DCAS testing campaign
String-stability requirements

A. Kriston, B. Ciuffo, D. Broggi, D. Maggi, D. Miotello, E. Rusciano, F. Minarini, F. Re, G. Morandin, K. Mattas, R. Donà, S. Vass
European Commission Joint Research Centre

DCAS Meeting
Brussels 13-16 May 2024

European Commission

Background

- In ADAS-29-08, the JRC proposed to (re-)introduce a string stability requirement for DCAS system
  - It is worth mentioning that since the beginning of the ADAS TF, the string stability requirement was in the text (inherited from R157), but postponed to phase 2 during the last iterations leading to Phase 1 completion.
- The JRC provided a new extensive description of the concept, its link to safe and comfortable driving, and substantial evidence that ACC systems available in the EU are inherently string unstable

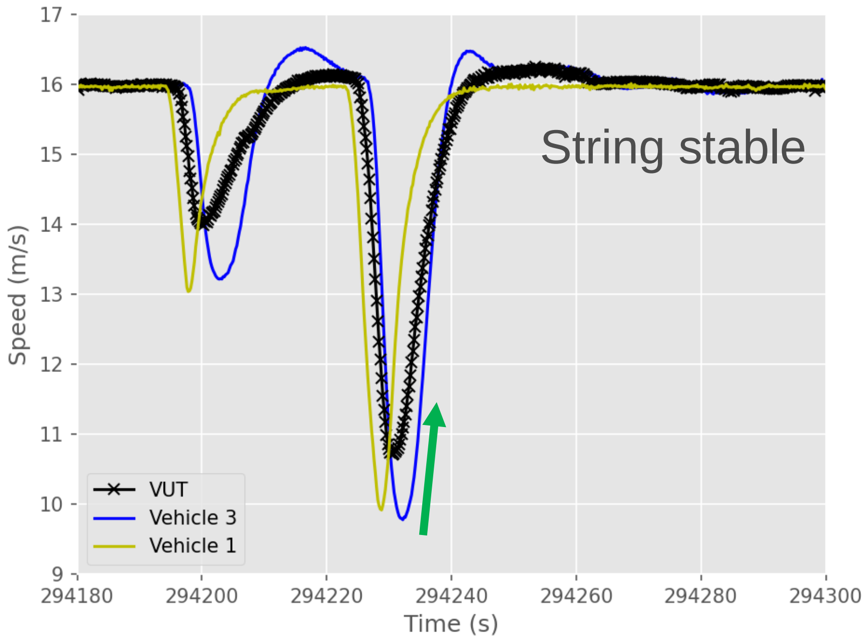
European Commission

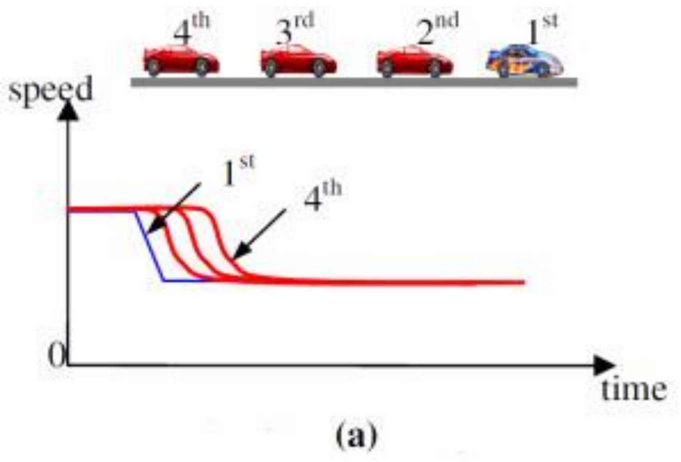
Background

- In response to the JRC proposal OICA-CLEPA first suggested the DCAS WG to **ideologically ignore it**
- As a second step, during ADAS-30-05, OICA-CLEPA provided a narrative about the impossibility for a DCAS to fulfil a string-stability requirement
- In this presentation we want to:
  - Recap what string stability is and why it is important
  - Address the comments submitted by OICA-CLEPA
  - Show evidence that a DCAS-like system is string-unstable

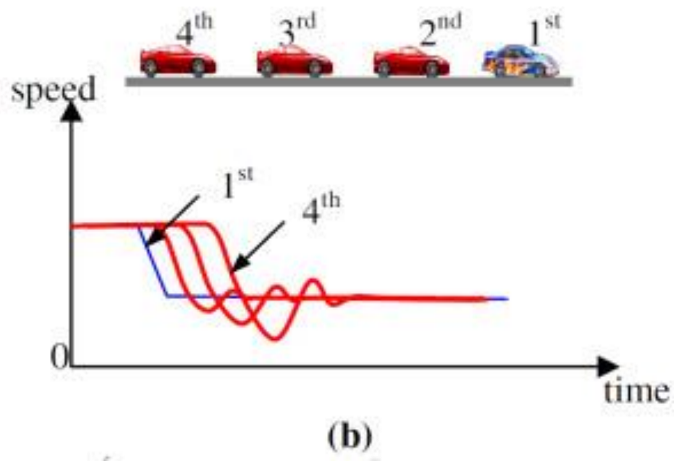
What is string stability?

Definition: "String instability" is when a disturbance in the speed profile of the vehicle in front is amplified by the following vehicle(s).

