IEEE

Abu Dhabi 2024 IROS

IROS 2024 CONFERENCE

Workshop SIAV-FM2L (Safety of Intelligent and Autonomous Vehicles: Formal Methods vs. Machine Learning approaches for reliable navigation)

Safe and Resilient Control Architecture for Autonomous Navigation in Complex Environments / Situations

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Abu Dhabi, UAE, 15th October, 2024

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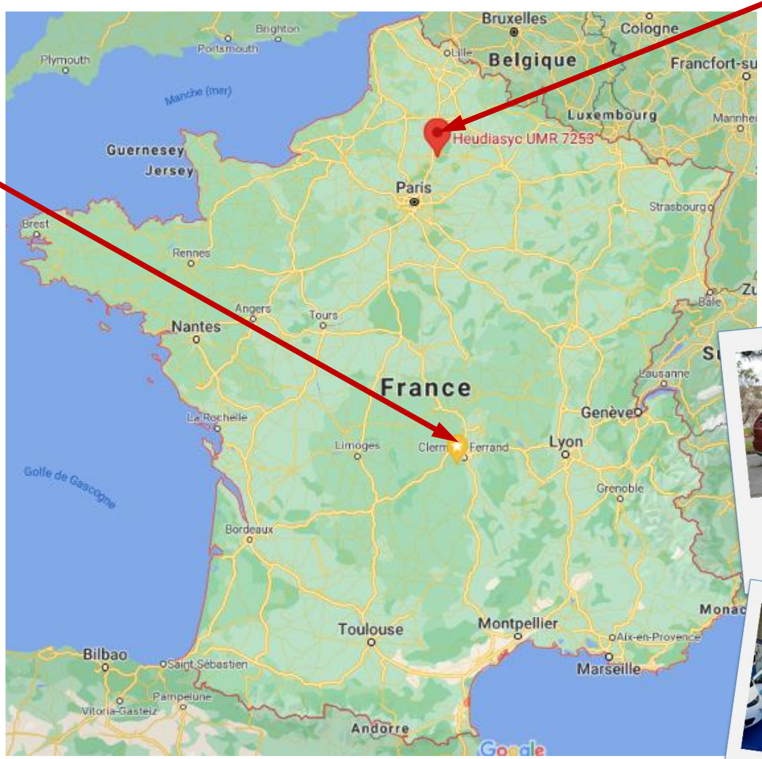
Few words on the University / Laboratory

UMR CNRS/UCA UMR 6602
→ From 2006 to 2019

IPcars shared vehicles on PAVIN platform



UMR CNRS/UTC 7253
→ 2019 - …

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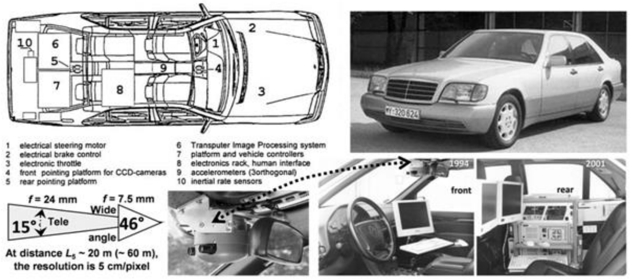
→ Ensure the reliability of autonomous navigation even in highly dynamic and uncertain complex Environments / Situations (E/S)

Autonomous vehicles: Key dates



VaMP
First autonomous car
Europe

Google Car

Responsibility-Sensitive Safety (RSS) by Mobileye

SAE 2015

Year

1970

First appearance of ADAS
Anti Block System (ABS)

1990

2004-2007

DARPA Grand Challenge

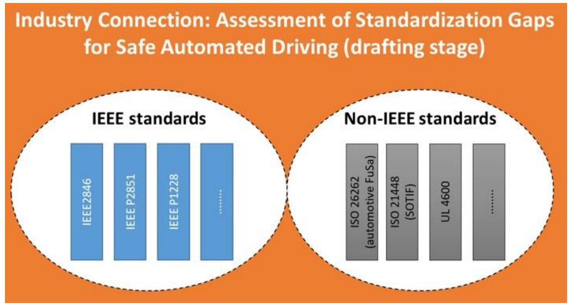
2010

2015-2018

First accidents with autonomous car:
Google, Uber, Tesla

2017

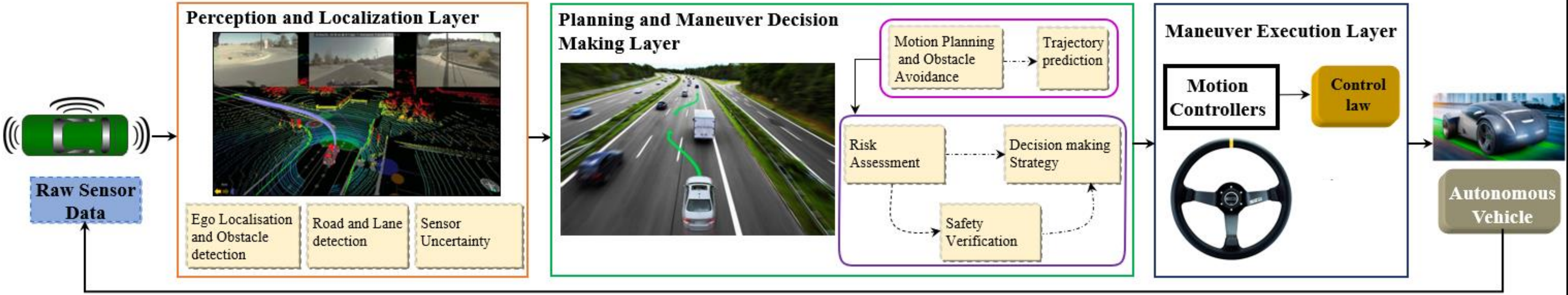
2020

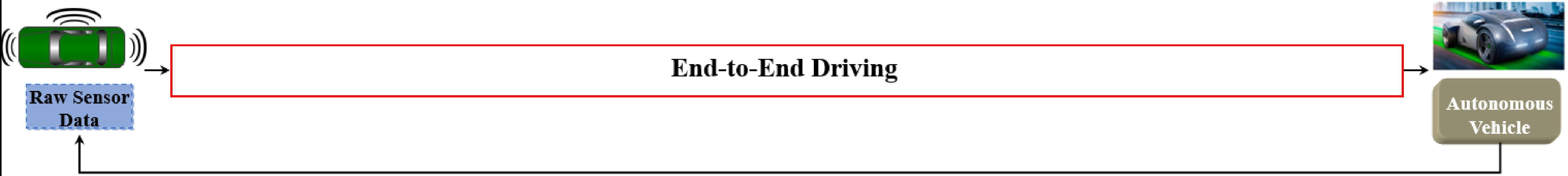


IEEE standardization of safety

ADAS: Advanced driver-assistance systems
SAE: Society of Automotive Engineers

Overview of the main control architectures





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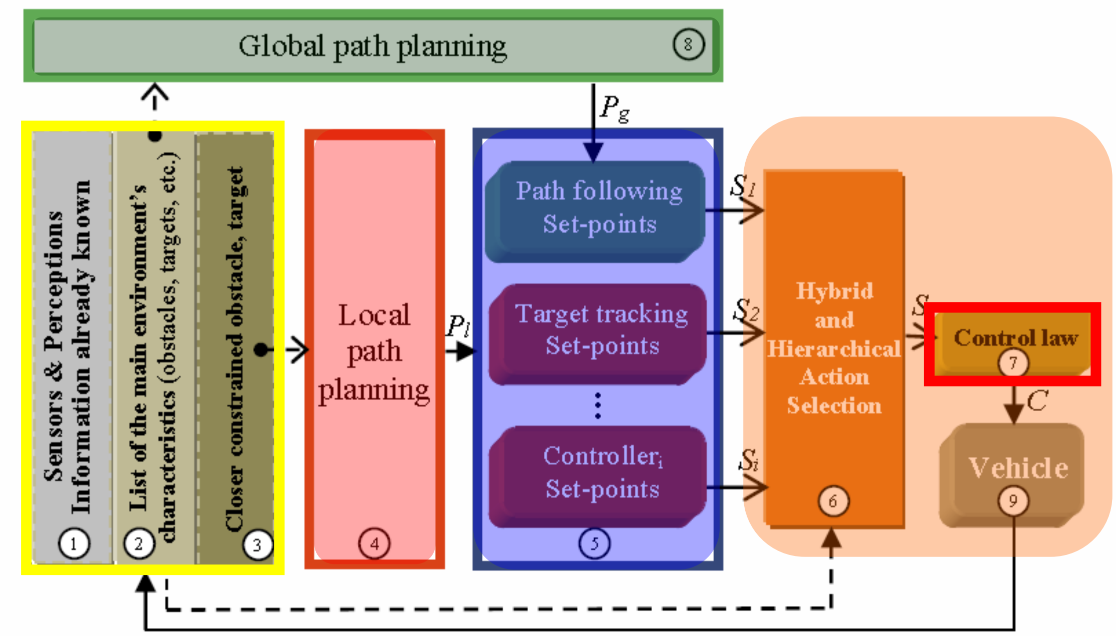
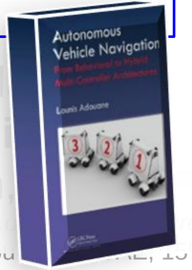
Homogenous and Generic Multi-controller Architectures for Autonomous vehicles

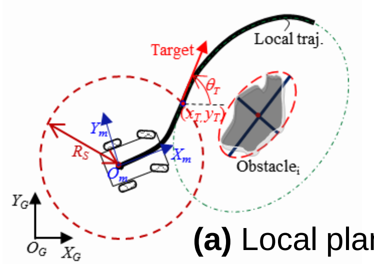


HHMCA for Flexible and Reliable Navigation in Complex and Uncertain Environment/Situation (embedded in each vehicle)

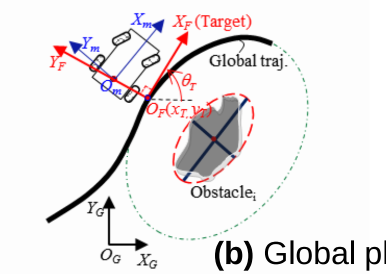
Adouane L., "***Autonomous Vehicle Navigation: From Behavioral to Hybrid Multi-Controller Architectures***", Book ISBN: 9781498715584, 228 pages, Taylor & Francis - CRC Press, April 2016.



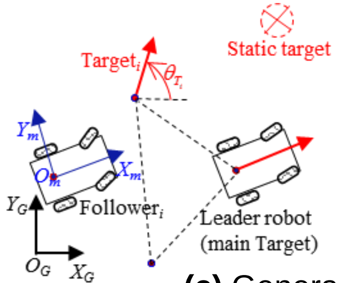
- ✓ Homogenous set-points definition to achieve sub-tasks
  Target ≡ *T* $(x_T, y_T, \theta_T, v_T, w_T)$



(a) Local planned path (based on R_S)



(b) Global planned path (based on Frenet ref. frame)



(c) General static/ dynamic targets

✓ Hybrid$_{RC}$ – Reactive/Cognitive (appropriate Ba
Hybrid$_{CD}$ – Continuous/Discrete (Global Stabili
Smoothness, Safety of controllers switch/fusion

Homogenous and Generic Multi-controller Architectures for Autonomous vehicles

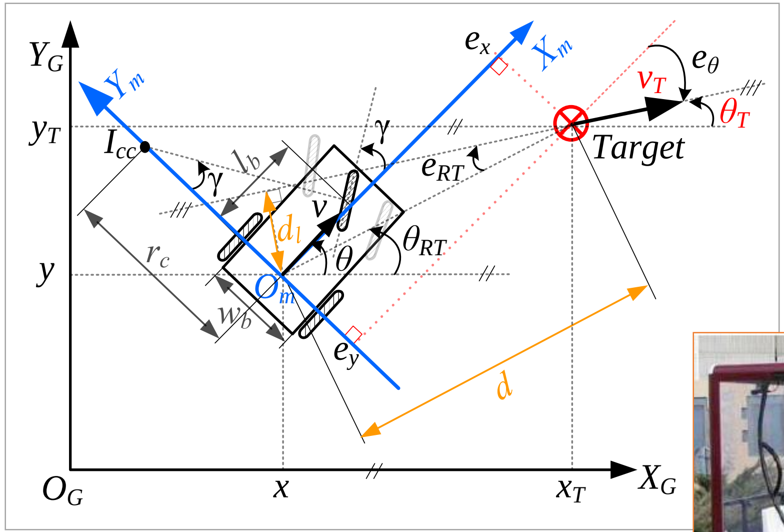
Appropriate control law for Tricycle robots [Vilca et al. RAS 2015]

Robot's Kinematic model

$$\begin{cases} \dot{x} &= v\cos(\theta) \\ \dot{y} &= v\sin(\theta) \\ \dot{\theta} &= v\tan(\gamma)/l_b \end{cases}$$

Target's kinematic model

$$\begin{cases} \dot{x}_T &= v_T\cos(\theta_T) \\ \dot{y}_T &= v_T\sin(\theta_T) \\ \dot{\theta}_T &= \omega_T \end{cases}$$



Control law (based on Lyapunov synthesis)

$$v = v_T\cos(e_\theta) + \underline{v_b}$$

$$\gamma = \arctan(l_b \underline{c_c})$$

Where: $\underline{v_b} = K_x\left[K_d e_x + K_l d\sin(e_{RT})\sin(e_\theta) + K_o\sin(e_\theta)c_c\right]$ **and**

$$\underline{c_c} = \frac{1}{r_{c_T}\cos(e_\theta)} + \frac{d^2 K_l\sin(e_{RT})\cos(e_{RT})}{r_{c_T}K_o\sin(e_\theta)\cos(e_\theta)} + K_\theta\tan(e_\theta) + \frac{K_d e_y - K_l d\sin(e_{RT})\cos(e_\theta)}{K_o\cos(e_\theta)} + \frac{K_{RT}\sin^2(e_{RT})}{\sin(e_\theta)\cos(e_\theta)}$$

$$e_{RT} \in \left]-\pi/2, \pi/2\right[$$

$$e_\theta \in \left]-\pi/2, \pi/2\right[$$

[Vilca et al. RAS 2015], J.M Vilca, L. Adouane and Y. Mezouar, A novel safe and flexible control strategy based on target reaching for the navigation of urban vehicles. Robotics and Autonomous Systems (RAS), volume 70, pages 215-226, August 2015.

