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Assessment of ALKS performance

Fuzzy Safety Model proposed by EC, Validation activities, Assessment of additional scenarios, Criticality-based scenario classification

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Joint Research Centre

Motivation

- Increasing the maximum ALKS speed from 60km/h -> 130km/h the **kinetic energy a vehicle can transfer to another road user is ~5 times higher**

$$\frac{E_{k,130}}{E_{k,60}} = \frac{130^2}{60^2} = 4.7$$

- Ensuring **proper requirements for ALKSs to be able to avoid collisions becomes very important**.

R157 performance requirements for car-following, cut-in and cut-out

- Paragraph 5.2.5 introduces two performance requirement models for car-following, cut-in and cut-out. They focus on **emergency conditions**:

R157

  - 5.2.5.2. defines the performance model for cut-in,

CC Driver

  - 5.2.5. refers to Appendix 3 to Annex 4 for the performance model for car-following and cut-out

Cut-in

5.2.5.2. The activated system shall avoid a collision with a cutting in vehicle,

(a) Provided the cutting in vehicle maintains its longitudinal speed which is lower than the longitudinal speed of the ALKS vehicle and

(b) Provided that the lateral movement of the cutting in vehicle has been visible for a time of at least 0.72 seconds before the reference point for *TTCLaneIntrusion* is reached,

(c) When the distance between the vehicle's front and the cutting in vehicle's rear corresponds to a TTC calculated by the following equation:

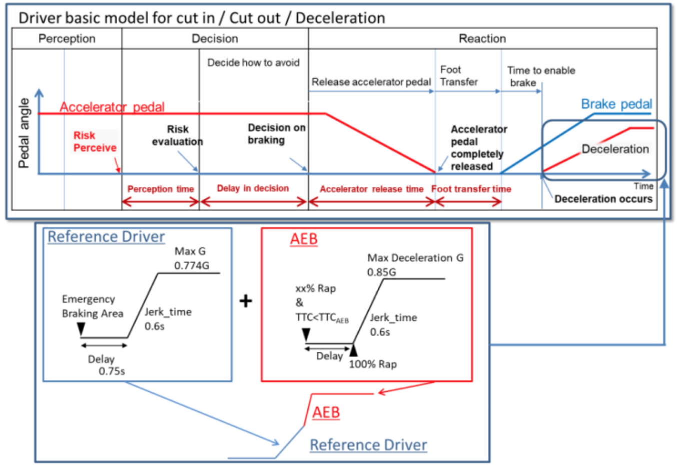
$$TTCLaneIntrusion > vrel/(2 \cdot 6\text{m/s}^2) + 0.35s$$

Where:

Vrel	=	relative velocity between both vehicles, positive for vehicle being faster than the cutting in vehicle
TTCLaneIntrusion	=	The TTC value, when the outside of the tyre of the intruding vehicle's front wheel closest to the lane markings crosses a line 0.3 m beyond the outside edge of the visible lane marking to which the intruding vehicle is being drifted.

Why?

Car-following and Cut-out



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Is emergency behaviour sufficient?

- Performance models in current R157 mainly focus on driver behaviour under **emergency situation**
- Most of the accidents are avoided by **anticipating** risky situations
- Our proposal is to **extend the existing model** of the Competent and Careful Humand Driver (R157-Appendix 3) by introducing this **human anticipatory behaviour**.
- At higher speed this seems very important to have a **robust and comprehensive model** to be used for the assessment of cut-in, car-following, and cut-out scenarios.

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EC proposal for a single performance model for cut-in, cut-out and deceleration scenarios

- The objective of the EC proposal is to have a single **performance model** used only to **CLASSIFY a concrete scenario** related to cut-in, cut-out and deceleration as **preventable or not for a careful and competent human driver**.
- There is **no intention** to introduce any **operational requirement** for the ALKS
- The model considers the capability of a C+C driver to anticipate a collision by **mild decelerations before reaching a safety critical situation**.

Cut-in Scenario Classification

Comparison of different approaches

Parameters used in the simulations

- **Reaction time:**
  - Reg157 -> 0.35 sec
  - CC human driver, FSM, RSS -> 0.75 sec
- **Maximum deceleration (ego-vehicle)**
  - CC human driver, RSS -> 0.774 G
  - Reg157, FSM -> 6 m/s^2
- **Maximum jerk (ego-vehicle, absolute)**
  - CC human driver, RSS, FSM -> 12.65 m/s^3

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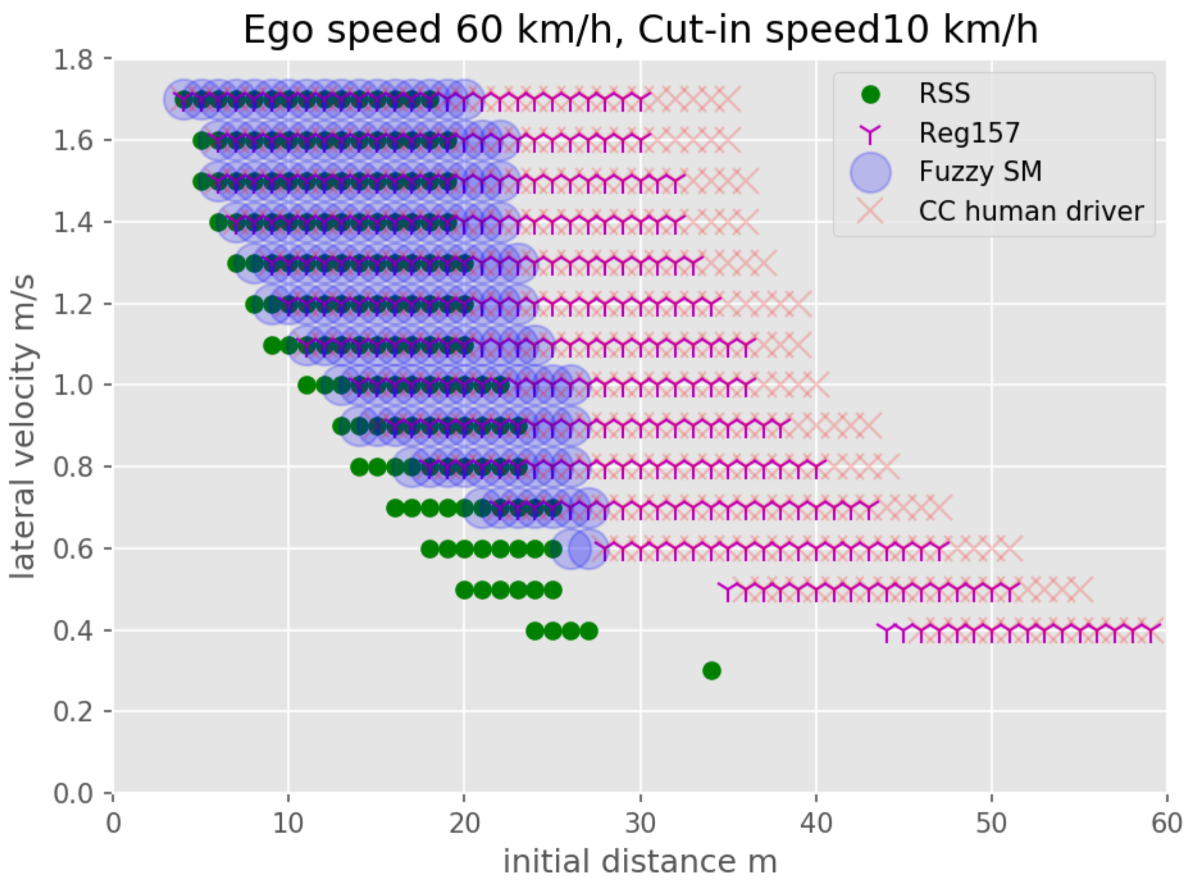
Results low speed (ego speed $\leq 60\ km/h$)

	CASES SIMULATED	UNPREVENTABLE CASES	PERCENTAGE
Reg157	15930	2417	15.17%
CC human driver	15930	2956	18.56%
RSS	15930	944	5.93%
FSM	15930	974	6.11%

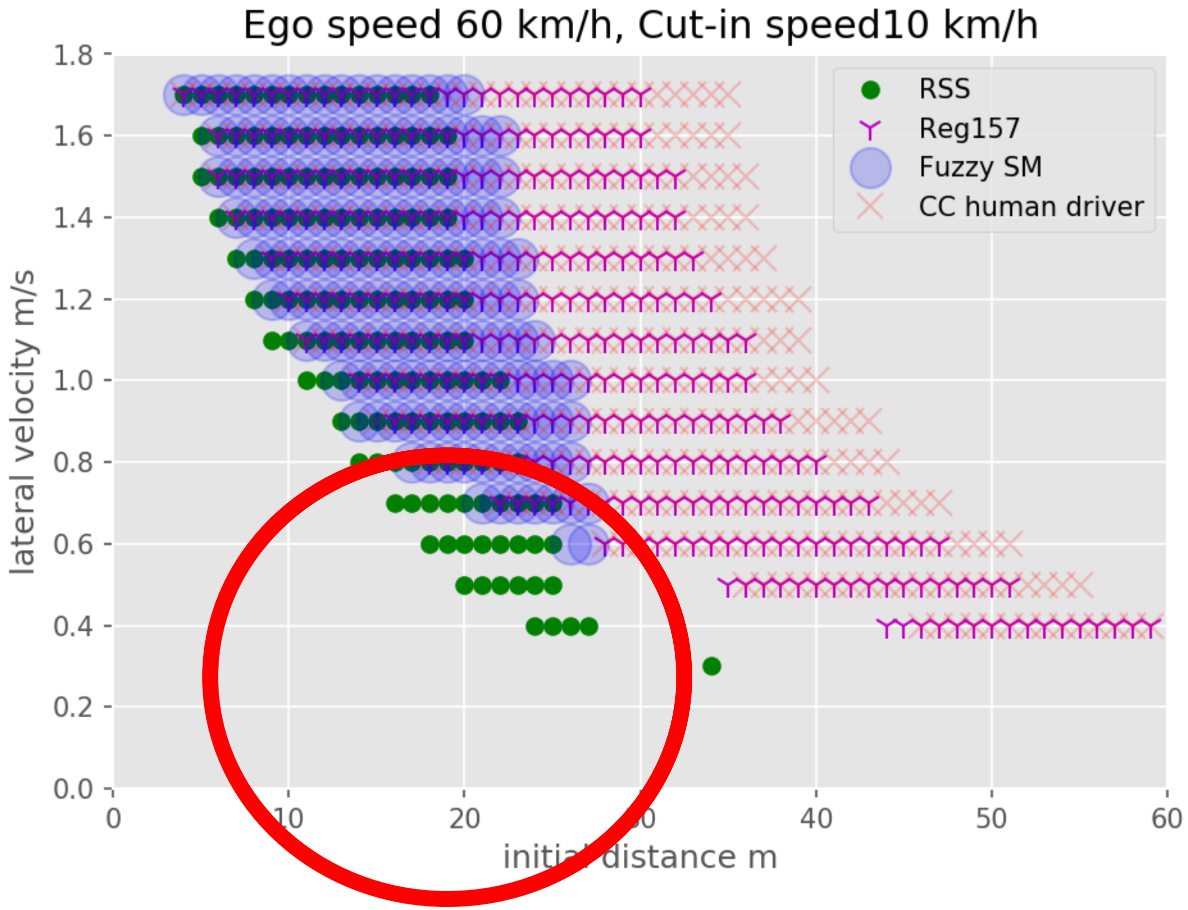


Results

Two areas of interest

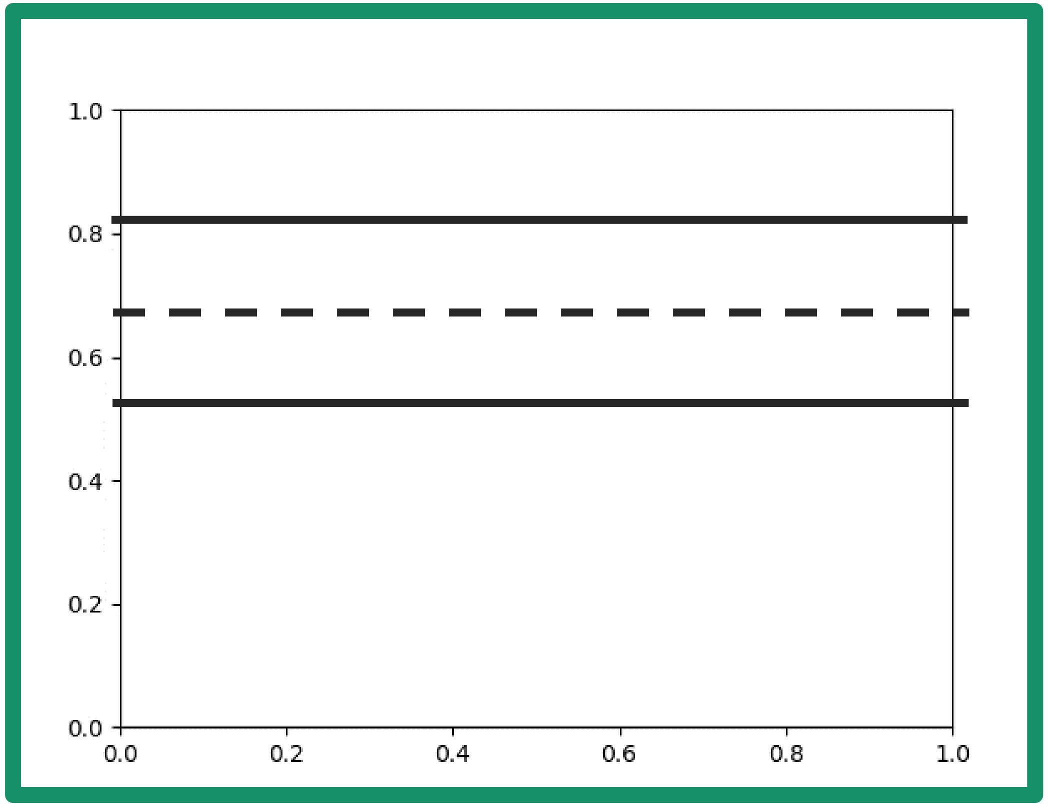
The first is about cases when the deceleration of RSS vehicles causes an accident

