FRAV-12-06, submitted by the European Commission
12th FRAV session, 8 April 2021

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Fuzzy-logic based performance model for motorway traffic scenarios

Description and first results

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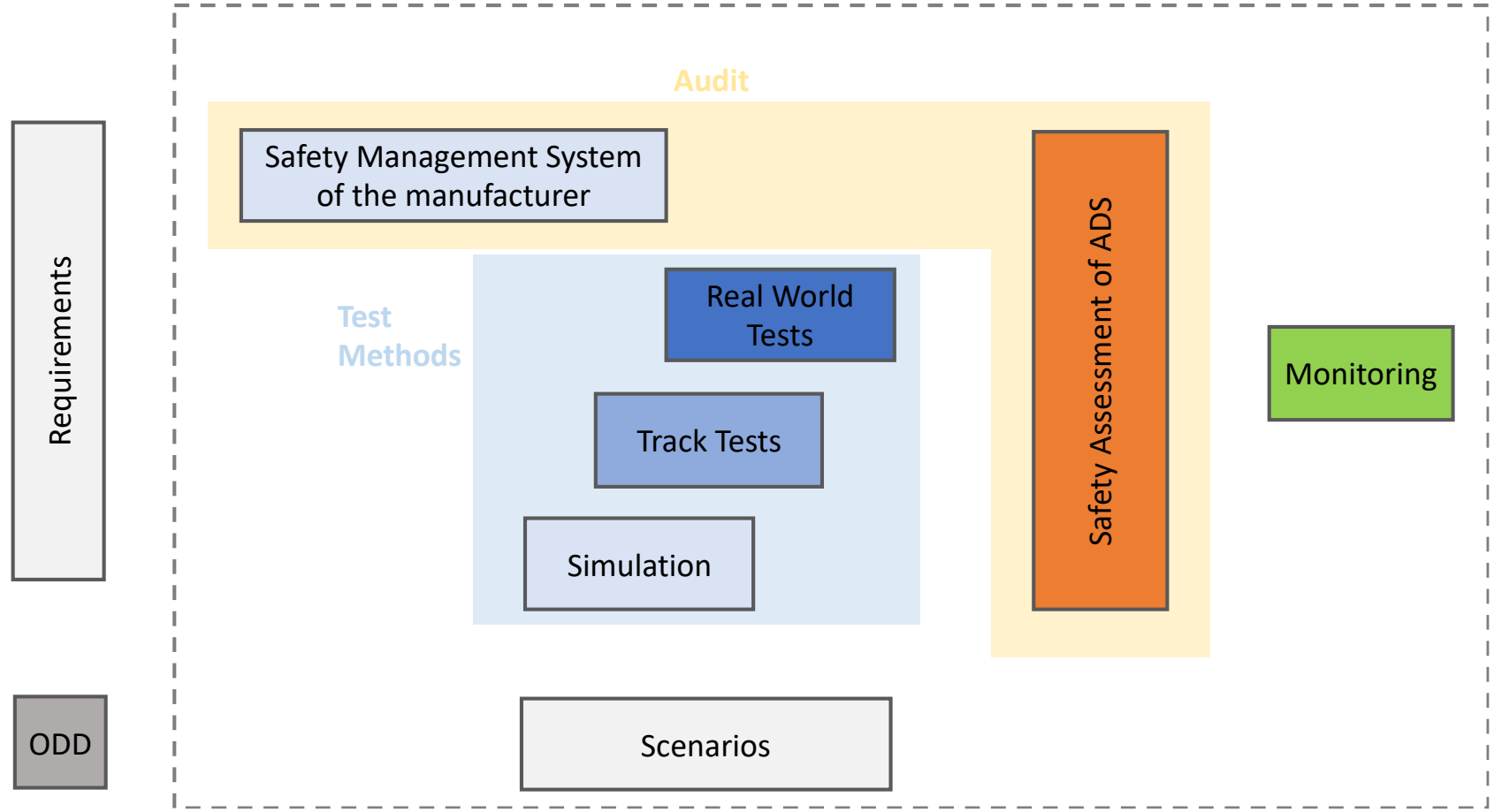
Joint Research Centre

Assessment of ADS safety in GRVA/VMAD*



* *VMAD-16-06 NATM MASTER DOCUMENT*

What type of Requirements?

- **Behavioural/Operational Requirements** affect parameters of ADSs operations (e.g. target speed, acceleration, deceleration, headway, etc.)
  - Pros. -> clear and easily verifiable
  - Cons. -> limit OEMs' freedom, may hinder innovation, side effects possible, difficult to be linked with overall safety/efficiency targets
- **Performance Requirements** define situations that the ADS shall be able to handle (e.g. should be able to avoid collision, have a collision probability of X etc.) without saying how to handle them
  - Pros. -> give freedom to OEMs and foster innovation, focus on safety/efficiency targets
  - Cons. -> not always easy to be verified

Use of performance requirements

- **Performance Requirements can be used to:**
  - Identify those scenarios that the vehicle shall be able to handle (**deterministic use**)
    - Pros -> no need to take into account severity and likelihood of the scenario
    - Cons -> too much related to the correctness of the performance criteria
  - Define the probability of an accident occurrence among the scenarios considered in the assessment (**probabilistic use**)
    - Pros -> uncertainty in performance requirements better handled
    - Cons -> need to complement the probability with other risk-related measures like severity and likelihood

Example. Cut-in scenarios in Reg 157

- Paragraph 5.2.5 introduces two performance requiremet models for car-following, cut-in and cut-out. In particular:
  - 5.2.5.2. defines the performance model for cut-in,
  - 5.2.5. refers to Appendix 3 to Annex 4 for the performance model for cut-in, 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:

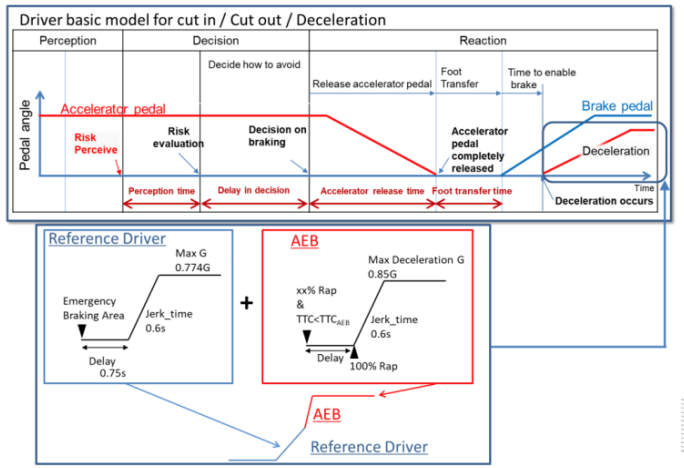
$$TTCLaneIntrusion > vrel/(2 \cdot 6m/s^2) + 0.35s$$

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.