Obstacle avoidance based on Parallel Elliptic Limit-Cycle (PELC) [Adouane, RAS 2017]

PELC mathematical formulation

$$\dot{x}_s = r y_s + \mu x_s (1 - \Psi)$$
$$\dot{y}_s = -r x_s + \mu y_s (1 - \Psi)$$

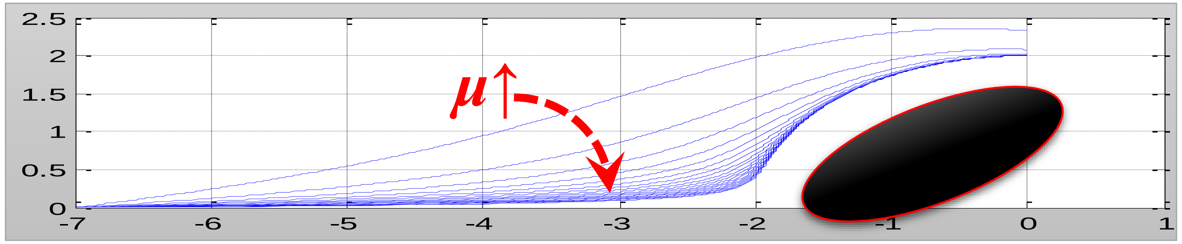
Where: $\Psi = [4(z_1^2 + 3z_2)(z_2^2 + 3z_1 z_3) - (z_1 z_2)^2 + 18 z_1 z_2 z_3]/(9z_3)^2$

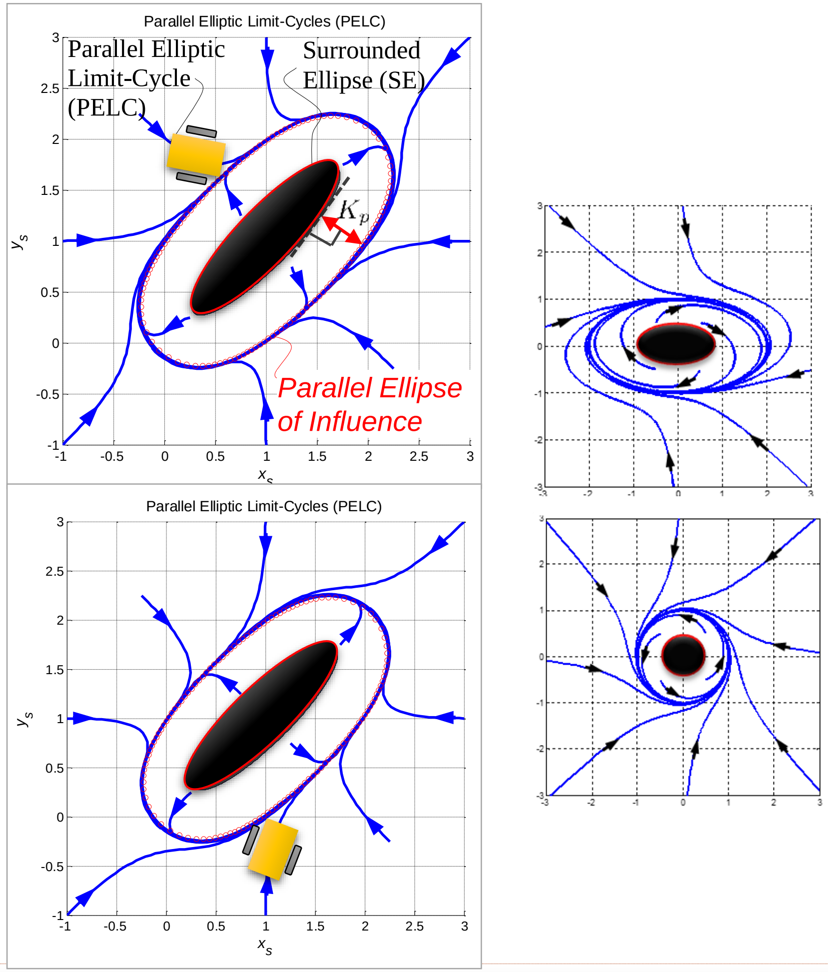
and: $z_1 = x_s^2 + y_s^2 - K_p^2 - A^2 - B^2$

$z_2 = B^2 x_s^2 + A^2 y_s^2 - A^2 K_p^2 - B^2 K_p^2 - A^2 B^2$

$z_3 = (A B K_p)^2$

- A and B characterize respectively major and minor surrounded ellipse axes
- K_p PELC offset
- r = 1 for Clockwise PELC and r = -1 for Counter-clockwise



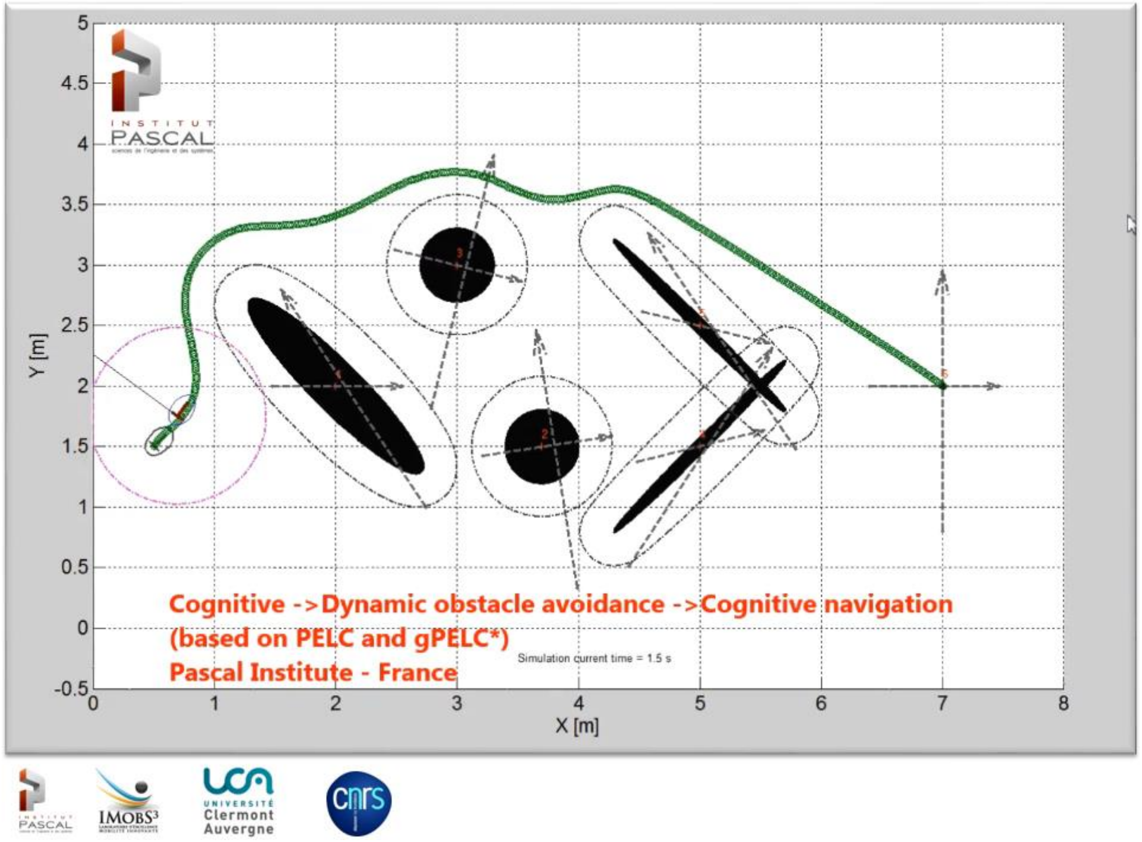


Homogenous and Generic Multi-controller Architectures for Autonomous vehicles

└Obstacle avoidance based on Parallel Elliptic Limit-Cycle (PELC) [Adouane. RAS 2017]

Some simulations and experiments

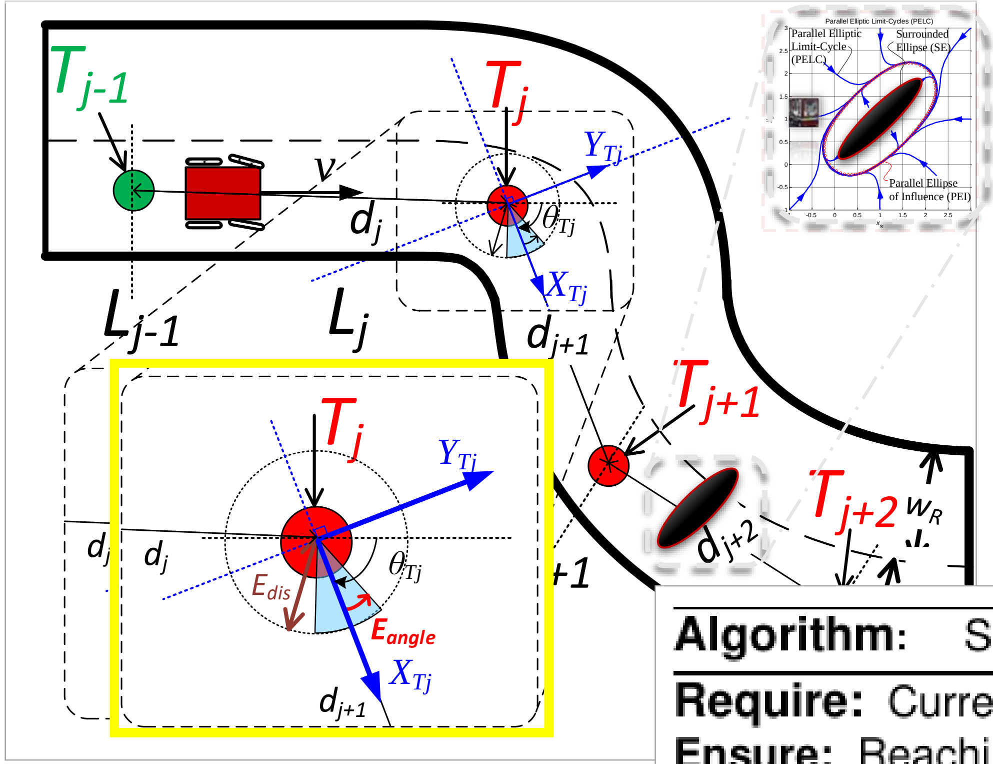
Obstacle-avoidance based on limit-cycles



Short- vs. long-term navigation based on PELC

Homogenous and Generic Multi-controller Architectures for Autonomous vehicles

Flexible and Smooth navigation through waypoints [Vilca. PhD 2015]



- ✓ **Flexible** navigation between **waypoints** (defined as static targets T $(x_T, y_T, \theta_T, v_T)$)
- ✓ **Smooth switch** between **waypoints** using **appropriate reference frames**
- ✓ **Ensure maximal distance** and **angular errors** (E_{dis} and E_{angle} respectively)

Algorithm: Sequential target assignment

Require: Current target T_j and a set of N sorted waypoints
Ensure: Reaching T_j while guaranteeing to reach after the next waypoint T_{j+1}

```
if ( (d ≤ E_dis and e_θ ≤ E_angle) or (x^{T_j} ≥ 0) ) then
    Switch from the current target T_j to T_{j+1}
else
    Keep going to waypoint T_j
end if
```

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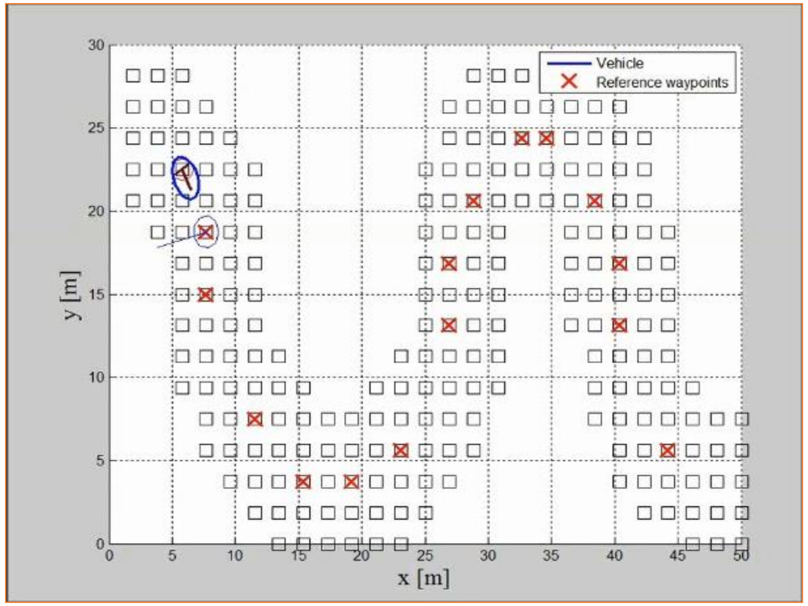
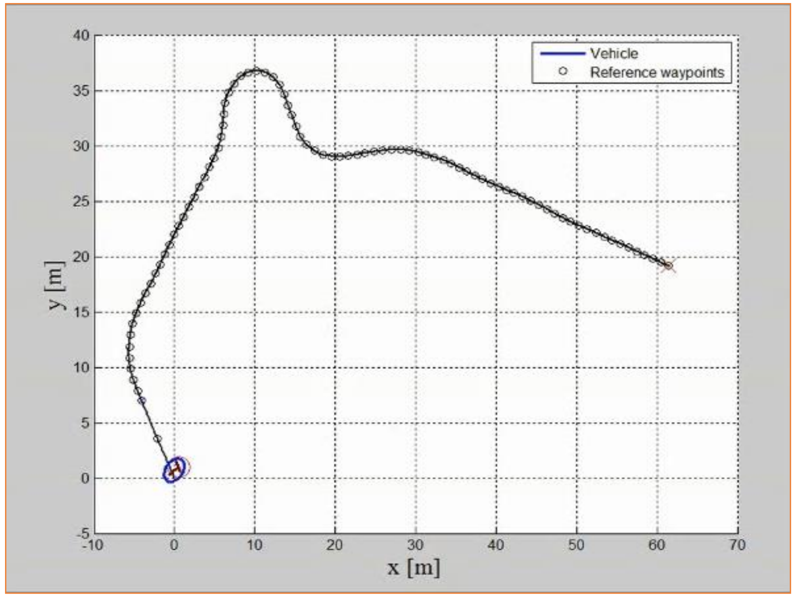
Homogenous and Generic Multi-controller Architectures for Autonomous vehicles