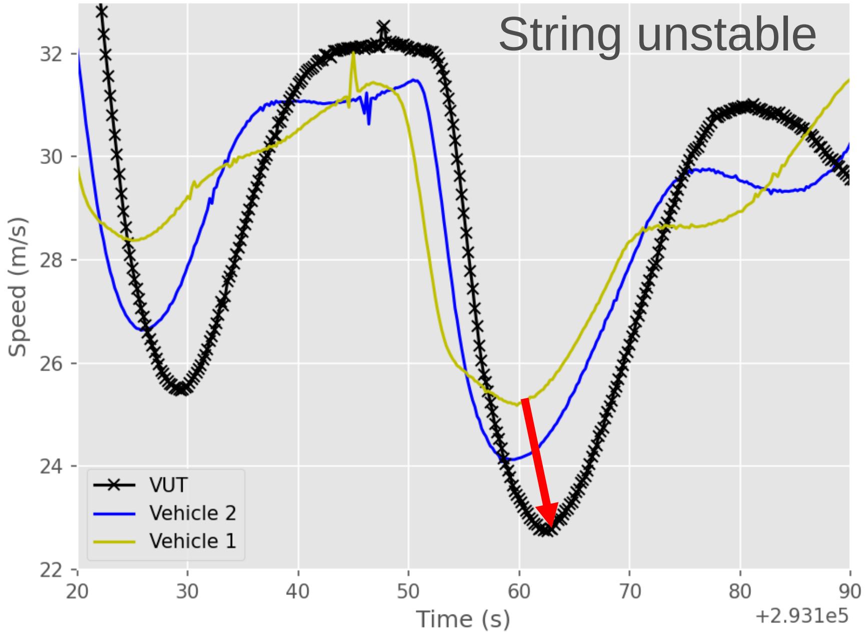




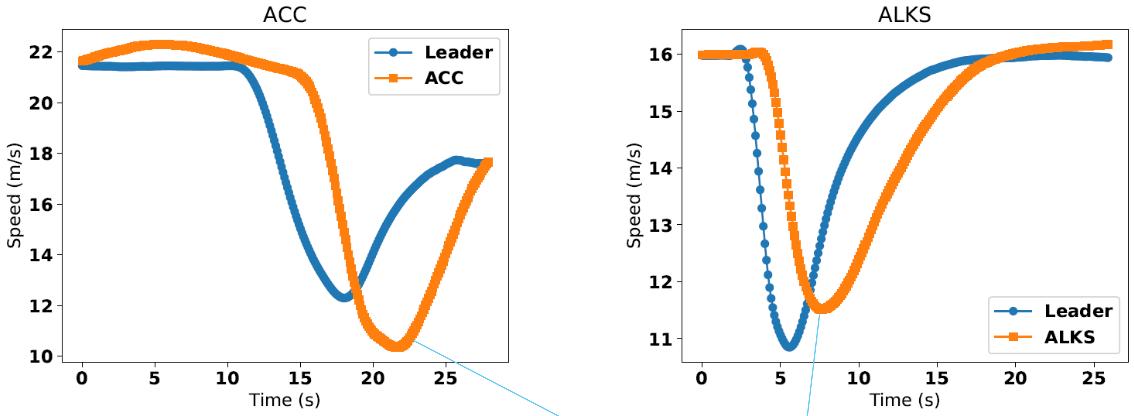
String stable

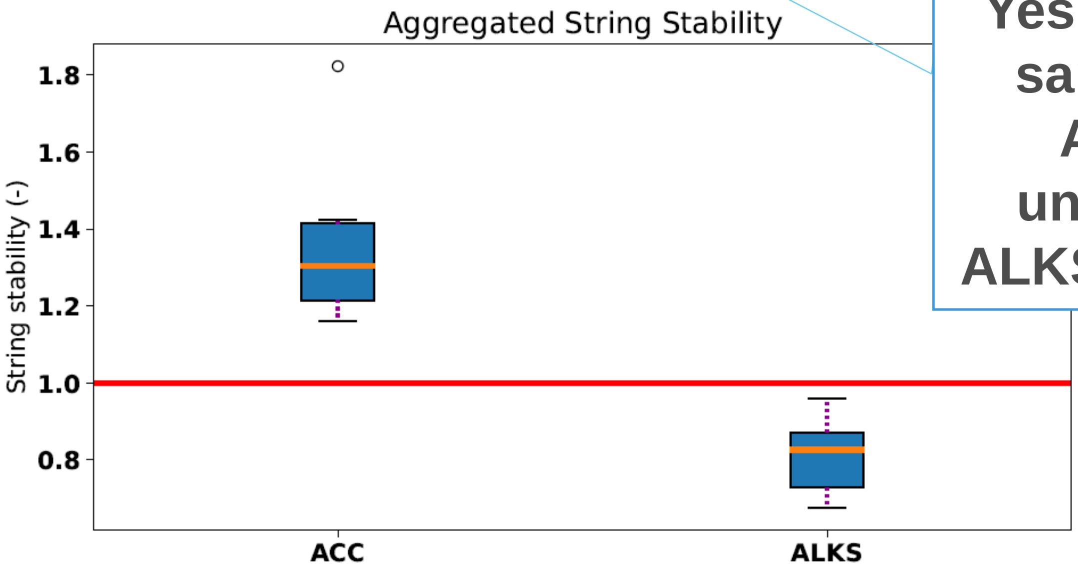


String unstable

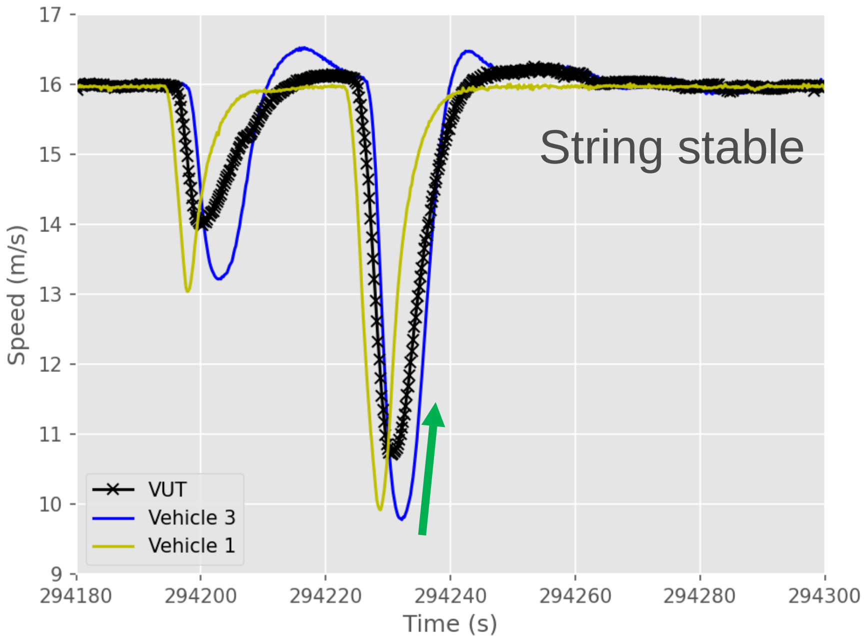


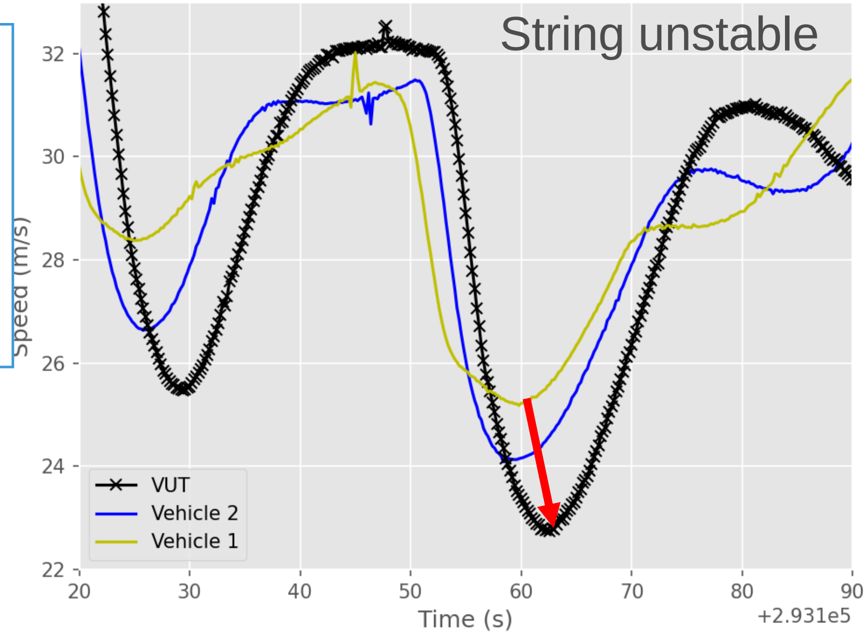
Can a vehicle be string stable without V2V connectivity?



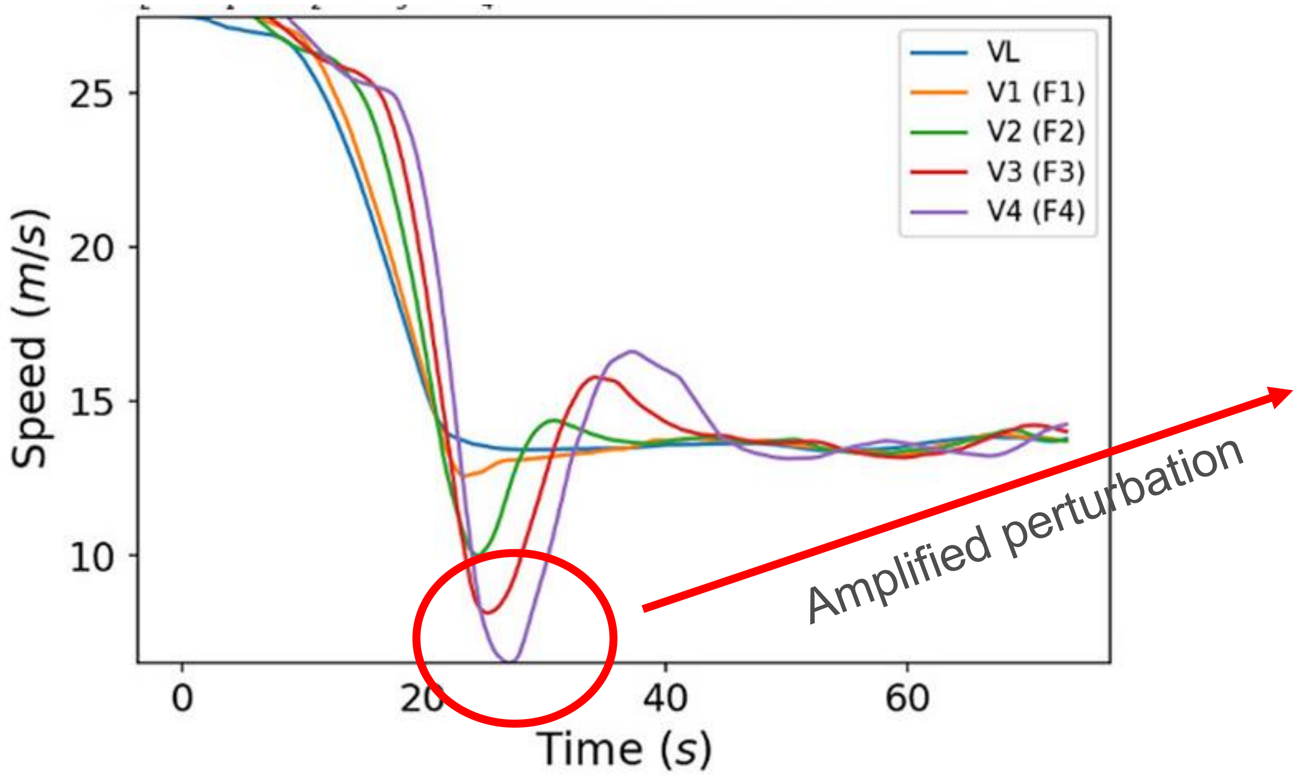


Yes! And within the same vehicle the ACC is string unstable and the ALKS is string stable





Why string stability is relevant?



Transportation Research Record, *2674*(4), 471-484.
Transportation Research Part C 130 (2021) 103305