Cut-in, car-following and cut-out



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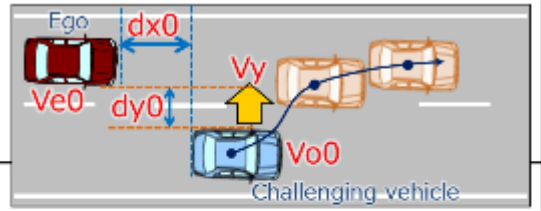
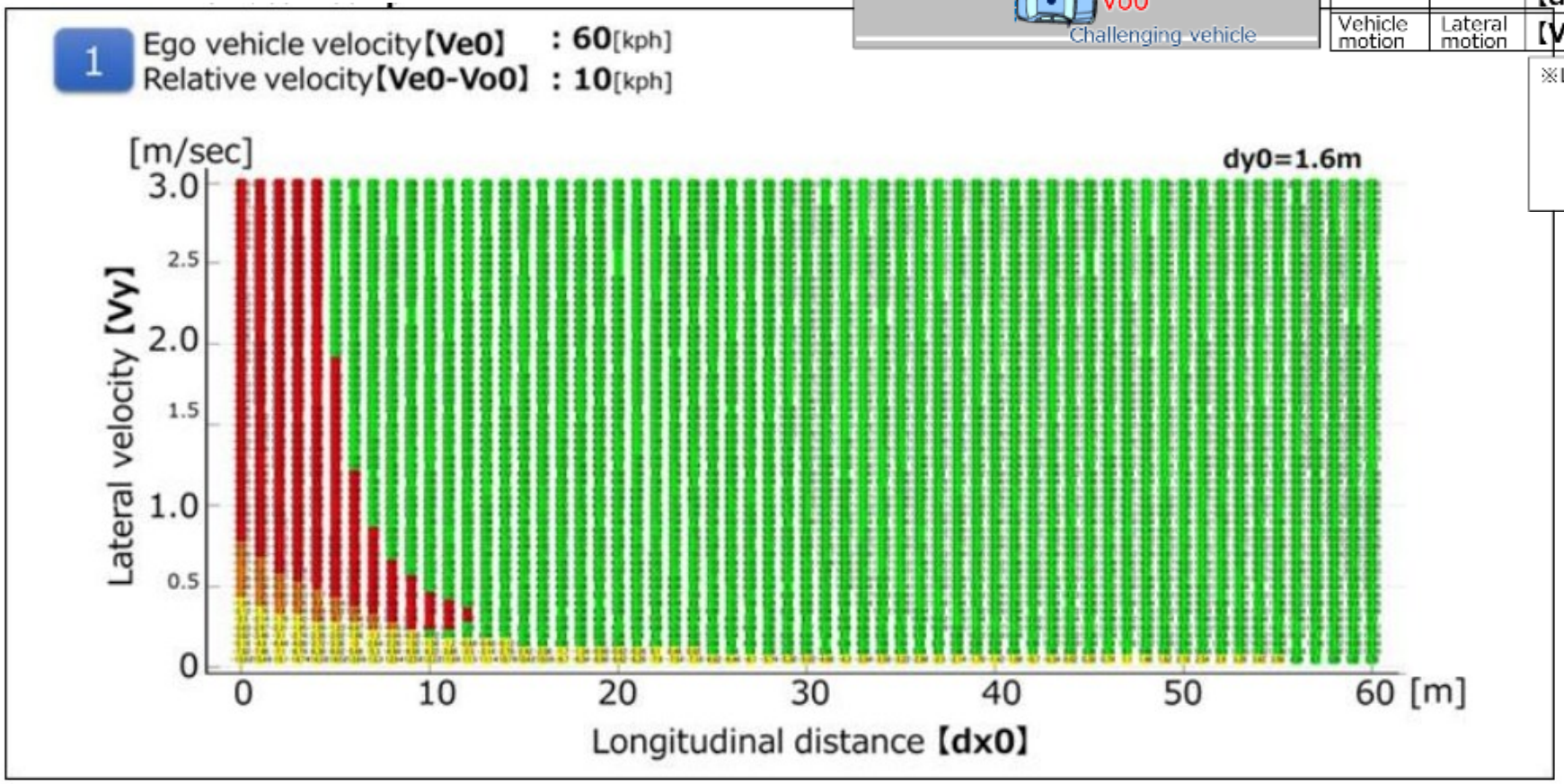
Example. Cut-in scenarios in Reg 157 Appendix 3 model



Initial condition	Initial velocity	【Ve0】	Ego vehicle velocity
		【Ve0-Vo0】	Relative velocity
	Initial distance	【dy0】	Latteral distance※
		【dx0】	Longitudinal distance
Vehicle motion	Lateral motion	【Vy】	Lateral velocity

※Latteral distance

ex) Lane width : 3.5[m]
Vehicle width:1.9[m]
Driving in the center of the lane
dy=1.6[m]



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Example. Cut-in scenarios in Reg 157

- The two proposed performance models are equally valid approaches to determine “unpreventable” cut-ins
- Their only limitation is to always treat the cut-in as an “emergency” situation in which the vehicle has either to do nothing or to apply maximum deceleration capabilities
- In reality humans (as well as the future ADSs) apply proportionate reactions and count very much on anticipation (***tactical safety***)

Assessment of current performance requirements

- In order to understand whether the two approaches are ambitious enough we have compared them with other two approaches recently being presented
  - **The Intel's Mobileye Responsibility-Sensitive Safety (RSS)***
  - **The JRC Fuzzy-logic based Model****
- Parameters used in the two models for the comparison (system reaction time, acceleration, deceleration, jerk) are the same proposed by the **Reg157 Appendix 3 model**

* Shalev-Shwartz, S., S. Shammah, and A. Shashua (2017) On a Formal Model of Safe and Scalable Self-Driving Cars. *arXiv:1708.06374 [cs, stat]*

** Mattas et al. (2020) Fuzzy Surrogate Safety Metrics for real-time assessment of rear-end collision risk. A study based on empirical observations. *Accident Analysis and Prevention 148*

New model based on fuzzy SSMs

The new model has 3 main differences with the previous ones

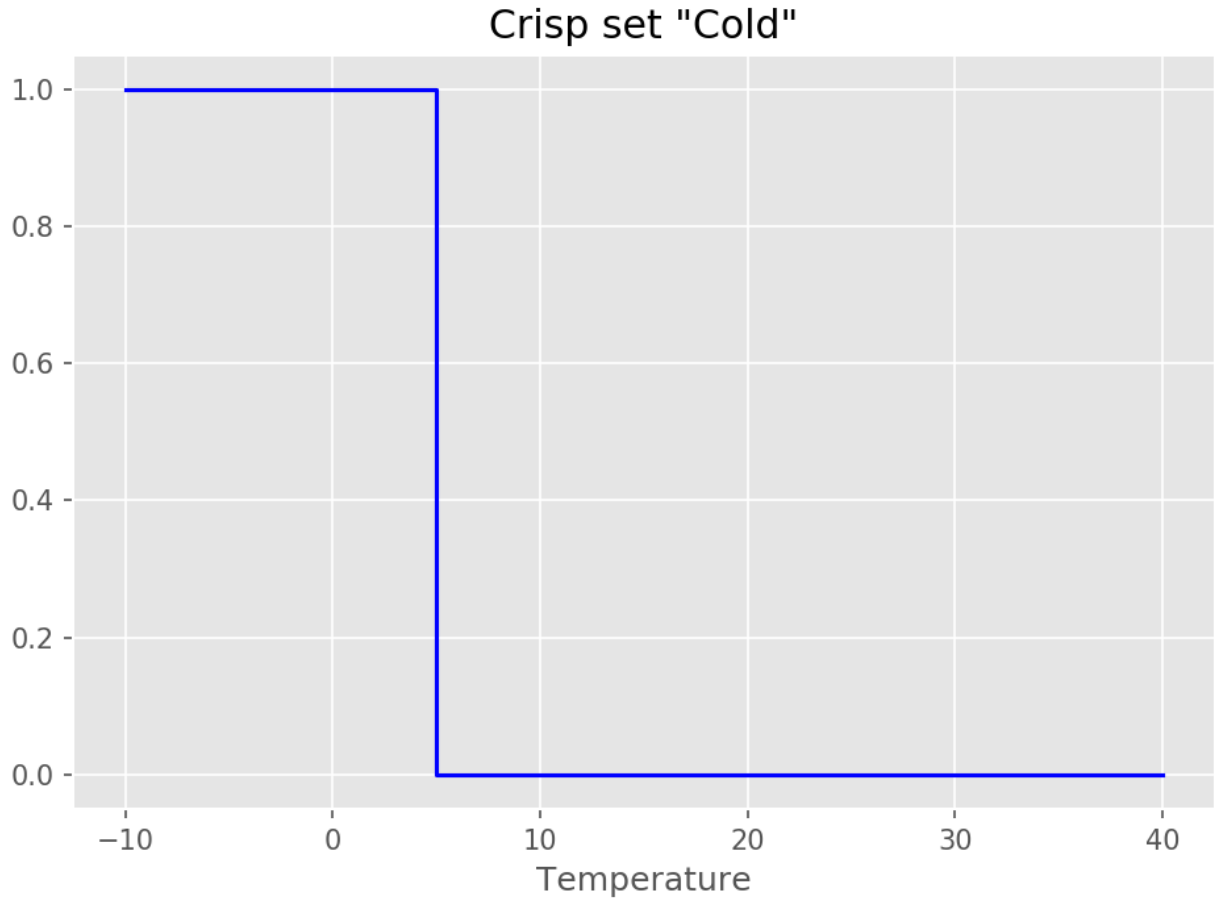
- Different calculation of lateral safe distance
- Longitudinal safe distance according to Fuzzy SSMs
- Capacity for calm proactive reaction

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’