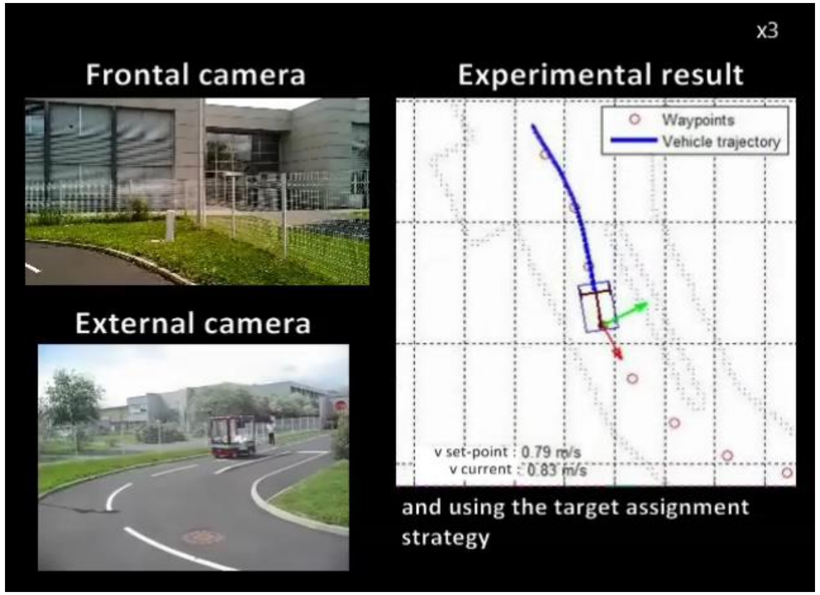
└ Flexible and Smooth navigation through waypoints [Vilca. PhD 2015]



Sequential scattered waypoints

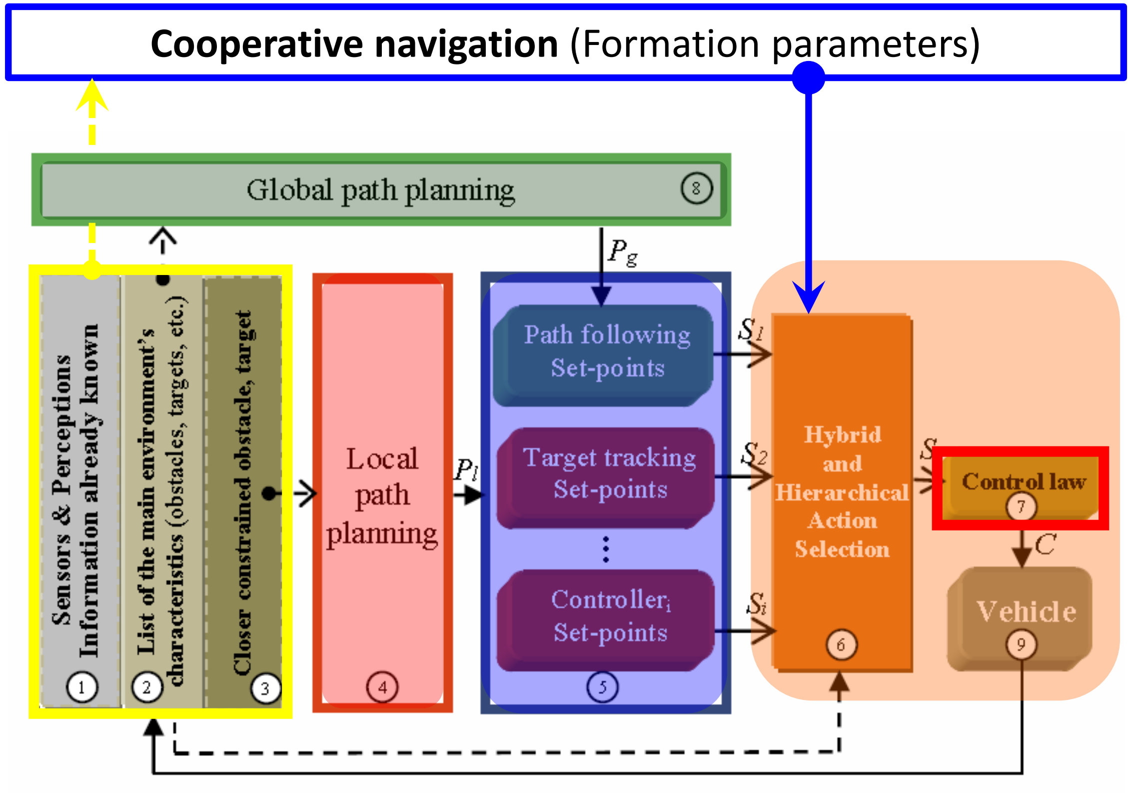


Close sequential waypoints

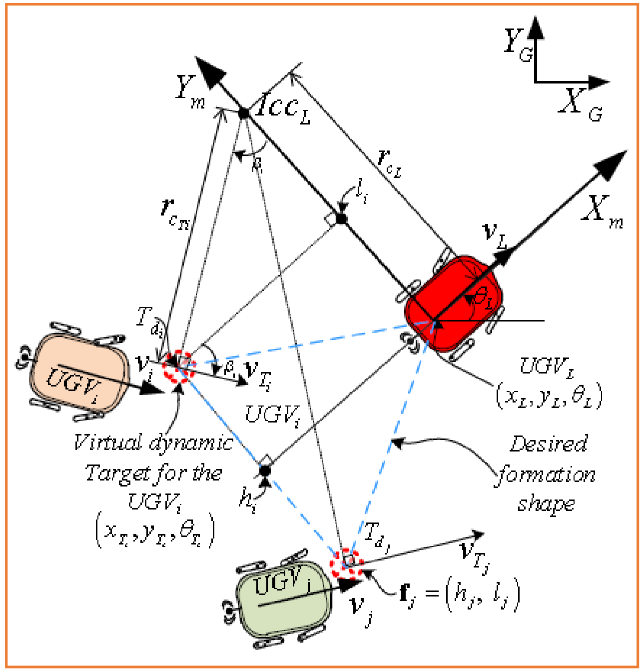


Experiments

Cooperative navigation based on sequential target reaching/tracking [Vilca et al. 2019, T-ITS]



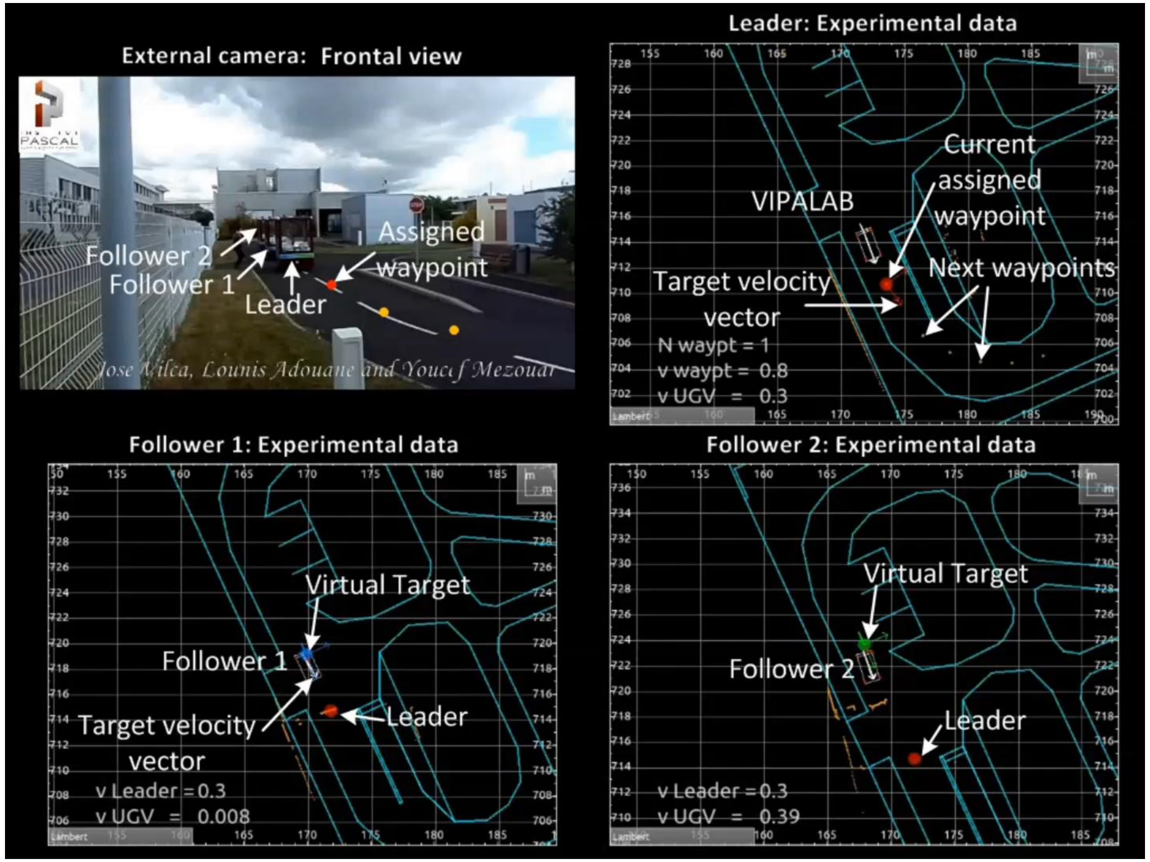
HHMCA for Flexible and Reliable Navigation in Complex and Uncertain Environment/Situation (embedded in each vehicle)



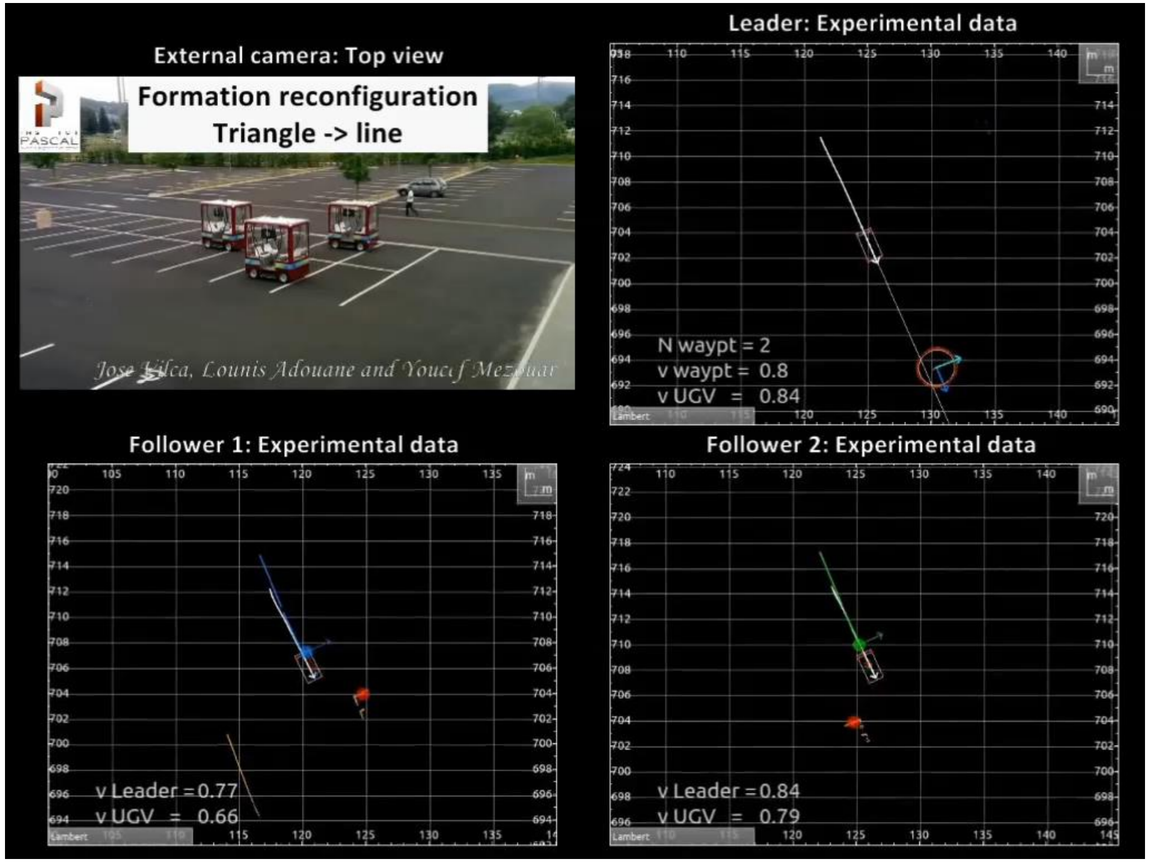
[Vilca et al. 2019, T-ITS], J.M Vilca, L. Adouane and Y. Mezouar, Stable and Flexible Multi-Vehicle Navigation based on Dynamic Inter-Target Distance Matrix, IEEE Transactions on Intelligent Transportation Systems, vol. 20, no. 4, pp. 1416-1431, April 2019.