Other models do not decelerate and avoid the accident

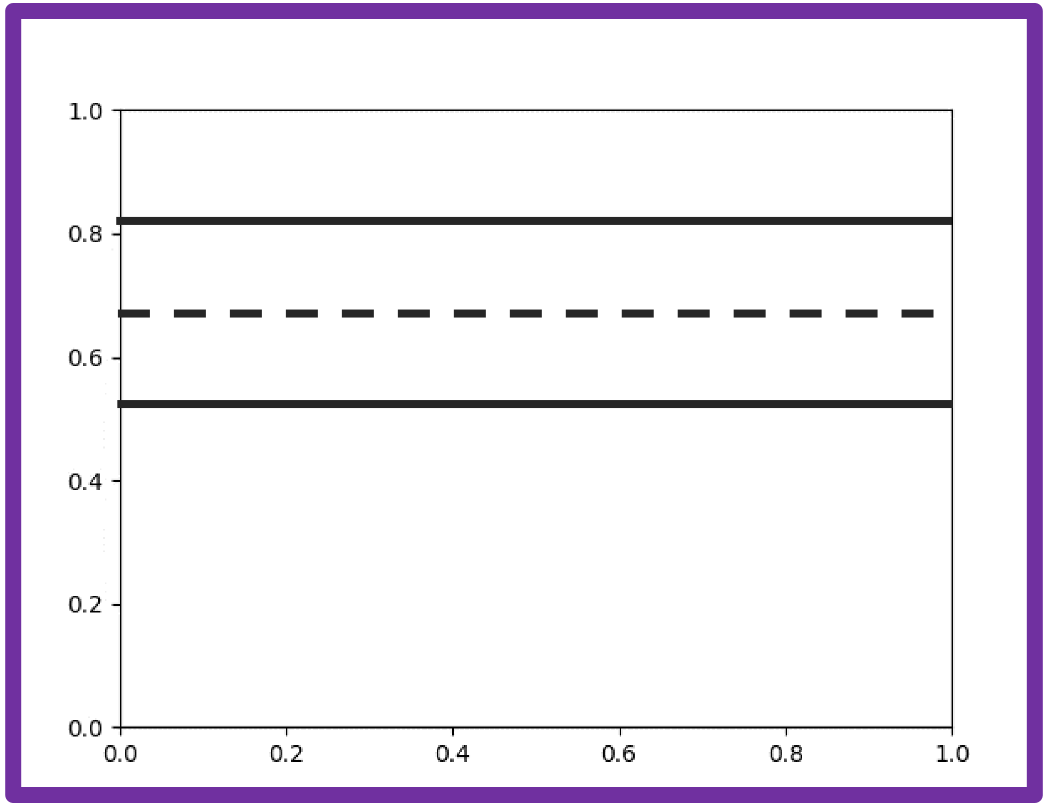


Results

RSS



Reg157



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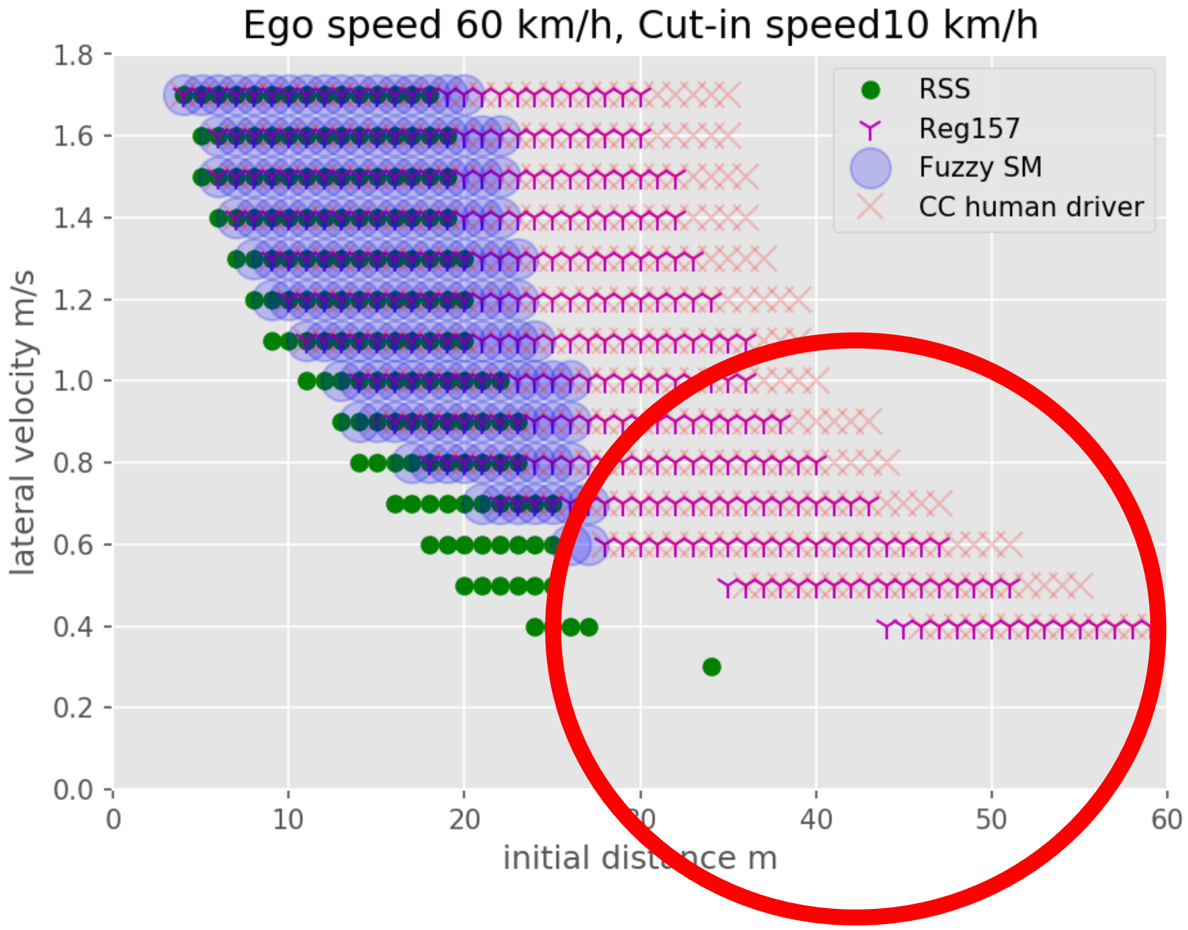
Results

Two areas of interest

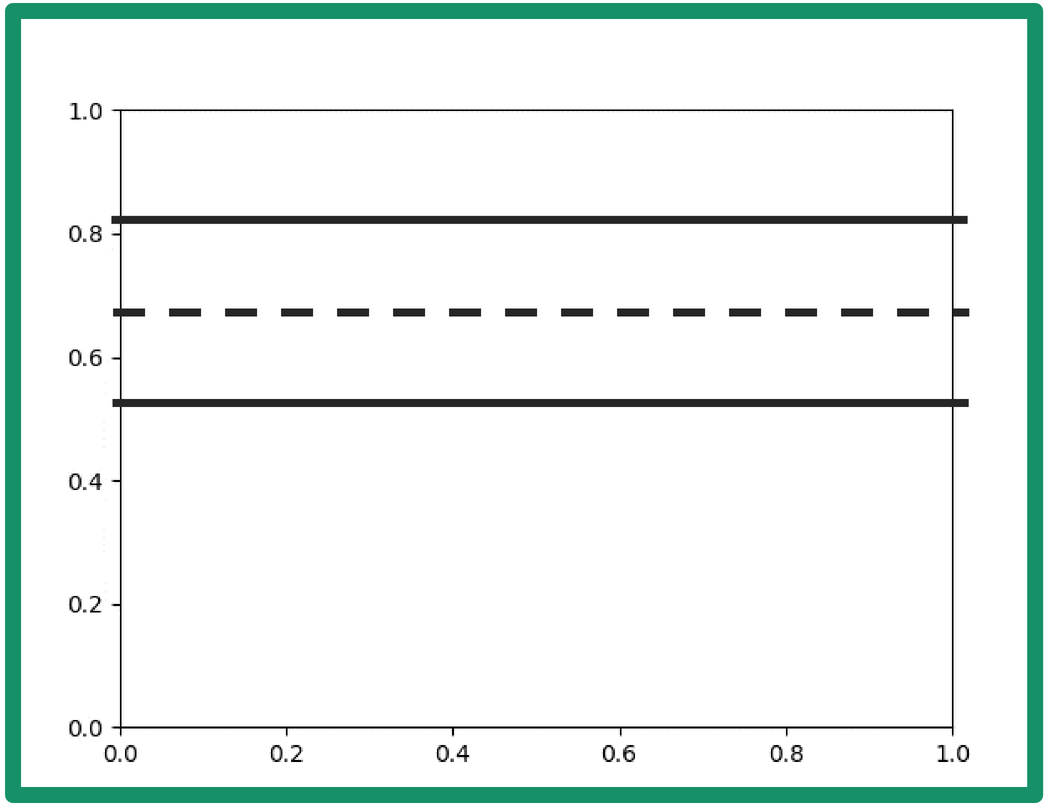
The second is for vehicles in large distance and small lateral speed