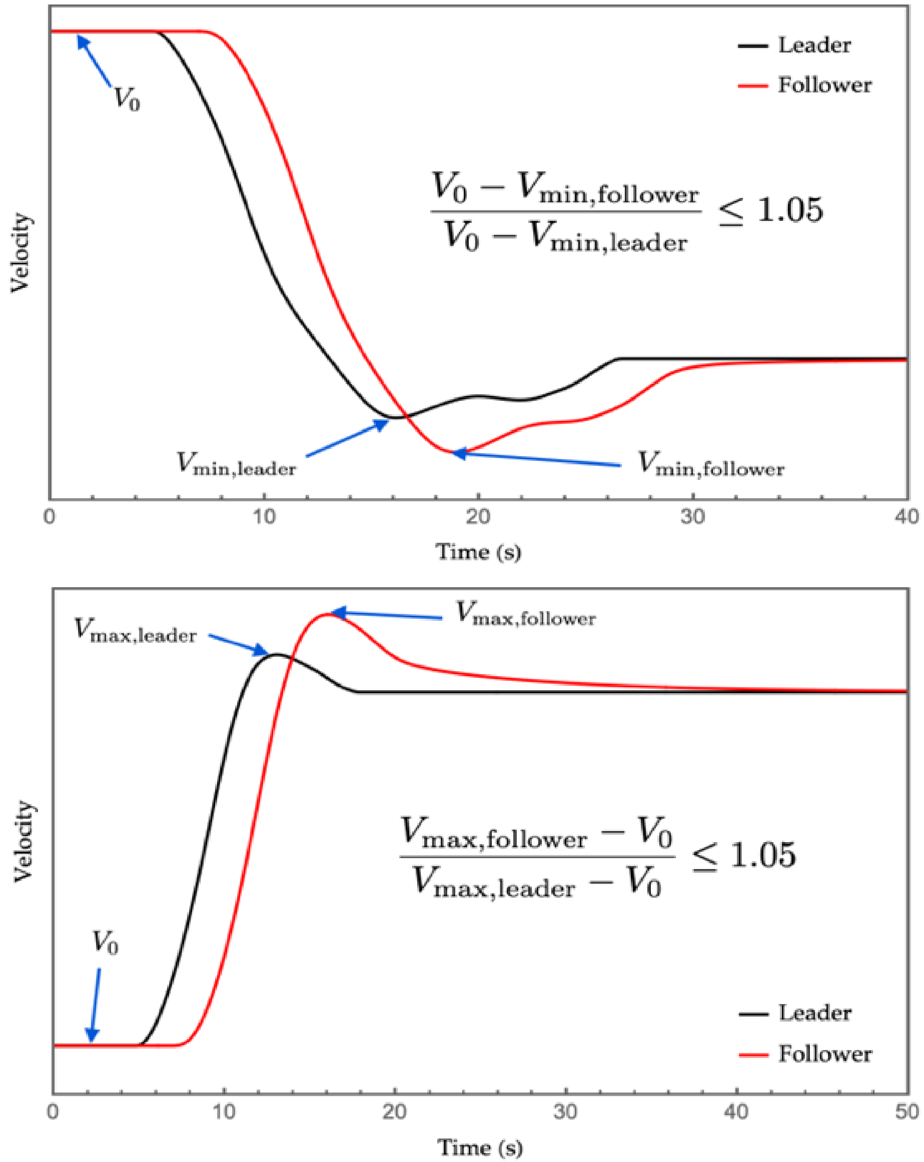
- Market ACC are string unstable
- Safety case: unstable strings may induce harsh barking and induce stop and go waves that are prone to rear-end crashes
- By designing string stable controllers, the vehicle logic shall change from reactive to proactive, with safety benefits going beyond the platoon case

Especially with DCAS capable of initiating manoeuvre and eyes-on only systems we suggest to require string stability

String stability requirements proposal

Version 1 (UNR157): In case the distance to a vehicle in front is temporarily disrupted (e.g. vehicle is cutting in, decelerating lead vehicle, etc.), the vehicle shall readjust the following distance at the next available opportunity without any harsh braking implementing strategies designed to address significant string instability, unless an emergency maneuver would become necessary.

Version 2: A DCAS vehicle following another vehicle at constant speed and at a distance such that the speed profile of the DCAS system is influenced by the speed profile of the vehicle in front, the activated DCAS system shall aim to respond to a perturbation in the speed of the vehicle in front with a perturbation in its speed profile by at most a [5%] increase in the maximum difference in speed compared to the vehicle in front before reaching a new equilibrium velocity.



Testing requirement (essence):

Base test:

Each test shall comprise the deceleration of the car target from steady state platoon formation to achieve a speed reduction of at least [3] m/s. The speed of the car target at the end of the deceleration shall not be lower than [5] m/s.

Extended test: The test shall be executed with

- different combinations of initial speed,
- final speed and deceleration adopted by the car target,
- on different roads (e.g. curvatures)
- different targets (i.e. motorcycle)

Comments by OICA/CLEPA (1)

- **Assisted driving should be compared to the behavior when driving manually -> are drivers really behaving any differently?**

  - Human drivers can be either string stable or not. See the following quote: "*However, string stability is not always observed in empirical data (depending on the characteristics of drivers and traffic regime).*" (Talebpour & Mahmassani, 2016). Moreover, one can see Fig.7 on the following paper, where string stability is evaluated for human drivers, using data gathered by drones in German highways (Mattas et al., 2023)

  - <u>Should we accept that DCASs (like ACCs) behave like of un-attentive human drivers or drivers not respecting an acceptable safety distance?</u>

Comments by OICA/CLEPA (2)

- Industry is not aware of any safety issues resulting from this scenario in the field today, as the scenario is artificial and does not occur in the real world.

  - In ADAS-29-08 we have provided clear empirical evidence that string instability substantially decreases the safety level. **A vehicle following another vehicle is an artificial scenario?**

  - The literature on string stability and its safety impacts is vast, and to our knowledge there is no study questioning the safety benefits of string stability, see e.g.:

    - "*A leading objective in the design of CACC systems is to prevent disturbance amplification in upstream direction, for instance induced by velocity variations of the lead vehicle, which would compromise throughput and safety. The disturbance propagation along interconnected systems, such as a vehicle platoon, is covered by the notion of string stability of which a vast amount of literature is available.*" (Ploeg, van de Wouw, et al., 2014).

Comments by OICA/CLEPA (3)

- **Platoon string stability is hardly compatible with a comfortable controller design**

  - There must be some misunderstanding on what string stability is. String stability leads to lower absolute value accelerations/decelerations and smaller speed fluctuations. By definition, such behavior corresponds to better comfort. This is again quite clear in the scientific literature:

    - “*If spacing errors and velocity errors amplify as they propagate upstream (this is the case when string instabilities are present), it not only is likely to provide poor ride quality but could also result in collisions*” (Xiao & Gao, 2011).

    - “*String stability is a property which ensures that spacing error does not grow as it propagates along a string of vehicles […] A spacing control algorithm that is not string stable is not only at best likely to provide poor ride quality but also could result in collisions*.” (Rajamani & Shladover, 2001).

Comments by OICA/CLEPA (4)

- **L1/L2 ADAS is intended to assist the driver in certain conditions/scenarios, it is not designed to handle all situation like ADS.**
    - We envisage this requirement especially for DCASs able to initiate maneouvers and with eyes-on only monitoring systems
    - Quasi-string stable DCAS-like systems are available on the market (see later slides)

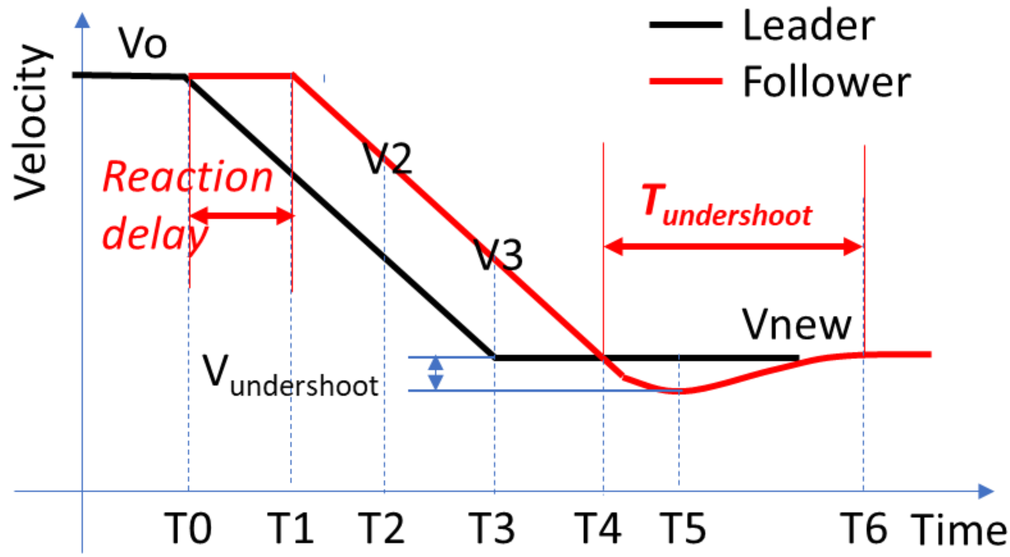
Comments by OICA/CLEPA (5)

- **Assisted driving needs to be designed to meet different, partially conflicting design targets**
  - **Drivers want the system to behave naturally (don’t overreact, be sufficiently dynamic, …)**
    - Again there must be a misunderstanding as a string stable controller would not overreact
  - **If system is designed too careful, other vehicles will constantly cut into gaps -> this will also be a disruption to traffic flow, and it will lower the customer acceptance of DCAS systems**
    - This might be partially true at constant speed (string stability does not require infinite gap) but by the reaction delays generate voids in the traffic flow that are also prone to continuous cut-ins

Comments by OICA/CLEPA (6)

- **Experience from the field shows drivers will not use /override L2 systems designed to ensure string stability.**
  - Again there must be a misunderstanding as a string stable controller would actually generate the opposite feeling
  - There are DCAS-like systems on the road showing a quasi-string stable behavior that are not known to be disliked by its drivers

Comments by OICA/CLEPA (7)



- **We have 2 possible approaches to minimize the $V_{undershoot}$.**
  - **Option 1). To take more time to recover the following distance. (To take longer "Tundershoot ")**
    - Possibly, if the OEM decides to maintain the same strategy. But it is up to the OEM to decide how to approach this requirement. The focus of the regulation is on the effects of the requirement and its applicability
  - **Option 2). To minimize the "reaction delay". Side effect : If the leader vehicle driven by low skill driver, the whole platoon would be affected.**
    - If the leader is a low-skill driver a string stable controller able to attenuate the related effects is even more desirable

