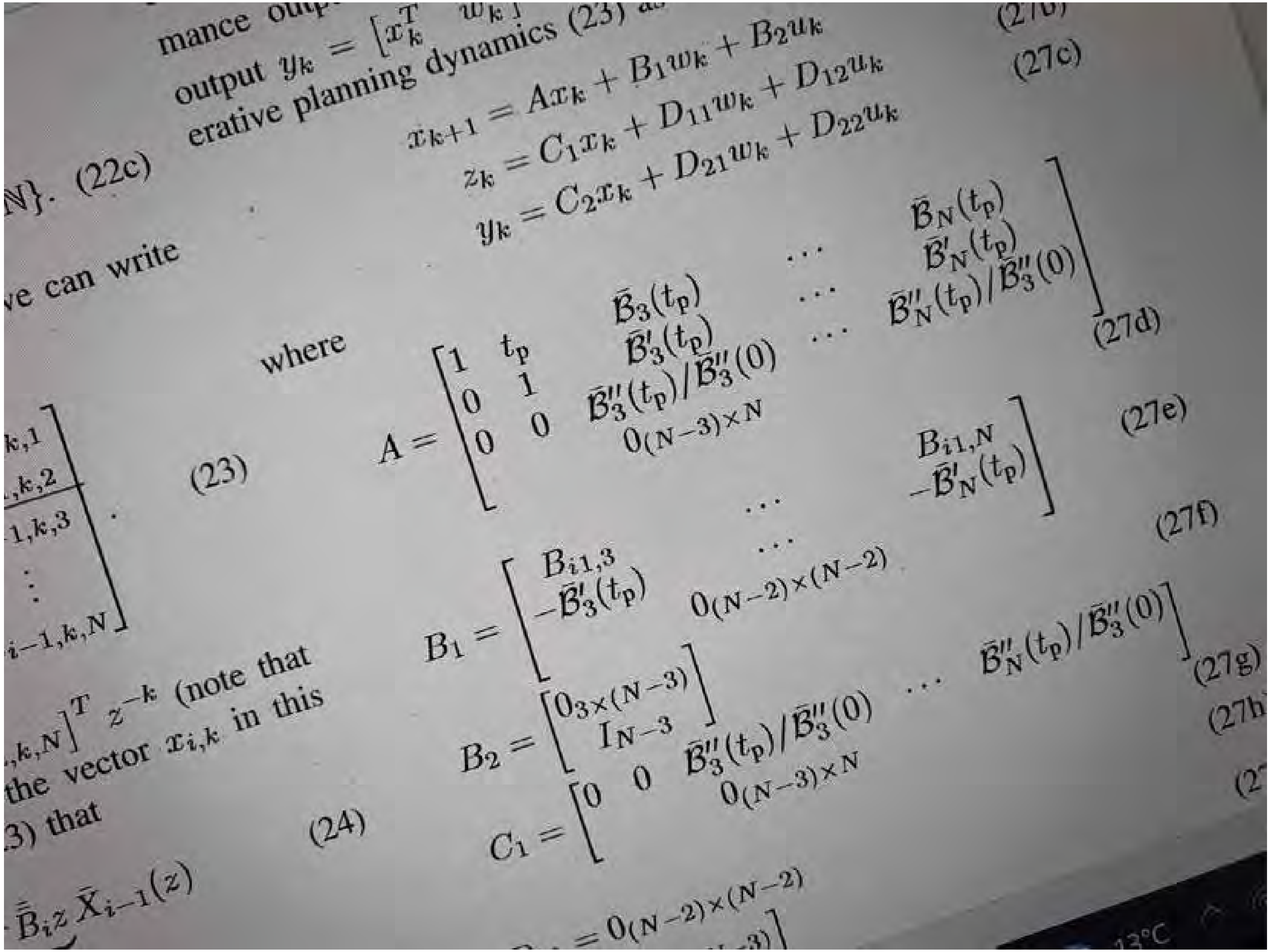
- Cooperative trajectories in s (1D)
  - *Especially relevant to know the distance between vehicles within a lane*
  - *Multiple lateral trajectories per cooperative trajectory*

- Generate a set of candidate trajectories
  - *Select the best trajectory for execution*

Combined Framework Example

- Combined cooperative and autonomous trajectories in single framework
- Single cost function represents how desirable each trajectory is




mance output $y_k = [x_k^T \quad w_k]$ …
output y_k … erative planning dynamics (23) as

N}. (22c)

$$x_{k+1} = Ax_k + B_1 w_k + B_2 u_k \quad (27b)$$
$$z_k = C_1 x_k + D_{11} w_k + D_{12} u_k \quad (27c)$$
$$y_k = C_2 x_k + D_{21} w_k + D_{22} u_k$$

we can write

(23) where

$$A = \begin{bmatrix} 1 & t_p & \bar{B}_3(t_p) & \dots & \bar{B}_N(t_p) \\ 0 & 1 & \bar{B}_3'(t_p) & \dots & \bar{B}_N'(t_p) \\ 0 & 0 & \bar{B}_3''(t_p)/\bar{B}_3''(0) & \dots & \bar{B}_N''(t_p)/\bar{B}_3''(0) \\ & & 0_{(N-3)\times N} & & \end{bmatrix} \quad (27d)$$

$$B_1 = \begin{bmatrix} B_{i1,3} & \dots & B_{i1,N} \\ -\bar{B}_3'(t_p) & \dots & -\bar{B}_N'(t_p) \\ & 0_{(N-2)\times(N-2)} & \end{bmatrix} \quad (27e)$$

$$B_2 = \begin{bmatrix} 0_{3\times(N-3)} \\ I_{N-3} \end{bmatrix} \quad (27f)$$

$$C_1 = \begin{bmatrix} 0 & 0 & \bar{B}_3''(t_p)/\bar{B}_3''(0) & \dots & \bar{B}_N''(t_p)/\bar{B}_3''(0) \\ & & 0_{(N-3)\times N} & & \end{bmatrix} \quad (27g)$$

$= 0_{(N-2)\times(N-2)}$ (27h)

$]^T z^{-k}$ (note that the vector $x_{i,k}$ in this

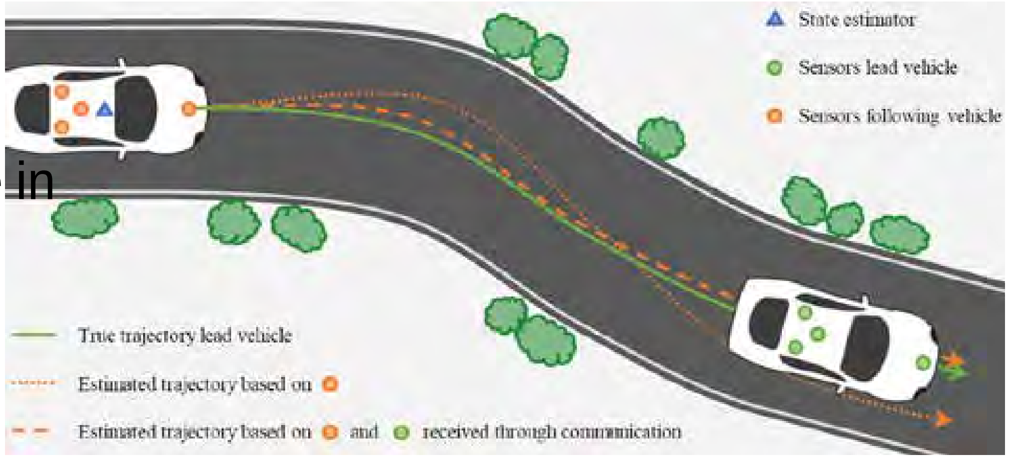
(24)

3) that

$\bar{\bar{B}}_i z \bar{X}_{i-1}(z)$

String stable? Almost ......