Those cases are avoidable by decelerating in a proactive manner

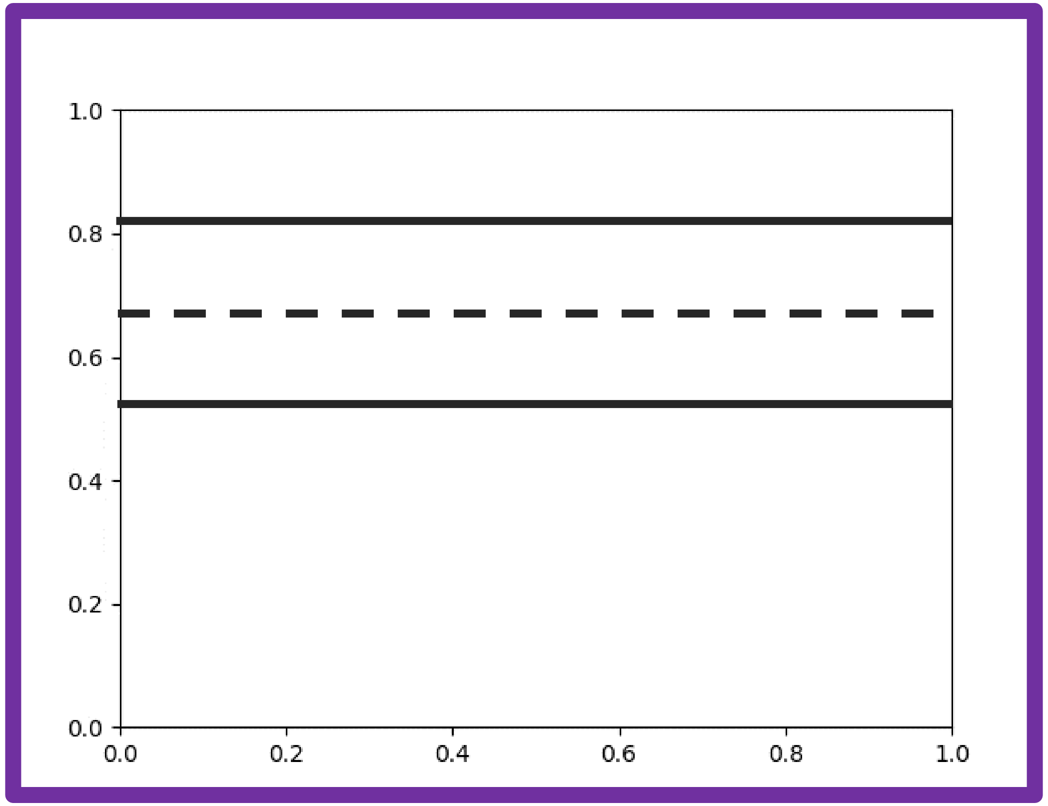


Results

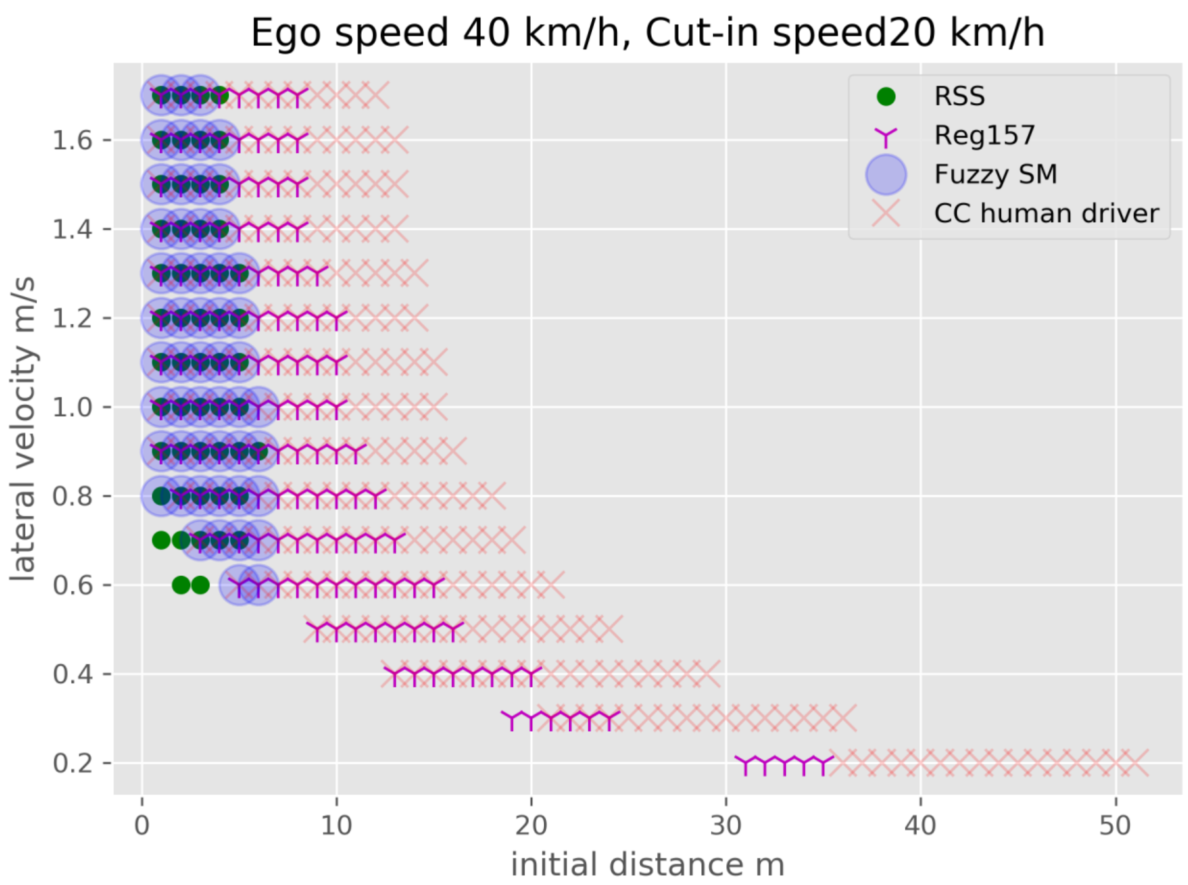
RSS

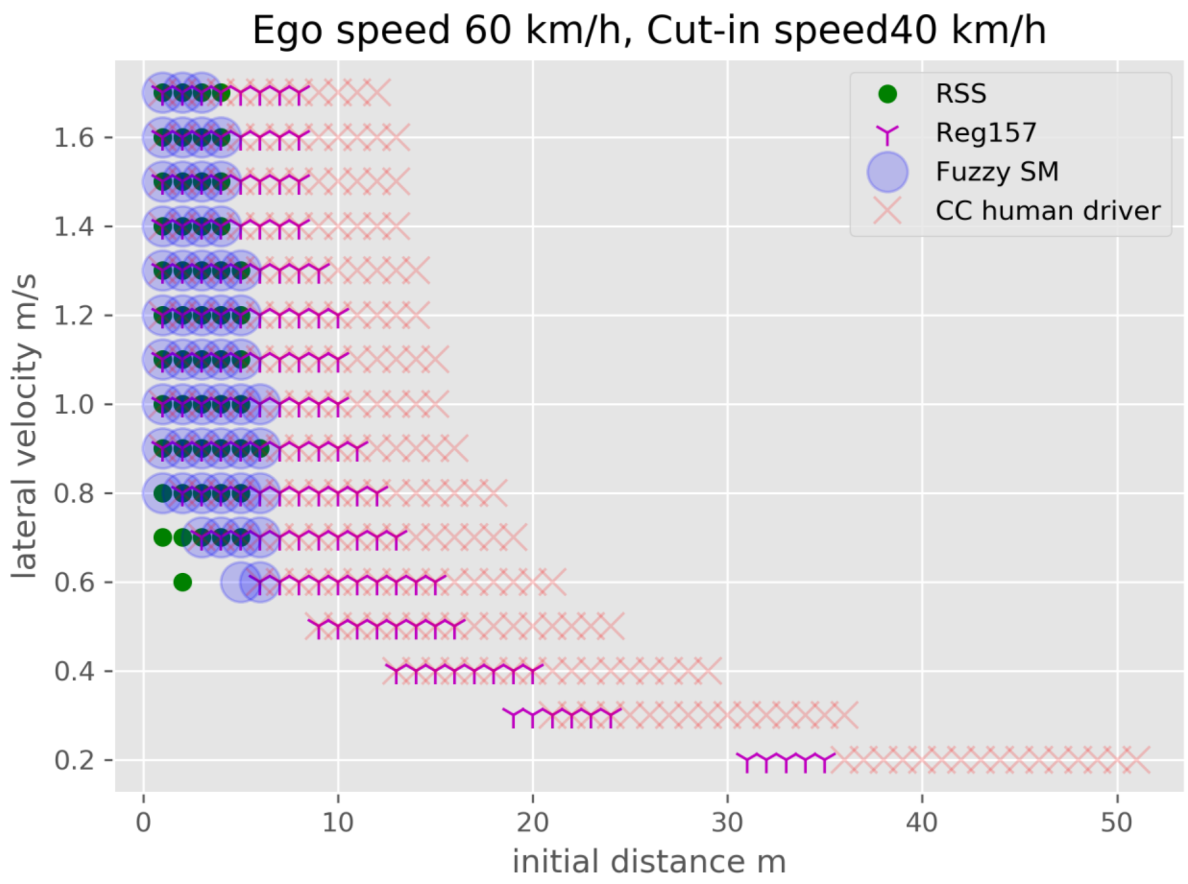


Reg157



Cut in Unpreventable





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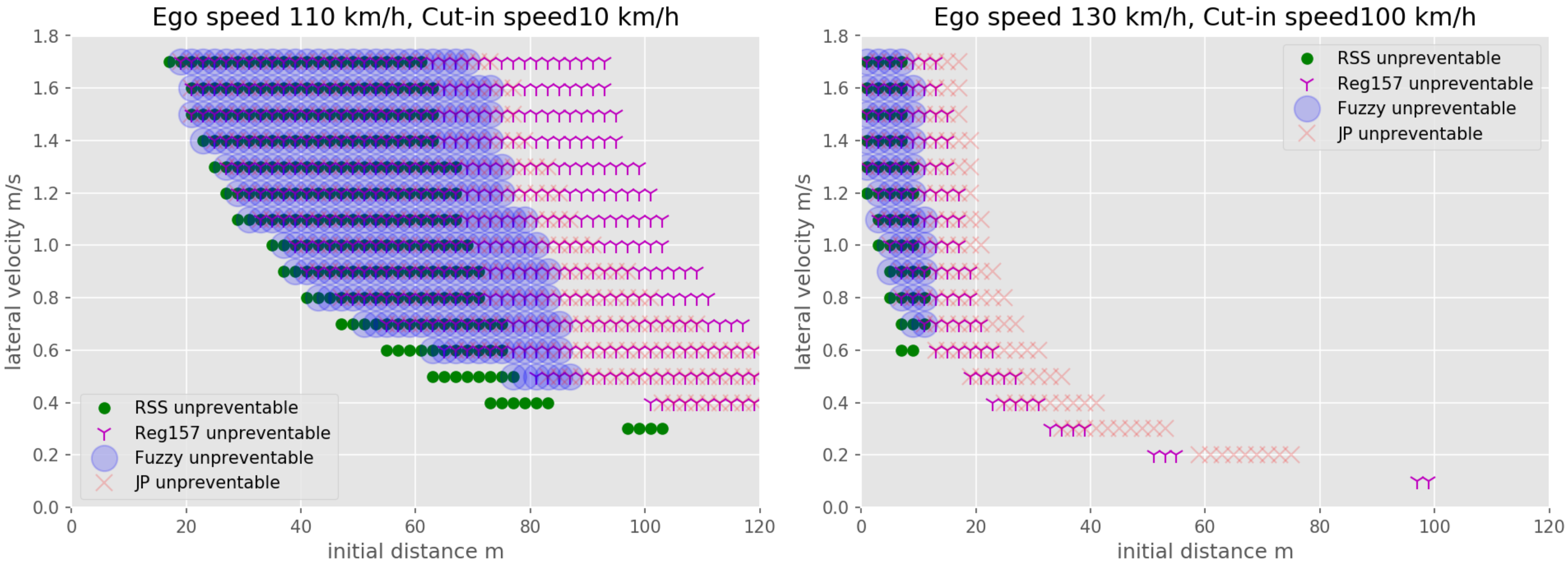
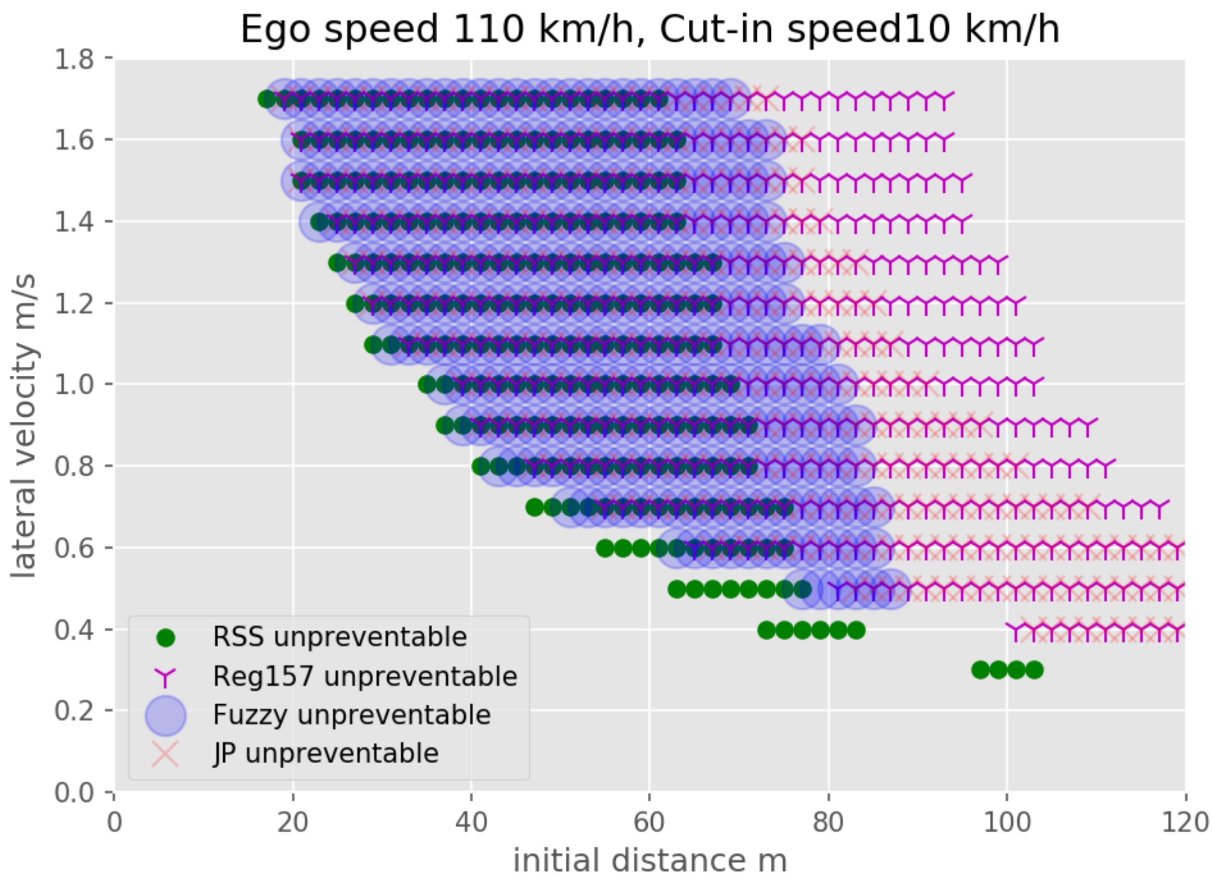
Cut in Unpreventable



Results high speed (ego speed > 60 km/h)

	CASES SIMULATED	UNPREVENTABLE CASES	PERCENTAGE
Reg157	14040	2988	21.28%
CC human driver	14040	2850	20.30%
RSS	14040	1567	11.16%
FSM	14040	1735	12.36%



Validation of cut-in scenario classification

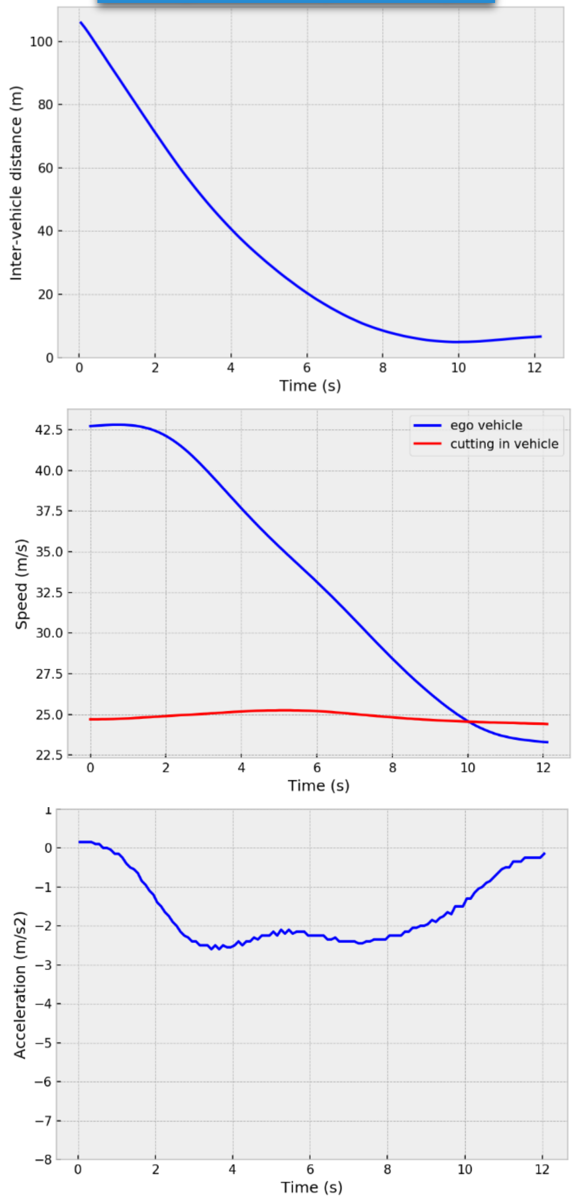
Initial validation activities

- In the spirit of the proposal, the first validation activity focused on the capability of the model to **correctly classify preventable scenarios**

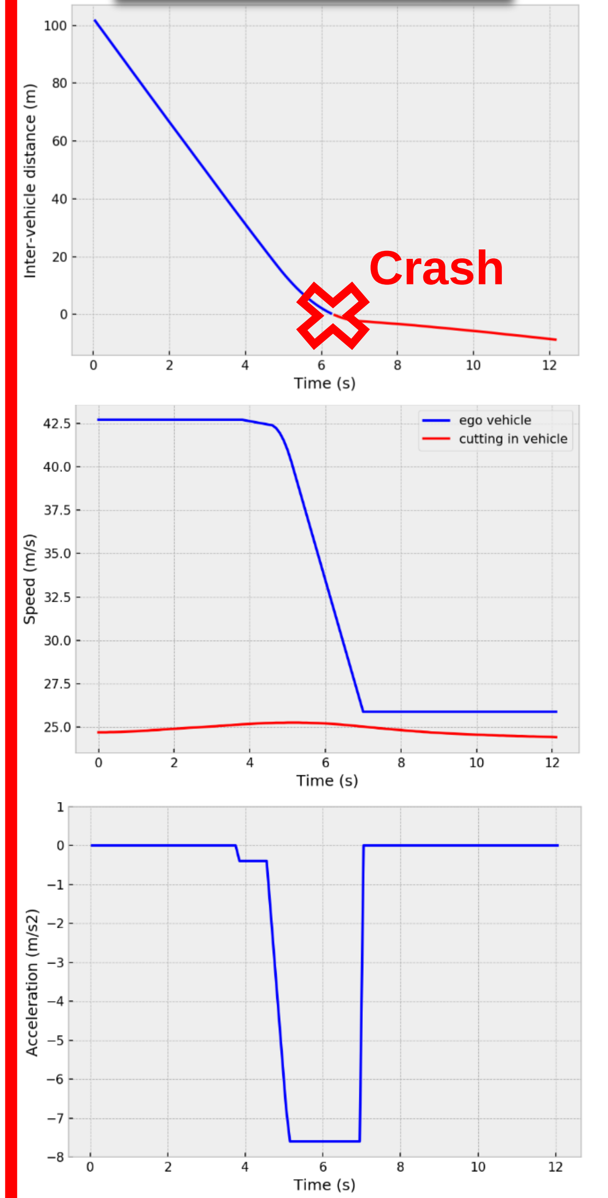
- **110,500 vehicle trajectories**
- **3,000 cut-in scenarios**
- **50 cut-ins with minimum TTC < 5”**
- **No accidents (all preventable scenarios)**
- **In all cases the Fuzzy Safety Model was able to classify the cut-in as preventable**

Results of cut-in scenarios: Case A

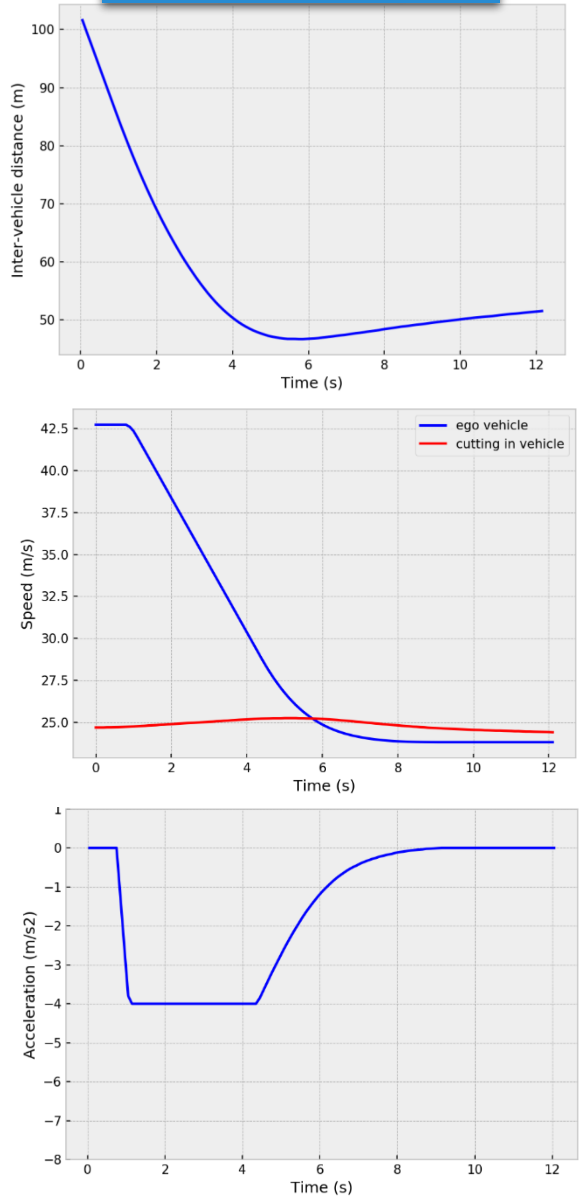
HighD trajectory



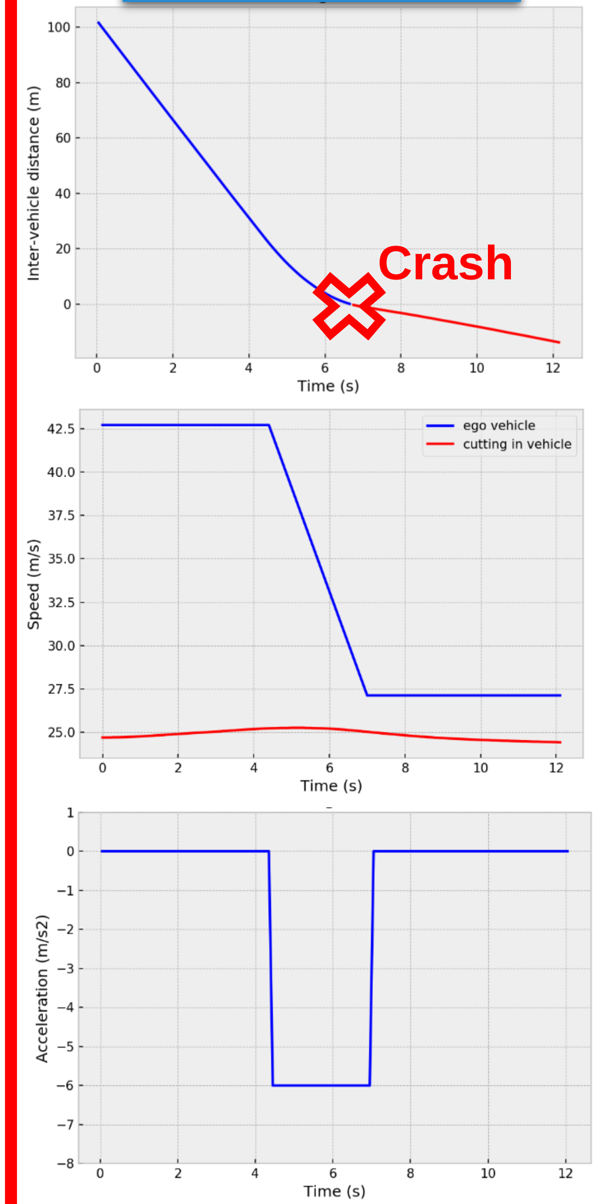
CC driver (JP)



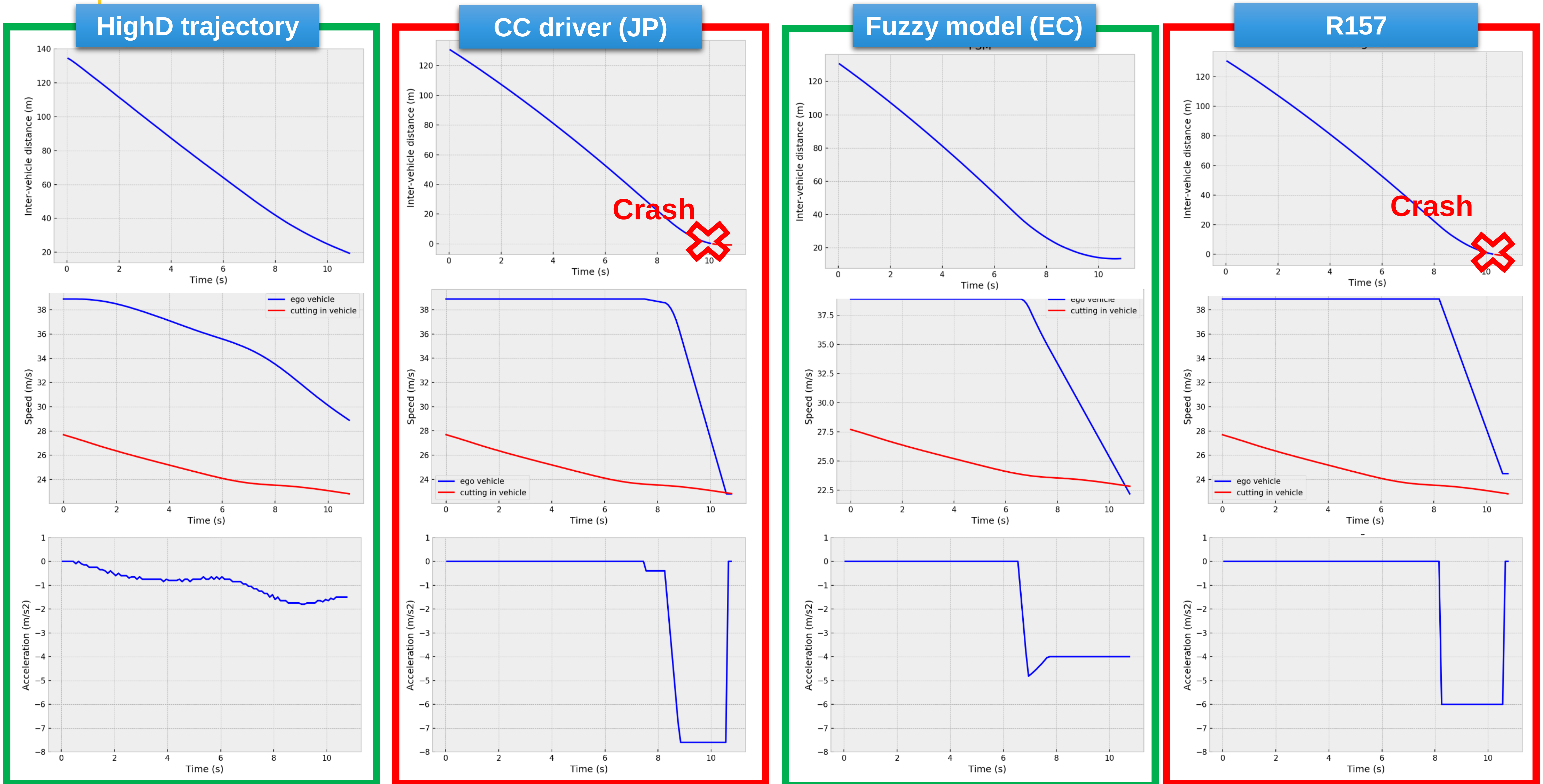
Fuzzy model (EC)