List of references

- Feng, S., Zhang, Y., Li, S. E., Cao, Z., Liu, H. X., & Li, L. (2019). String stability for vehicular platoon control: Definitions and analysis methods. Annual Reviews in Control, 47, 81–97. https://doi.org/10.1016/j.arcontrol.2019.03.001
- Mattas, K., Albano, G., Donà, R., He, Y., & Ciuffo, B. (2023). On the Relationship between Traffic Hysteresis and String Stability of Vehicle Platoons. Transportation Research Part B: Methodological, 174, 102785. https://doi.org/10.1016/j.trb.2023.102785
- Ploeg, J., Shukla, D. P., Van De Wouw, N., & Nijmeijer, H. (2014). Controller synthesis for string stability of vehicle platoons. IEEE Transactions on Intelligent Transportation Systems, 15(2), 854–865. Scopus. https://doi.org/10.1109/TITS.2013.2291493
- Ploeg, J., van de Wouw, N., & Nijmeijer, H. (2014). Lp String Stability of Cascaded Systems: Application to Vehicle Platooning. IEEE Transactions on Control Systems Technology, 22(2), 786–793. https://doi.org/10.1109/TCST.2013.2258346
- Rajamani, R., & Shladover, S. E. (2001). An experimental comparative study of autonomous and co-operative vehicle-follower control systems. Transportation Research Part C: Emerging Technologies, 9(1), 15–31. https://doi.org/10.1016/S0968-090X(00)00021-8
- Seiler, P., Pant, A., & Hedrick, K. (2004). Disturbance propagation in vehicle strings. IEEE Transactions on Automatic Control, 49(10), 1835–1842. https://doi.org/10.1109/TAC.2004.835586
- Talebpour, A., & Mahmassani, H. S. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. Transportation Research Part C: Emerging Technologies, 71, 143–163. https://doi.org/10.1016/j.trc.2016.07.007
- Wang, M., Li, H., Gao, J., Huang, Z., Li, B., & van Arem, B. (2017). String stability of heterogeneous platoons with non-connected automated vehicles. 2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC), 1–8. https://doi.org/10.1109/ITSC.2017.8317792
- Xiao, L., & Gao, F. (2011). Practical string stability of platoon of adaptive cruise control vehicles. IEEE Transactions on Intelligent Transportation Systems, 12(4), 1184–1194. Scopus. https://doi.org/10.1109/TITS.2011.2143407

Evidence from US test campaign. General

- The test campaign carried out in the US with two DCAS-like systems allowed to experience two very different approaches to system design
  - In one case the system had a reactive approach very similar to normal ACC vehicles
  - In the other case the system showed proactivity and to the extent possible anticipatory behaviour
- None of the two systems generated discomfort in the drivers although the experience with the proactive approach was considered more natural by the professional drivers

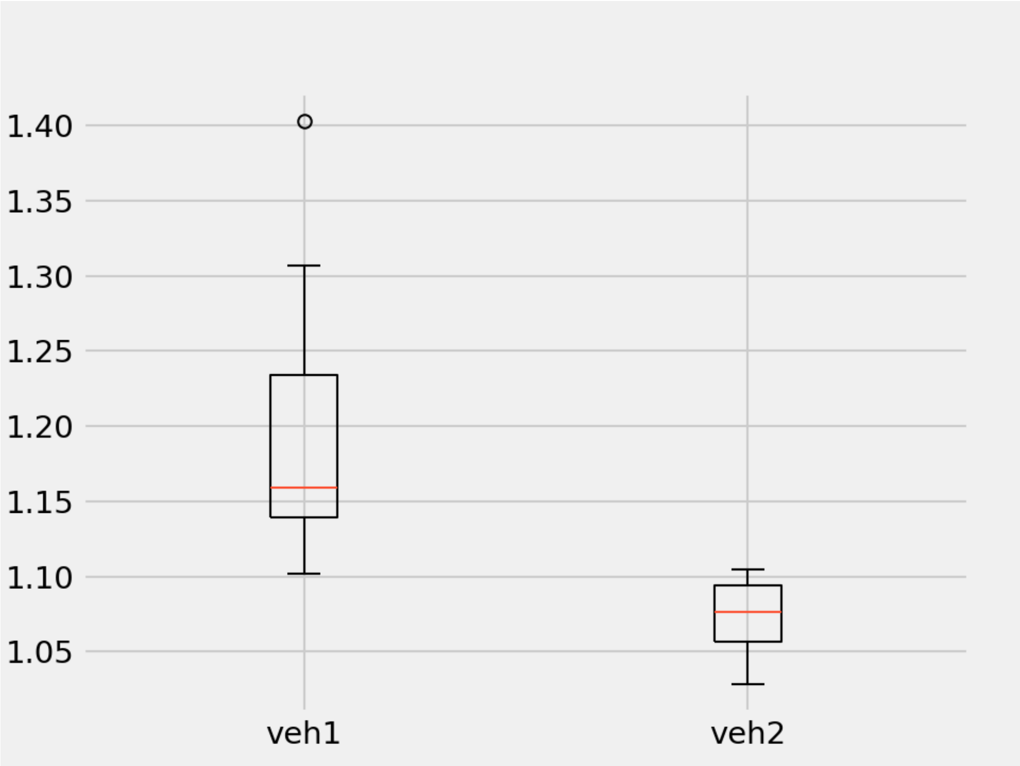
Evidence from US test campaign. Test-track

- Tests carried out on the oval with the two vehicles following a target vehicle keeping constant speed before applying a predefined perturbation

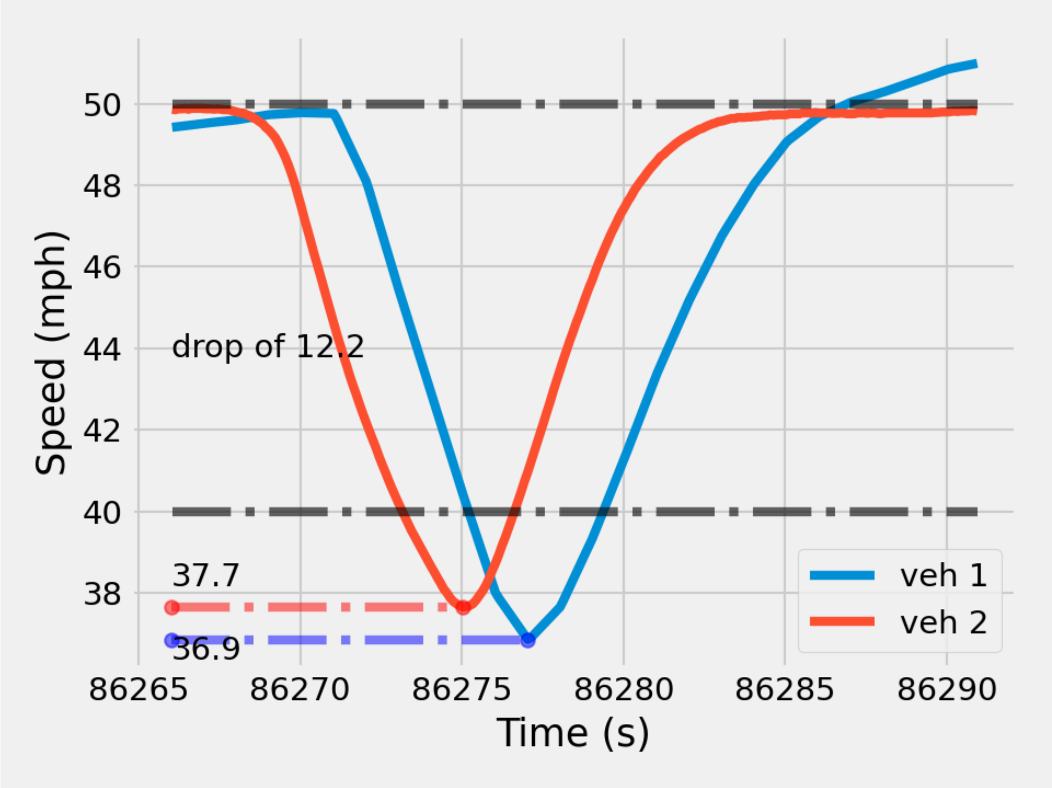
- Several combinations of initial speeds and perturbations were performed

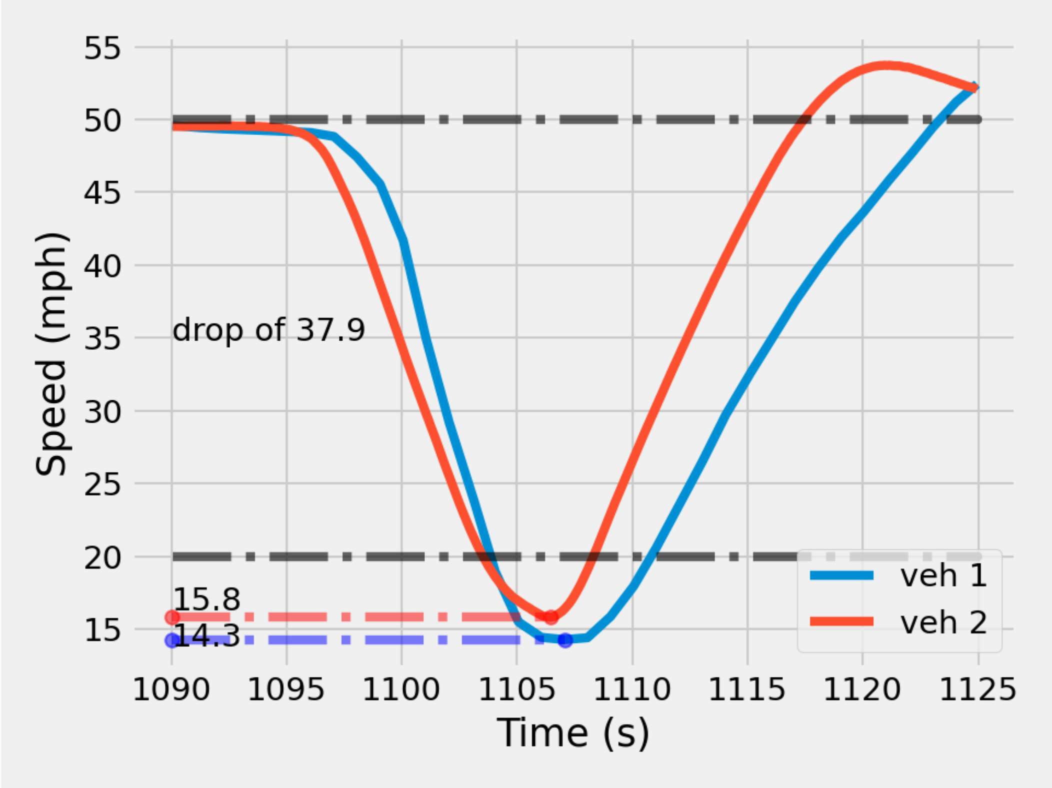
- DCAS systems set with minimum time-gap settings