Homogenous and Generic Multi-controller Architectures for Autonomous vehicles

Cooperative navigation based on sequential target reaching/tracking [Vilca et al. 2019, T-ITS]



Navigation in formation in urban environment



Dynamic and smooth formation reconfiguration

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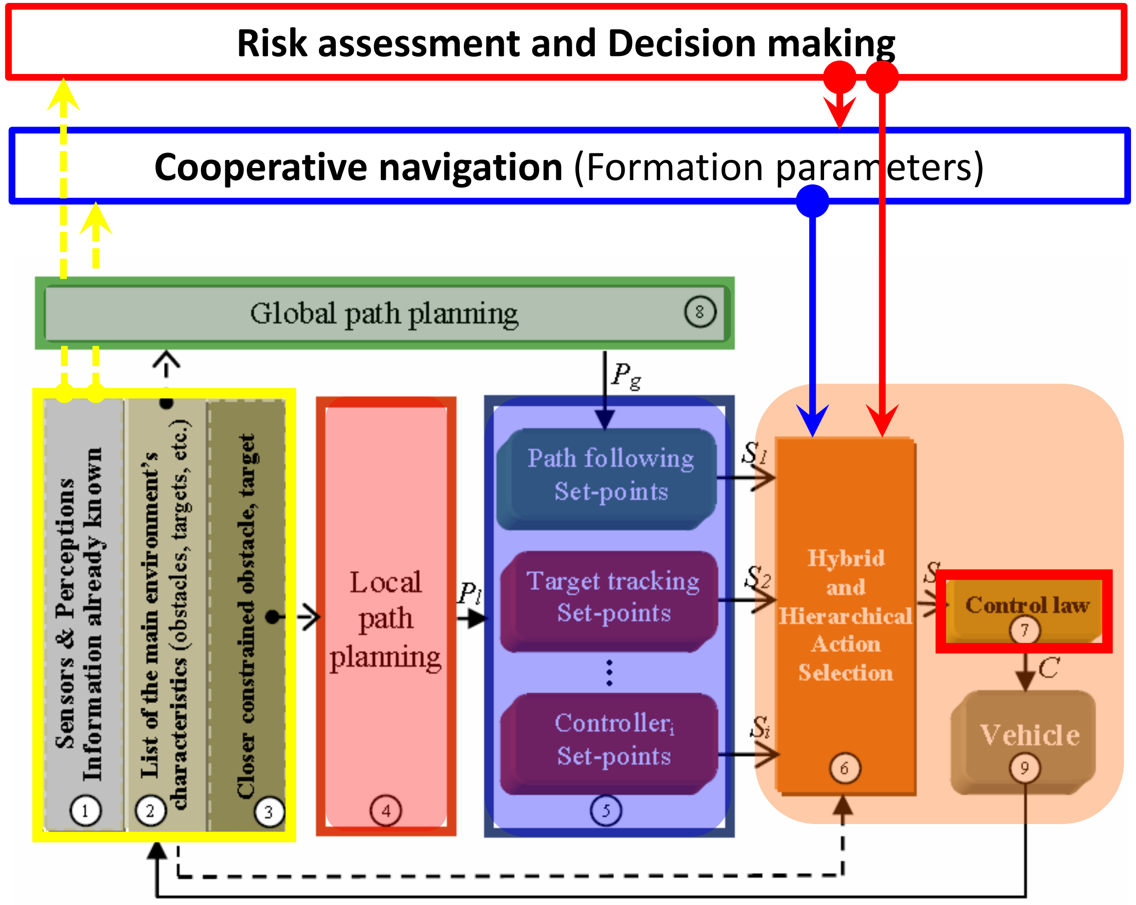
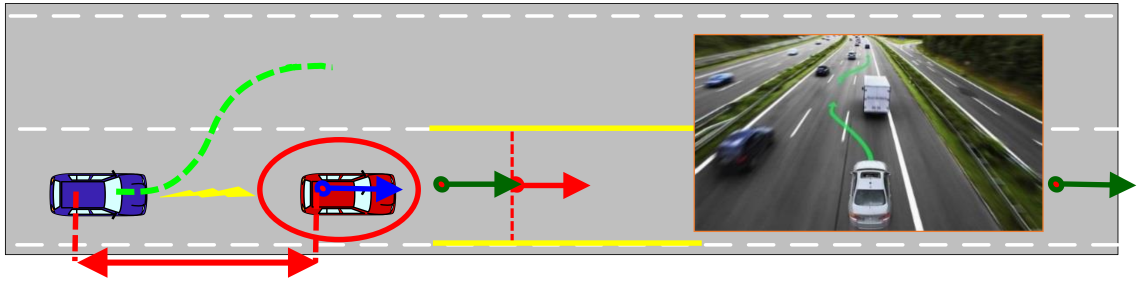
Risk Assessment / Management for Safe Navigation in Complex E/S



HHMCA for Flexible and Reliable Navigation in Complex and Uncertain Environment/Situation (embedded in each vehicle)

Risk Assessment / Management for Safe Navigation in Complex E/S

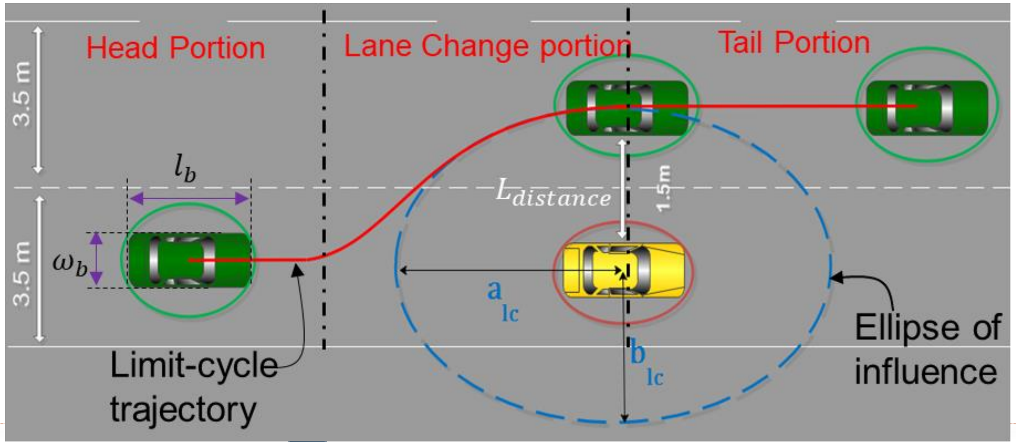
Application for highway environment [Iberraken. PhD 2020]



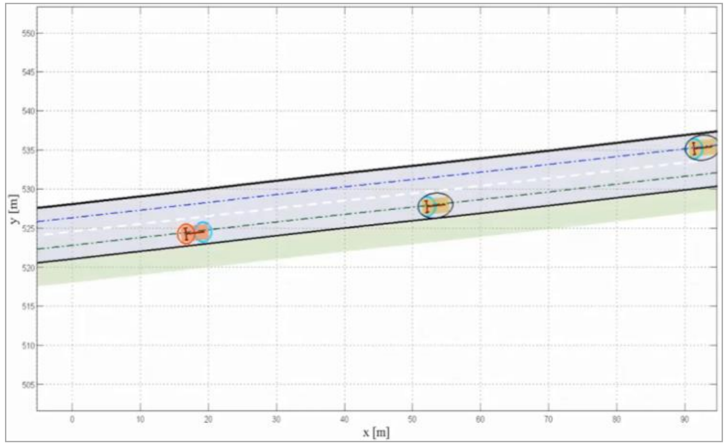
Elliptic Limit-Cycles parameters updated for highway environments:

- a_{lc} Longitudinal safety distance $a_{lc} = 0.5 l_b + t_s v_r$
- b_{lc} Lateral safety distance $b_{lc} = w_b + L_{distance}$

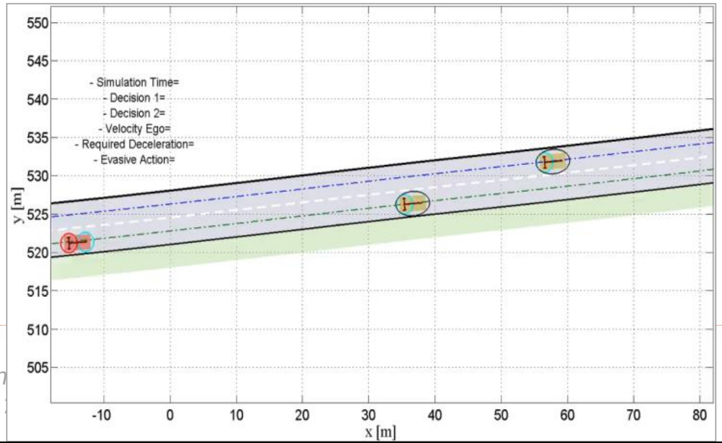
With: $t_s = 2s$, $L_{distance} = 1{,}5\text{m}$ and v_r the relative velocity



1 Derive appropriate decision maneuver in **nominal driving**

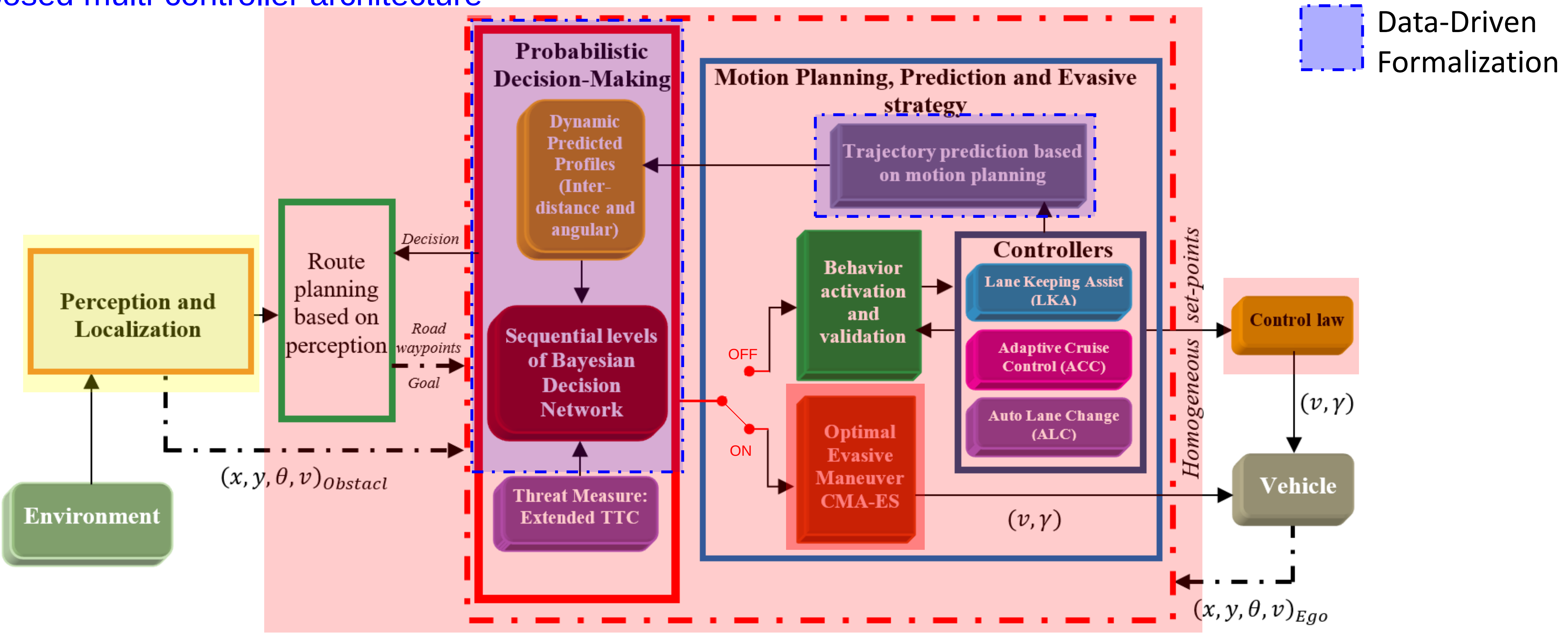


2 Guarantee safety of navigation in **emergency situations**



Risk Assessment / Management for Safe Navigation in Complex E/S

Proposed multi-controller architecture

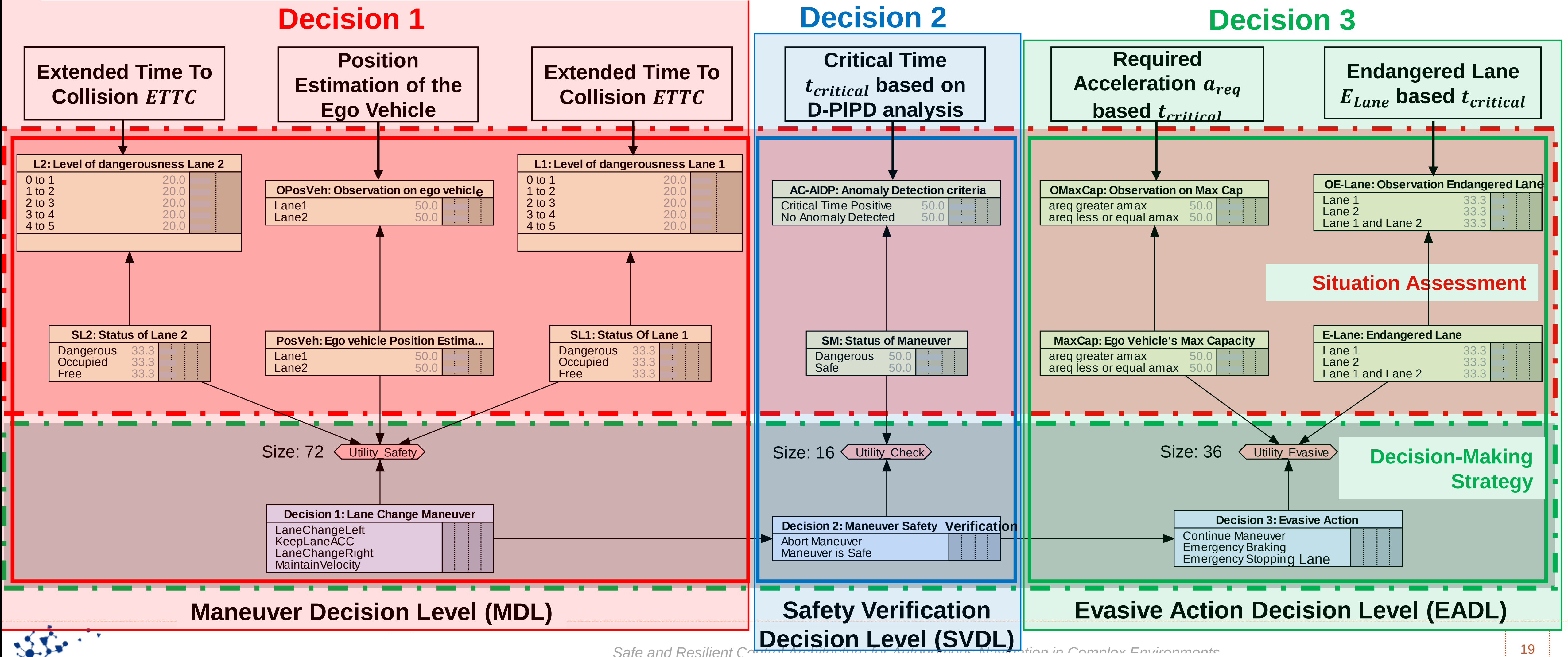


Iberraken, D. and Adouane, L., *Safe Navigation and Evasive Maneuvers based on Probabilistic Multi-Controller Architecture*, IEEE Transactions on Intelligent Transportation Systems, December 2021.