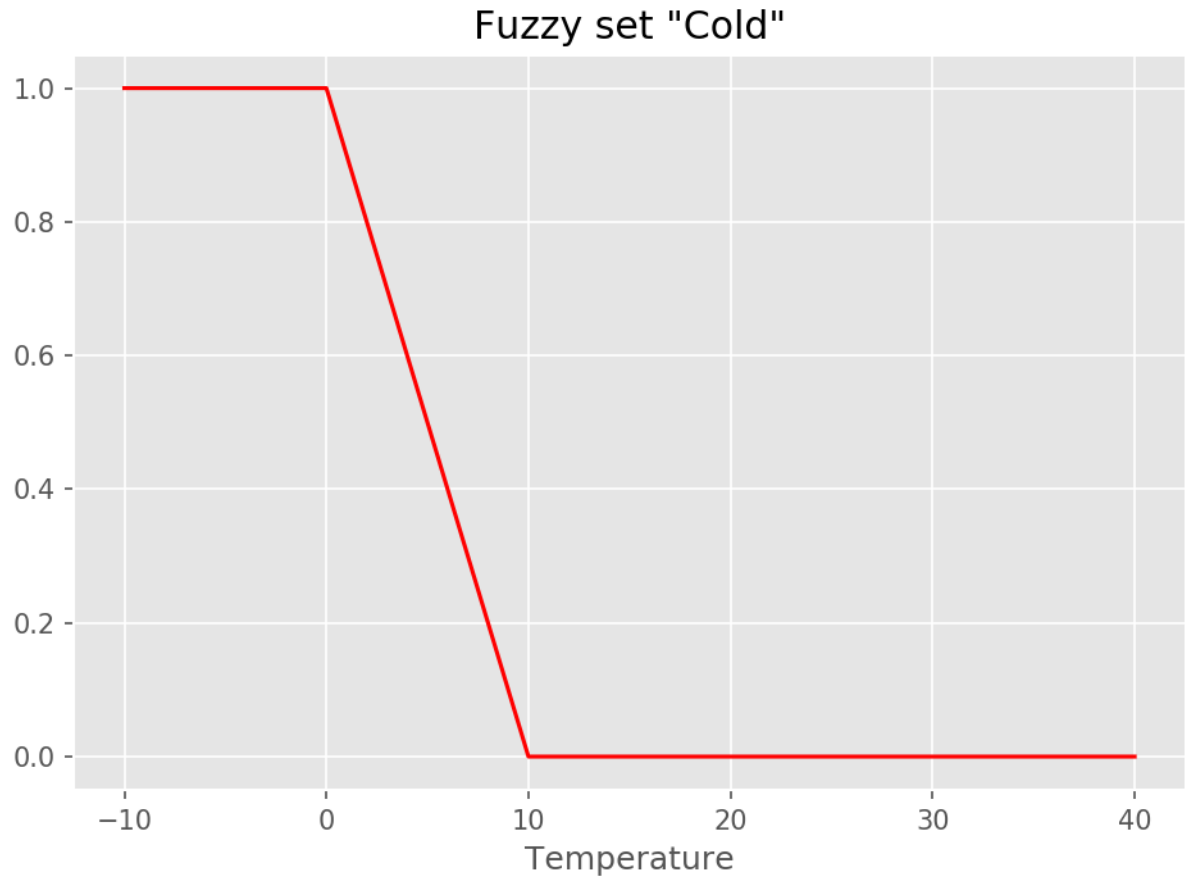


What is Fuzzy Logic? Fuzzy sets

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

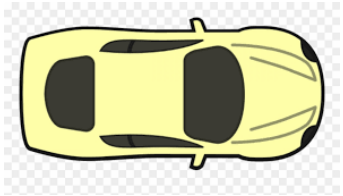
This can be helpful in many cases to better describe a situation

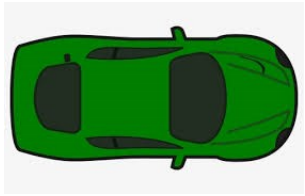
Based on those we can create fuzzy rules



Why Fuzzy logic

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



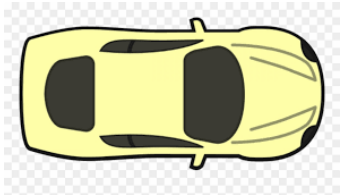


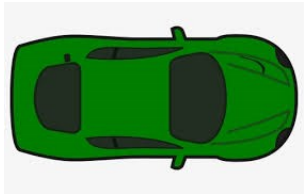
Safe

Unsafe

Why Fuzzy logic

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





Safe
Do nothing

Unsafe
Decelerate hard

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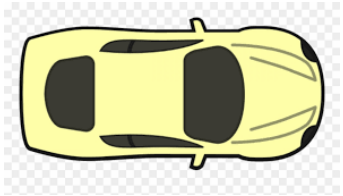

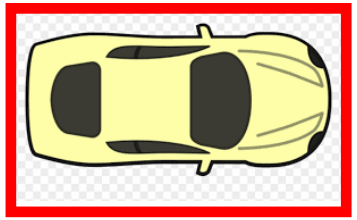

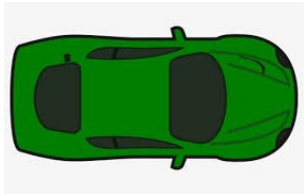

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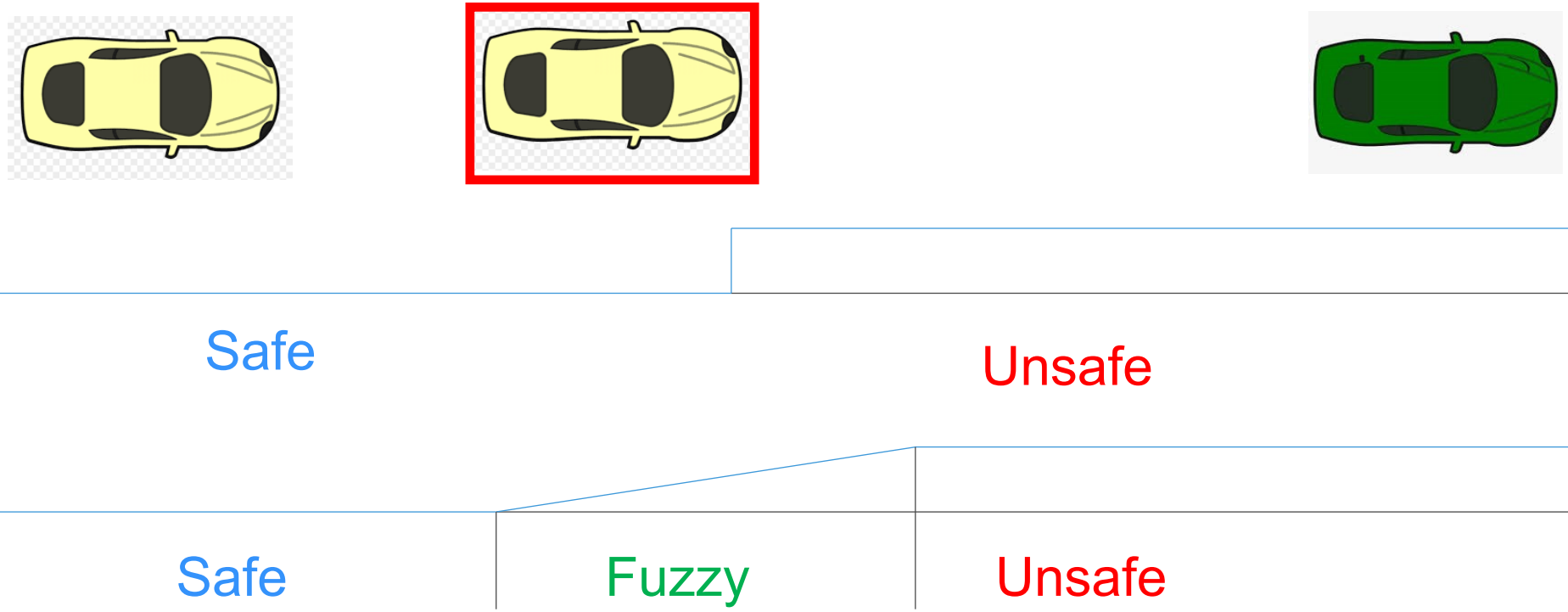
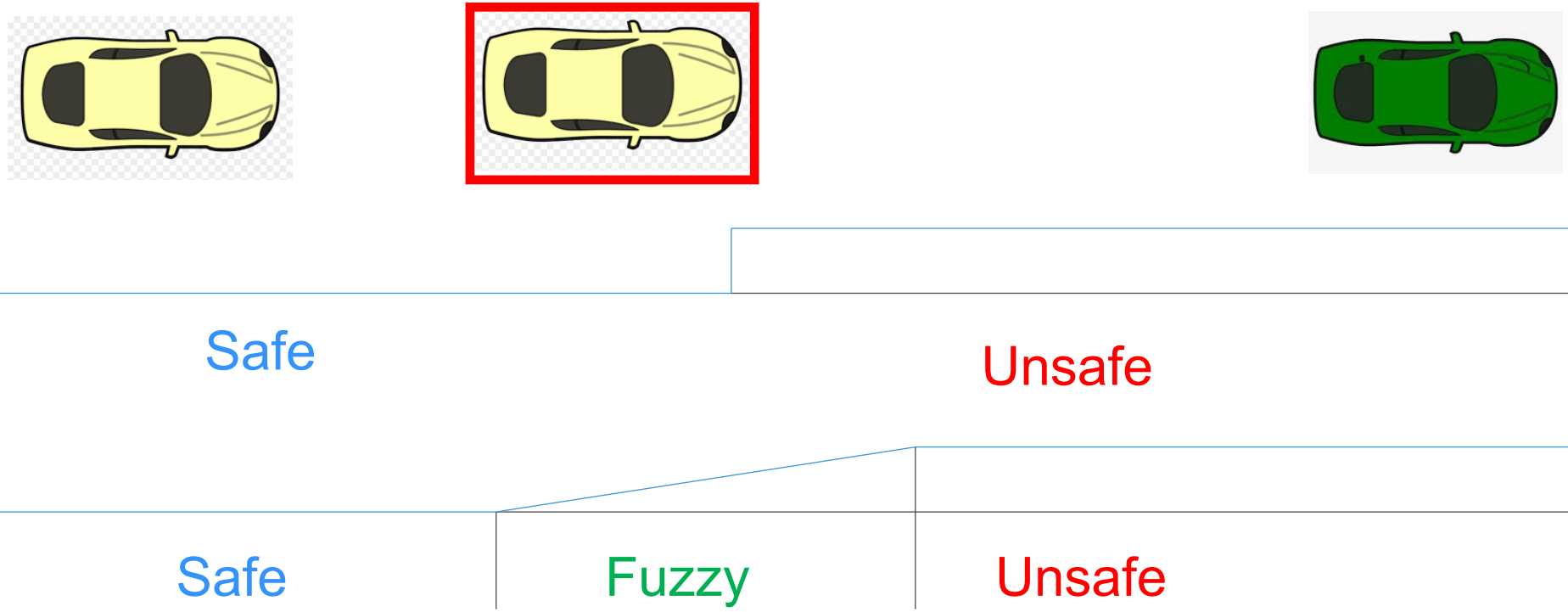