  - **By adopting a more proactive approach one of the two vehicles is almost able to already satisfy the suggested requirement**



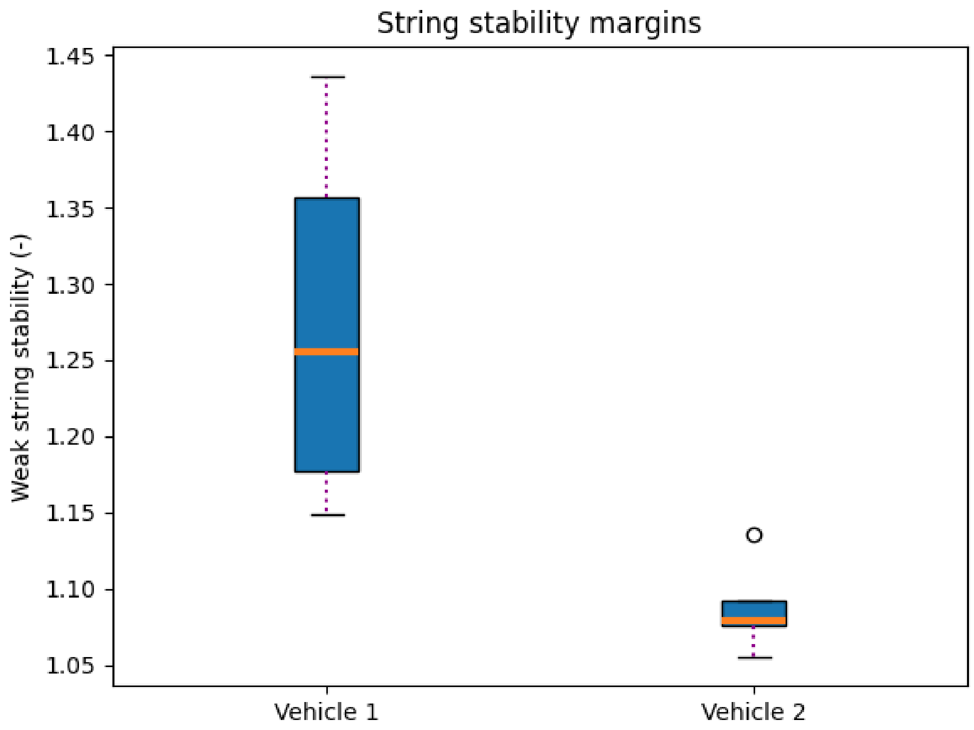
Example of trajectories



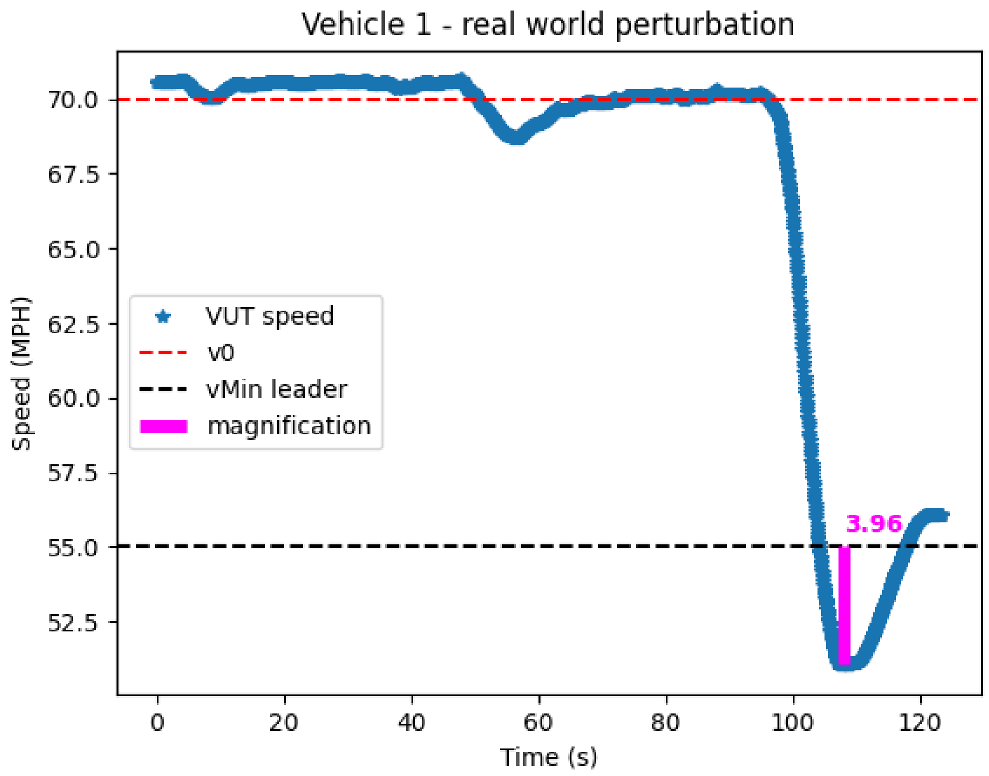


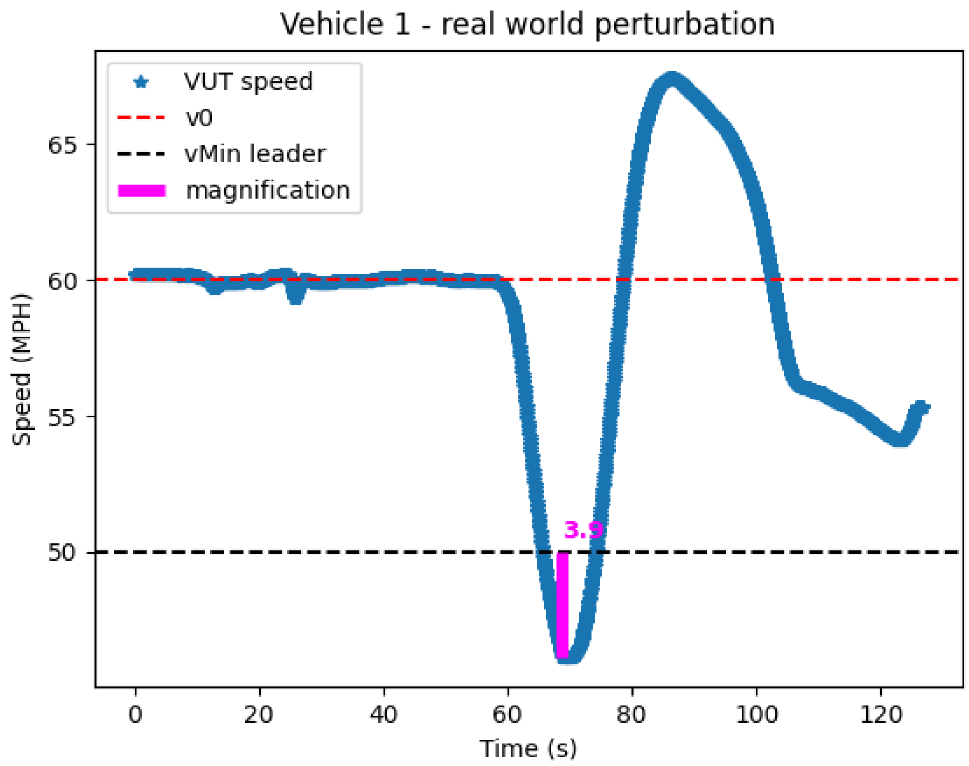
Evidence from US test campaign. Public roads

- Tests repeated during the tests on public roads
- Tests included further disturbances induced by road geometry and traffic
- Vehicles using again the minimum time gap setting
    - **Even in this case the results did not change substantially for vehicle 2, whereas they further deteriorate for vehicle 1, showing the intrinsic limitations of a purely reactive design**