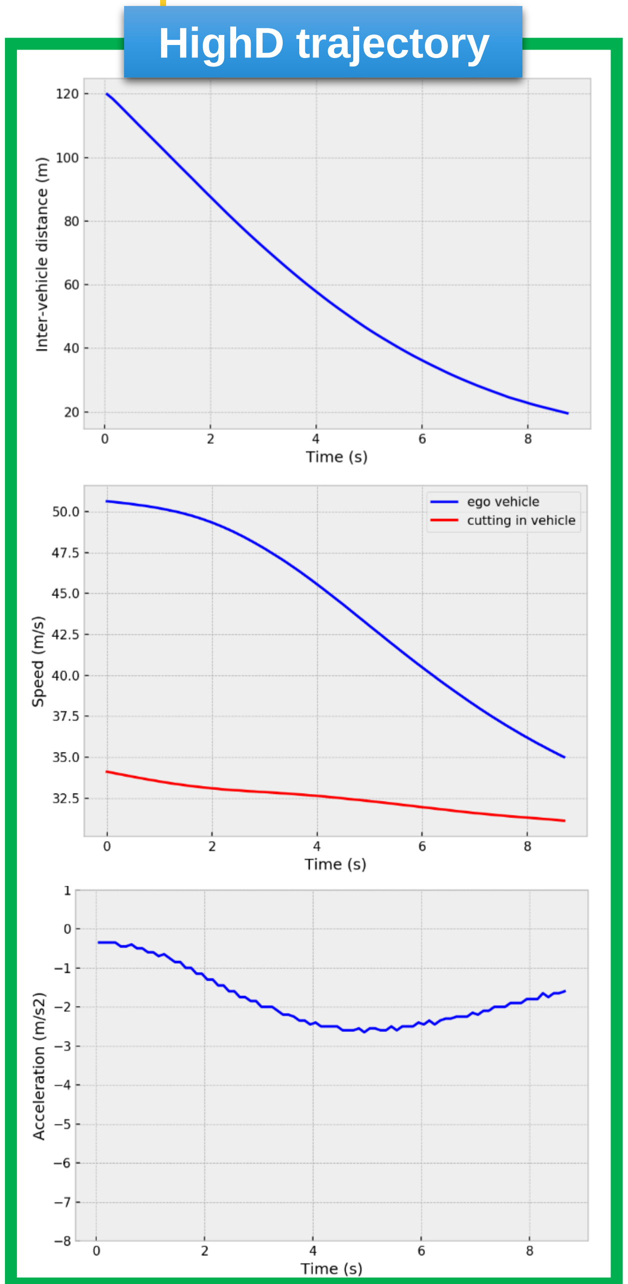
R157

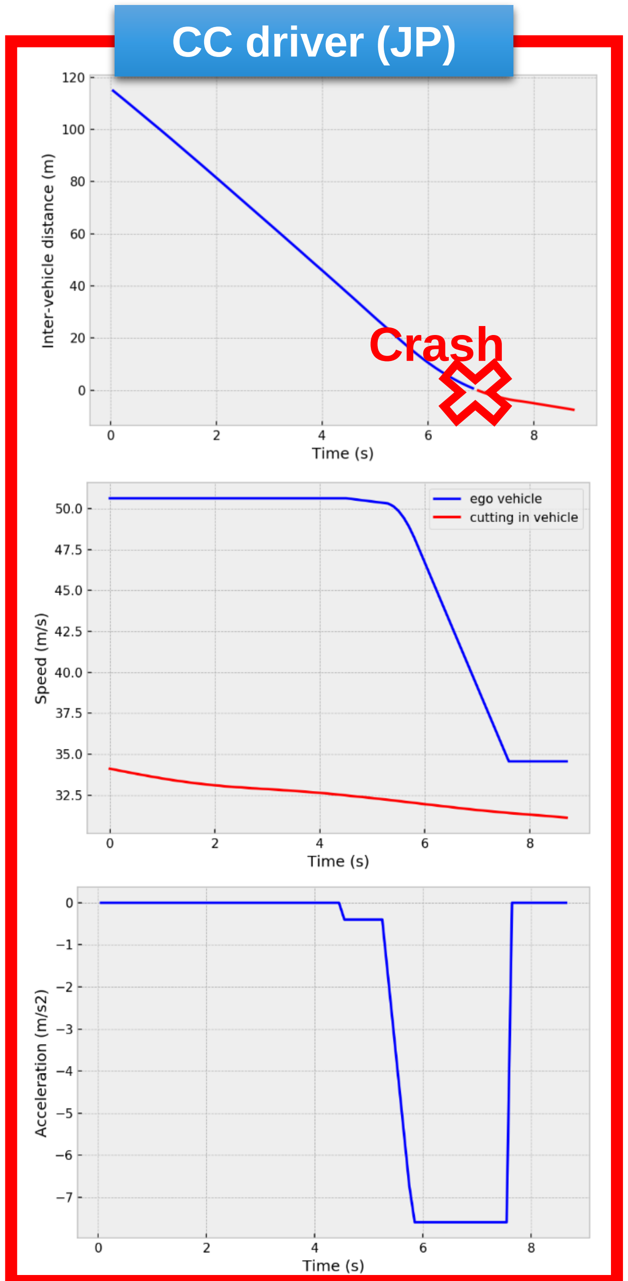


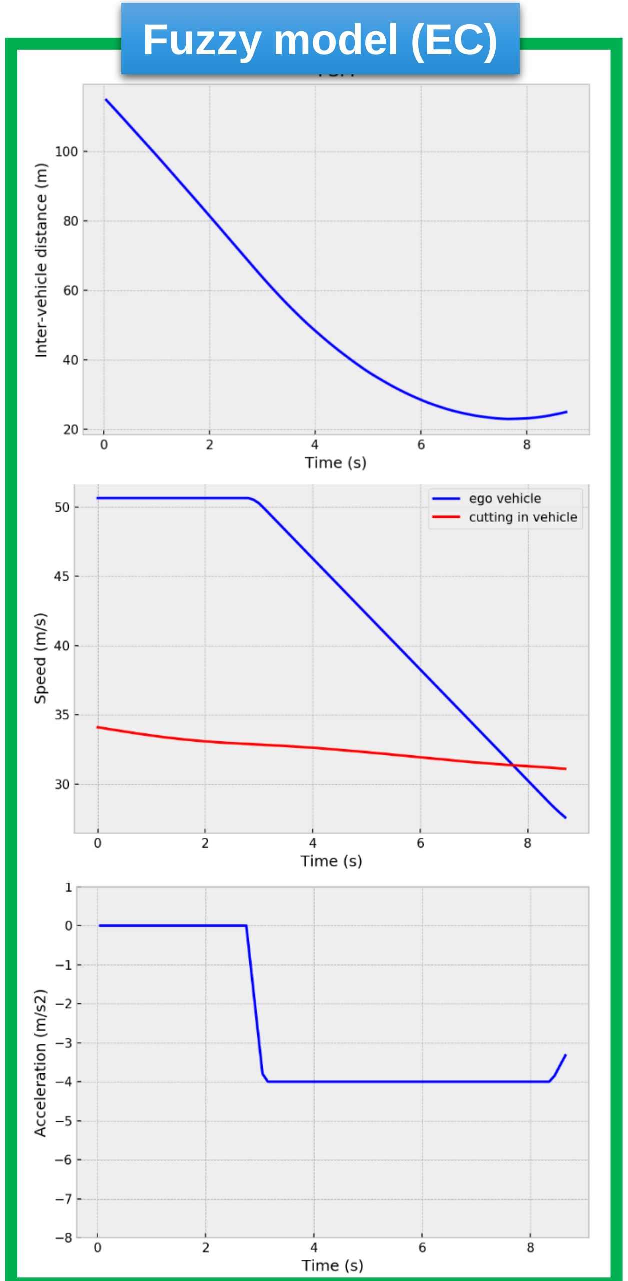
Results of cut-in scenarios: Case B

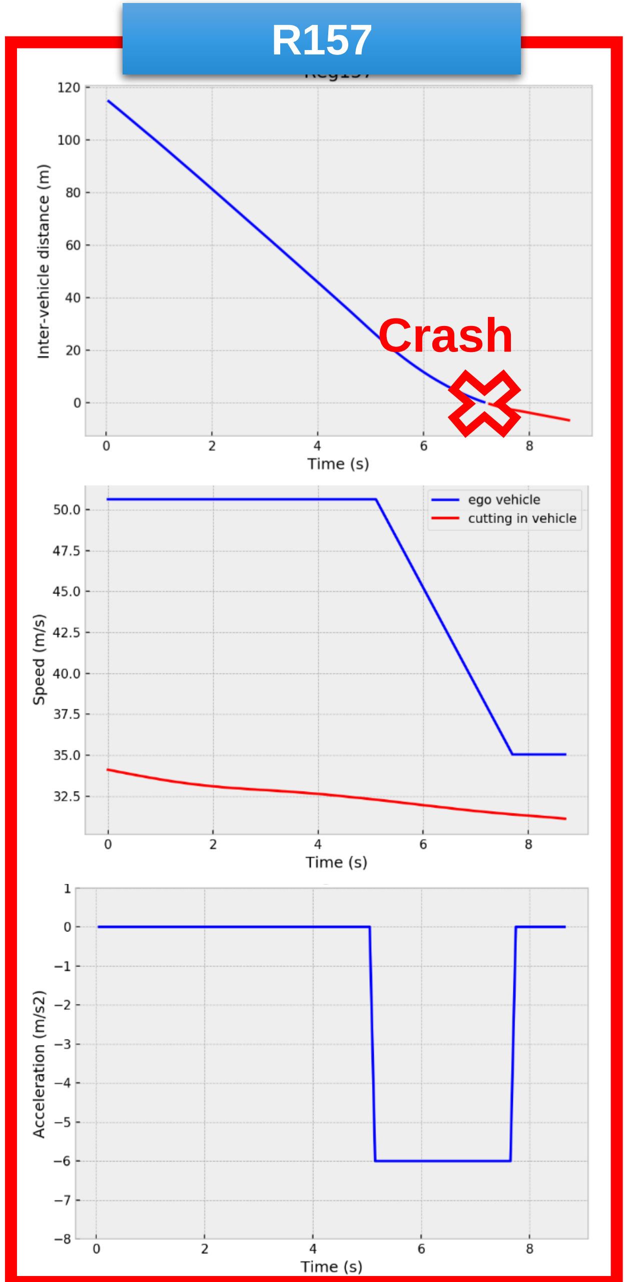


Results of cut-in scenarios: Case C









Results of cut-in scenarios

- **All cases have been correctly classified as preventable using the FSM**

- Overall FSM has shown a behavior that is more similar to a human driver, being able to decelerate earlier and softer to avoid an accident

- For both the **CC human driver model and the Reg157 model, there have been cases that would be considered to be un-preventable**

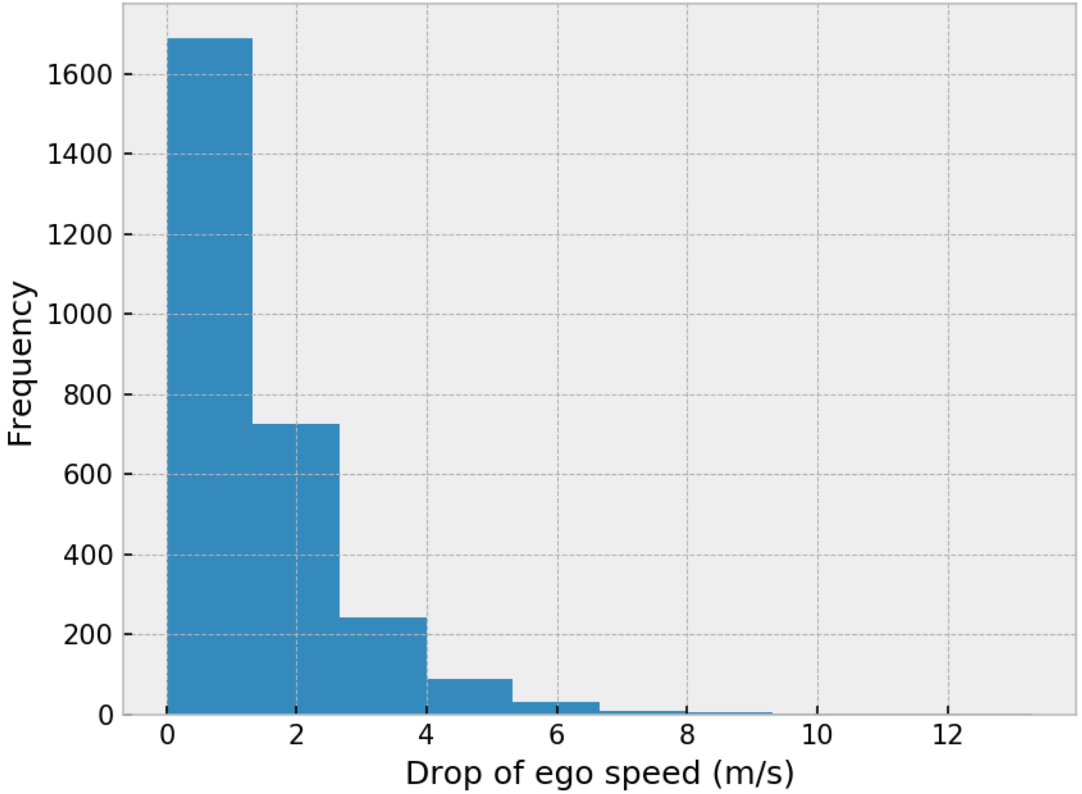
False positives assessment

- Concerns were raised about the possibility that the model would require **too many false positive decelerations in order to achieve a lower number of unpreventable scenarios** compared to the existing performance models
- The highD was used to test false positive cases as well
  - We extracted all trajectories where two vehicles are proceeding in two different lanes without changing lane -> **158,394 observations**

False positives assessment

Even hard decelerations used by the FSM were maintain shortly, only to avoid an imminent danger.

On the cases where the real vehicle didn't decelerate, we see the histogram of the speed drop.



False positives assessment

- Results
  - Due to the lateral movements of the vehicle in the adjacent lane the FSM required a mild deceleration of the ego vehicle in 2,802 cases (1.51%)
  - Only in about 300 cases (0.18%) the drop in velocity was bigger than 2 m/s
  - In less than 50 (0.03%) cases it was bigger than 5 m/s
- These types of speed drops can be explained by a driver **removing the foot from the acceleration pedal** which is compatible with the strategy of a competent and careful human driver
- **Conclusion: false positives do not seem to represent a major issue for the model**

Next steps in the validation

- Look forward to **receiving additional data where to test our model or evidence** that the model **would not be able to perform a correct classification** of preventable or unpreventable scenarios for a C+C human driver

Criticality of cut-in scenarios

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Cut in scenario classification

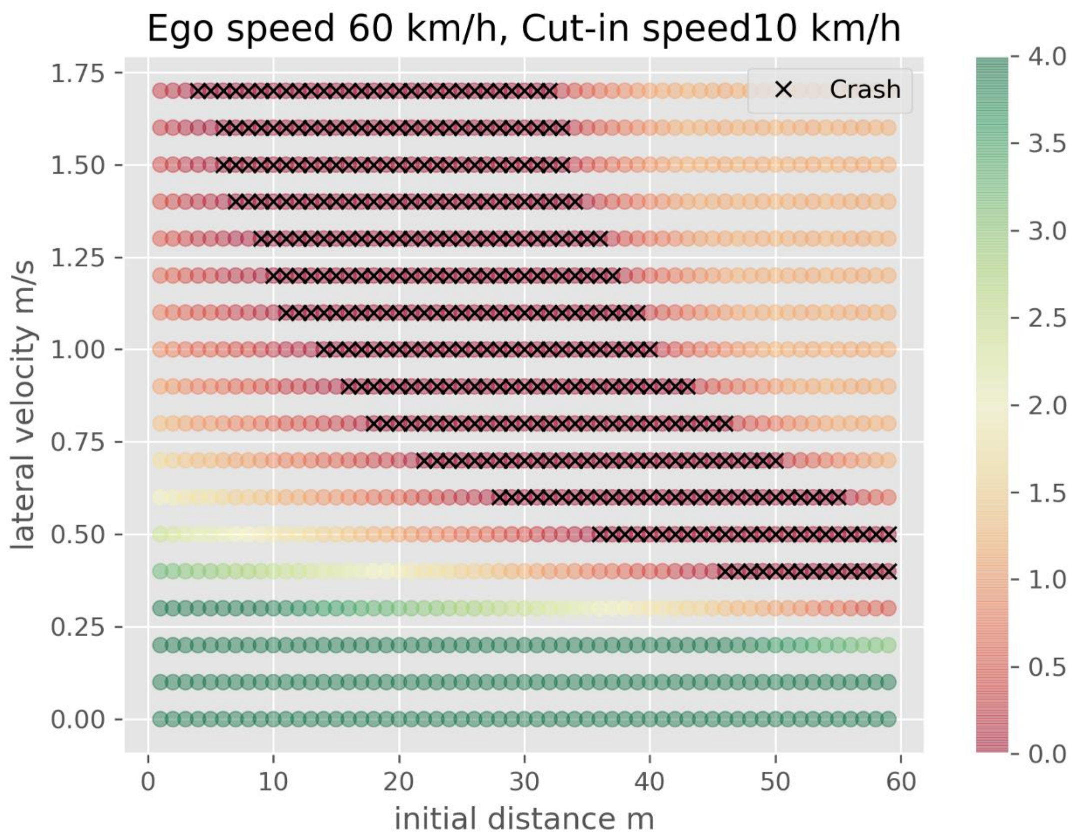
A simulation framework is developed to identify preventable and unpreventable cases.