Iberraken, D., Adouane, L. and Denis D. *Multi-Controller Architecture for Reliable Autonomous Vehicle Navigation: Combination of Model-Driven and Data-Driven Formalization*, IEEE IV'19, Workshop 2019 (FRCA-IAV), Paris, France

Risk Assessment / Management for Safe Navigation in Complex E/S

Sequential Decision Network for Maneuver Selection and Verification (SDN-MSV)

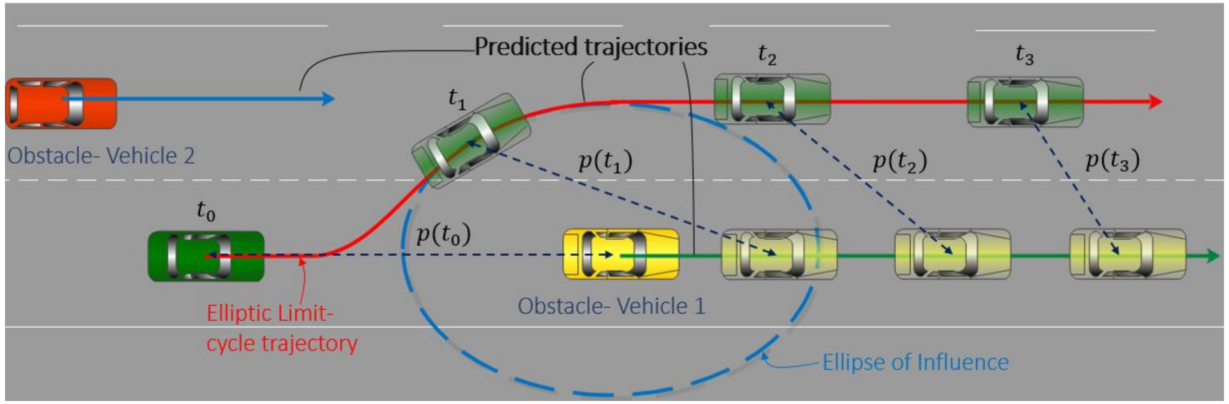


→ ***Drive the most suitable maneuver***

→ **Safety retrospection over the current maneuver risks**

Risk Assessment / Management for Safe Navigation in Complex E/S

Safety Verification Decision Level based on **Predicted Inter-Distance Profile (PIDP)**

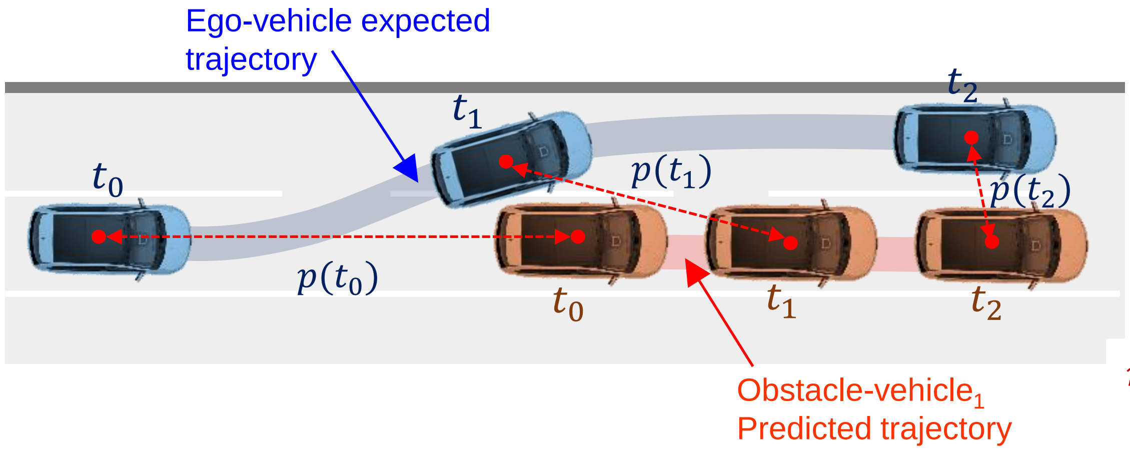


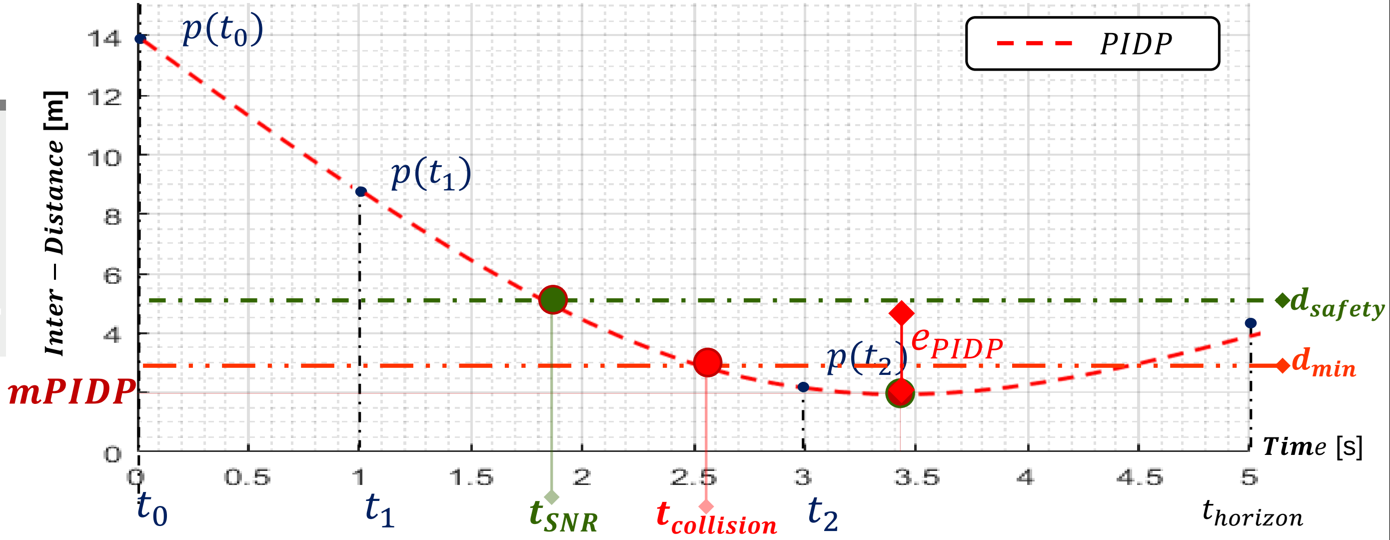
$t_{Collision}$: Time To Collision

$mPIDP$: Minimum de PIDP

$e_{PIDP} = d_{safety} - mPIDP$

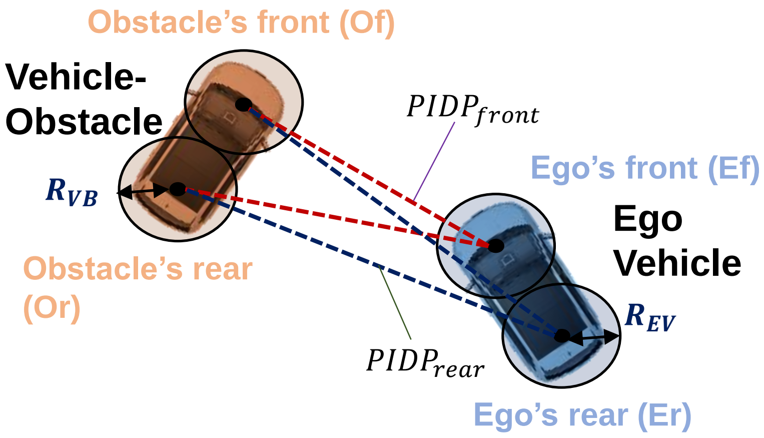
t_{SNR} : Time "Safety Not Respected"



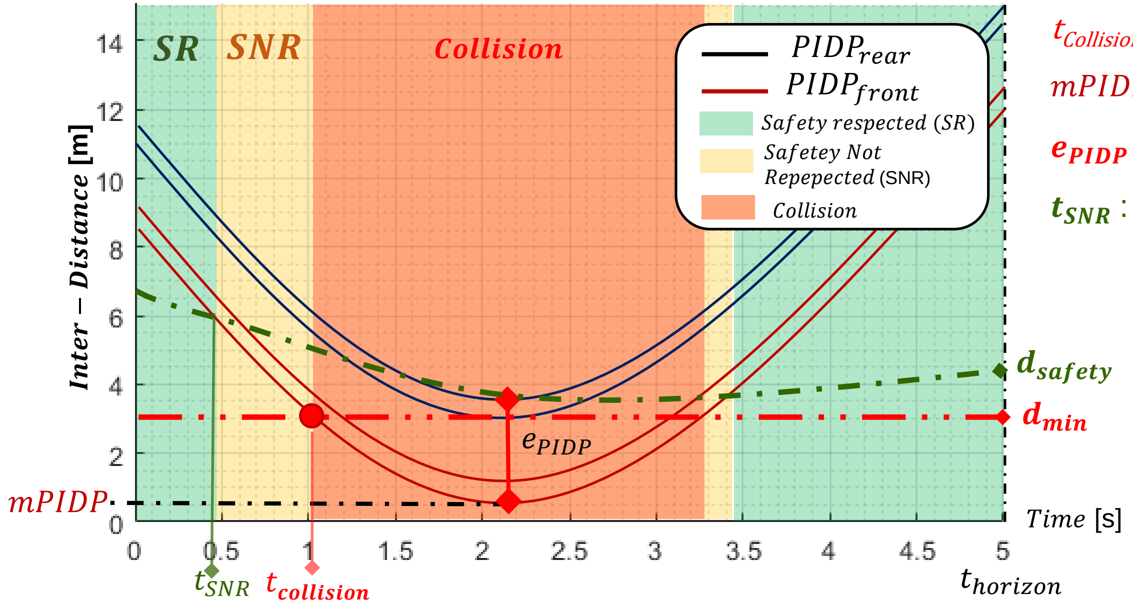


Risk Assessment / Management for Safe Navigation in Complex E/S

Safety Verification Decision Level based on **Predicted Inter-Distance Profile (PIDP)**



Circles used as buffers to characterize the different possible collisions



$t_{Collision}$: Time To Collision

$mPIDP$: Minimum of PIDP

$e_{PIDP} = d_{safety} - mPIDP$

t_{SNR} : Time "Safety Not Respected"

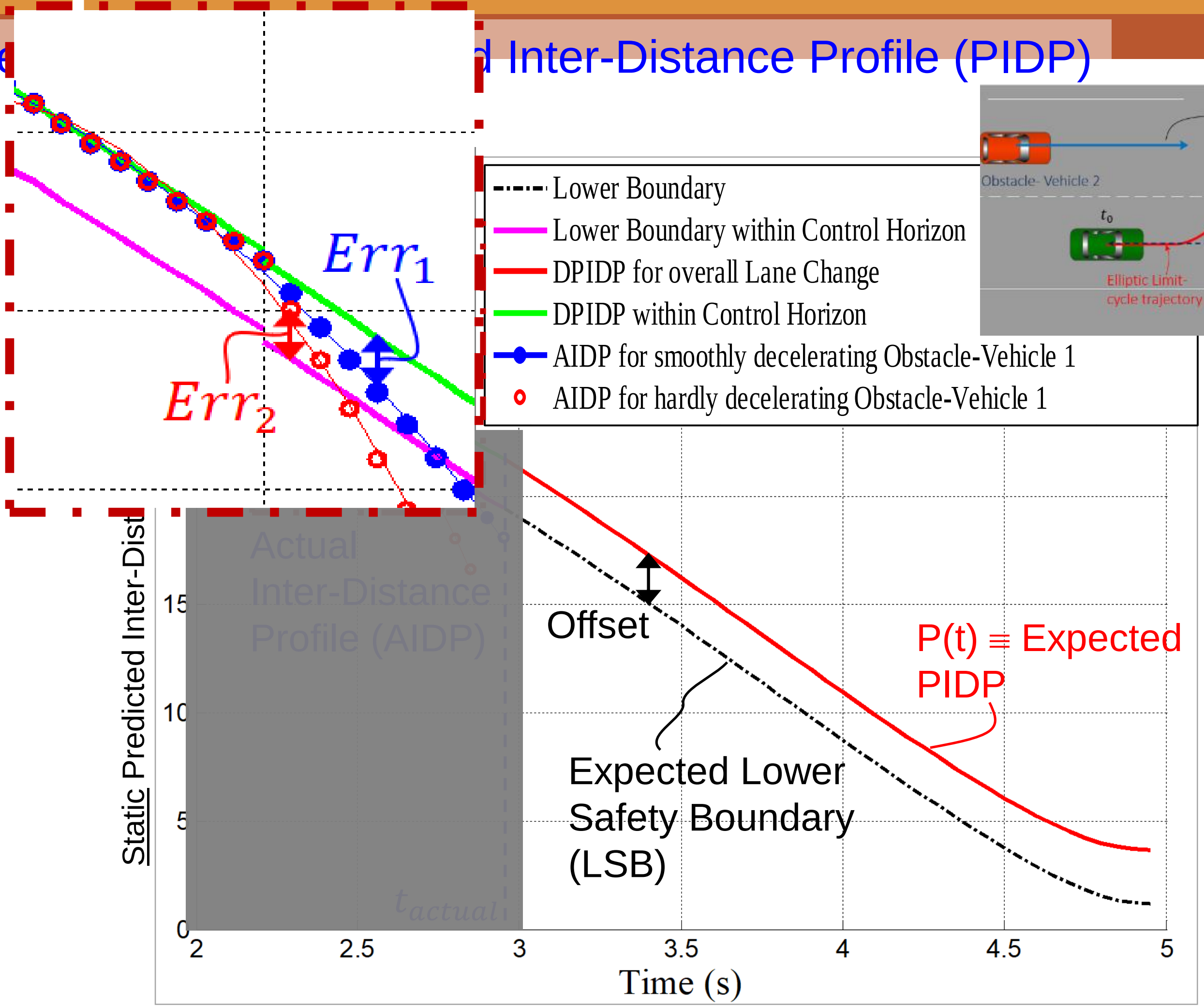
$$d_{safety} = d_{min} + t_{safety} v_r$$