Why Fuzzy logic

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



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

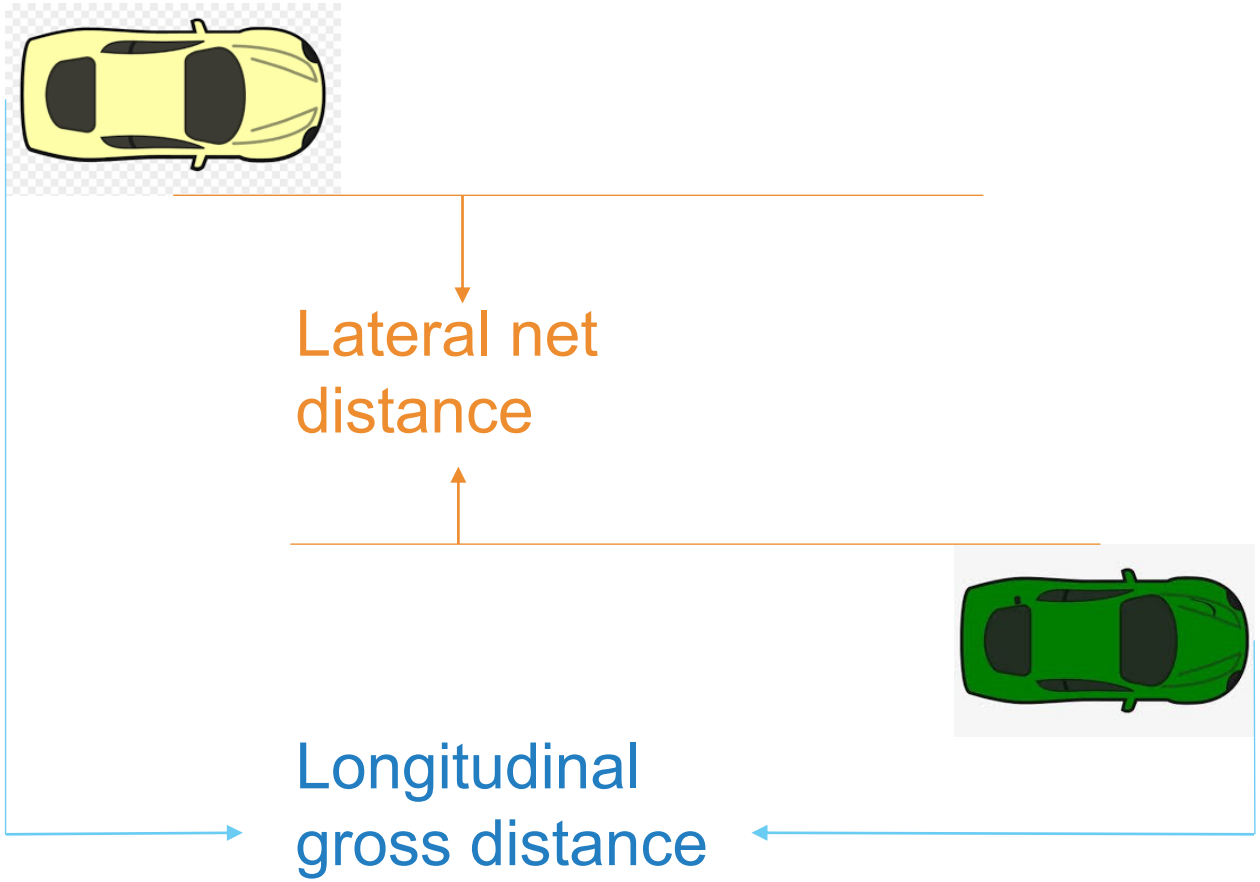
- Different calculation of lateral safe distance
- Longitudinal safe distance according to Fuzzy SSMs
- Capacity for calm proactive reaction

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

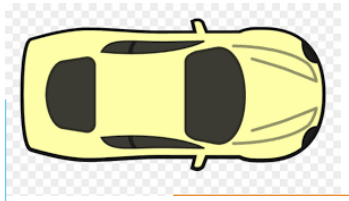
If all three restrictions apply, then we have to check the situation for the longitudinal safe distance

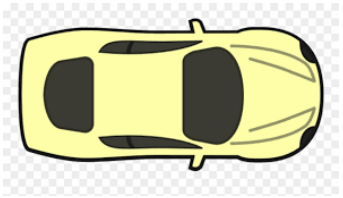
Different calculation of lateral safe distance

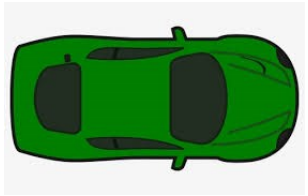


- The lateral net distance the space between the vehicles laterally
- The longitudinal gross distance is the longitudinal space from the rear of the ego vehicle to the front of the cutting in vehicle
- To calculate headway, they have to be divided to the cutting in vehicle lateral speed and the approaching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

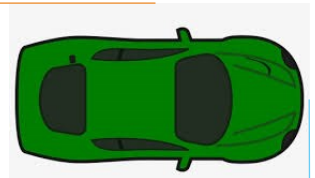
Different calculation of lateral safe distance