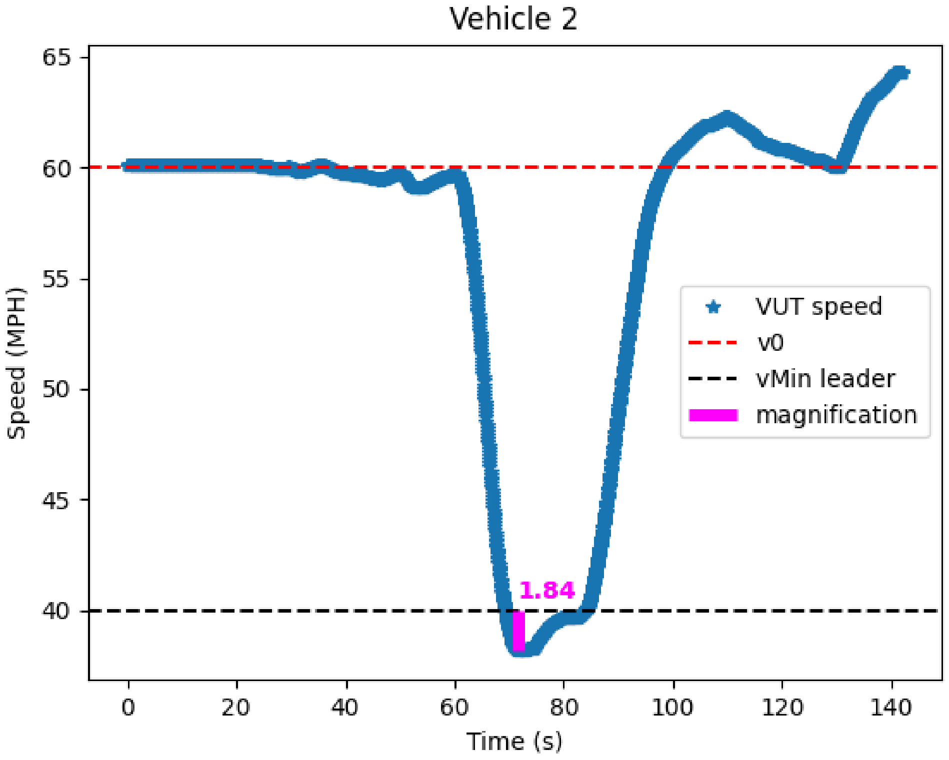


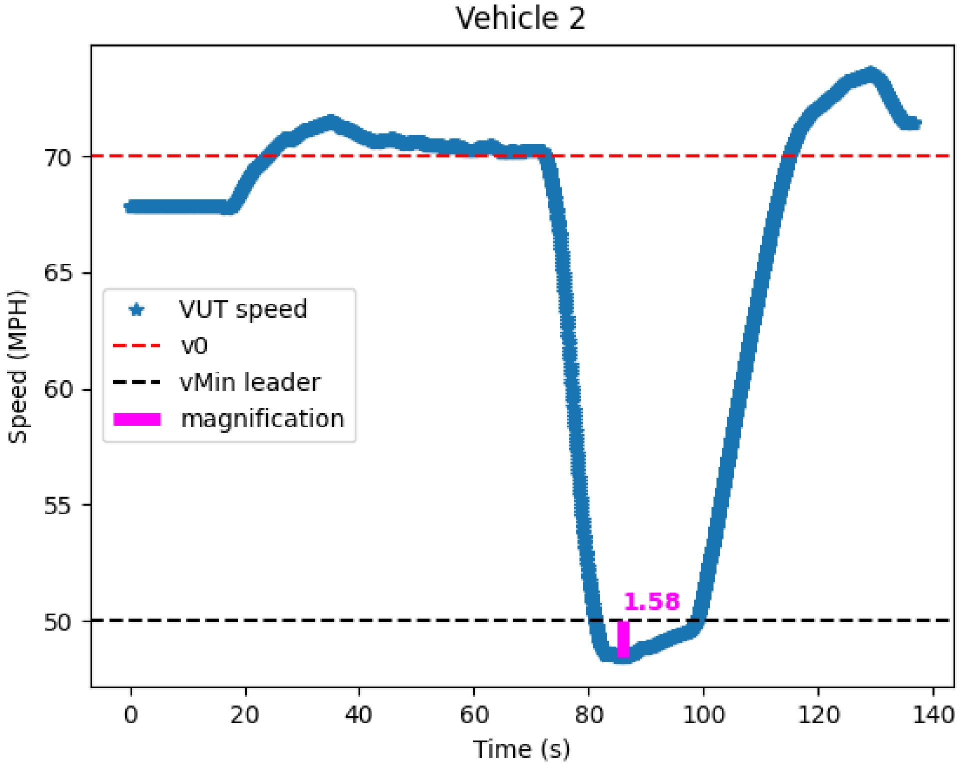
Vehicle 1- Trajectories





Vehicle 2- Trajectories





Evidence from US test campaign. Test-track (Car to Car Braking)

- In order to assess the effect of the proactive versus reactive design in case of emergency situations the tests were repeated on the test-track using a soft target as lead vehicle
- The target proceeded at constant speed before applying a deceleration (4 and 6 m/s2)
- 3 different offsets (0, 25, 50%) and 2 time gap settings (minimum and medium)

Evidence from US test campaign. Test-track (Car to Car Braking)

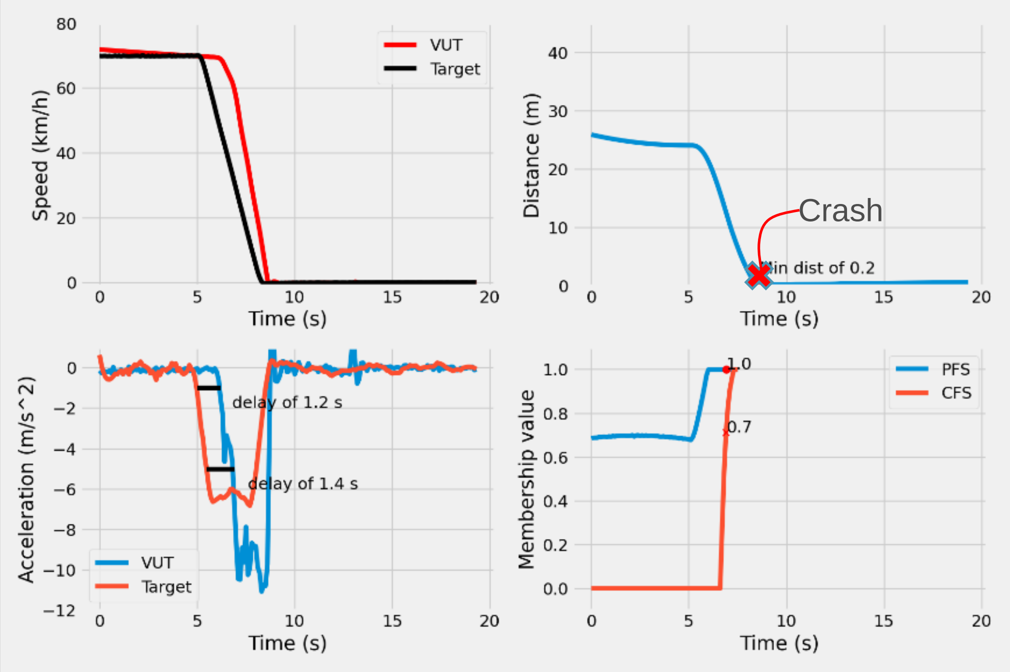
Video Vehicle 1

Video Vehicle 2

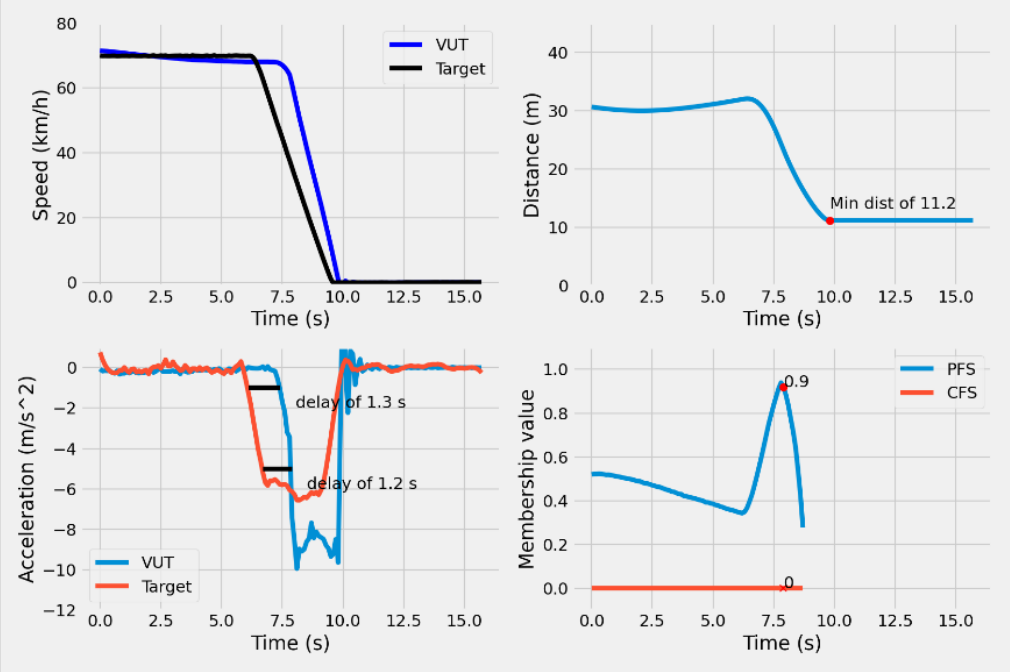
Evidence from US test campaign. Test-track (Car to Car Braking)