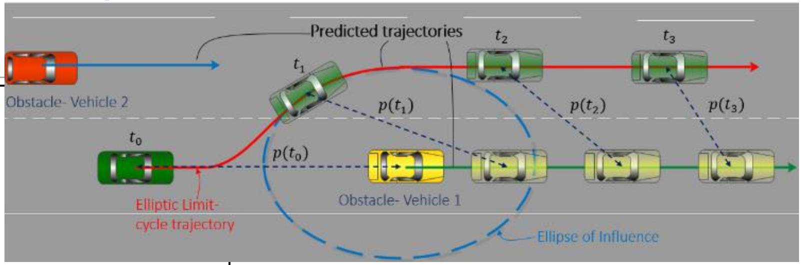
With: $d_{min} = R_{EA} + R_{OB} + Marge$; v_r relative velocity (between EV and VO)

Risk Assessment / Management for Safe Navigation in Complex E/S

Safety Verification Decision Level ... d Inter-Distance Profile (PIDP)

Anomaly Detection

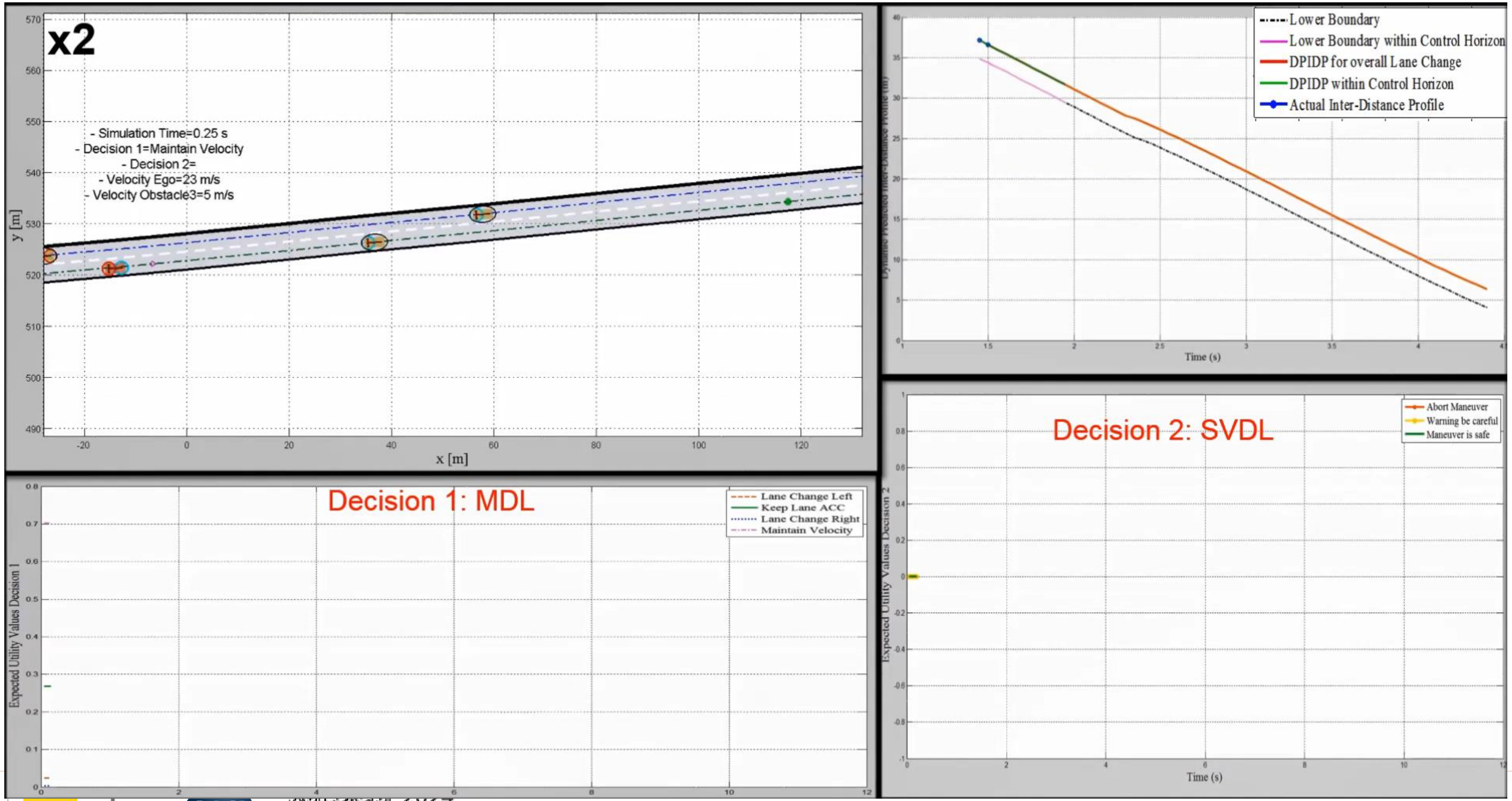




The risk of collision increases when the progress of the Actual Inter-Distance Profile (AIDP) goes closer to the Expected Lower Safety Boundary (LSB)

Risk Assessment / Management for Safe Navigation in Complex E/S

Safety Verification Decision Level based on Predicted Inter-Distance Profile (PIDP)



Obstacle-vehicle 1 strongly braking during overtaking and Obstacle-vehicle 3 accelerating in lane 2

Risk Assessment / Management for Safe Navigation in Complex E/S

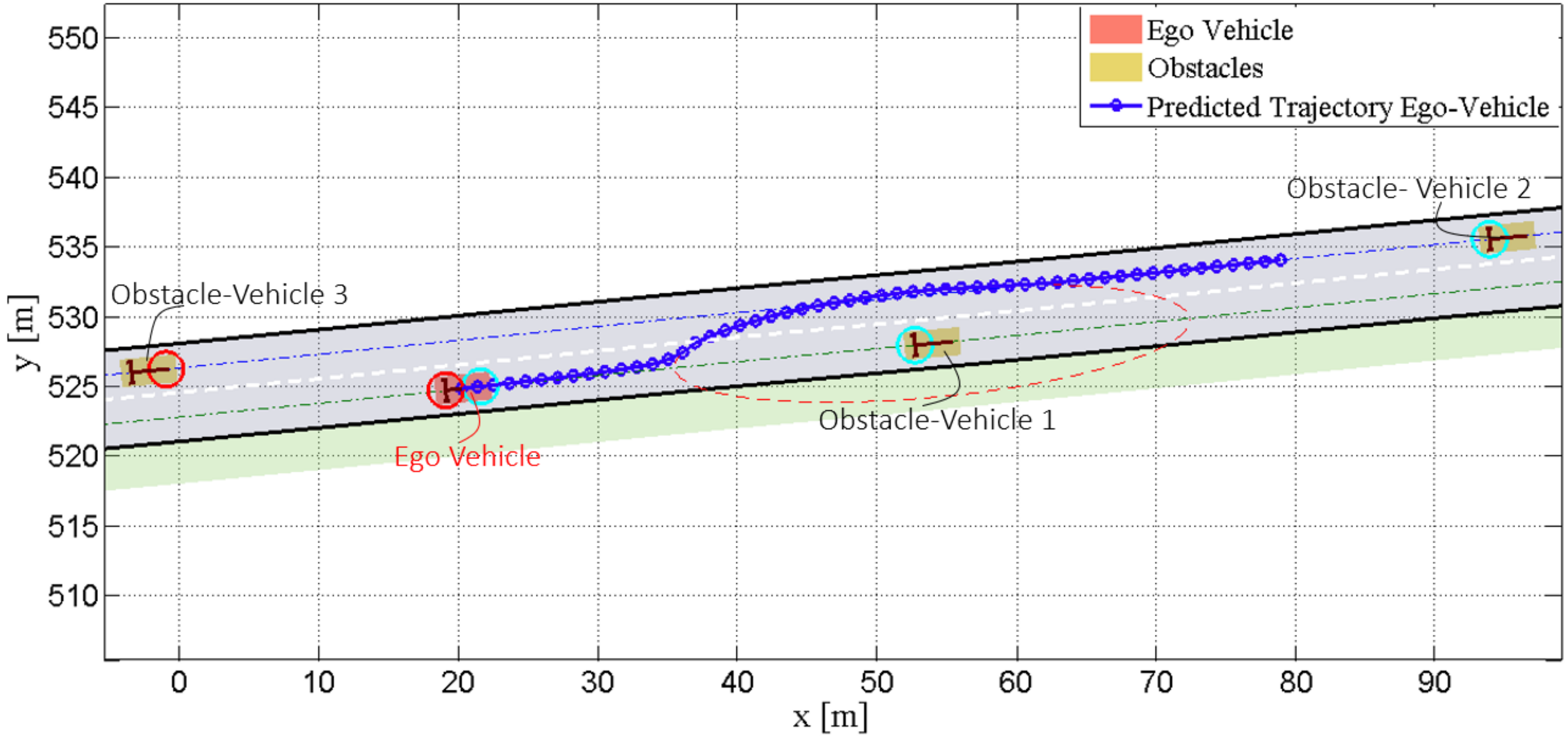
Safety Verification Decision Level based on Predicted Inter-Distance Profile (PIDP)

Demonstrative examples in Emergency Situations

Setup of the simulation environment

The initial velocities of the vehicles:

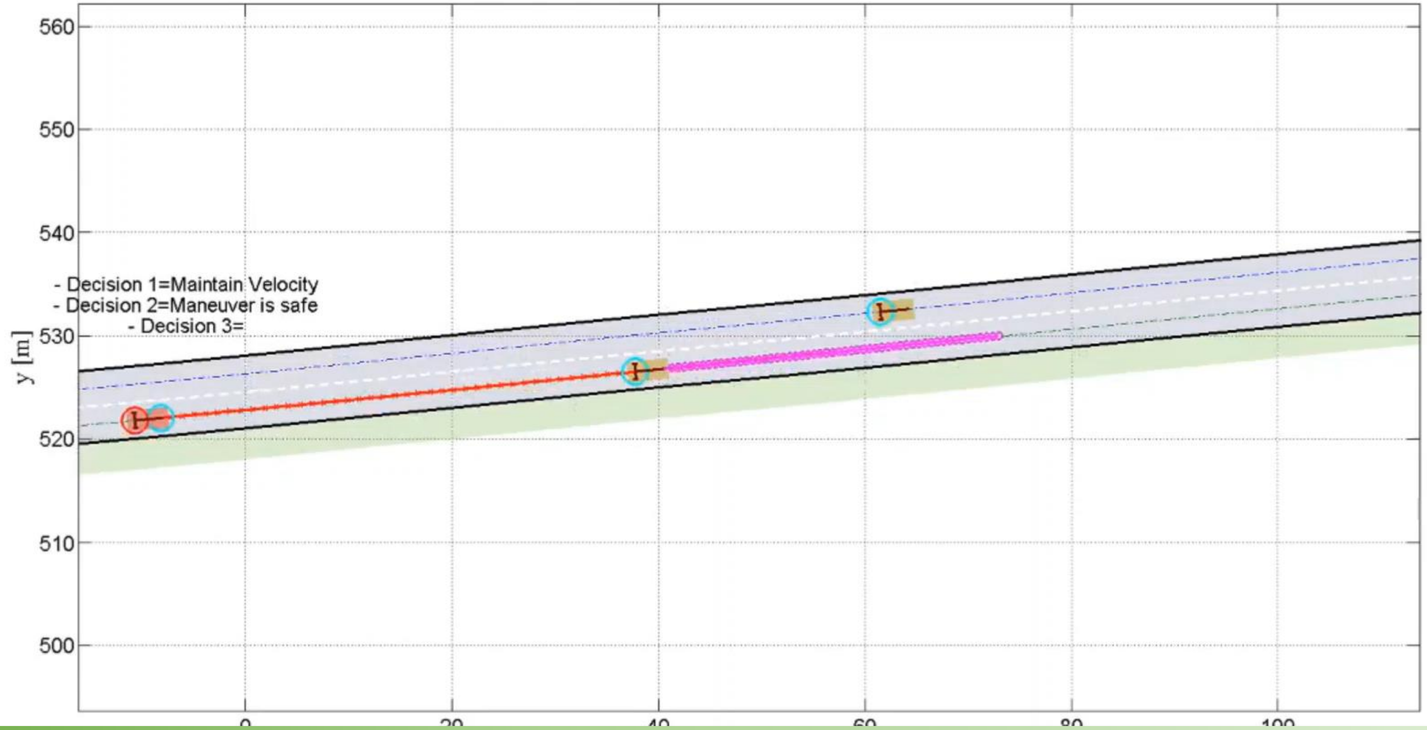
- $V_{ego_{max}} = 30\ m/s$
- $V_{O_1} = 12\ m/s$
- $V_{O_2} = 25\ m/s$
- $V_{O_3} = 20\ m/s$