P2 - Cooperative vehicle control



Cooperative state estimation

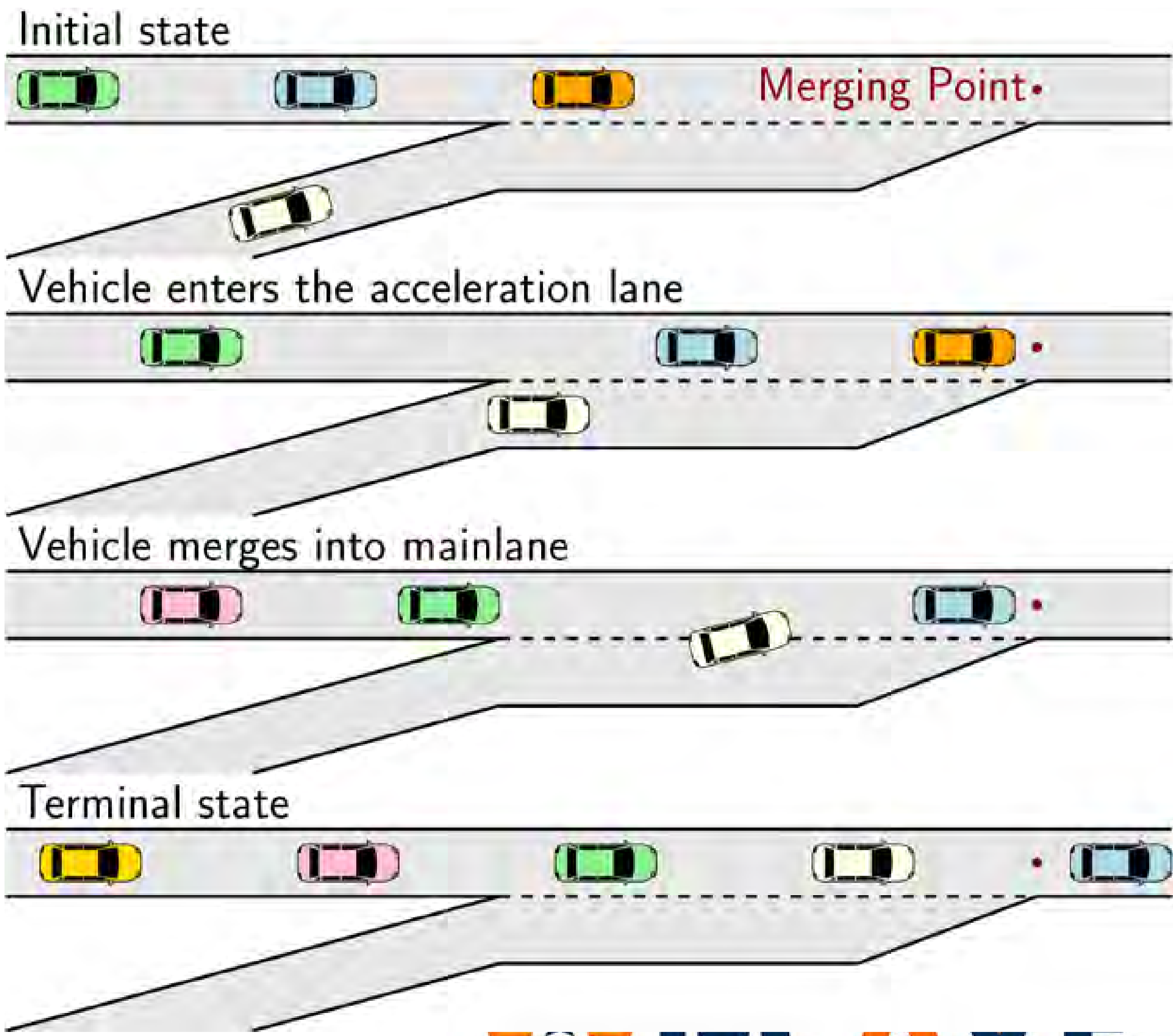
- An automated vehicle measures the motion of the vehicle in front of it: how to exploit this?
- e.g. Measurement noise reduction

Merging into a cooperative platoon

- Merging onto a busy highway is difficult and requires a social aspect
- Deciding optimal placement, gap creation and subsequent merging all require some form of autonomy and cooperation

Merging

- New vehicle (white) aims to join a platoon on the highway
- Must be done before a *Merging Point*
- Vehicle in the platoon (green) needs to open a gap and transition CACC target
- New vehicle needs to align with the gap and transition to CACC
- New vehicle is the focus for the presented work