Minimum time-gap

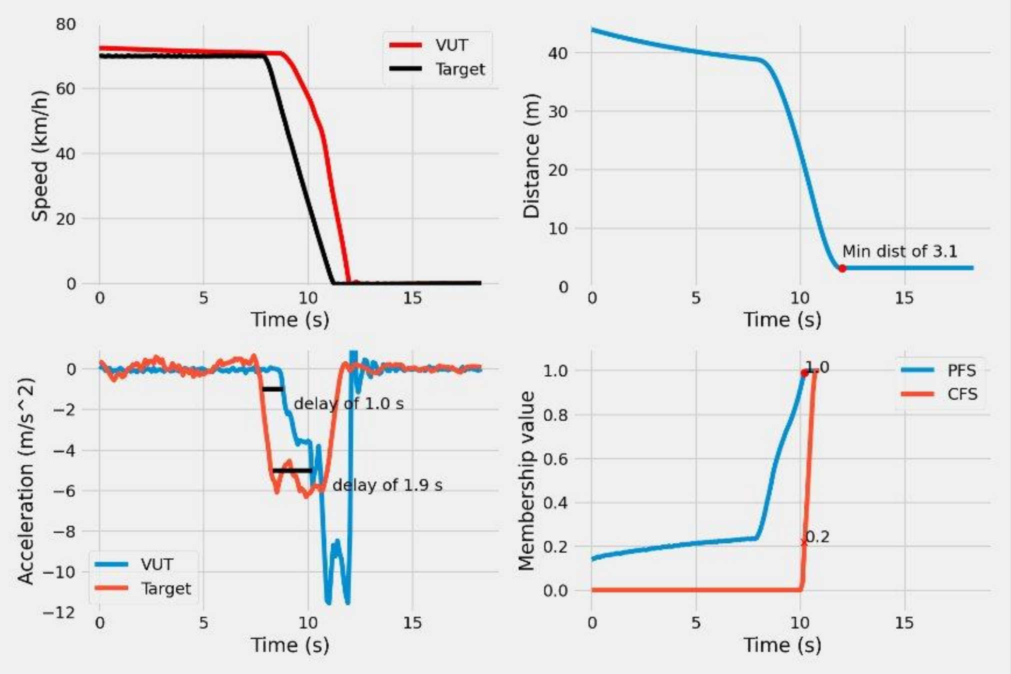
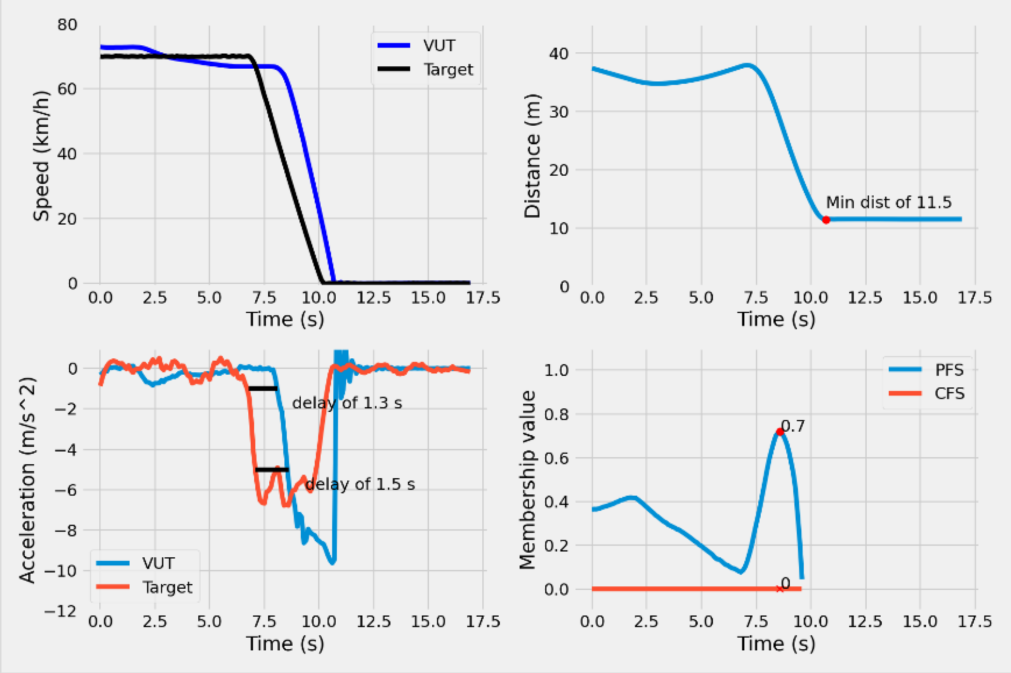
Vehicle 1



Vehicle 2



Evidence from US test campaign. Test-track (Car to Car Braking)

	Vehicle 1	Vehicle 2
Medium time-gap		

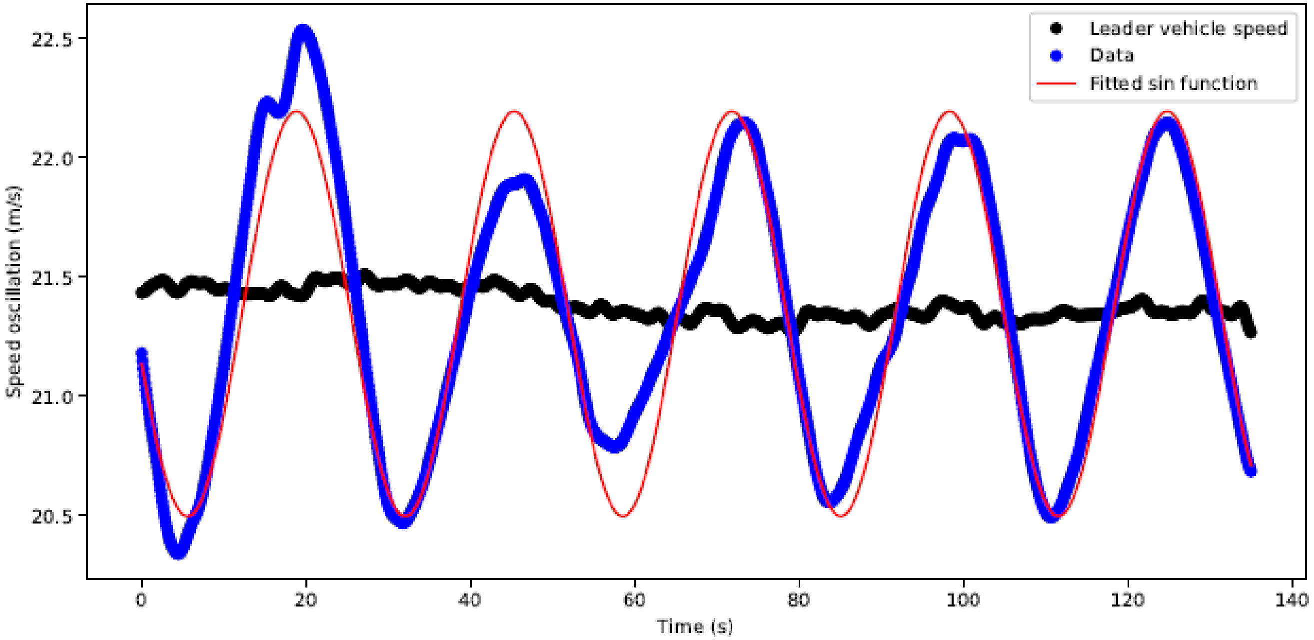
Evidence from US test campaign. Test-track (Car to Car Braking)

- The proactive design used in Vehicle 2 allows not only the vehicle to be string stable but also readier to handle safety critical situations
- In all tests Vehicle 2 needed to apply a lower (in absolute terms) deceleration and was able to maintain a substantially higher distance at stop with significant benefits in terms of safety and comfort
- String-stability proves to be a robust indicators of proactive vehicle control that, although working under the responsibility of the driver, can bring safety benefits even in the case of system-initiated manoeuvres and eyes-on only monitoring system
- More evidence is available from the cut-in scenarios

Additional issues – local stability

One of the tested ACC also showed local stability problems (the controller unable to reach and maintain a constant speed)

Combined with string instability it can activate traffic oscillations and generate motion sickness in the following vehicles



We introduced in the text a proposal for a local stability requirement

Background slides on PFS and CFS

European Commission

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

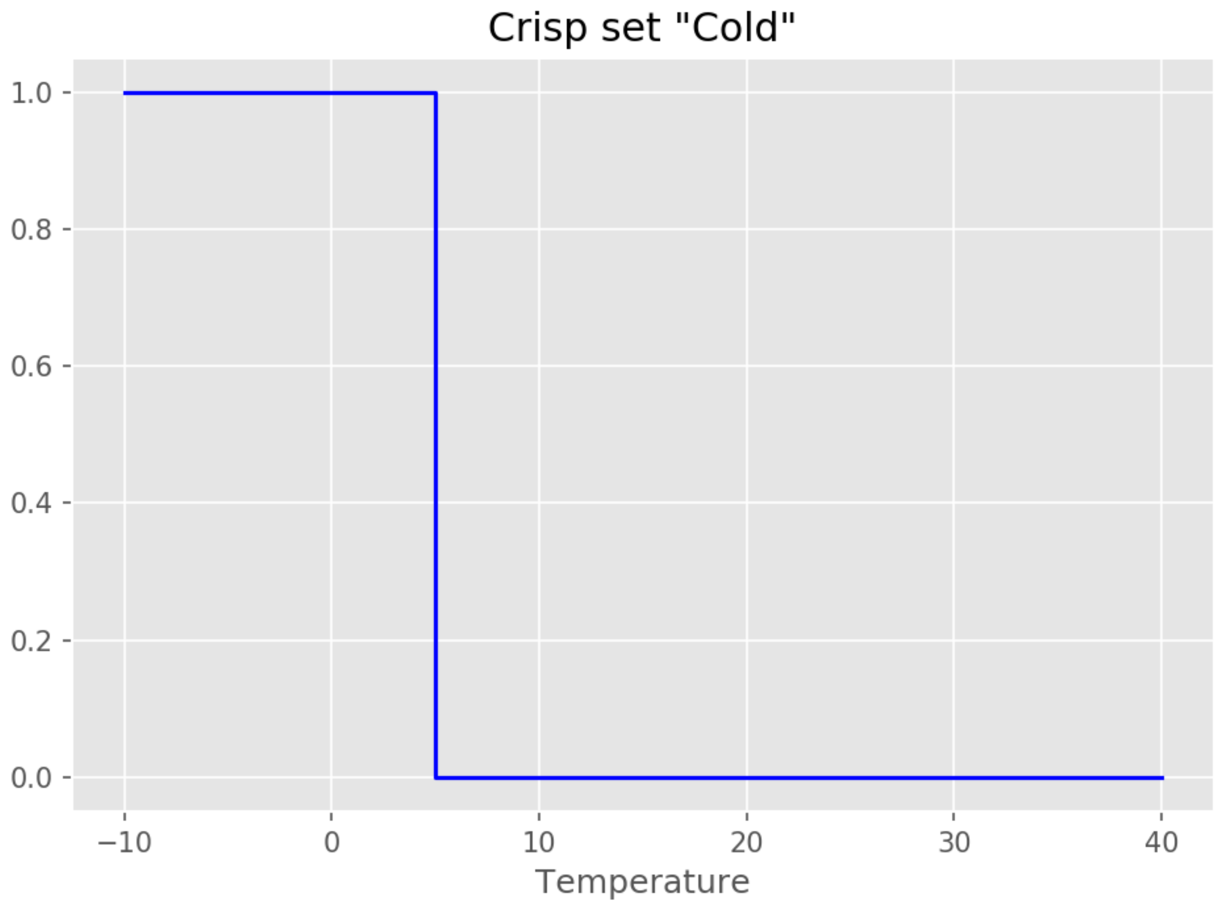
Capacity for calm proactive reaction

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’