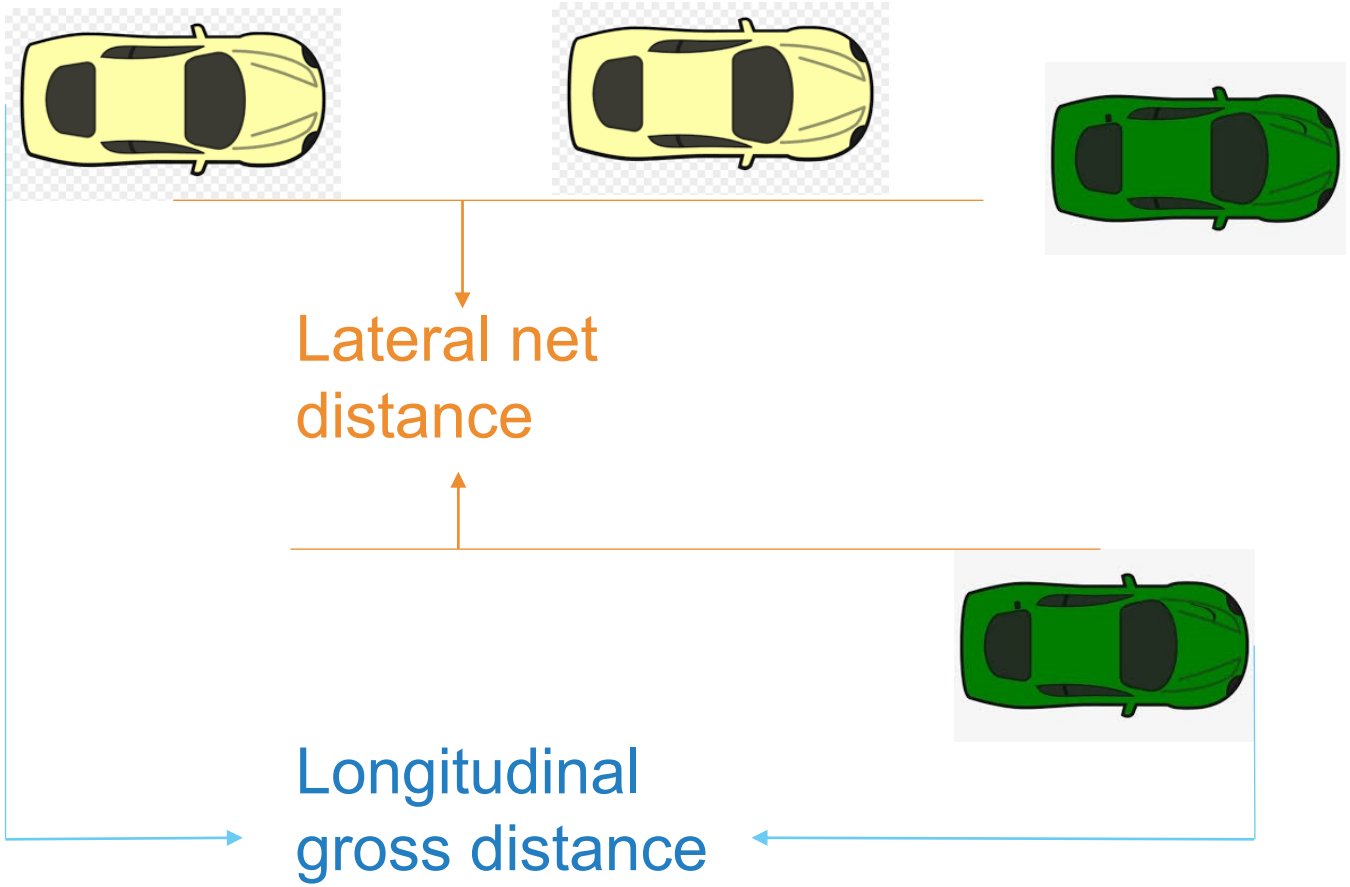
Lateral net distance



Longitudinal gross 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)

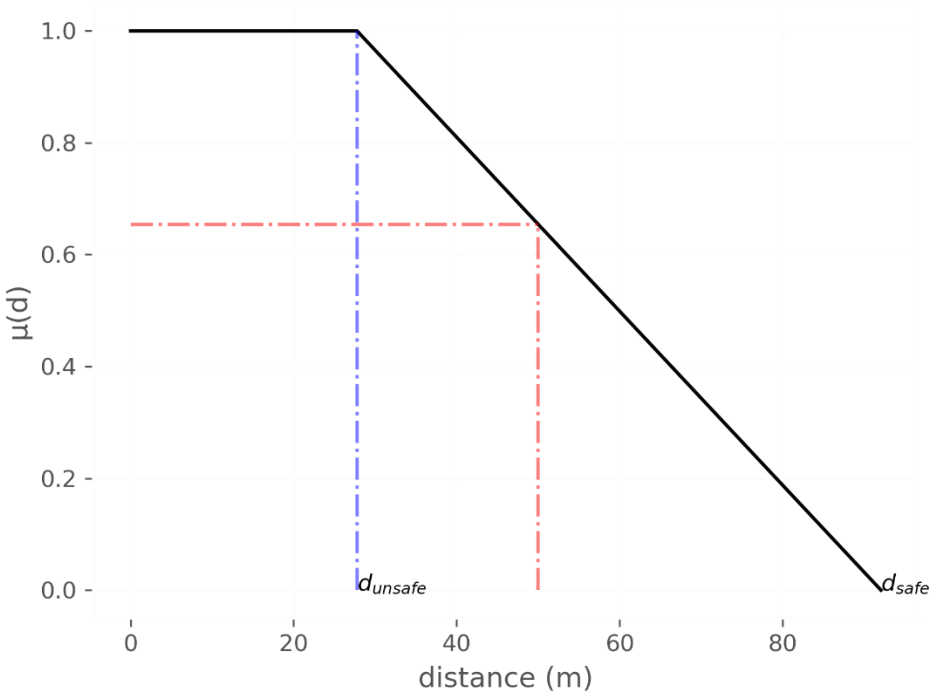
We calculated the Proactive Fuzzy SSM (PFS) and the Critical Fuzzy SSM (CFS)

Longitudinal safe distance according to Fuzzy SSMs

Maximum Unsafe distance

Minimum Safe distance

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



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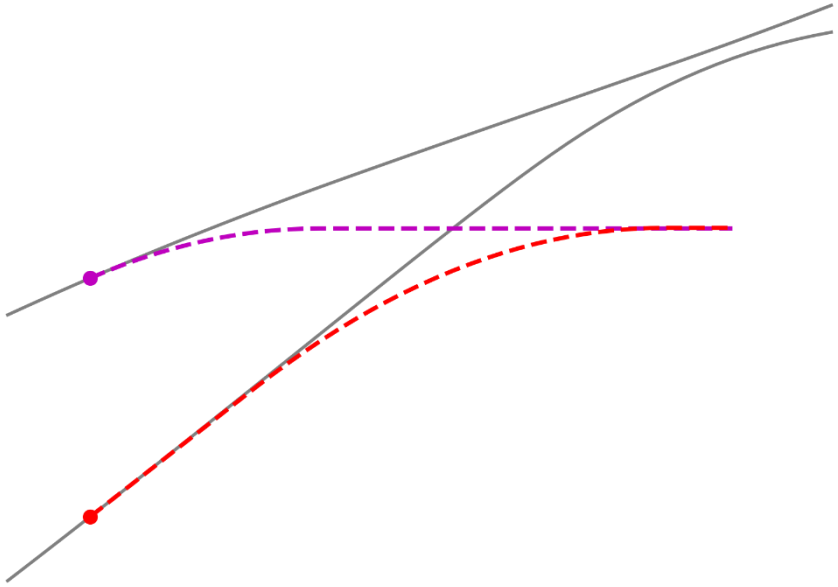
Longitudinal safe distance according to Fuzzy SSMs

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 $u_2(t+\tau) \le u_1(t)$*:*

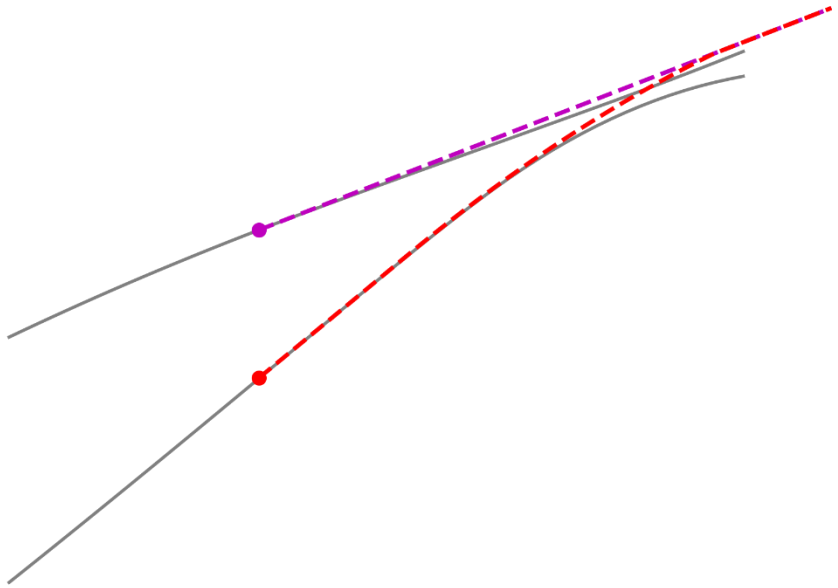
$$d_{safe}(t) \;=\; d_{unsafe}(t) = \frac{(u_2(t) - u_1(t))^2}{2a_2'(t)}$$

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

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

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

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



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/s²)

CFS value of 1 induces full deceleration (e.g. 6 m/s²)