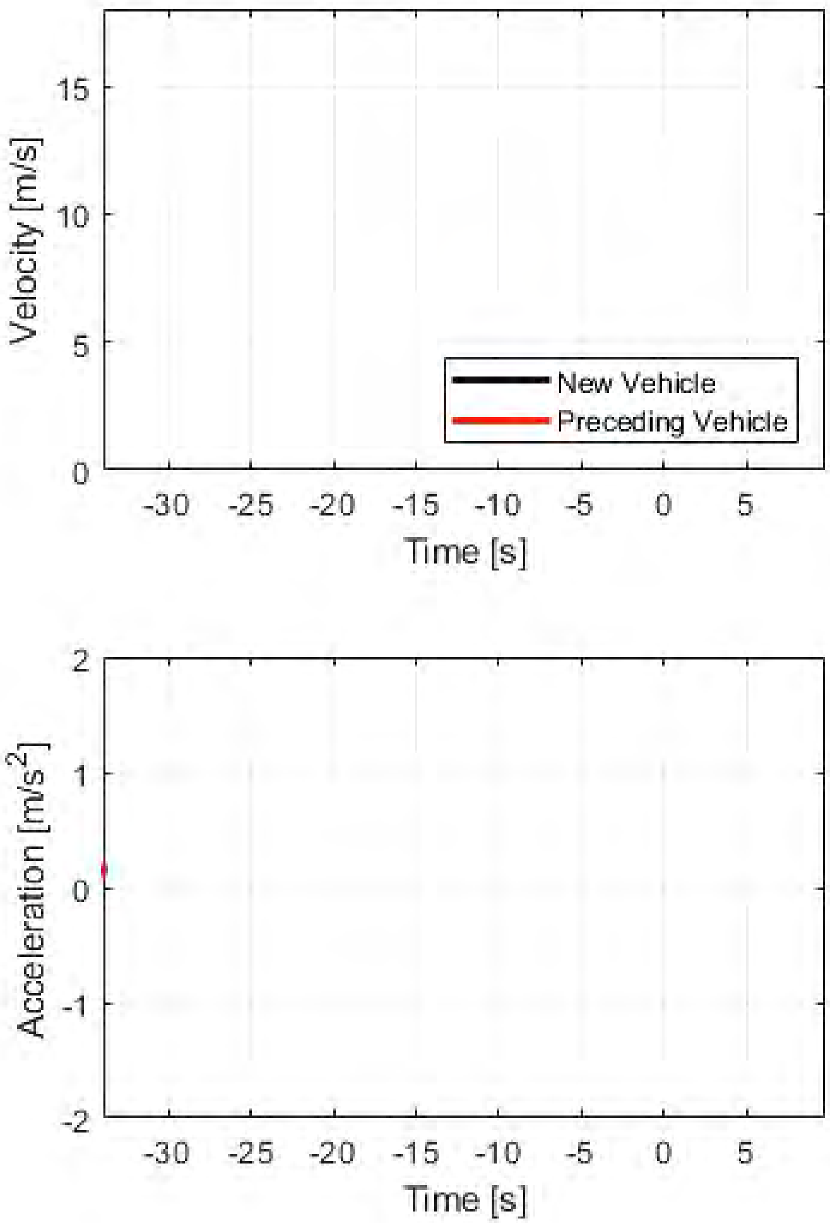
Transitioning to a CACC controller

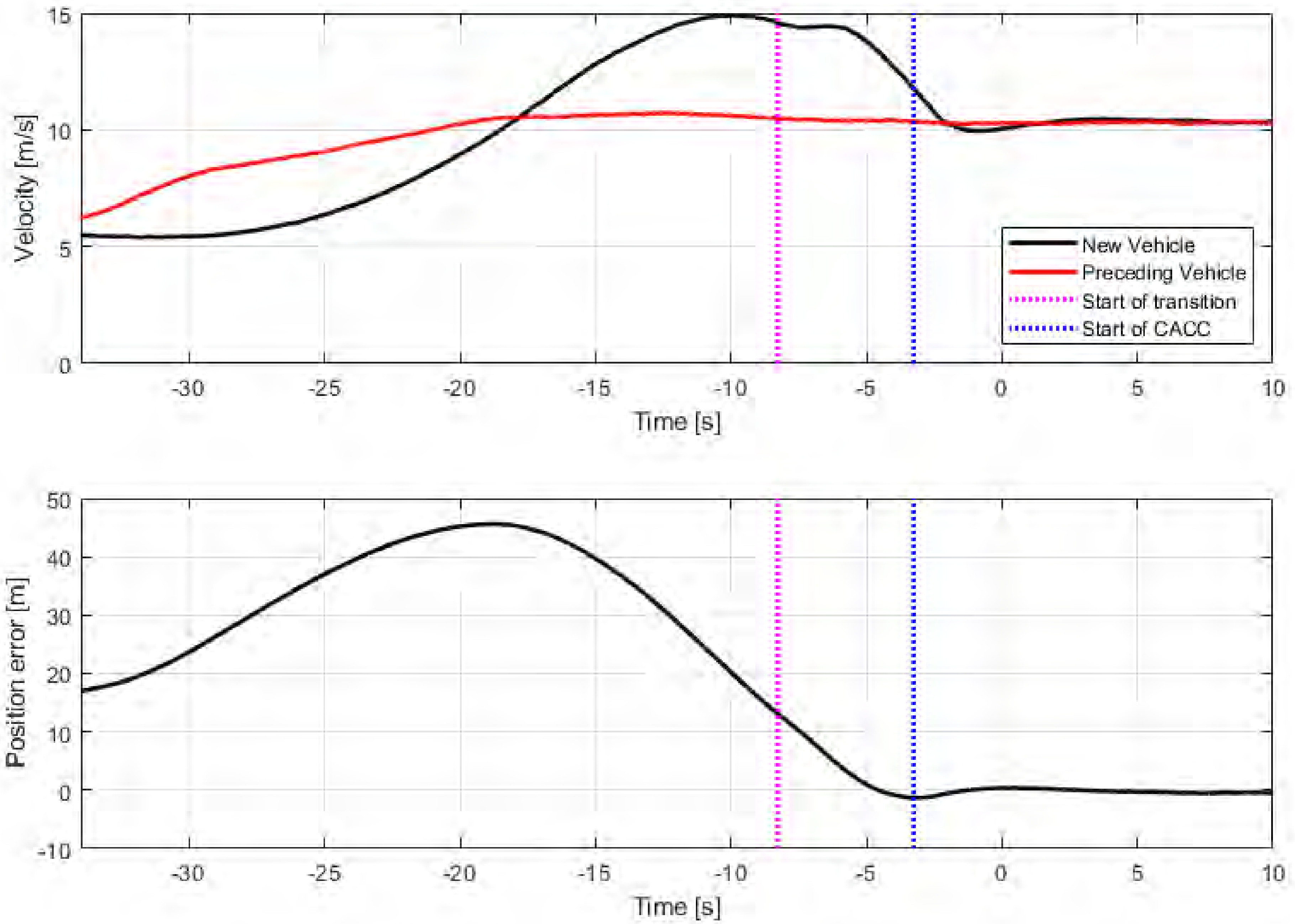
- Transition from an individual MPC to a CACC controller while driving
- Transition controller to close a residual gap when switching
- Ensures a timely execution of the switch

Experimental setup

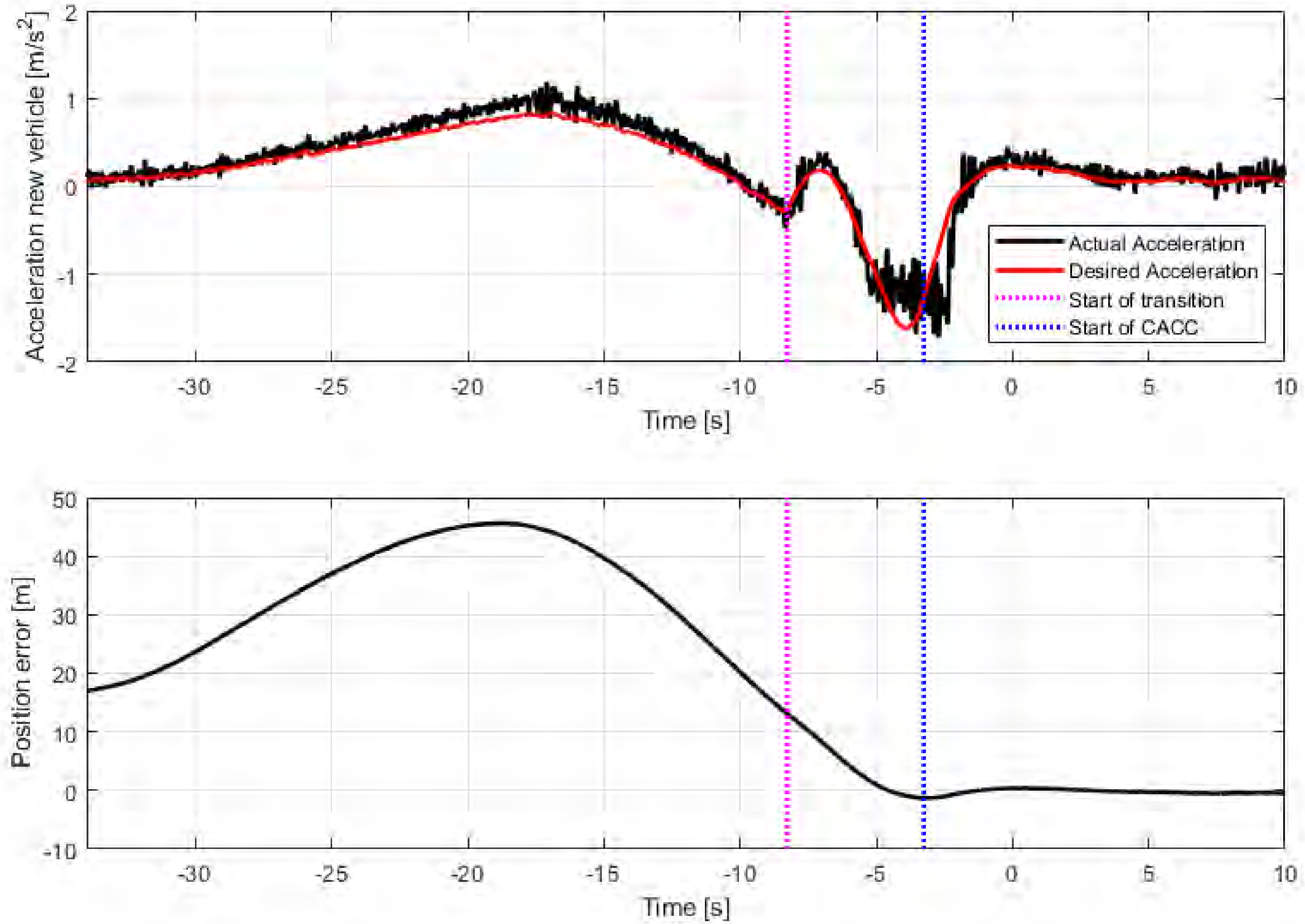
- One manual driven vehicle and one automated vehicle
- Automated vehicle drives with an individual MPC controller and transitions to a CACC controller
- Transition must be completed 5 seconds before the *Merging Point* is reached
- Maximum final time of the transition indicated with $t = 0$ in graphs

Individual MPC controller





15
10
5
0
Velocity [m/s]
-30
-25
-20
-15
-10
-5
0
5
10
Time [s]
New Vehicle
Preceding Vehicle
Start of transition
Start of CACC
50
40
30
20
10
0
-10
Position error [m]
-30
-25
-20
-15
-10
-5
0
5
10
Time [s]