For the preventable scenarios, it is intuitive that different scenarios would have a **different level of challenge or criticality**. This is of importance to test-track testing, as a number of preventable but challenging scenarios should be tested, but the decision could still be randomized.

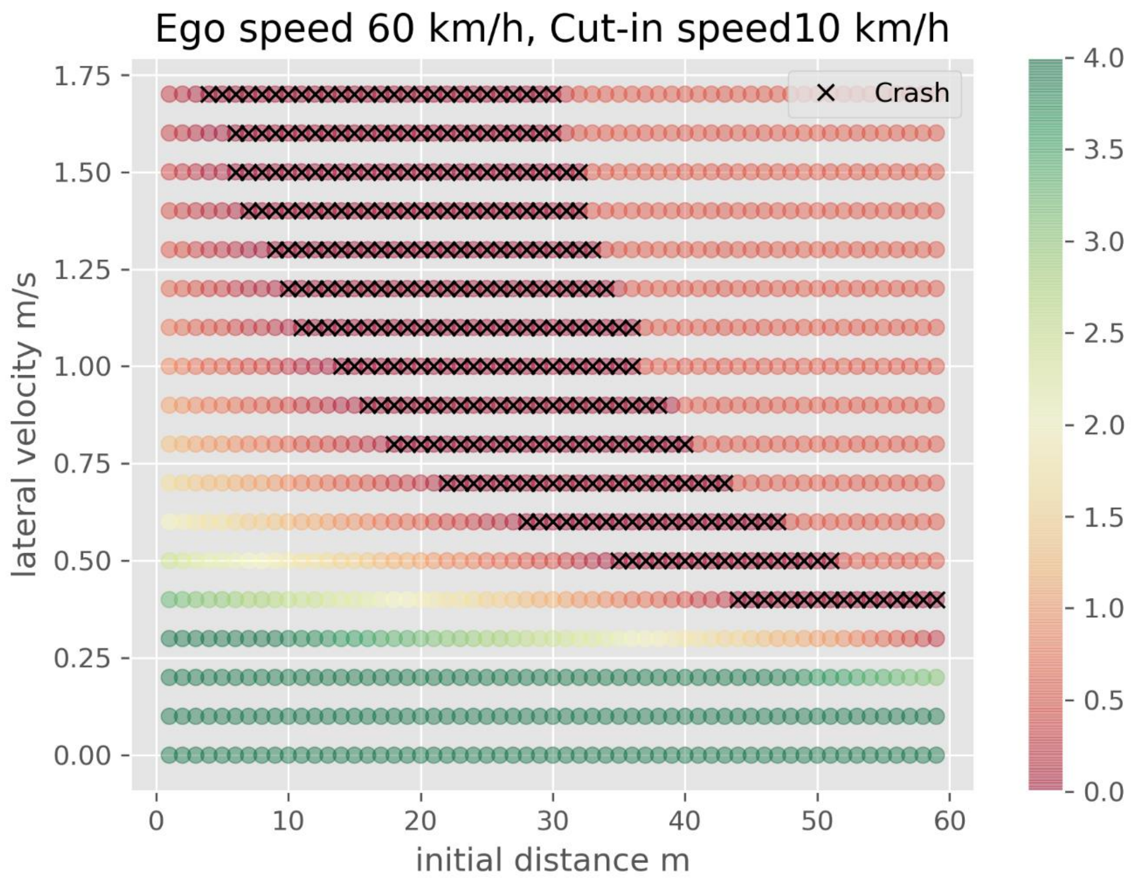
For the preventable cases, using the simulation results, we can try to classify either using the minimum TTC (on 2d) observed, or the Fuzzy SSMs.

Cut in scenario, minimum TTC

CC human driver model



Reg 157 model

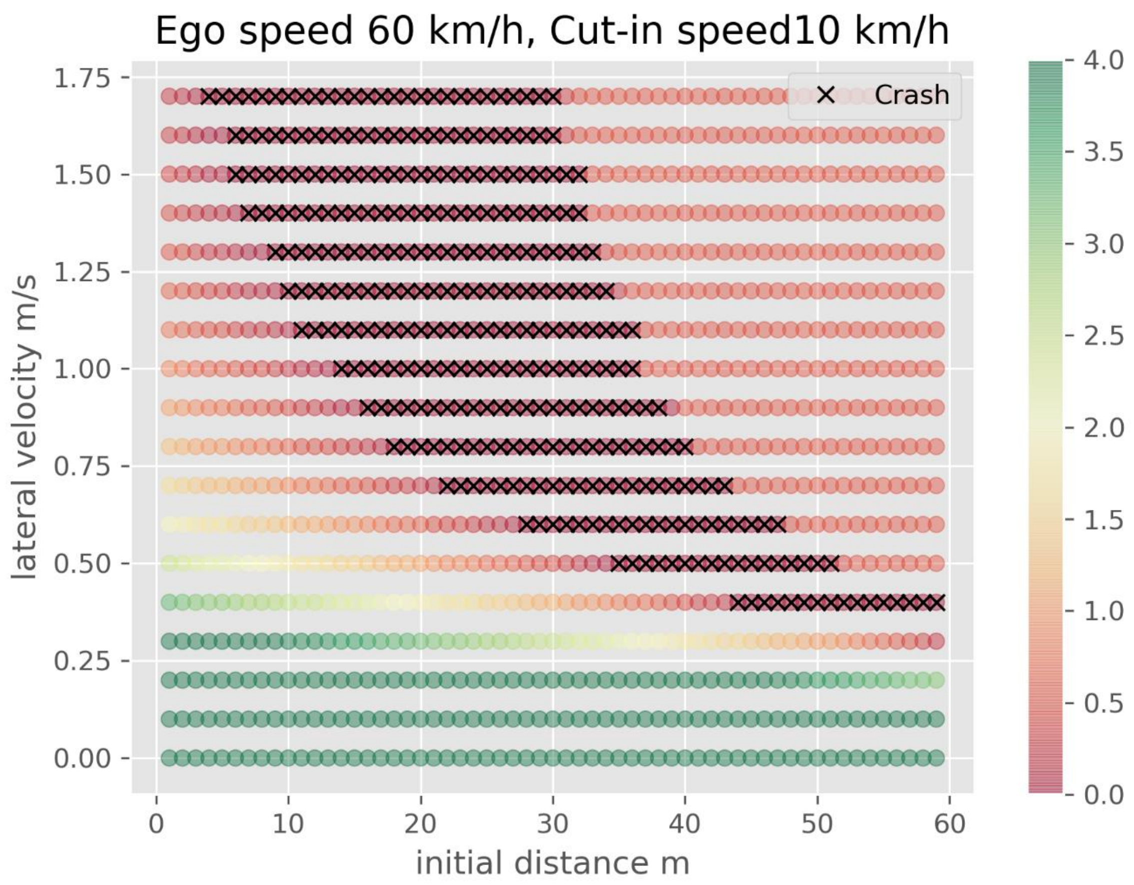


Cut in scenario, minimum TTC

In both cases, the response of the simulated behavior is governed by the TTC value, and the vehicle would react only when the TTC value is small.

Therefore, the TTC values are always critical (when a deceleration is needed).

Reg 157 model



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Cut in scenario, using Fuzzy SSMs

In each simulation, PFS and CFS are calculated for each simulation step. They take values for 0 to 1, with:

PFS = 1, the situation is “proactively unsafe”, the ego vehicle would not avoid an accident in case of a hard deceleration of the preceding vehicle

CFS = 1, the situation is “critically unsafe”, there is a severe conflict, and a very hard deceleration is required

By the maximum value of each scenario we classify in:

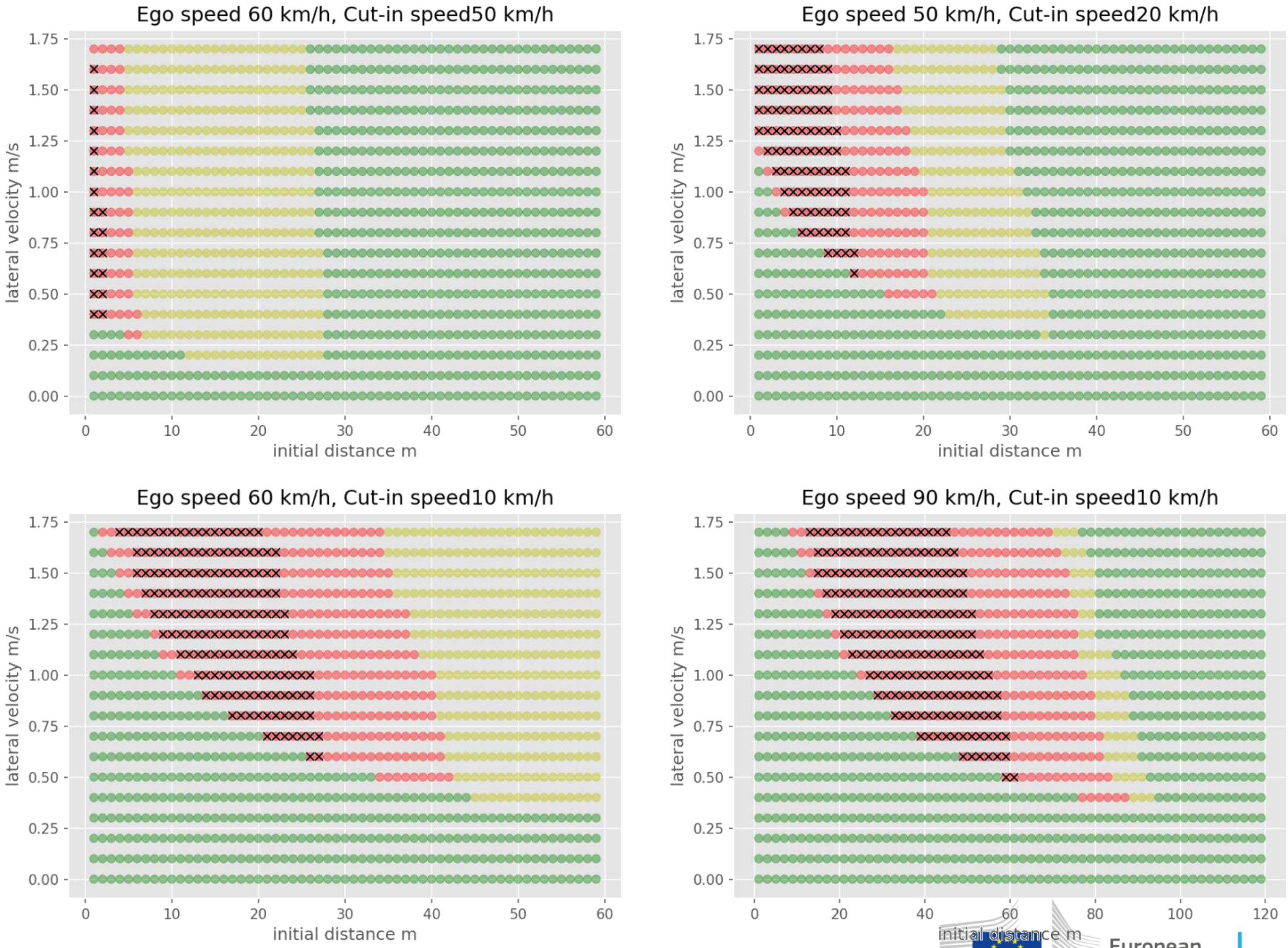
Easy: PFS <=0.85, Medium: PFS>0.85 and CFS <0.9, Hard: CFS=>0.9

Cut in scenario, using Fuzzy SSMs examples

Green: Easy
Not a big challenge for the ADS

Yellow: Medium
More interesting than easy cases

Red: Hard
Most of the scenarios in test track should be hard cases, as they represent the most important challenge to the control



Classification of cut-out and deceleration scenarios

Comparison of different approaches

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Car following scenarios simulated

Steady state speed 2 – 130 kph

Leader's deceleration rate 0.05 – 1 G

Initial distance:

- CC human driver model → 2 sec THW
- RSS model → For time equal to τ, do not enter in d_{unsafe} if the leader vehicle decelerates
- Fuzzy logic model → PFS and CFS = 0

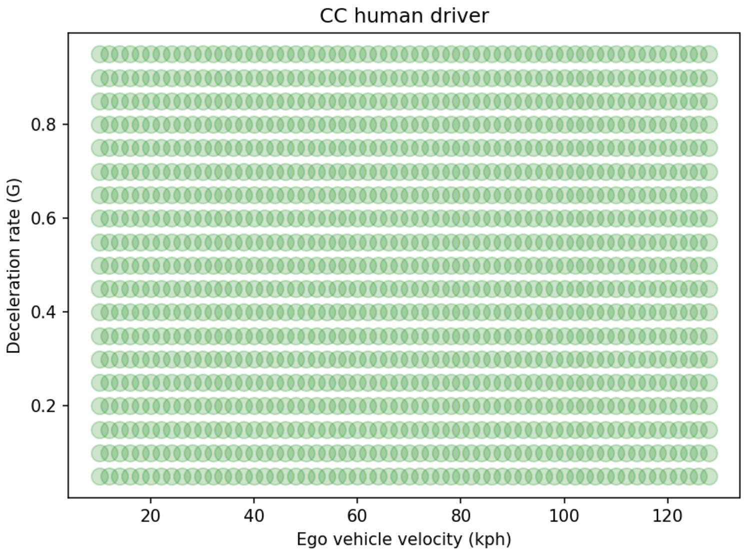
Car following scenarios simulated

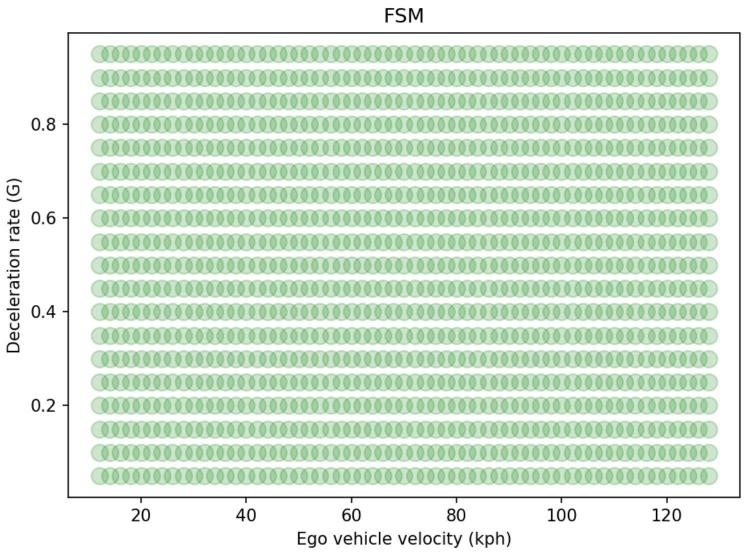
Reaction time starts when:

- CC human driver model → Leader vehicles deceleration harder than 5 m/s^2
- RSS model → Ego vehicle enters d_{unsafe} (could be avoided with calm deceleration)
- Fuzzy logic model → PFS or CFS > 0

Results

- CC human driver model
- RSS model
- Fuzzy logic model





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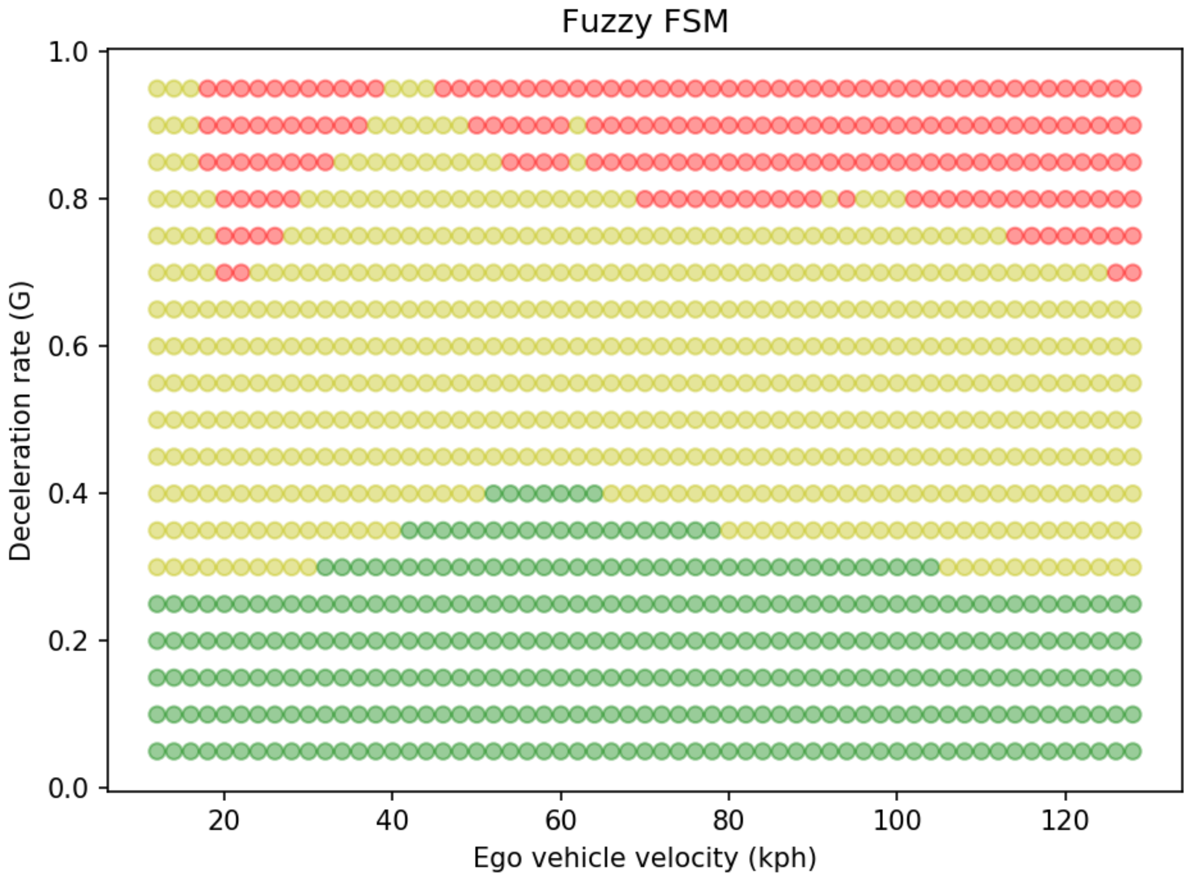
Criticality of deceleration scenarios

The classification works exactly the same as in the cut in.