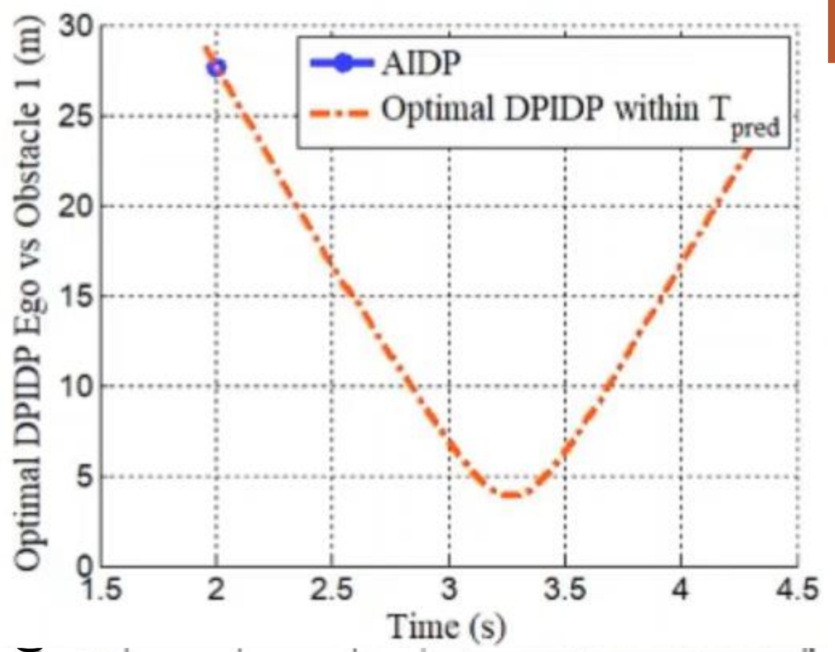


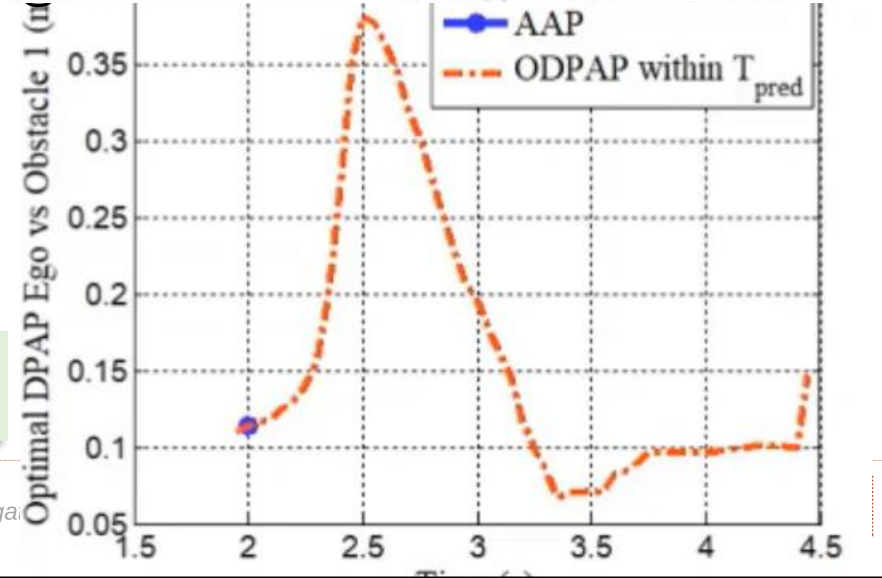
Risk Assessment / Management for Safe Navigation in Complex E/S

Safety Verification Decision Level based on Predicted Inter-Distance Profile

Simulation Case: The obstacle-vehicle 1 strongly braking during overtaking and comes to standstill





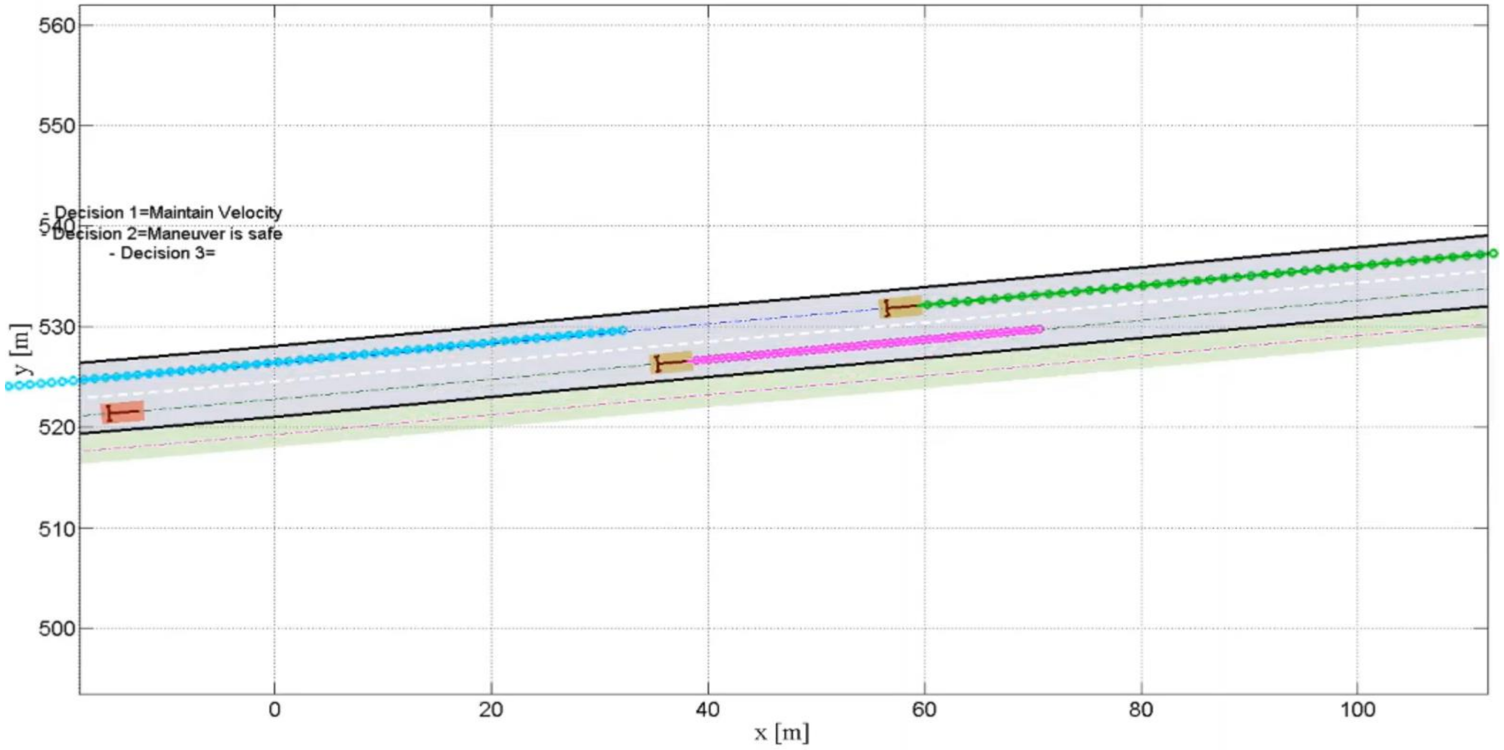


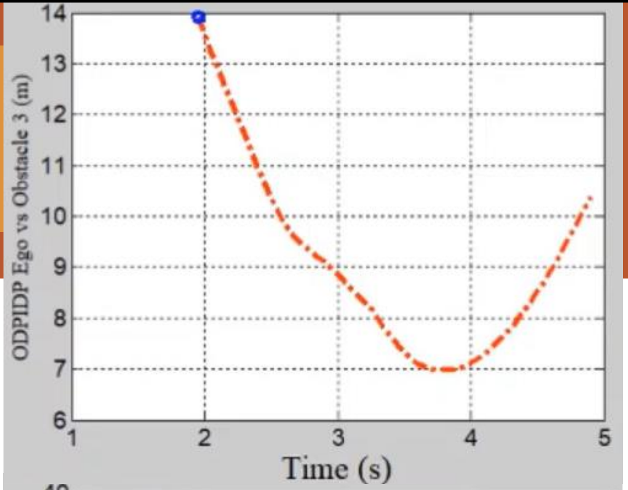
Evasive action is to continue the lane change maneuver

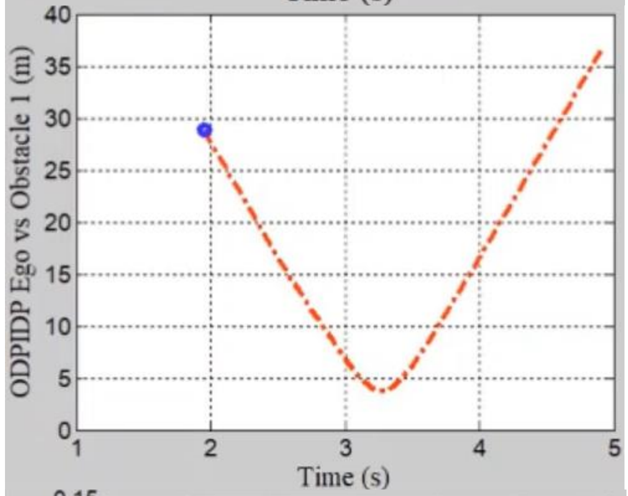
Risk Assessment / Management for Safe Navigation in Complex E/S

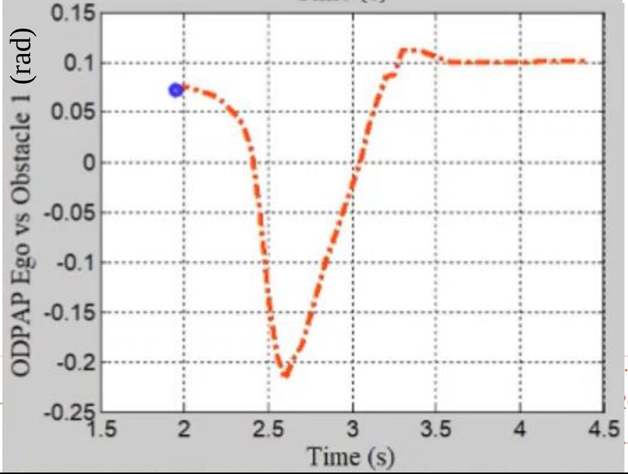
Safety Verification Decision Level based on Predicted Inter-Distance Profile (PIDP)

Simulation Case: The obstacle-vehicle 1 strongly braking during overtaking and comes to standstill and obstacle-vehicle 3 accelerating on Lane 2.







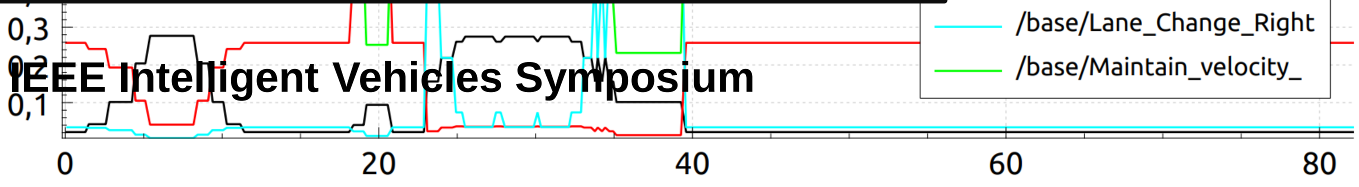


Evasive action is to swerve to the emergency lane

Risk Assessment / Management for Safe Navigation in Complex E/S

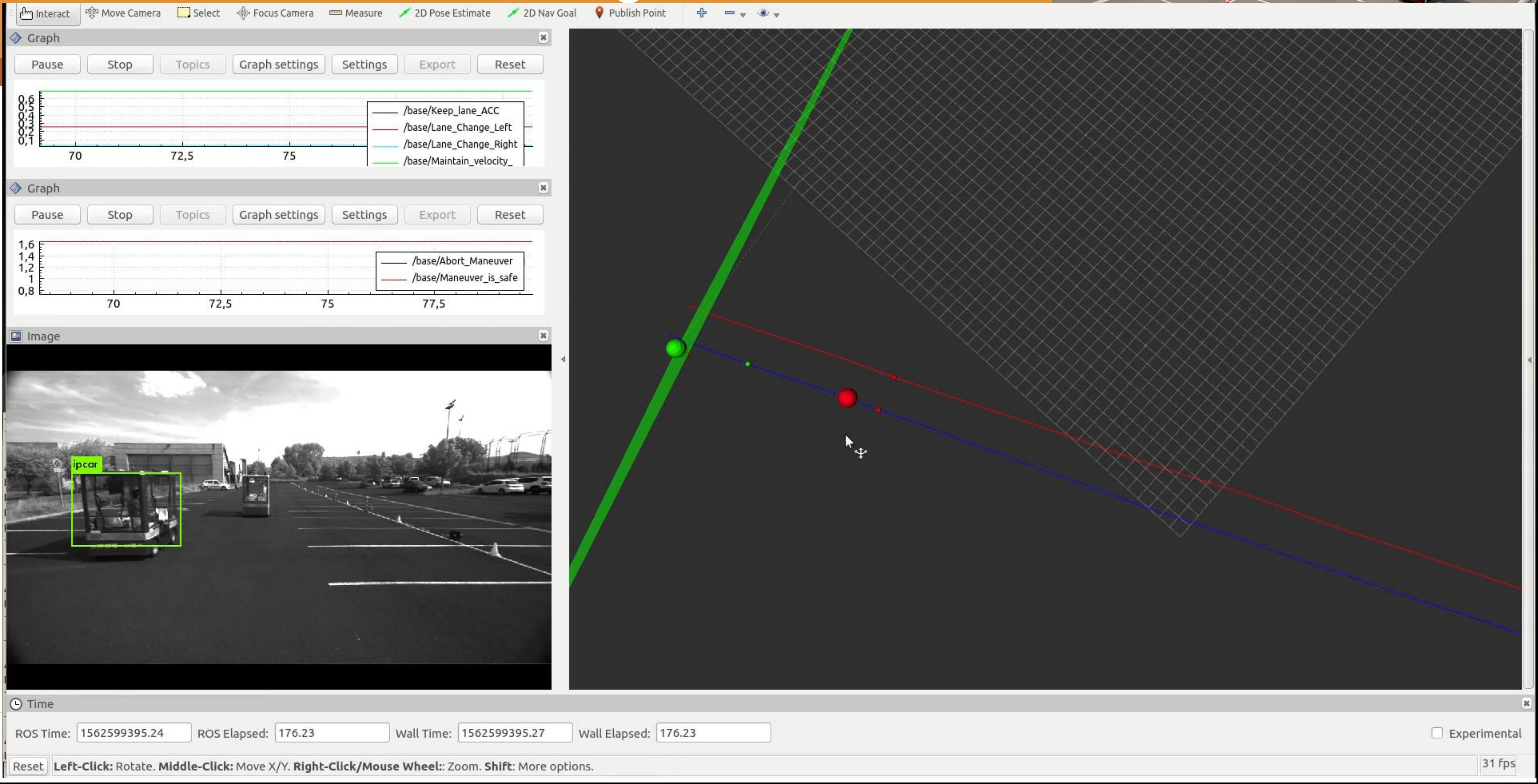
└ Safety Verification Decision Level based on Predict