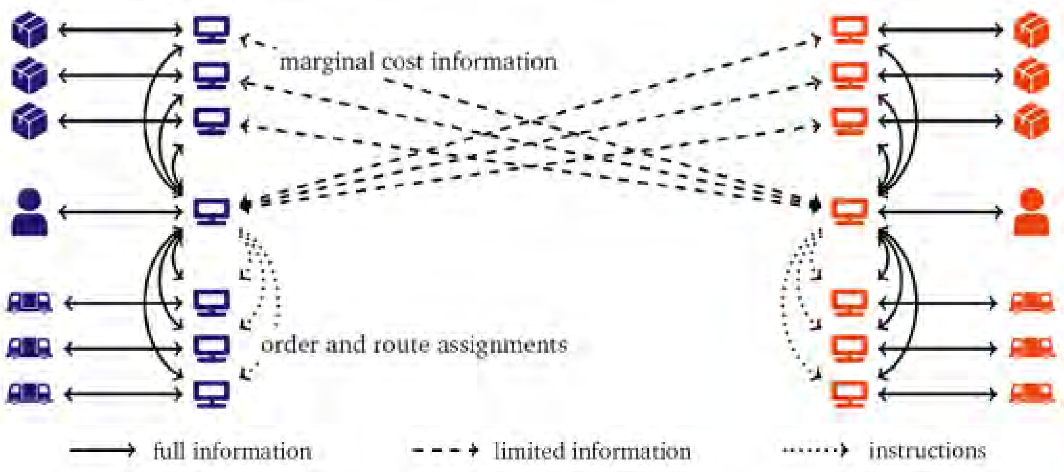
Acceleration new vehicle [m/s^2]
Actual Acceleration
Desired Acceleration
Start of transition
Start of CACC
Time [s]
Position error [m]
Time [s]

P3 - Dynamic Fleet Management

How can we manage (dispatch, route and reposition) a fleet of cooperative autonomous vehicles for passenger and cargo transport in an efficient and cooperative way?

Solving Large-Scale Dynamic Collaborative Vehicle Routing Problems: An Auction-Based Multi-Agent Approach

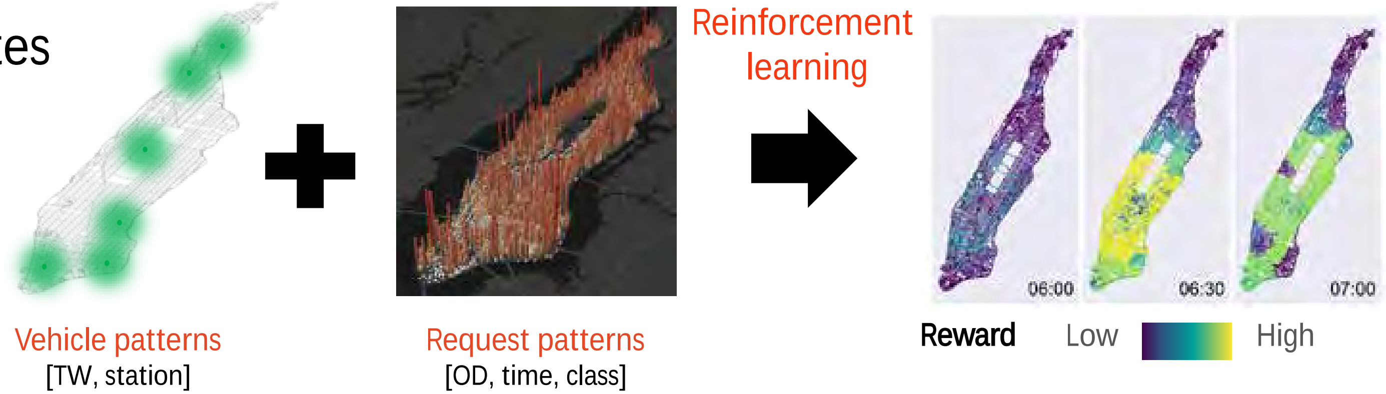
- Individuals are allowed to act as auctioneers
- Collaboration enabled between many carriers
- Number of kilometers driven significantly reduced



P3 - Dynamic Fleet Management

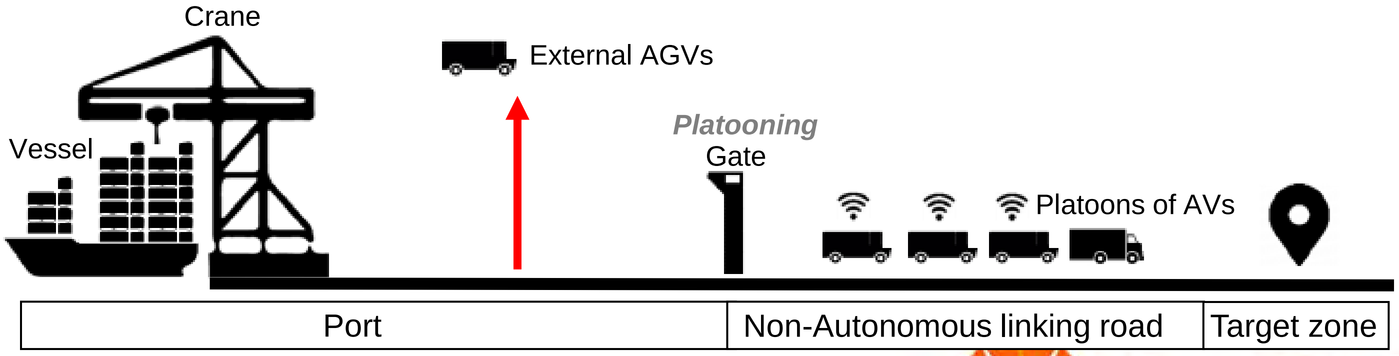
Dynamic fleet management for autonomous vehicles: Learning- and optimization-based strategies

- AV use in rideshare platforms
- Use historic information to anticipate routes



Platooning as a transfer mode to connect distinct autonomous zones in a heterogeneous vehicle network

- Automated in port area
- Platooning on linking roads



P4 – Communication (Radar)

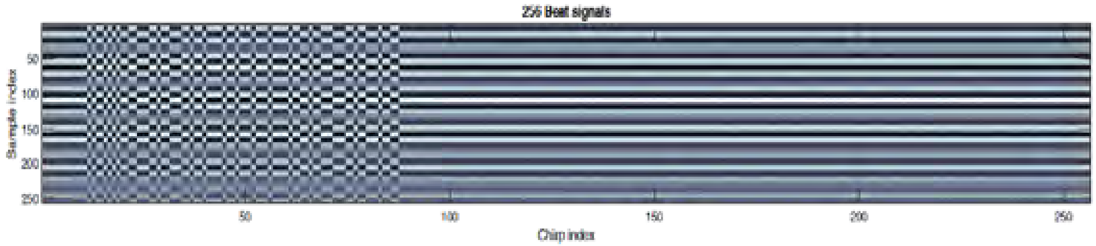
How can we obtain an intrinsically fail-safe, fault tolerance system of Vehicle-to-Vehicle (V2V) communication to support cooperative driving?

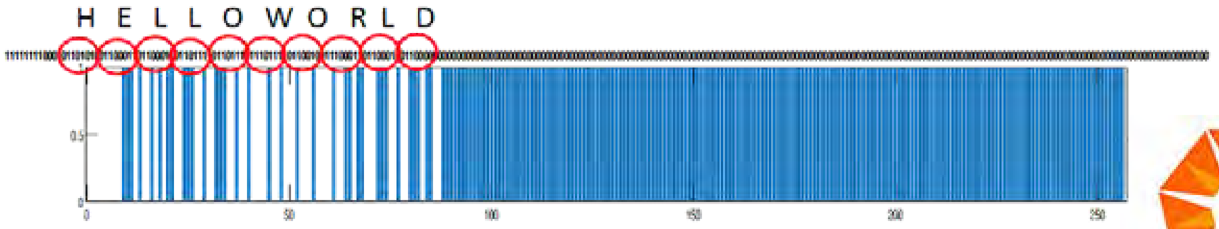
Analysis of Synchronization of frequency modulated continuous waves Radars for Communications.

- GPS based synchronization between two NXP radars is established, and stability is experimentally studied.