An issue rises, that the level of challenge of the scenario is affected by the steady state distance.

However, the steady state distance is not a controllable parameter, as it is a function of the AD control.

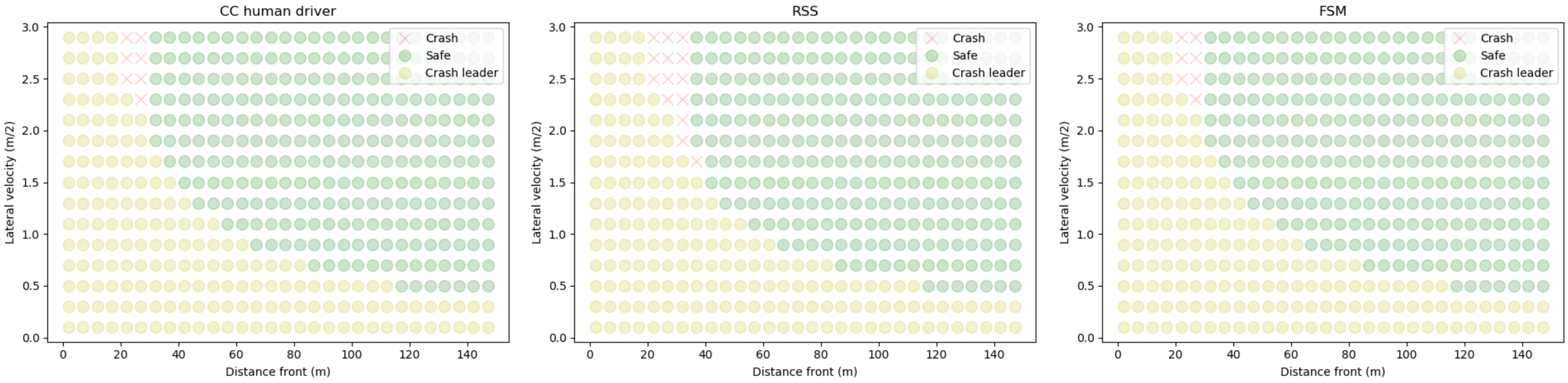
In this case we start with an initial distance for which PFS =0. This is very conservative, but vehicles could have smaller distances if they can show they are safe.



Cut out scenarios Results

For higher speeds there are some crashes for all models.

Example for ego vehicle speed of 110 km/h



Classification for cut out scenarios

As for the car following deceleration scenario, the results are affected by the initial distance.

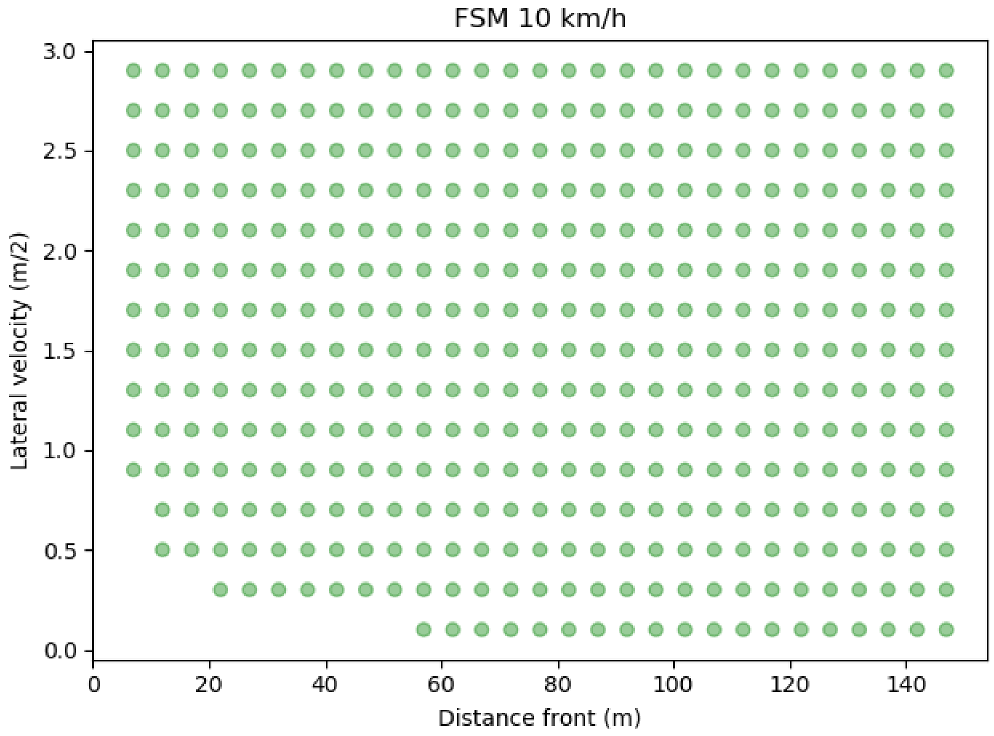
Another issue rises

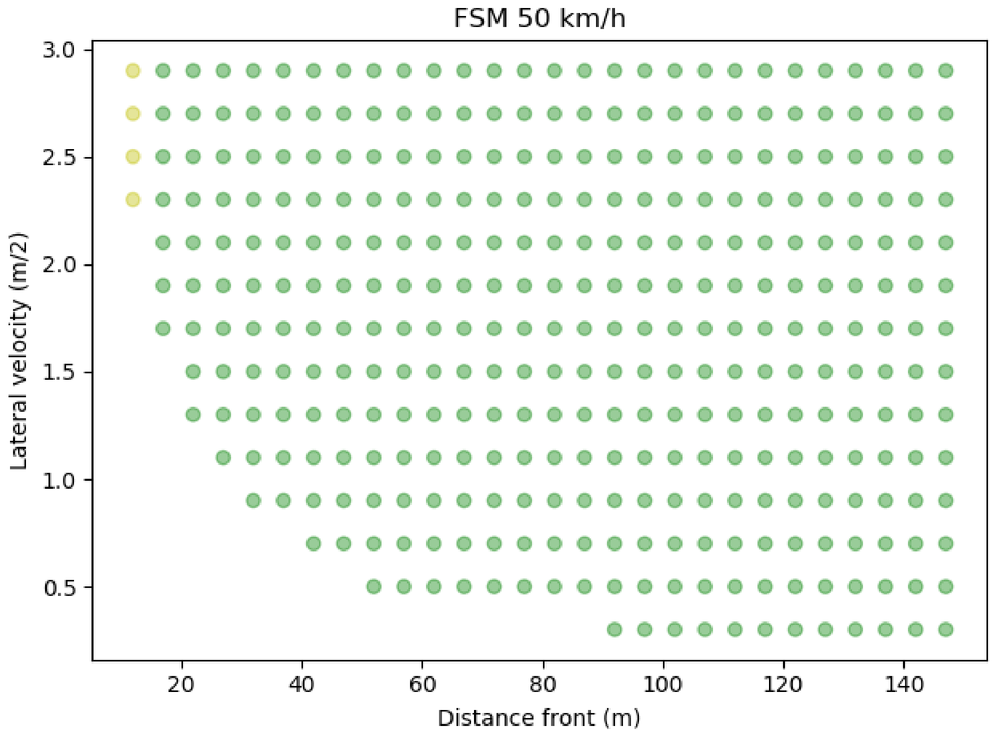
The fuzzy driver model is a very simplistic one. One of the disadvantages is that when approaching a stopped vehicle, PFS and CFS are not that different. Therefore, for this simplistic controller, CFS increases when approaching a stopped target, so the same process for classification as in the other scenarios would produce biased results. This does not affect the preventable/unpreventable scenarios.

This problem is alleviated if the PFS and CFS value used are the values when the risk is first identified (when the preceding vehicle steps out of the wandering zone). However, new classification thresholds can be used. The results seam reasonable.

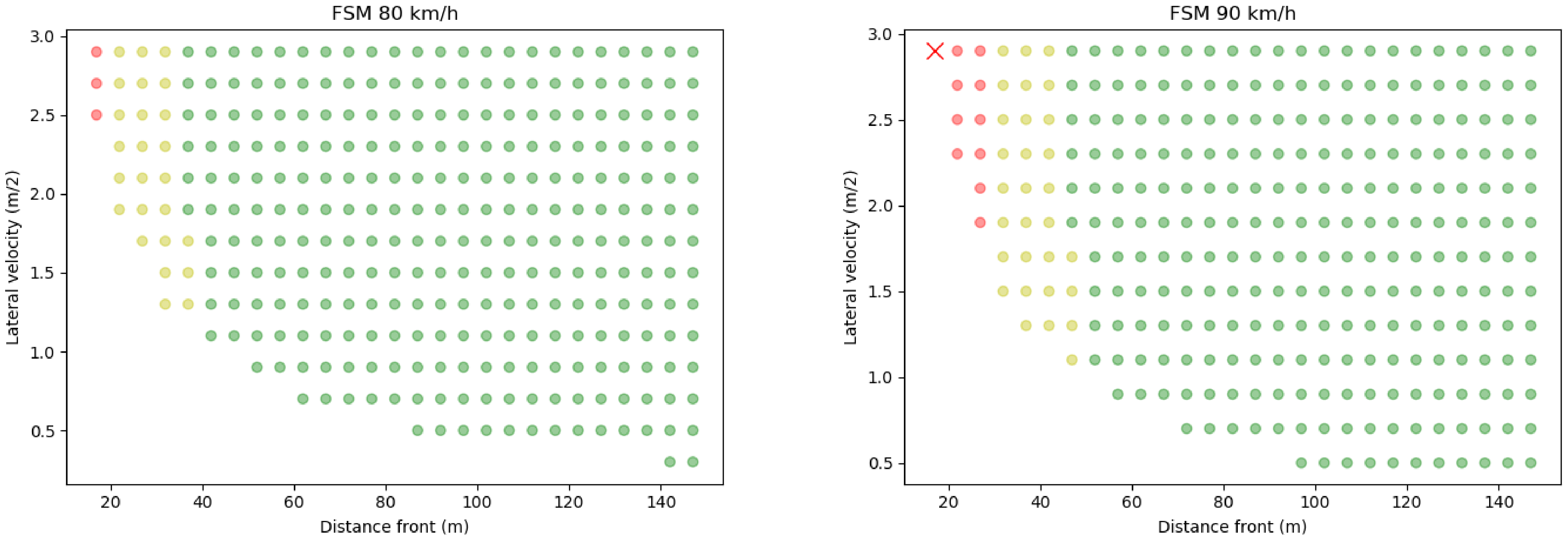
Easy: PFS =0, Medium: PFS>0 and CFS <0.5, Hard: CFS=>0.5

Criticality of cut out scenarios

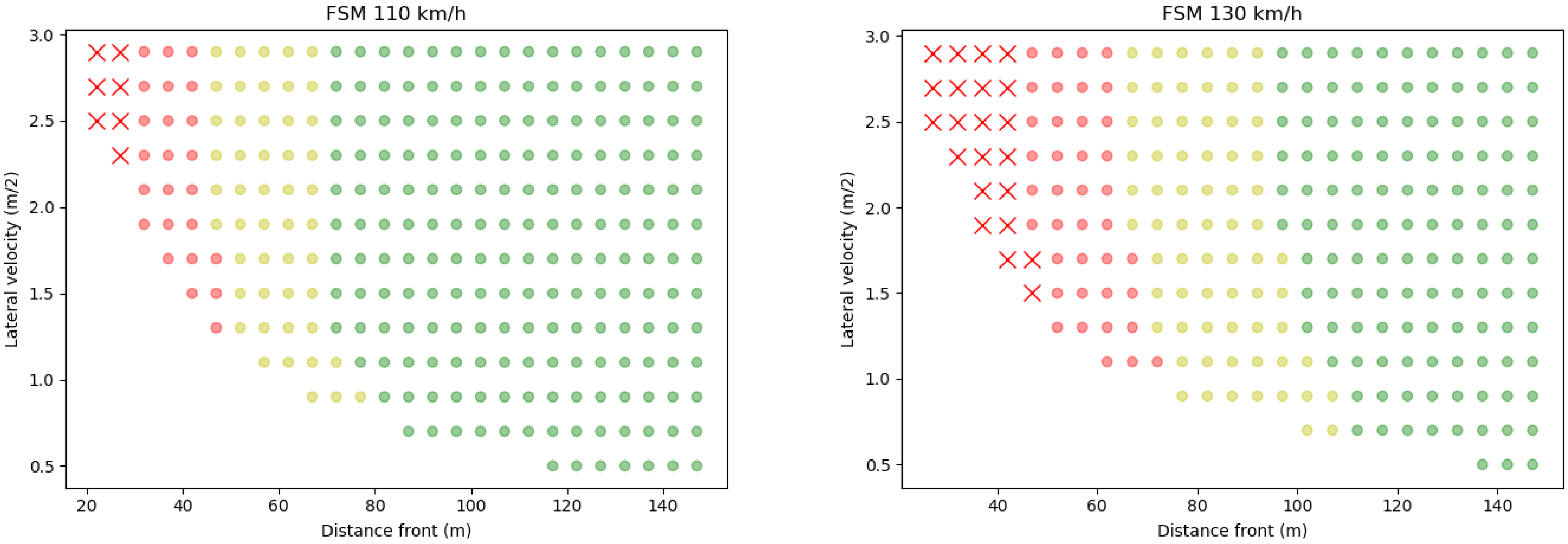




Classification for cut out scenarios



Classification for cut out scenarios



Background on the FSM

New model based on fuzzy SSMs

The new model has 3 main differences with the previous ones

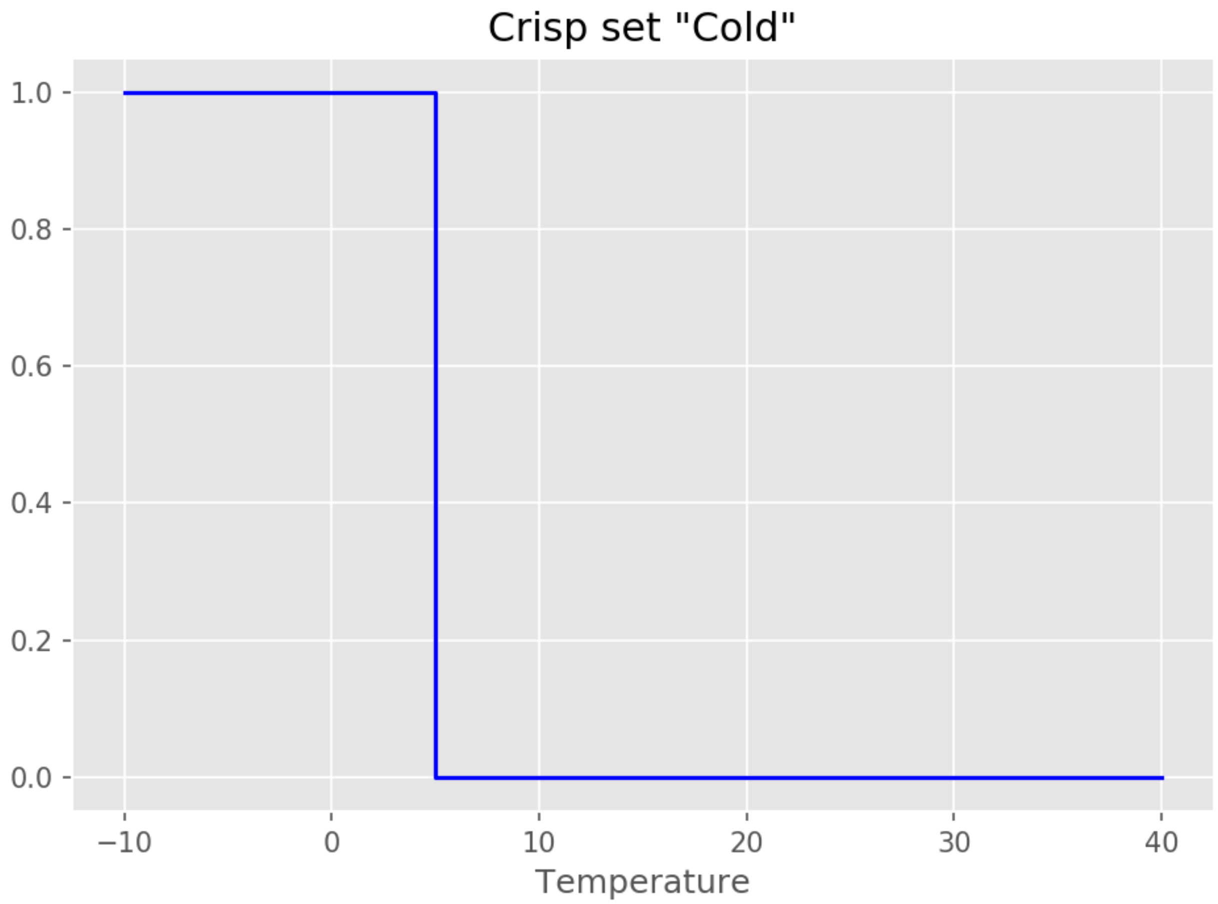
- Different calculation of lateral safe distance
- Longitudinal safe distance according to Fuzzy SSMs
- Capacity for calm proactive reaction

What is Fuzzy Logic? Crisp sets

Classical set is a collection of distinct objects. Any element is either in a set or not.