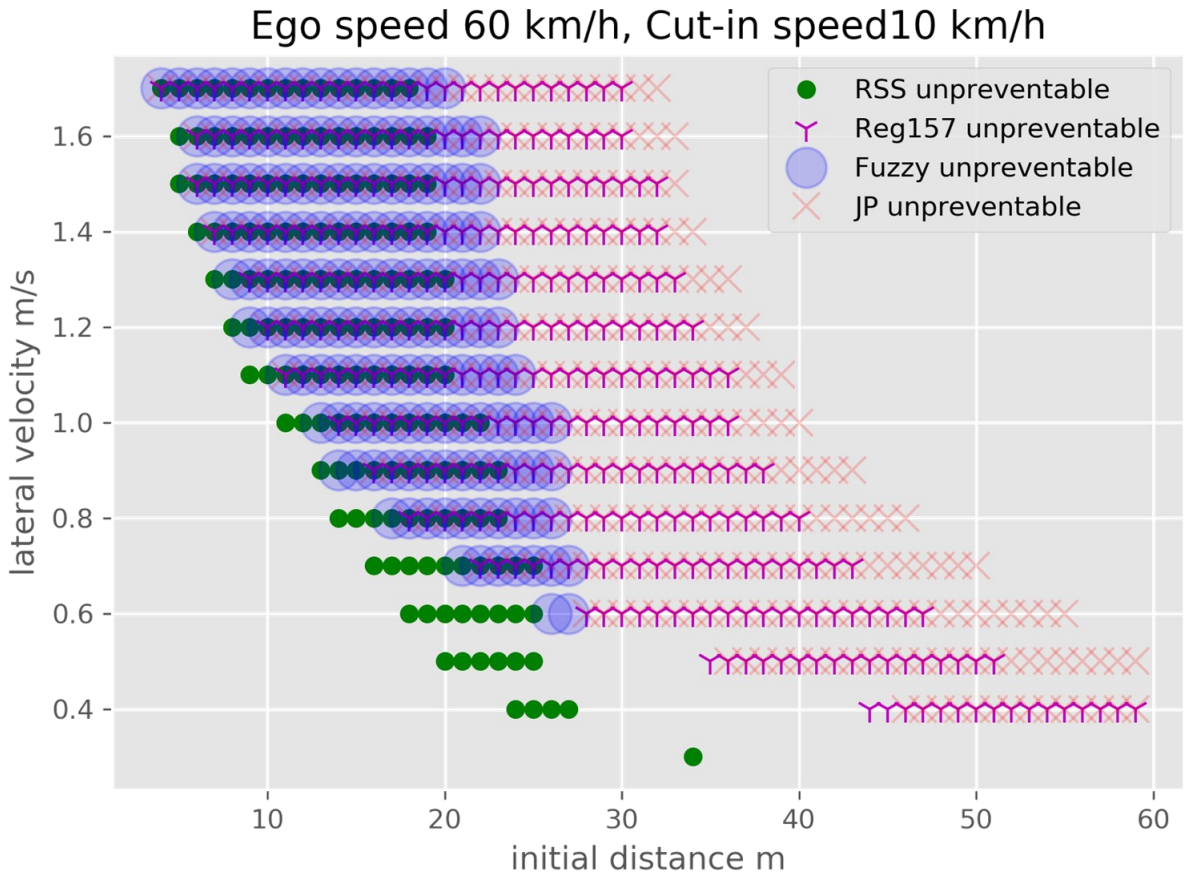
PFS value of 0.2 induces 20% of comfortable deceleration (e.g. 0.6 m/s²)

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

Results

The parameters are to be discussed, and they may change the picture

We see the new Fuzzy model being close to the intersection between the others

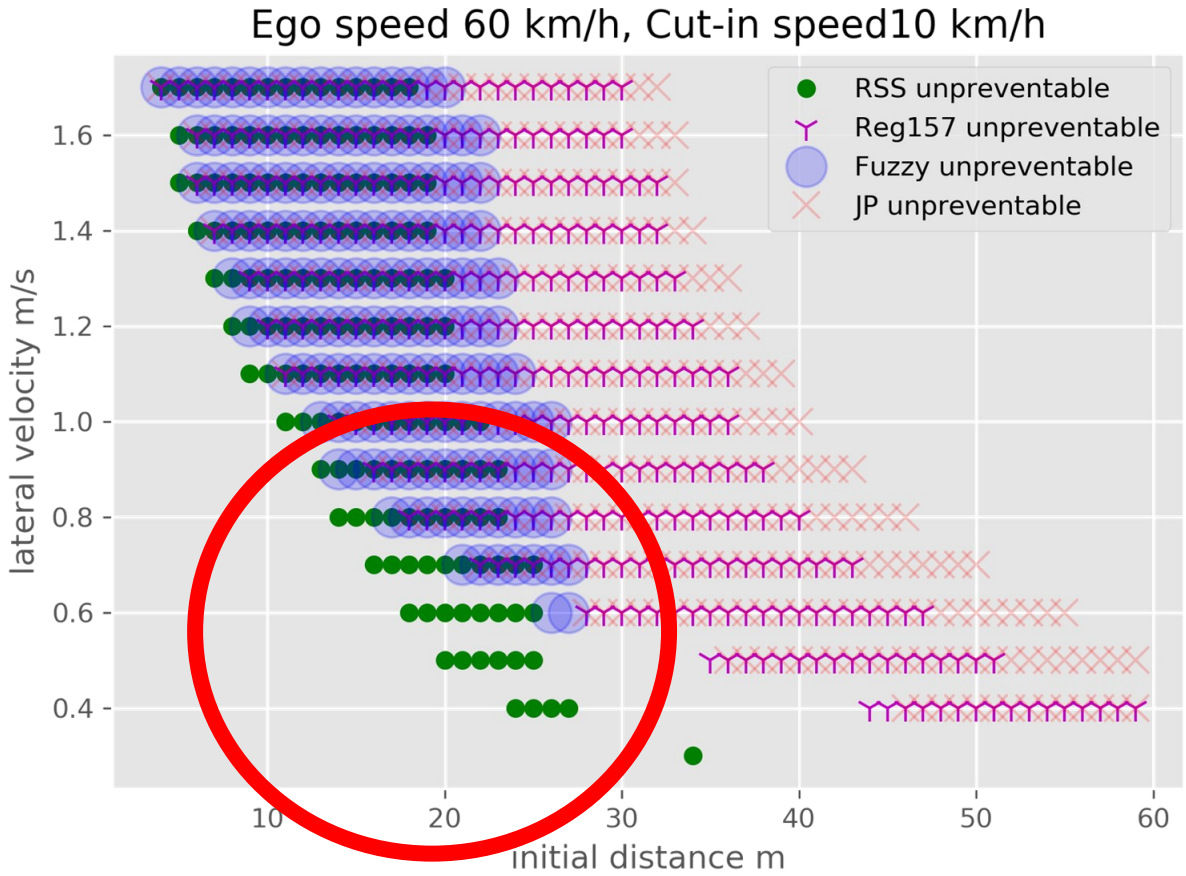


Results

Two areas of interest

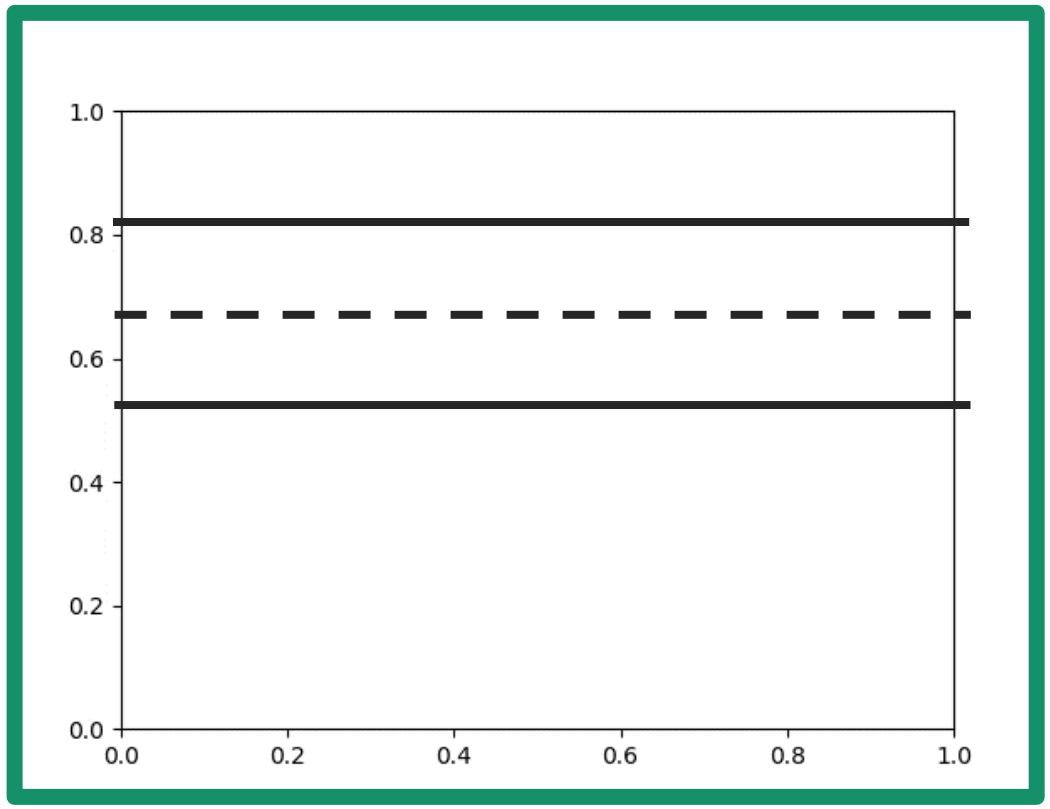
The first is about cases when the deceleration of RSS vehicles causes an accident