Communication frequency modulated continuous waves Radar TX & RX

- Lab set-up has been made

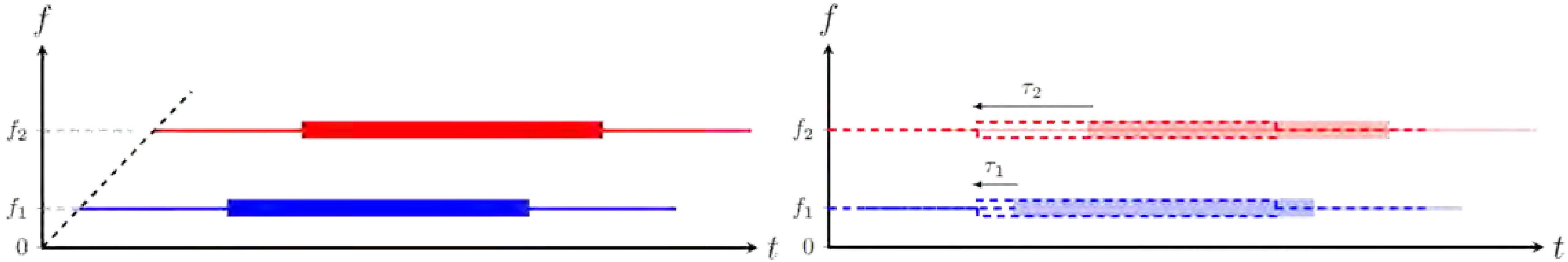




P4 - Communication

Communication is embedded in a frequency modulated continuous waves radar

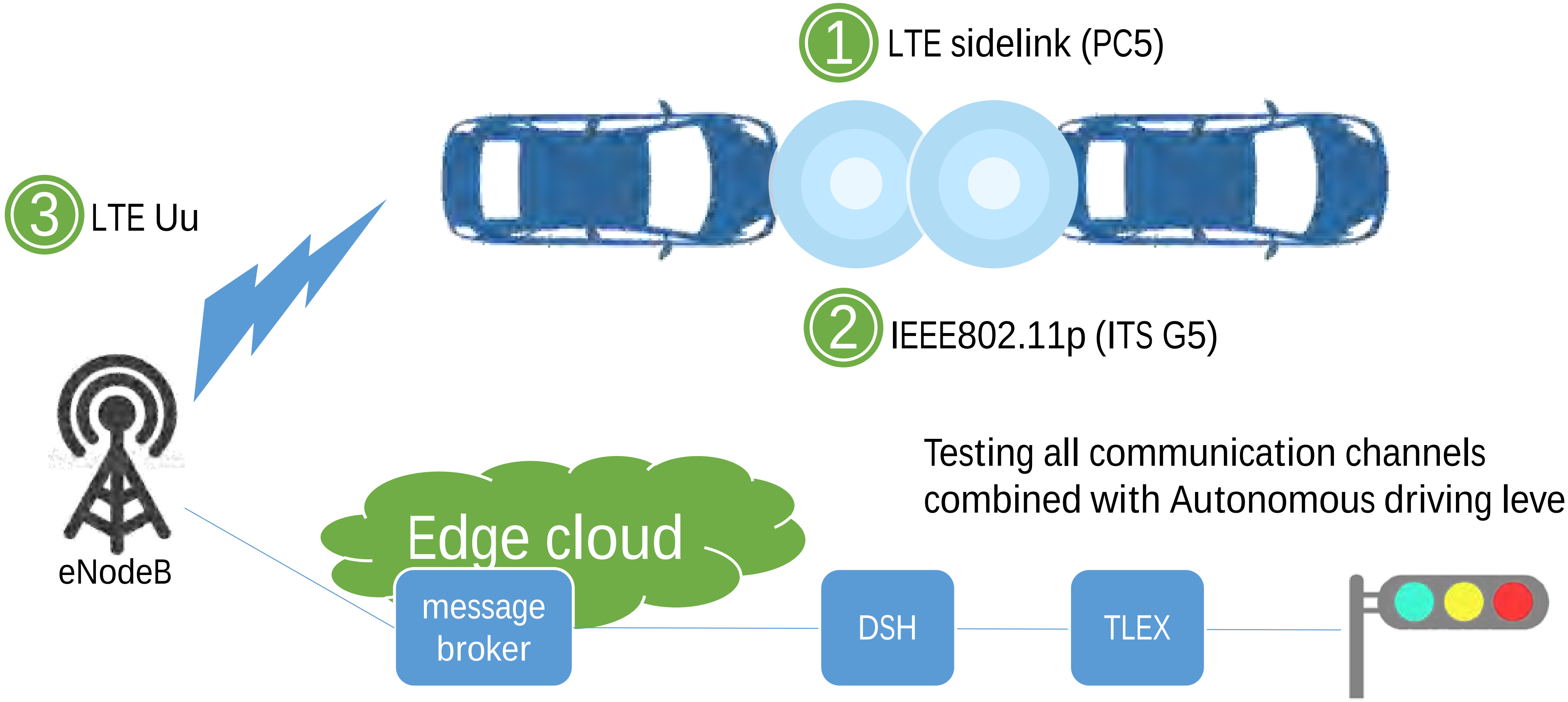
- By shifting the signal in time the communication signal can be distilled
- By employing a quadratic phase filter, a linear group delay is achieved, aligning the communication signal



Coordinated Operation of Multiple Radars; Trade-off and Cooperation between frequency modulated continuous wave Radar and Communication Functions

- A tradeoff between communication and sensing is achieved, combining the best of both worlds

WIRELESS COMMUNICATION, BEYOND I-CAVE



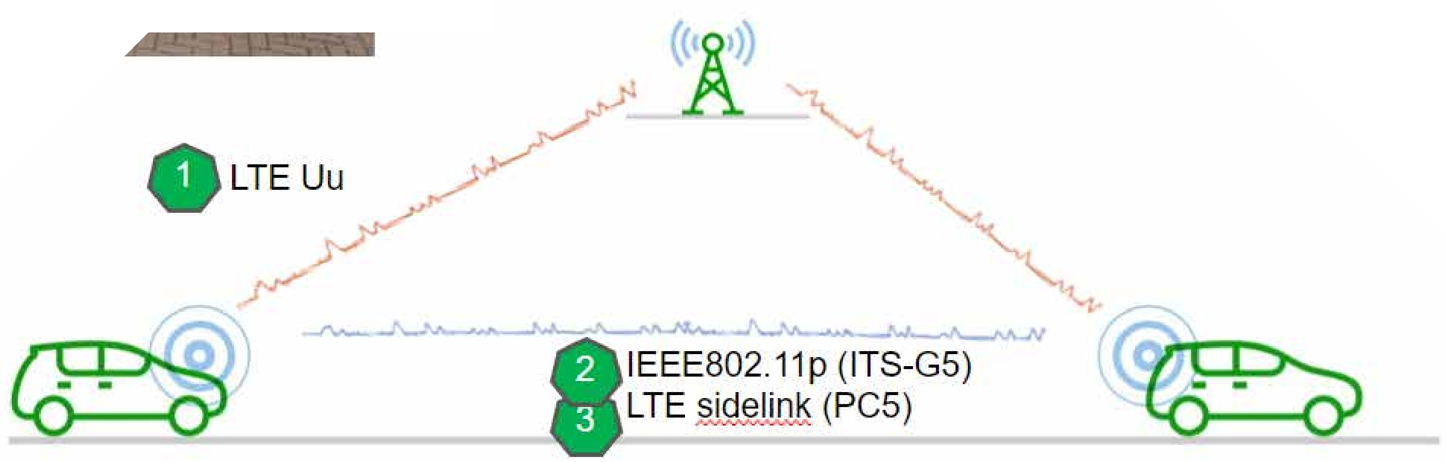
Testing all communication channels combined with Autonomous driving level 4.

CACC application

- CACC employs wireless vehicle-to-vehicle (V2V) communications to share more vehicle information.