We can describe a set by its characteristic function. It takes the value 1 for elements that are in the set and the value 0 for elements that are not in the set

The sets are ‘Crisp’

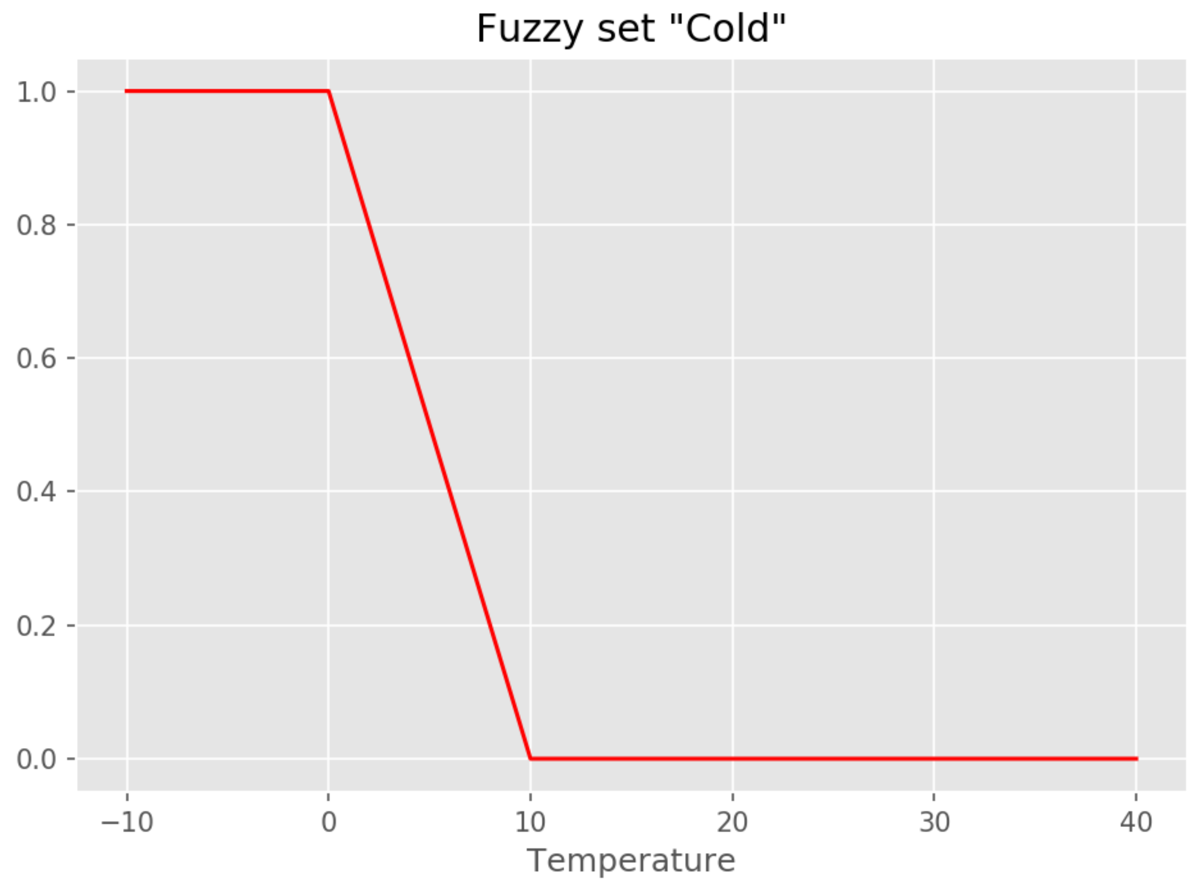


What is Fuzzy Logic? Fuzzy sets

Characteristic functions of Fuzzy sets can take all values from 0 to 1

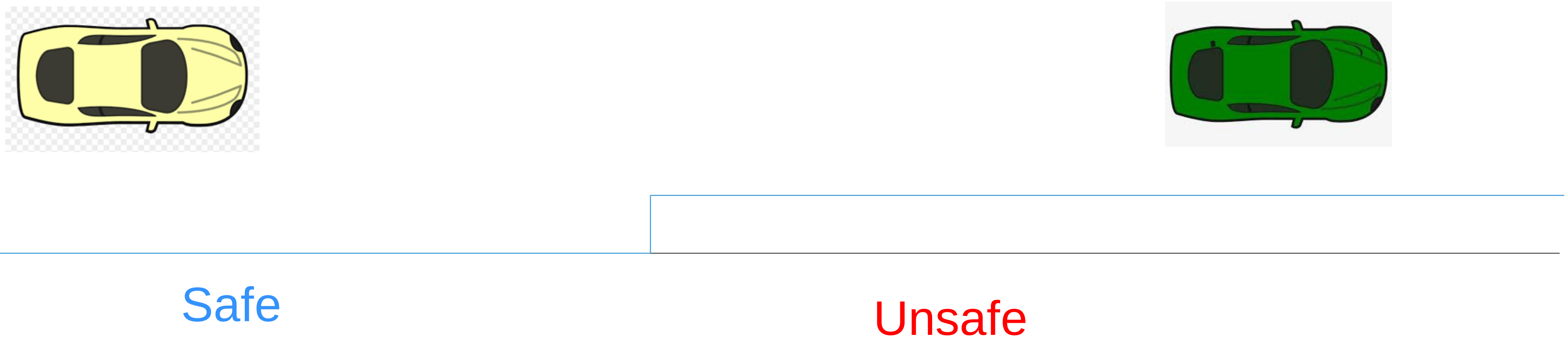
This can be helpful in many cases to better describe a situation

Based on those we can create fuzzy rules



Why Fuzzy logic

Two vehicles with known speeds. What is a safe distance?



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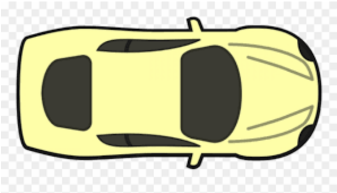

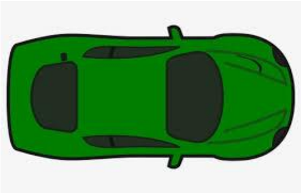

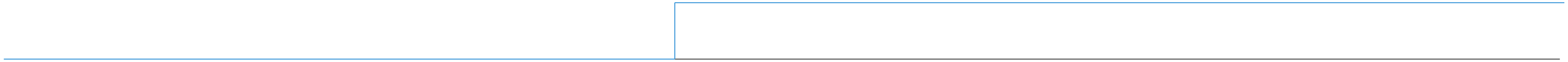

Safe
Do nothing

Unsafe
Decelerate hard

Why Fuzzy logic

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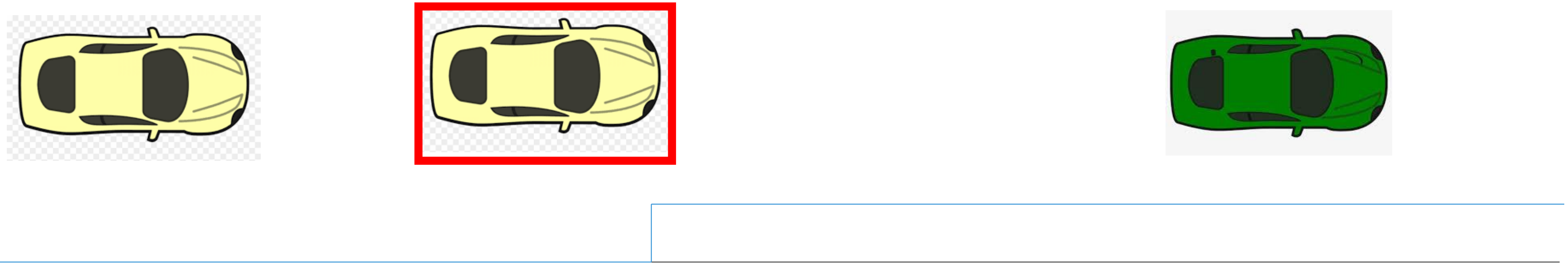

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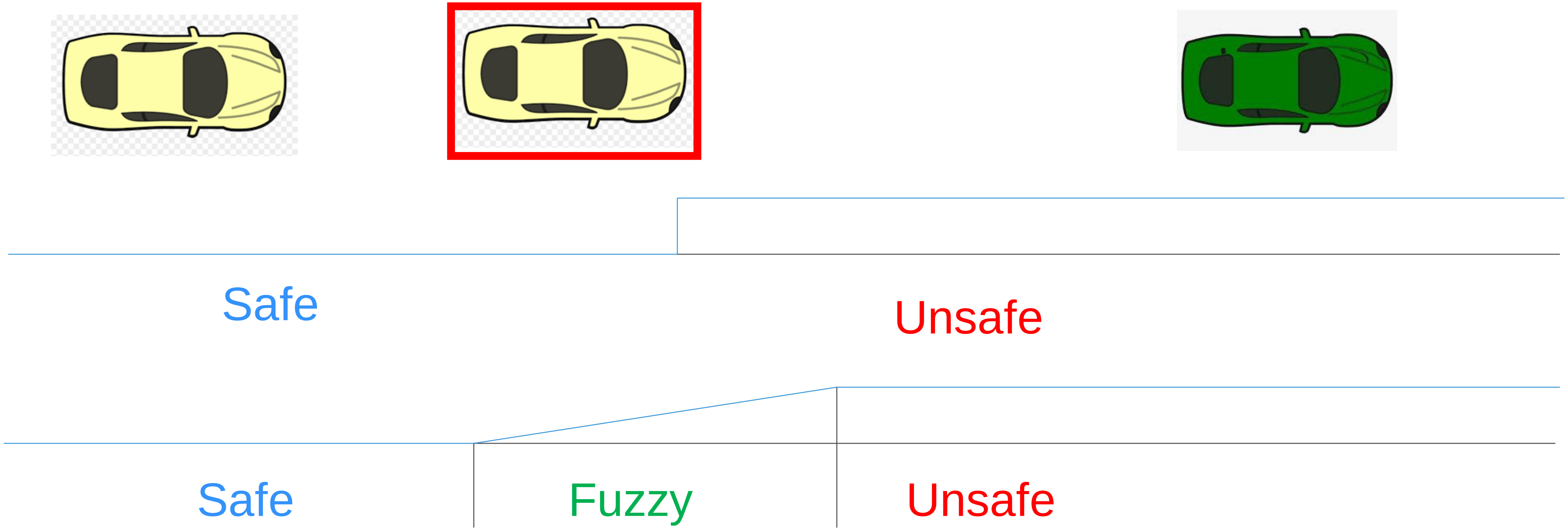

Why Fuzzy logic

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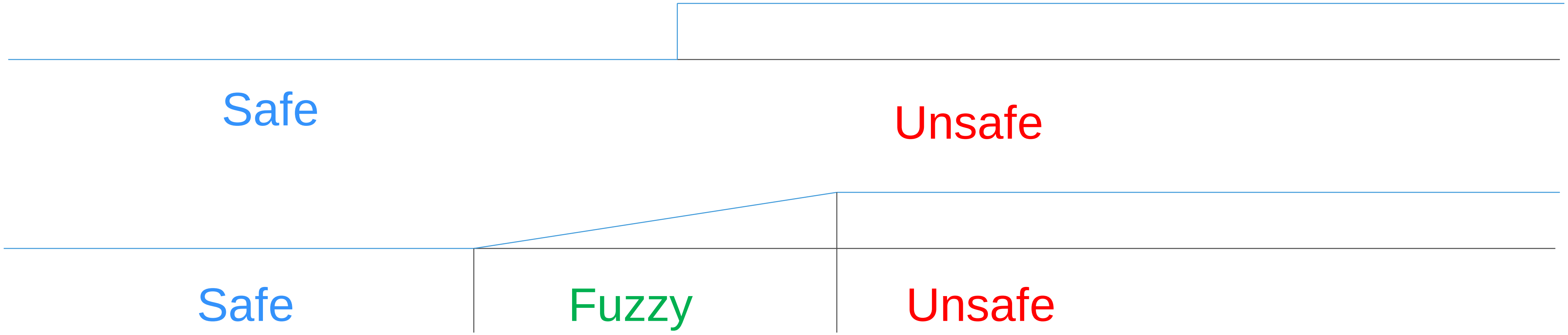


The more unsafe, the harder the vehicle must decelerate

New model based on fuzzy SSMs

The new model has a number of differences with the previous ones

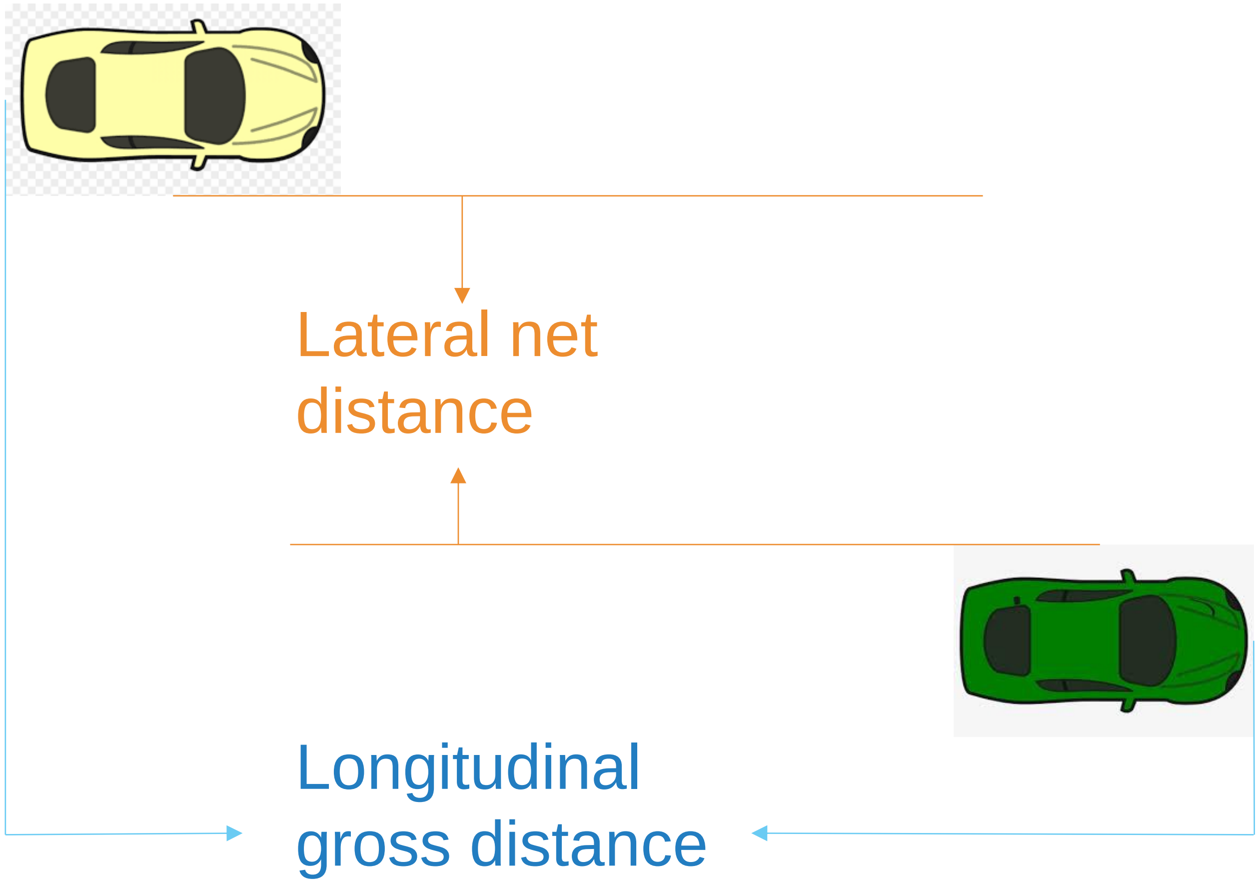
- Different calculation of lateral safe distance (cut-in scenario)
- Longitudinal safe distance according to Fuzzy SSMs
- Capacity for calm proactive reaction

Different calculation of lateral safe distance

1. The cutting in vehicle has to be in front of the ego vehicle
2. The cutting in vehicle has lateral speed towards the ego vehicle
3. The lateral net time headway < The longitudinal gross TTC + 0.1 sec