Some experimental evaluation



Experiment performed during the **IEEE Intelligent Vehicles Symposium IV'19**, (Paris, June 2019)

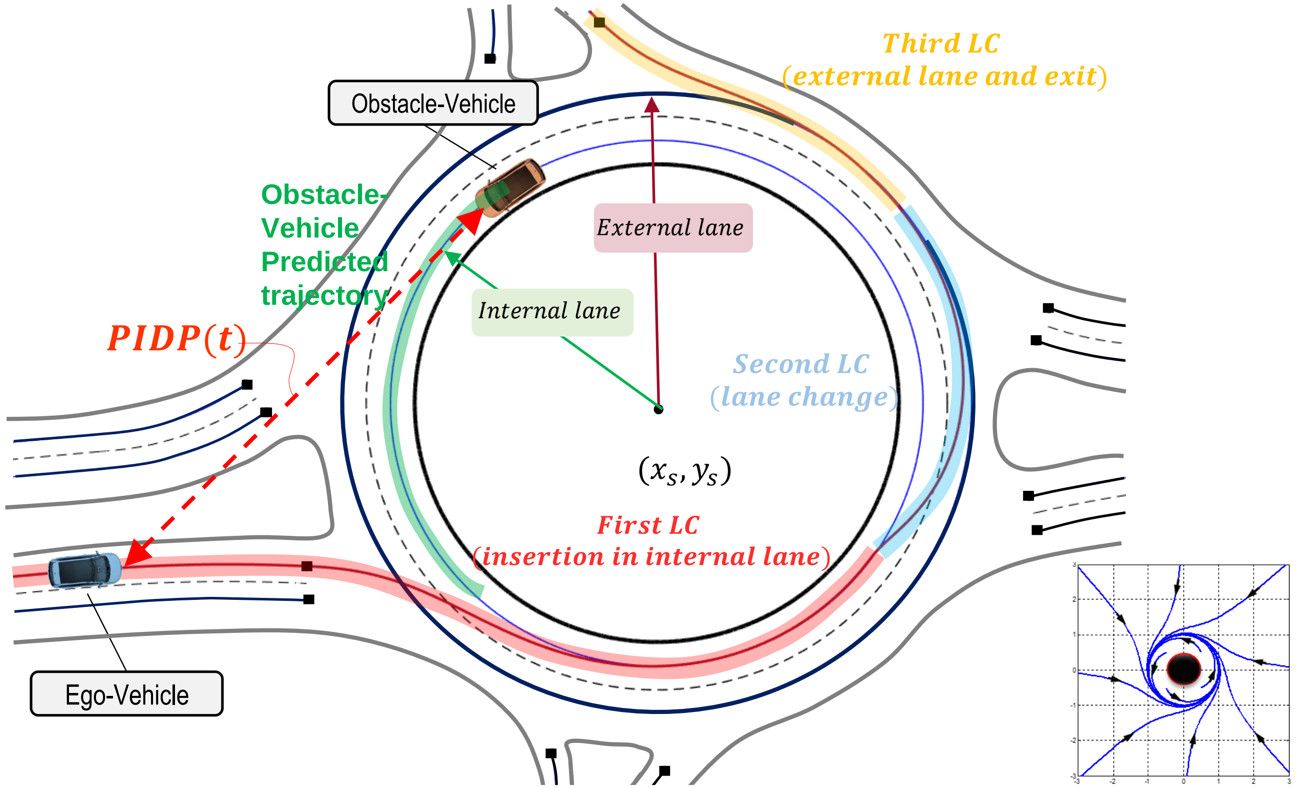
Risk Assessment / Management for Safe



Risk Assessment / Management for Safe Navigation in Complex E/S

Application for crossing dense roundabout [Bellingard. PhD 2023]

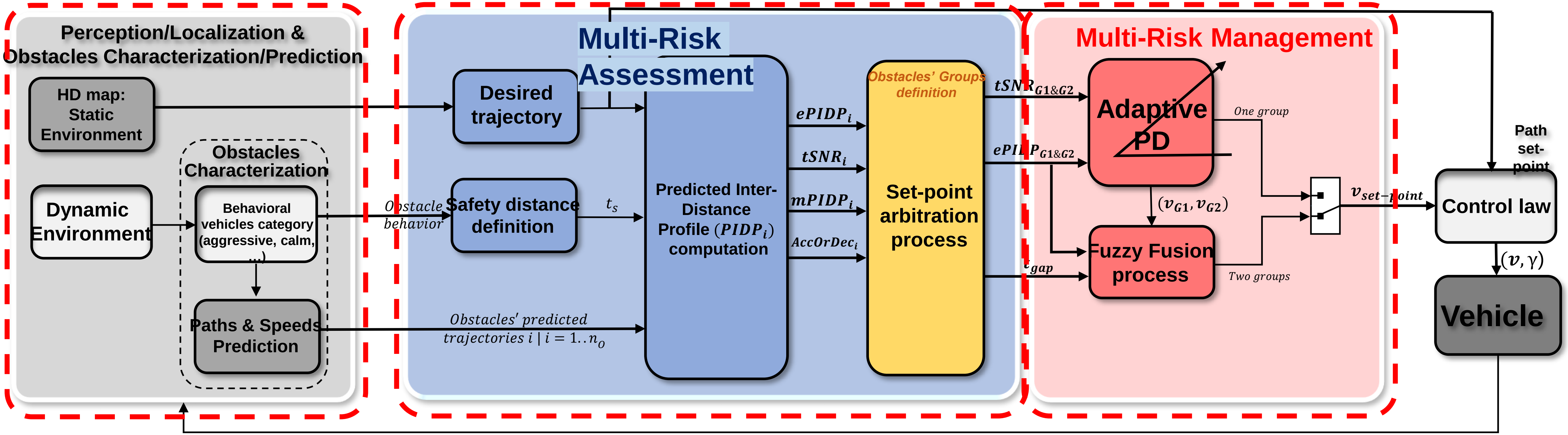
Use of Limit-Cycles and PIDP to ensure safe and flexible roundabout crossing



Defined **circular limit-cycles** paths to manage the entire roundabout

Risk Assessment / Management for Safe Navigation in Complex E/S

Overview of the proposed Multi-Risk Assessment and Management (MRAM) control architecture



K. Bellingard, L. Adouane and F. Peyrin, "Safe and Adaptive Roundabout Insertion for Autonomous Vehicle based Limit-cycle and Predicted Inter-Distance Profiles", European Control Conference (ECC). 2023.

K. Bellingard, L. Adouane and F. Peyrin, "Risk Assessment and Management based on Neuro-Fuzzy System for Safe and Flexible Navigation in Unsignalized Intersection", IEEE Intelligent Vehicles Symposium (IV). 2023

Risk Assessment / Management for Safe Navigation in Complex E/S

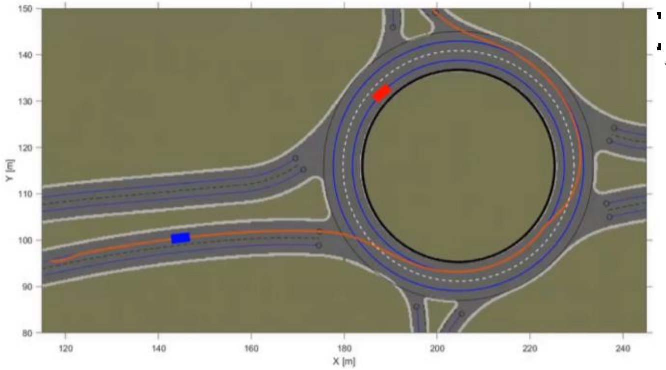
Multi-Risk Assessment and Management proposed Strategy

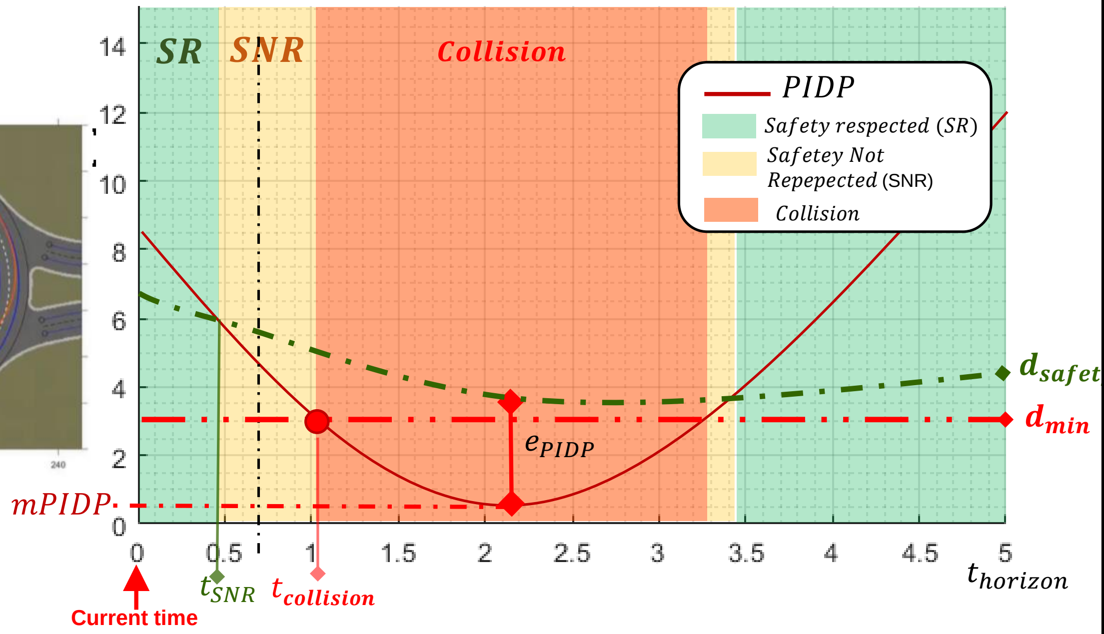
I) Adaptive Neuro-Fuzzy PD controller for each dangerous vehicle

$$v(t) = K_p e_{PIDP}(t) + K_d \frac{\partial e_{PIDP}}{\partial t}$$

Where:

K_p, K_d are updated dynamically according to a Neuro-Fuzzy controller $F(t_{SNR}, e_{PIDP})$





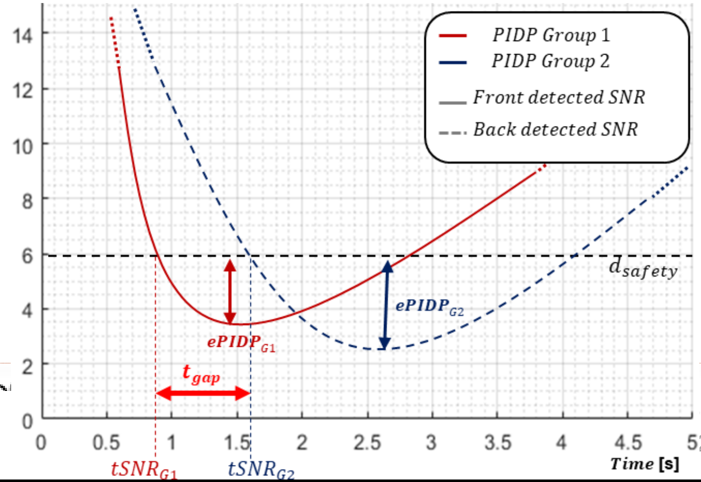
II) Select the most dangerous Obstacle-Vehicle for each group

(G1 and G2 : Respectively With Front and Back Risk of Collision)

$$v(t) = \omega . v_{G1}(t) + (1 - \omega)\, v_{G2}(t)$$

Where:

ω is a Fuzzy variable to obtain the right balance between the speed profiles computed for the two groups



PIDP of the most dangerous vehicles of the two identified groups

Risk Assessment / Management for Safe Navigation in Complex E/S

Simulations and experiments

Statistical study with realistic simulator

Experimental validation

Table of content

Conclusion and Prospects

- **Homogenous** and **Hybrid Multi-Controller Architectures** to lead **gradually**, and in a **generic way** **toward fully autonomous navigation** even in **complex contexts** / **environments**

- **Homogenization** and **Standardization** of tasks' **modeling/planning/control/risk assessment & management**:
  - ✓ **Homogenous set-points definition** and appropriate **stable** and **Robust control laws**
  - ✓ **Reference frames** to **guide the tasks achievements** (e.g., obstacle avoidance, navigation though successive waypoints)

- **Decision-making** process to deal with **uncertainty** and to **anticipate dangerous situations** though the behaviors' prediction of the surrounding entities
  ➔ **Good balance** between **risk management** and the AV **operationality** (not too conservative)
  - ✓ Appropriate **metrics** for **risk assessment** and **management** (PIDP, sPIDP, etc.) and to anticipate the future actions
  - ✓ **Probabilistic robotics** as efficient framework for sequential and real-time risk assessment & management.

- **Flexible** and **reliable obstacle avoidance** controller as an important component for **safe navigation**

- **Even more Homogenization** and **Standardization** of **multi-controller architectures**
- **Reach the good balance** between the contribution/use of "**Model based**" and "**Machine learning**" approaches.

Many thanks for your attention!

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A special acknowledgment goes to all the PhD, MSc students and Engineers who have contributed actively to reach the results highlighted in this presentation.