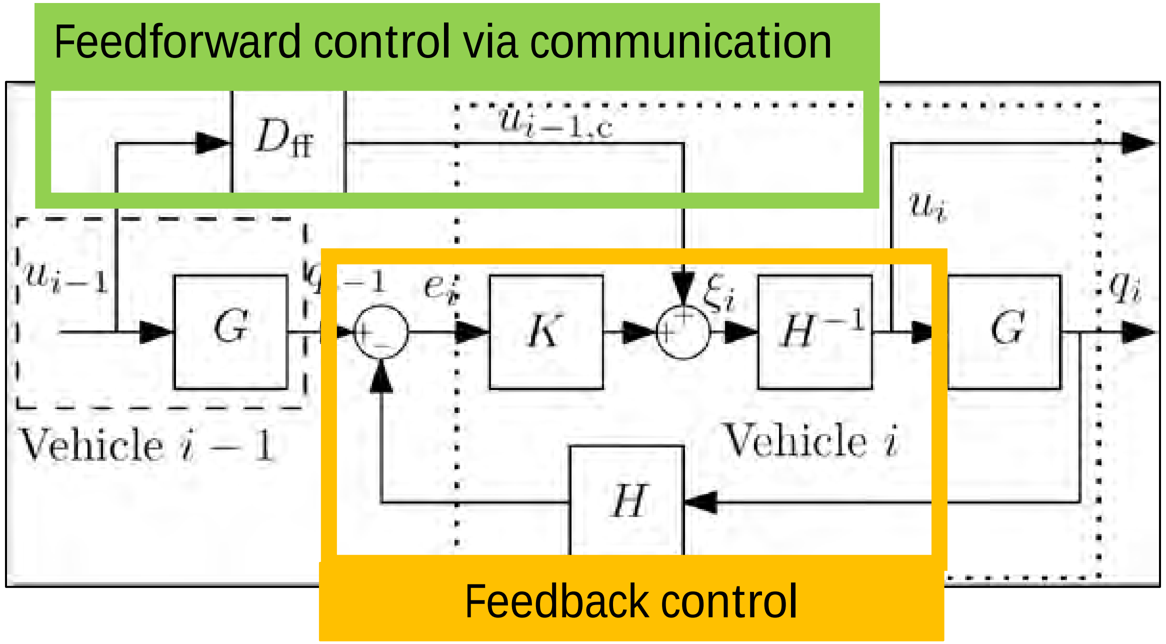
ü String stability: amplification in upstream direction of the signal of interest.

ü Benefits of CACC with respect to throughput, fuel consumption, safety, and driving comfort



Communication performance requirements for CACC

- CACC performance heavily depends on the feedforward information via communication.
- String stability (minimum string stable time gap) would be compromised by the large delay and packet error.



CONCORDA

Experiment setup

- **Siemens Carlabs - Toyota Prius (XW30)**

ü Real-Time CACC Platform.

ü ITS messages - CAM & iCLCM(platoon message)

4 bytes CAM, 39 bytes iCLCM; 25 Hz CAM/iCLCM.

- **Helmond setup**

ü 6 mobile sites using RAN sharing.

ü Edge computing at Helmond using CUPS.

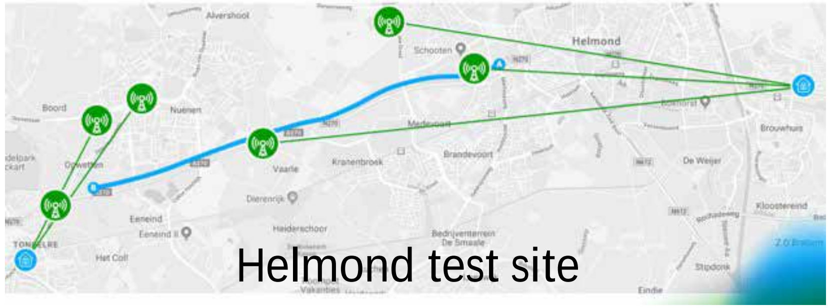
ü Prescheduling of uplink traffic.

- **Lelystad setup**

ü In Lelystad a sinlge site was used via RAN sharing.

ü Long transmission path between site and edge: 8ms.

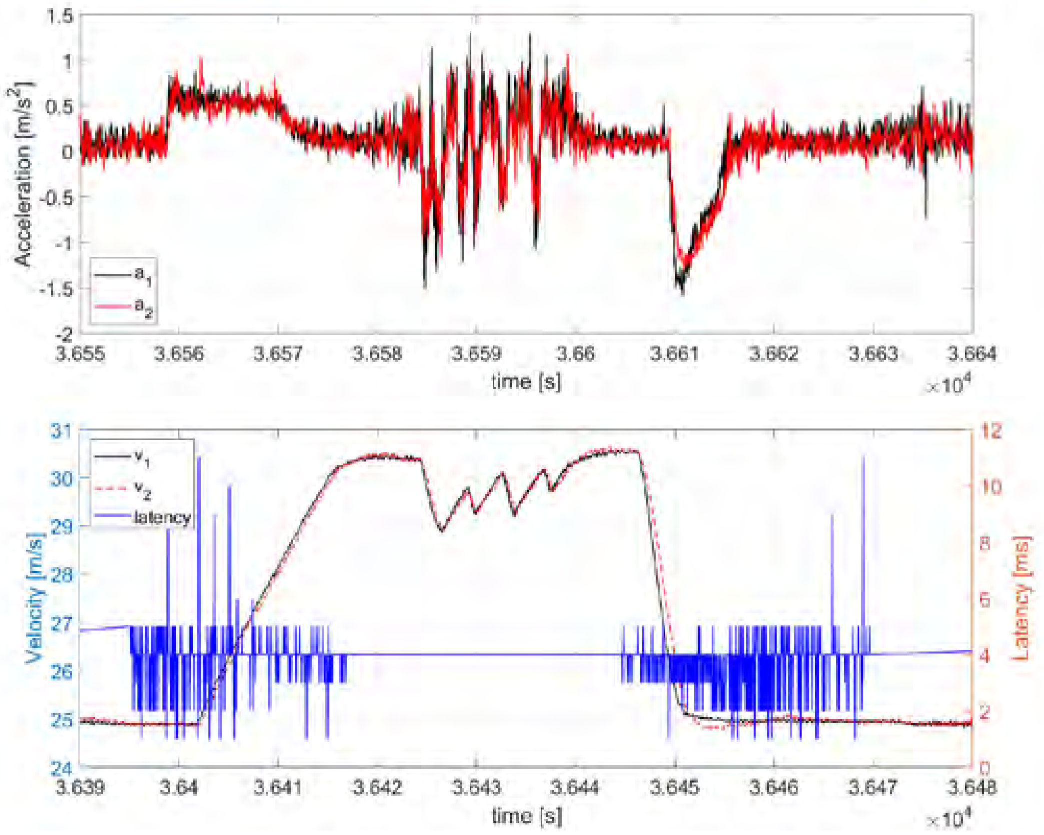
ü Bad signal strength in Lelystad causing the extra delay.



Helmond test site

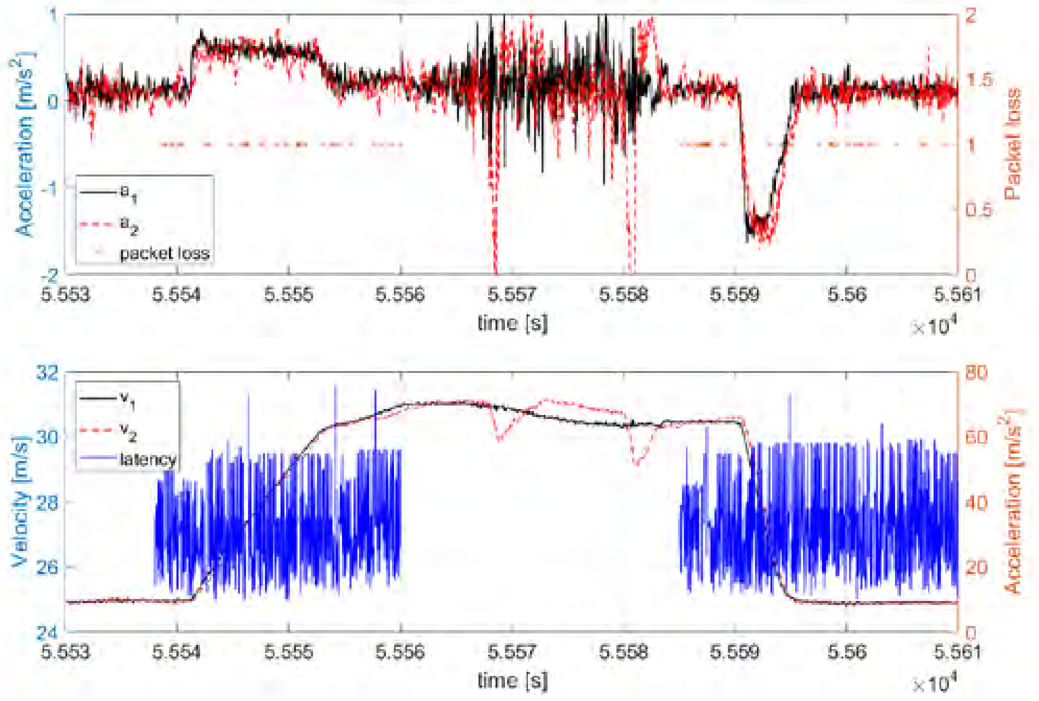
CACC-equipped vehicle performances

- ITS G5 with the inter-vehicle time gap as 0.3 s. Delay mode 25ms, PER 4.51%.