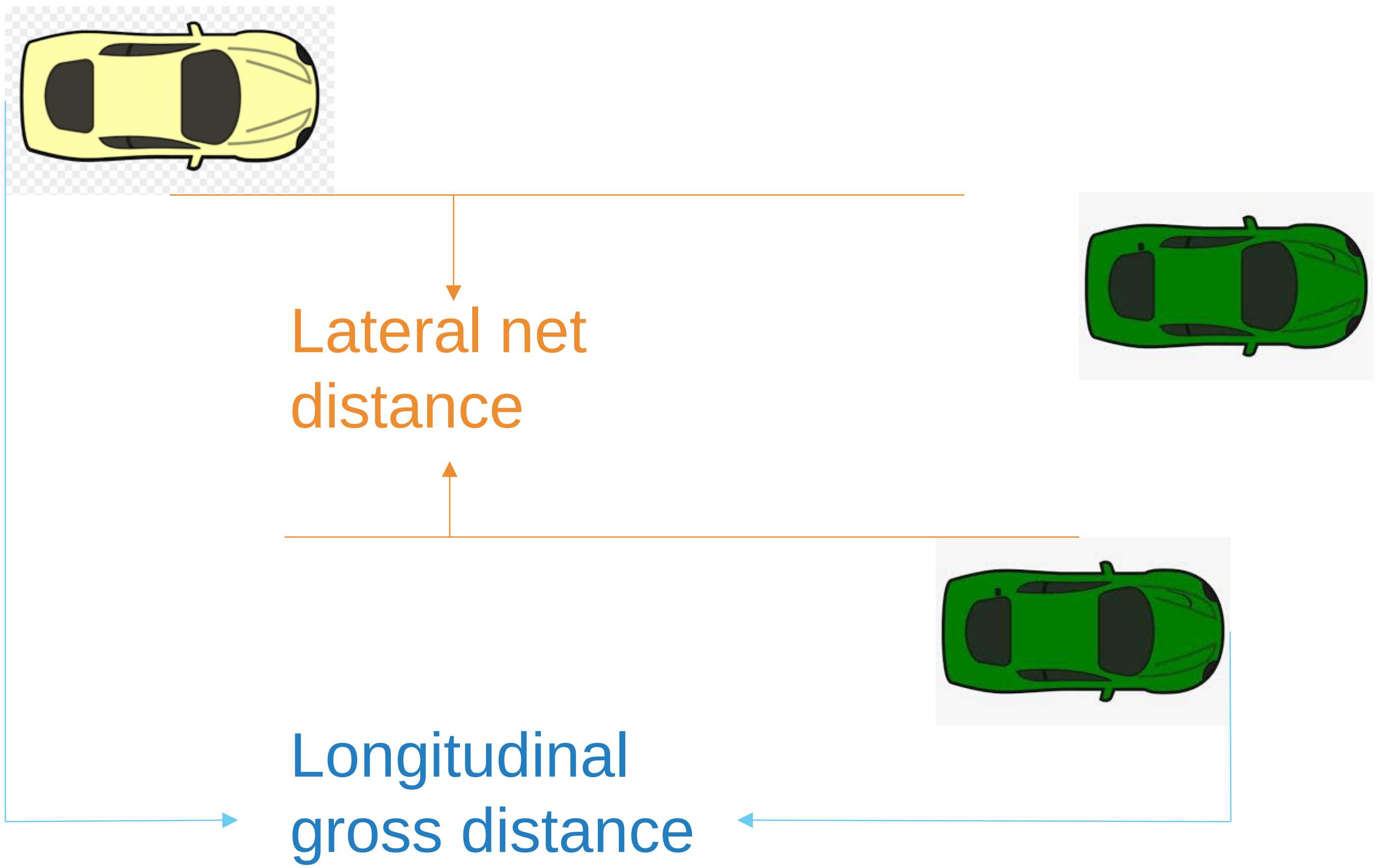
If all three restrictions apply, then we have to check the situation for the longitudinal safe distance

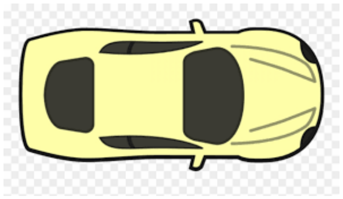
Different calculation of lateral safe distance



- The lateral net distance the space between the vehicles laterally
- The longitudinal gross distance is the longitudinal space from the rear of the ego vehicle to the front of the cutting in vehicle
- To calculate headway, they have to be divided to the cutting in vehicle lateral speed and the approaching speed respectively

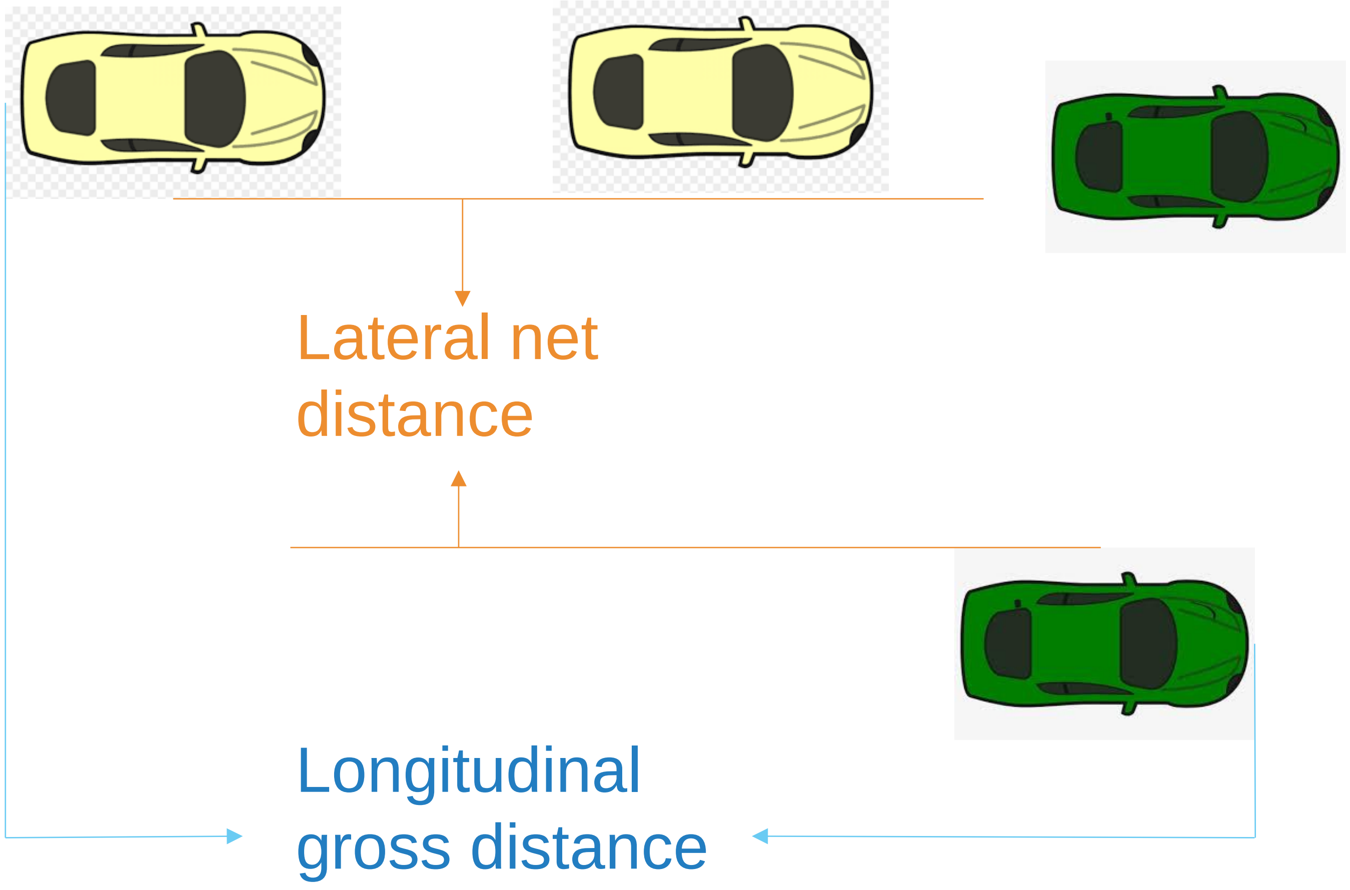
Different calculation of lateral safe distance





If the lateral net time headway > The longitudinal gross TTC+ 0.1 sec, the cut-in is very slow and the ego vehicle will not have to decelerate

Different calculation of lateral safe distance



Else, if the longitudinal distance is long and the cut-in speed is slow, it goes to the longitudinal safety part and may be considered safe at the end

Different calculation of lateral safe distance

Advantages

- Less parameters needed
- Less information that may induce errors (lane markings)
- Cases when the vehicles deceleration causes an accident are avoided
- Slow lane changes for vehicles in a distance are also considered

Longitudinal safe distance according to Fuzzy SSMs

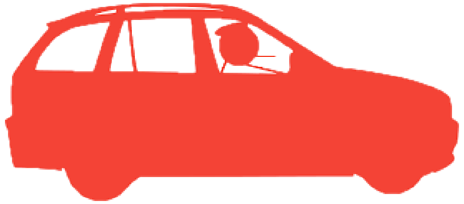
Two different definitions of unsafe:

- If the leader vehicle decelerates, the follower vehicle cannot avoid an accident (Vienna Convention on Road Traffic)
- If nothing changes, there will be a collision in x sec (TTC)

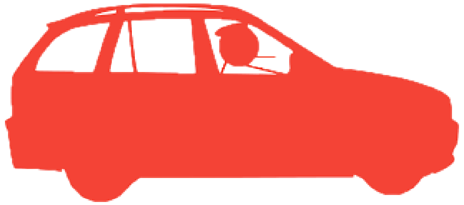
We calculated the Proactive Fuzzy SSM (PFS) and the Critical Fuzzy SSM (CFS)

Longitudinal safe distance according to Fuzzy SSMs

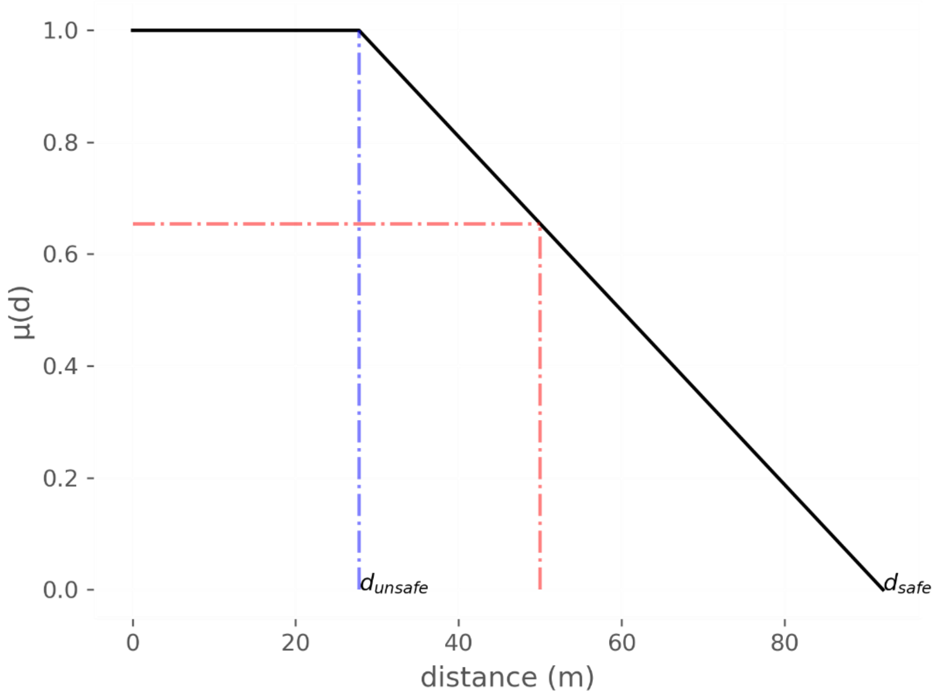
Maximum
Unsafe
distance



Minimum
Safe
distance



$$\mu_A(d) = \begin{cases} 1 & , \quad 0 < d < d_{unsafe} \\ 0 & , \quad d > d_{safe} \\ \dfrac{d - d_{safe}}{d_{unsafe} - d_{safe}} & , \quad d_{unsafe} < d < d_{safe} \end{cases}$$

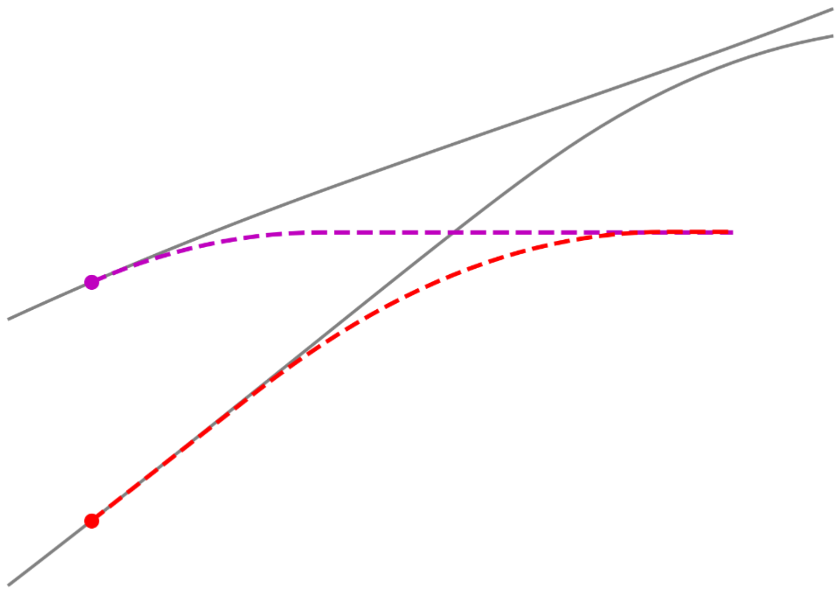


Longitudinal safe distance according to Fuzzy SSMs

PFS: If the leader vehicle decelerates, the follower vehicle cannot avoid an accident

$$d_{safe}(t) = u_2(t)\tau + \frac{u_2^2(t)}{2b_{2comf}} - \frac{u_1^2(t)}{2b_{1max}}$$

$$d_{unsafe}(t) = u_2(t)\tau + \frac{u_2^2(t)}{2b_{2max}} - \frac{u_1^2(t)}{2b_{1max}}$$



Longitudinal safe distance according to Fuzzy SSMs

CFS: If nothing changes, there will be a collision

$$a_2'(t) = \max(\, a_2(t), -b_{2comf})$$

$$u_2(t+\tau) = u_2\, a_2'(t)$$

If $u_2(t+\tau) \leq u_1(t)$*:*

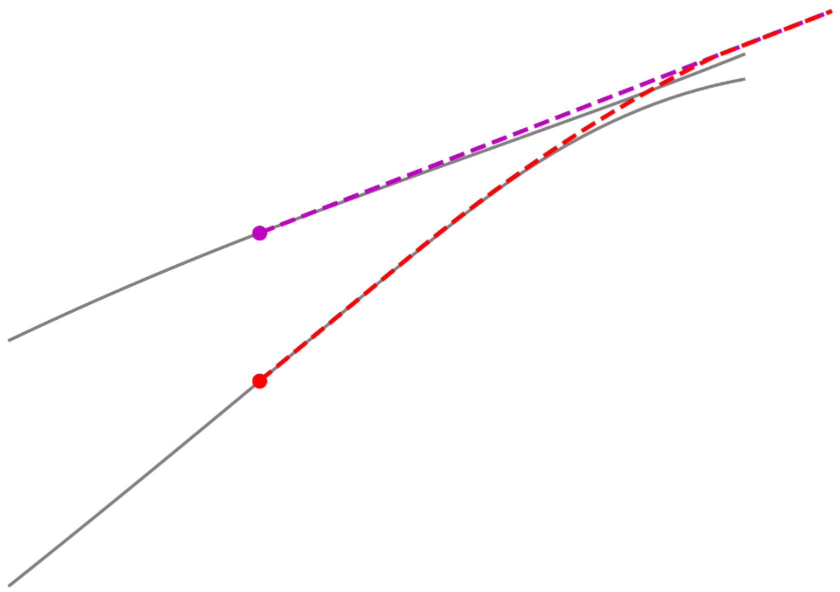
$$d_{safe}(t) = d_{unsafe}(t) = \frac{(u_2(t) - u_1(t))^2}{2a_2'(t)}$$

Else if $u_2(t+\tau) > u_1(t)$*:*

$$d_{new} = \left(\frac{(u_2(t)+u_2(t+\tau))}{2} - u_1(t)\right)\tau$$

$$d_{safe}(t) = d_{new} + \frac{\left(u_2(t)+a_2'(t)\tau - u_1(t)\right)^2}{2b_{2comf}}$$

$$d_{unsafe}(t) = d_{new} + \frac{\left(u_2(t)+a_2'(t)\tau - u_1(t)\right)^2}{2b_{2max}}$$



Capacity for calm proactive reaction

The deceleration is relative to the values of PFS and CFS

PFS value of 1 induces full comfortable deceleration (e.g. 3 m/s^2)

CFS value of 1 induces full deceleration (e.g. 6 m/s^2)

PFS value of 0.2 induces 20% of comfortable deceleration (e.g. 0.6 m/s^2)

- The suggested model has the ability to apply a calm deceleration proactively, to avoid getting into a more serious (and possibly unavoidable) conflict

Thank you