Other models do not decelerate and avoid the accident



Results

RSS



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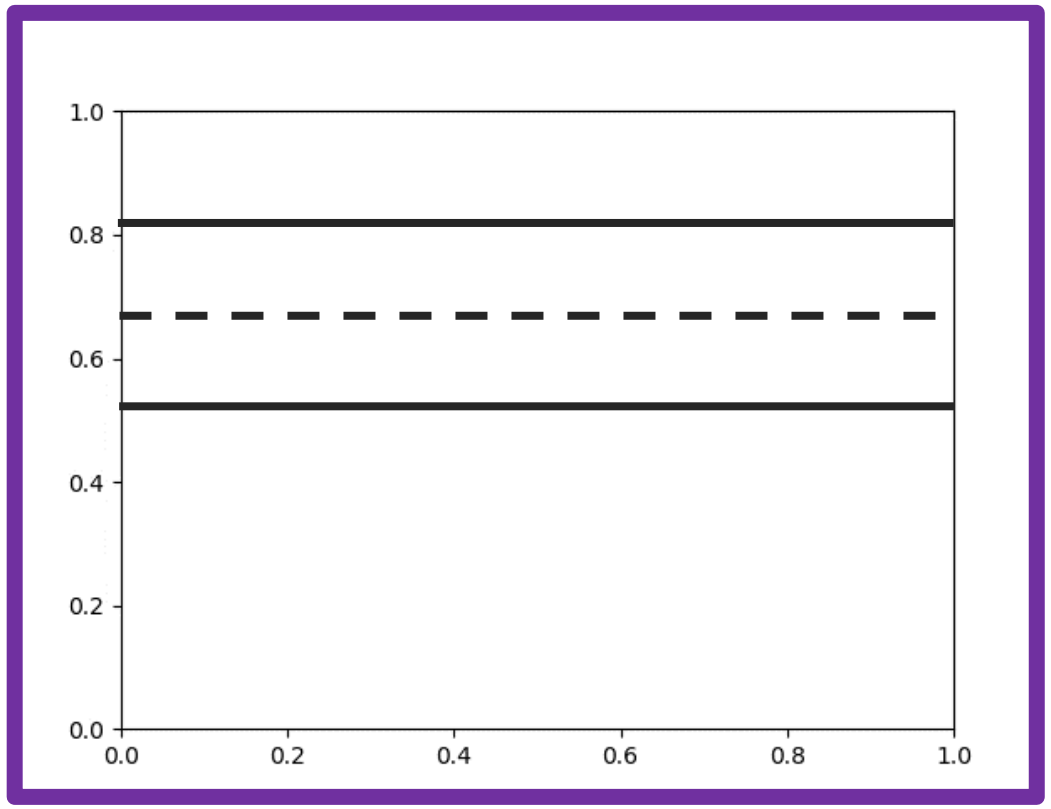
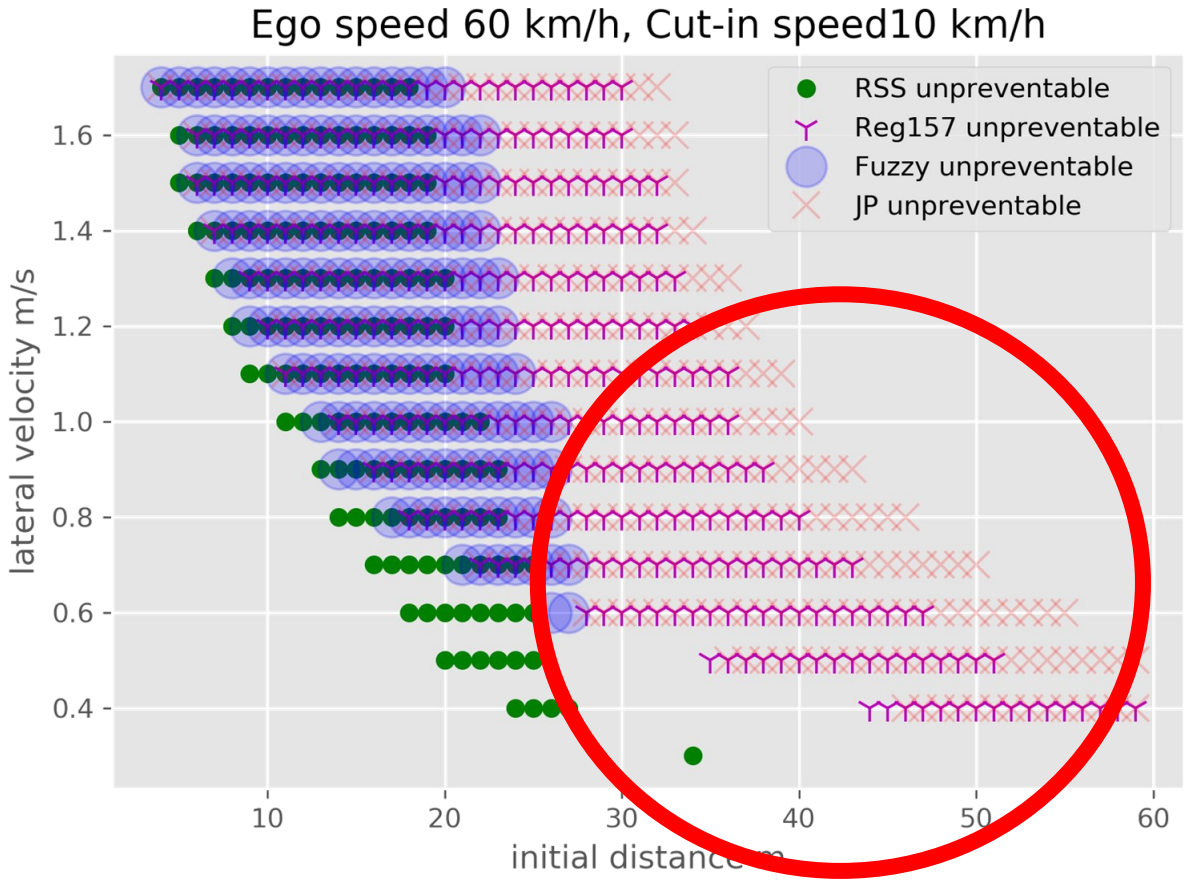