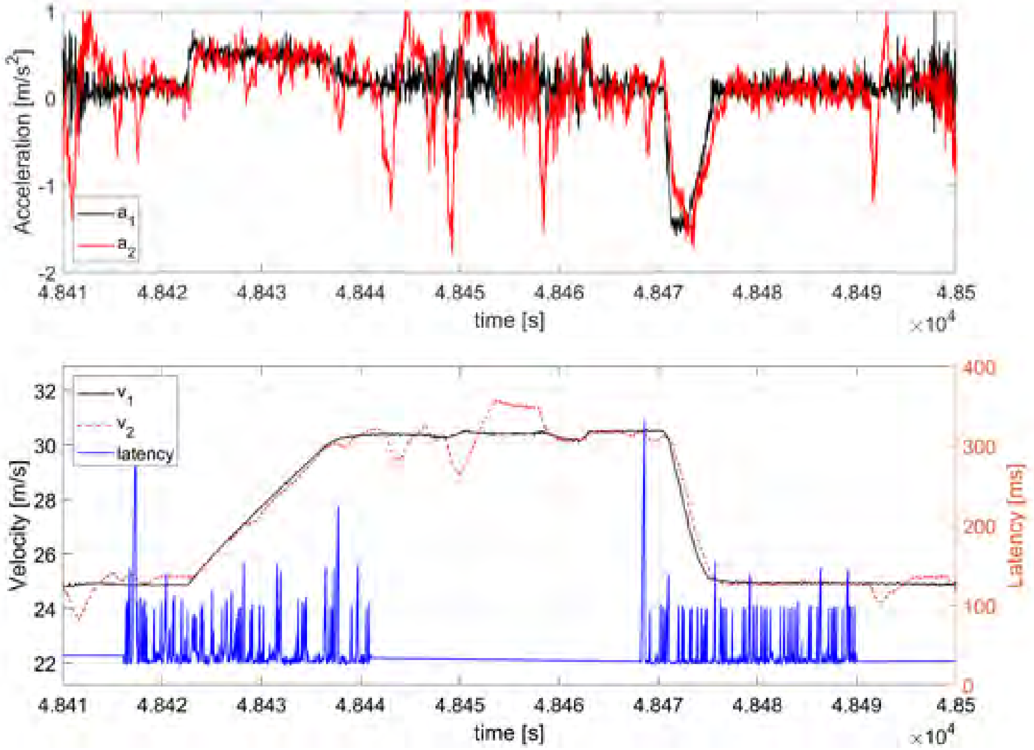
CACC-equipped vehicle performances

- LTE Sidelink PC5 with the inter-vehicle time gap as 0.3 s. Delay mode 25ms, PER 0.09%.



CACC-equipped vehicle performances

- LTE Uu with the inter-vehicle time gap as 0.3 s. Delay mode 30ms, delay mean 80.99ms.



CACC-equipped vehicle performances

	Accel. (m/s²) V2/V1	Decel. (m/s²) V2/V1	Max velocity of V2(m/s)	Min velocity of V2 (m/s)	Max distance (m)	Min distance (m)	Max error (m)	min error (m)
ITS G5	0.74/0.79	1.52/1.59	30.6	24.8	13.1	10.4	4.09	2.79
LTE PC5	0.82/0.82	1.60/1.65	30.5	24.9	13.2	11.1	4.33	3.35
LTE Uu	0.80/0.79	1.68/1.57	30.6	24.9	14.4	11.4	5.35	3.89

Considering CACC safety functionality, it is required that the delay is not over the threshold (100ms) and there is no three consecutive packets lost.

- The CACC is string stable with both ITS G5 and LTE PC5.
- For LTE Uu, CACC should be string stable for the communication in Helmond.

P5 – Human factors

Take human factor issues into account for drivers, as well as guarantee the safe interaction with other road users including vulnerable road users?

In-car HMI support for automated vehicles

- Numerous drivers are not well informed of their car's driver assistance systems
- In car training can solve this

Overcoming trust issues in automated vehicles

- There are even objective ways to measure drivers' trust in the AV by means of glance behaviour and electrodermal activity

P5 – Human factors

Interaction with pedestrians: e-HMI

- At large distances the behavior of the car is the main source of trust for pedestrians
- At close distances pedestrians need an external HMI to interact with automated vehicles

Responses to new technology

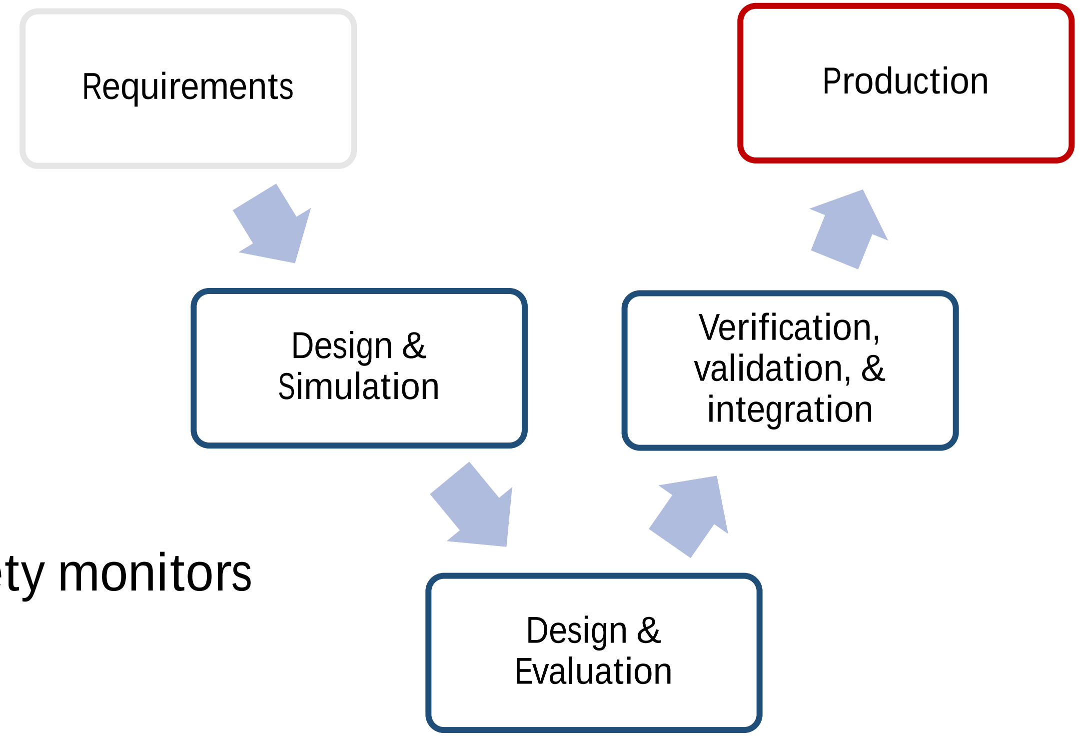
- People who are more familiar with automated vehicles are more likely to take risks around them

P6 – Architecture and functional safety

Design and evaluate the functional architecture and quality model of autonomous and cooperative vehicles software?

Engineering functional safety in automotive

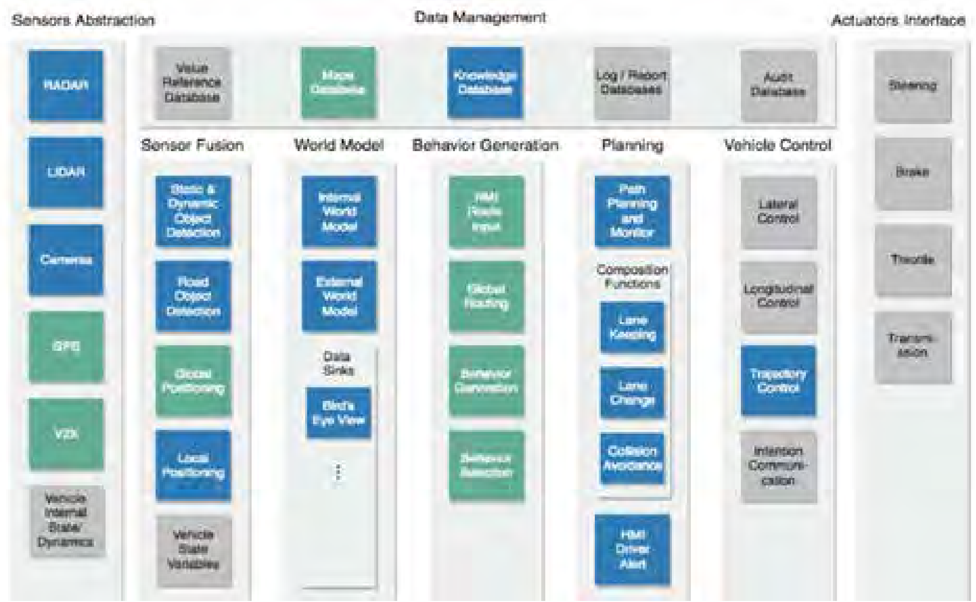
- Deriving safety requirements for connected driving
- Architecture assessment for safety requirements
- Safety monitor generator for i-CAVE Vehicles
- Safety evaluation for highway driving (L4)
- Provably correct generator for deterministic timed safety monitors



P6 – Architecture and functional safety

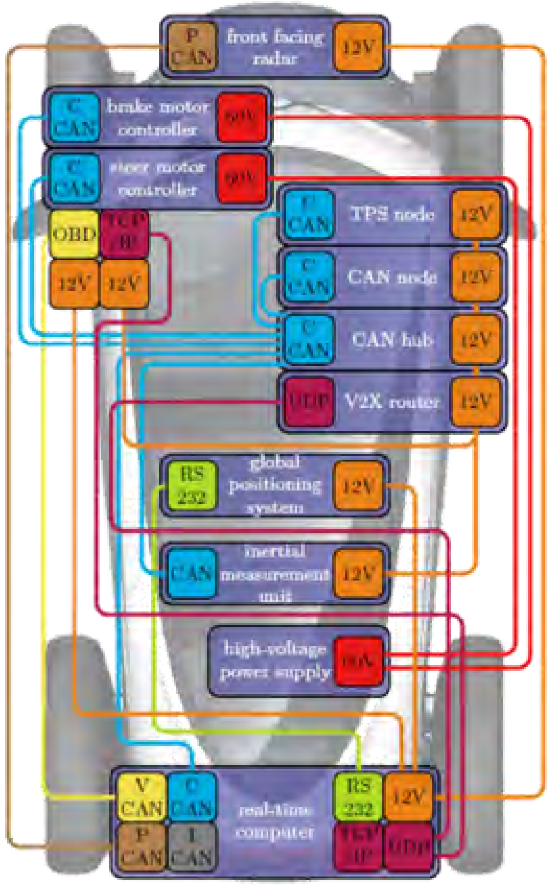
Functional architecture for autonomous vehicles

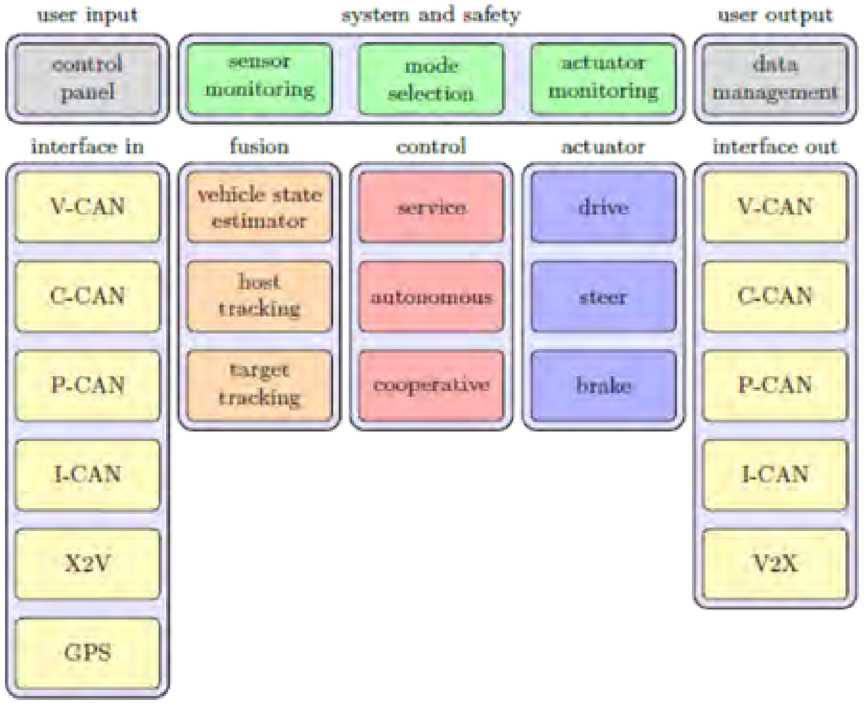
- Robustness against perturbations
- Defenses against adversarial examples
- Robustness of planning algorithms
- Robustness of machine learning (ML):
  ML engineering practices & ML Architecture
- Comparisons of different architectures for ML



P7 - Demonstrator platform

The objective of this project is to develop a Living Lab Demonstrator Platform, which integrates the research outcomes of the other 6 projects of the i-CAVE program.





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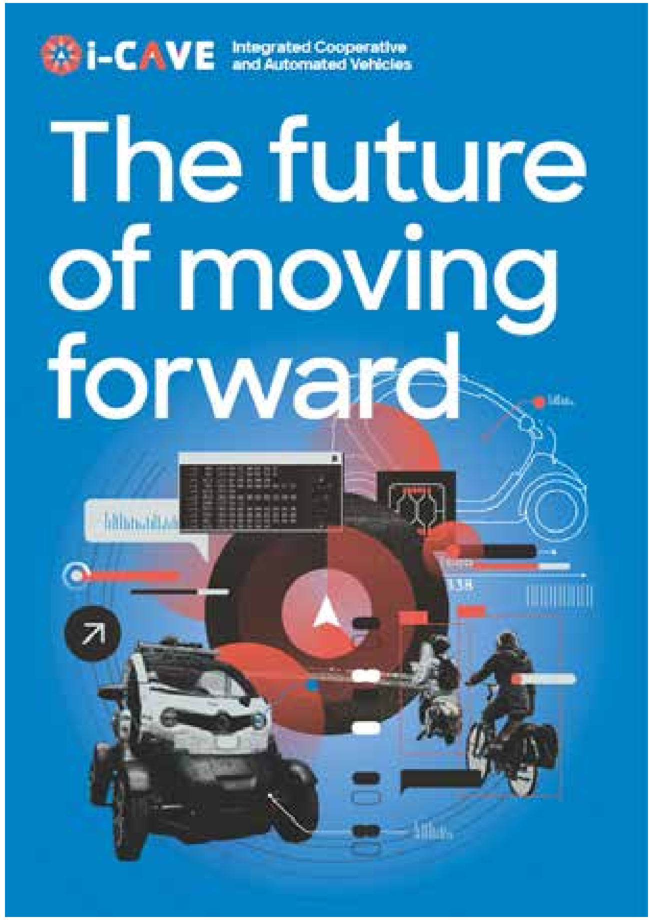
P7 - Demonstrator platform

Concluding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Thank you, questions?