Results

Two areas of interest

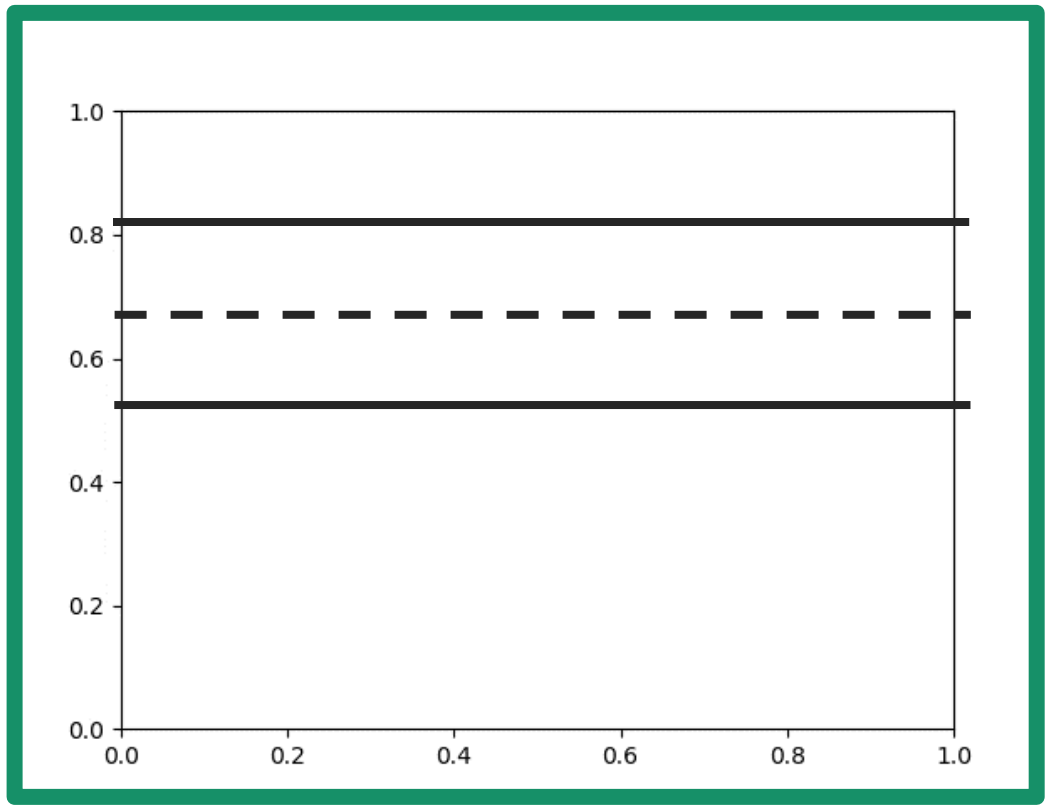
The second is for vehicles in large distance and small lateral speed

Those cases are avoidable by decelerating in a proactive manner



Results

RSS



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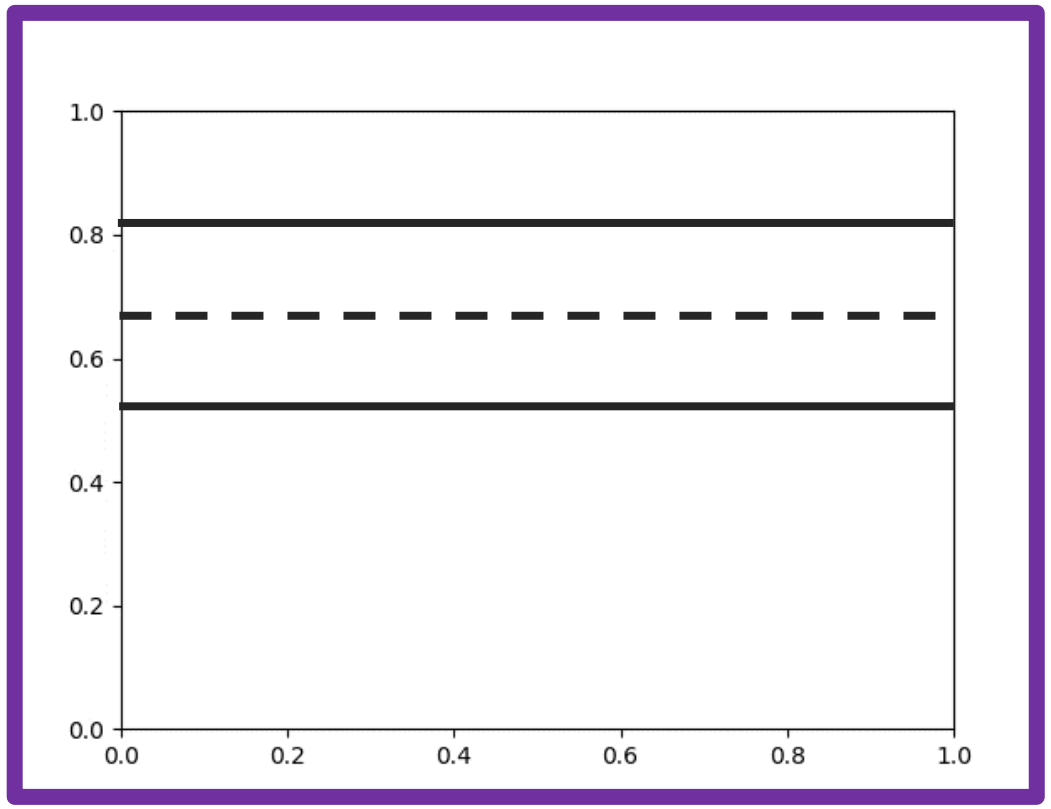
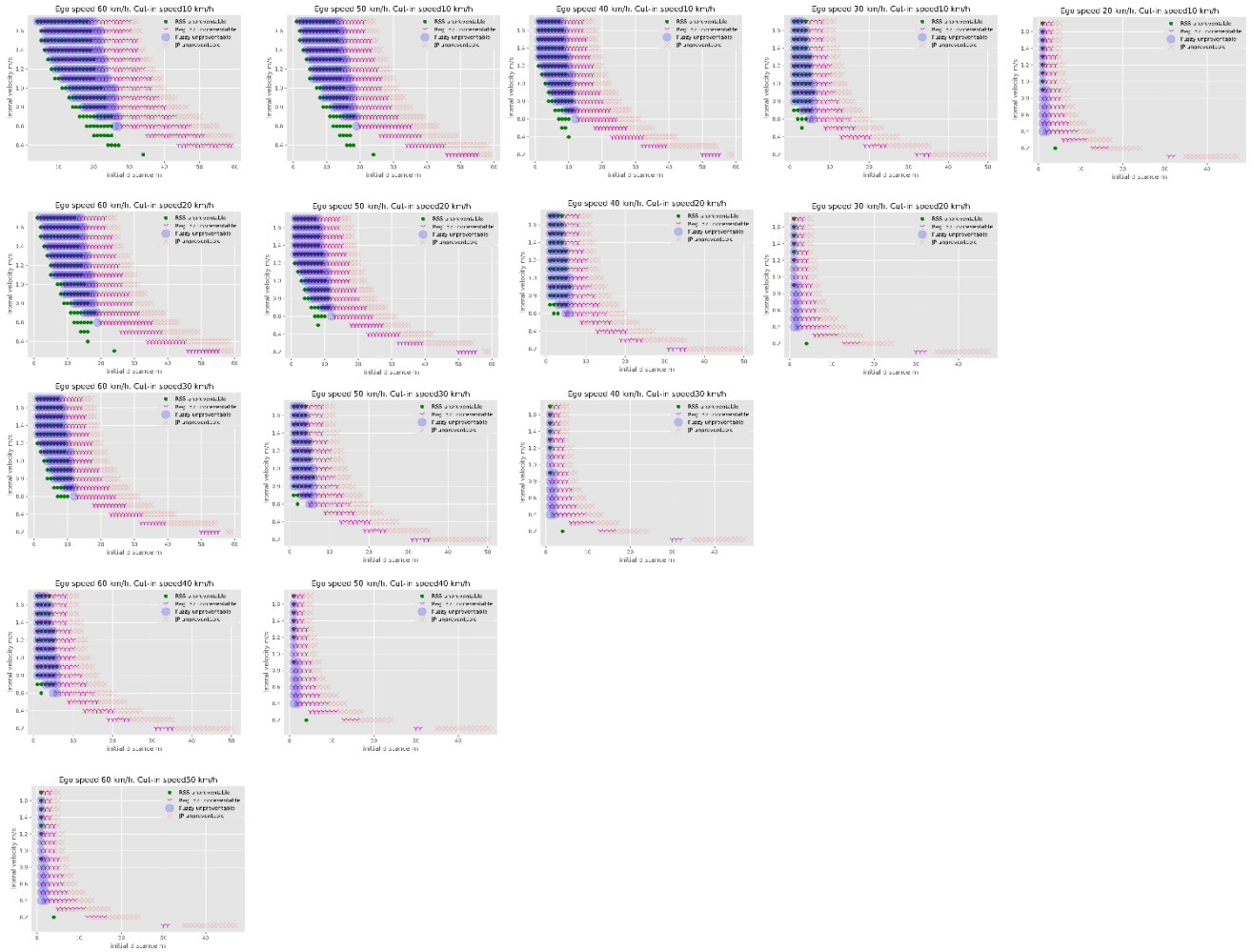


Results

The model is tested for a number of cases of different ego vehicle and cutting-in speeds.

There are no obvious problems for those cases.



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Conclusions

- Performance models for setting the safety requirements of future ADSs seem more appropriate than operational requirements
- Current approaches suggested by first Regulation on ADSs base accident avoidance on the capability to handle emergency situations
  - Anticipation capability by humans (and also by AVs) have also an important role in defining driving safety (tactical safety)
  - A model based on fuzzy-logic is proposed and compared with existing models available in the literature. It shows its **capability to address limitations of existing approaches**
- The use of performance models in deterministic rather than probabilistic settings is to be further explored

Thank you

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