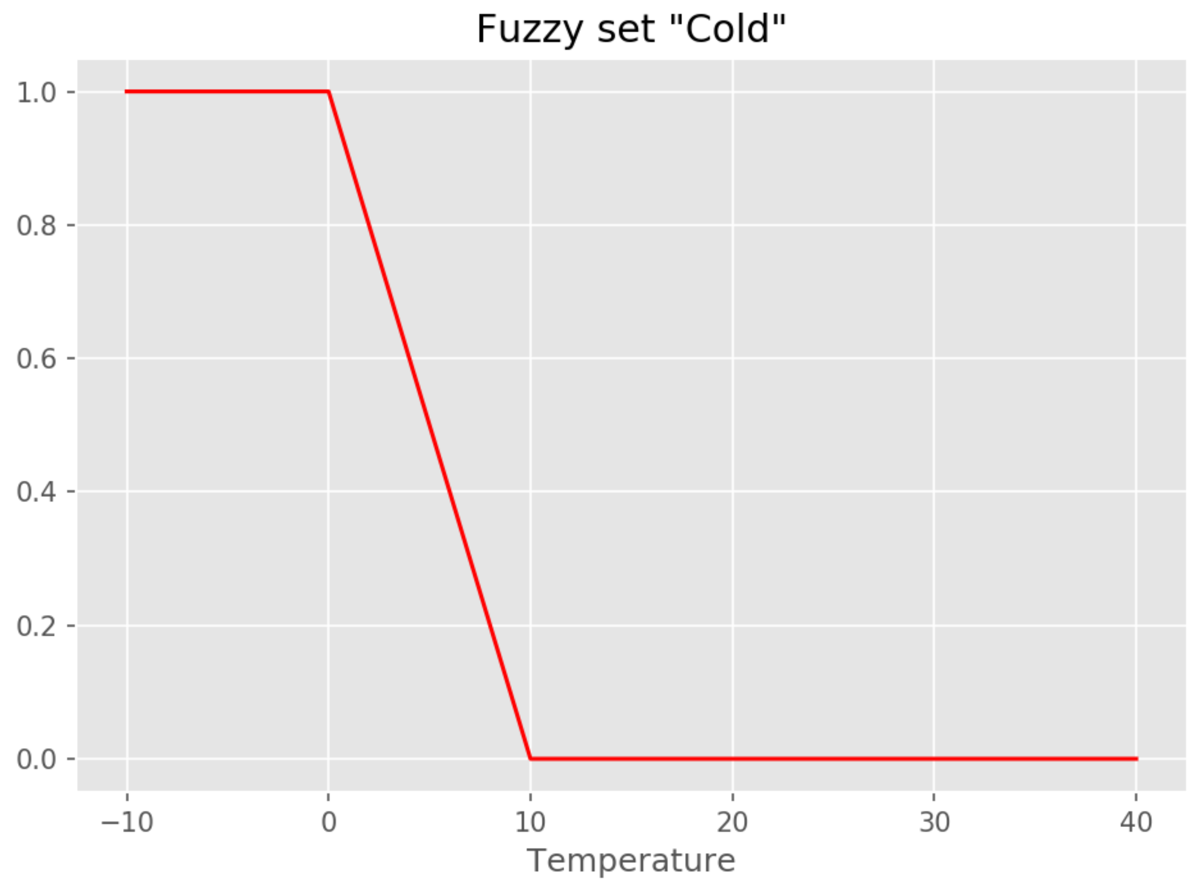


What is Fuzzy Logic? Fuzzy sets

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

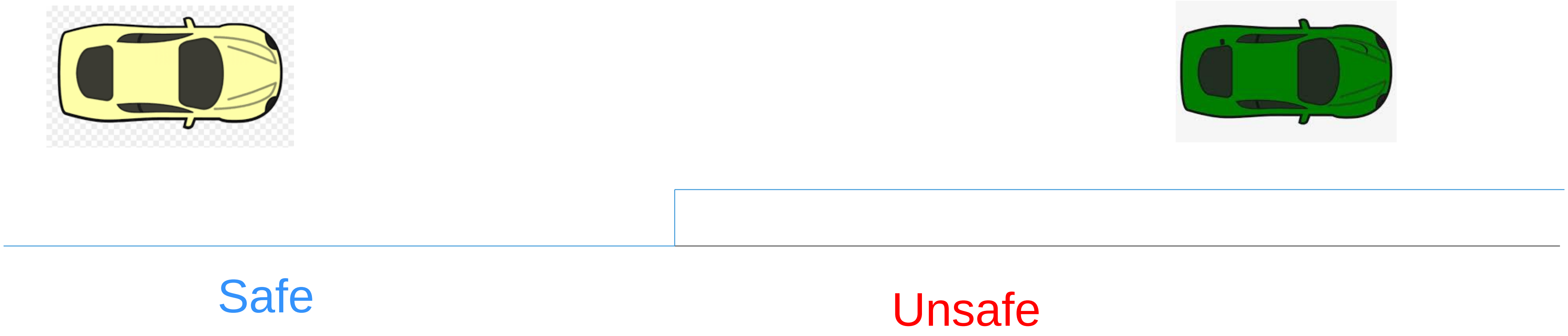
This can be helpful in many cases to better describe a situation

Based on those we can create fuzzy rules



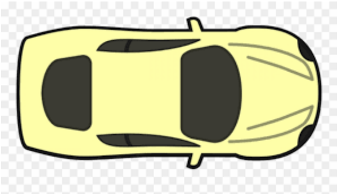
Why Fuzzy logic

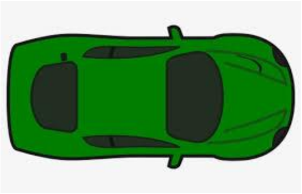
Two vehicles with known speeds. What is a safe distance?



Why Fuzzy logic

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



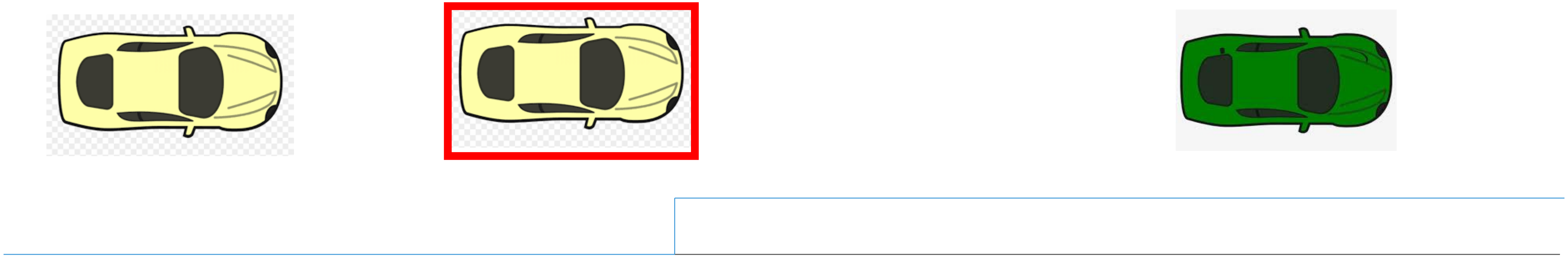


Safe
Do nothing

Unsafe
Decelerate hard

Why Fuzzy logic

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

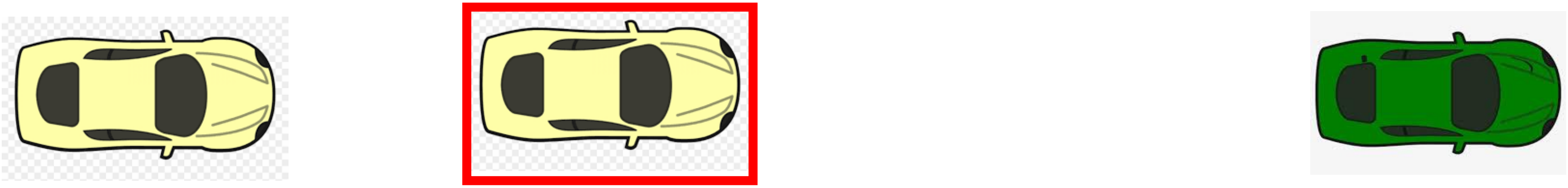


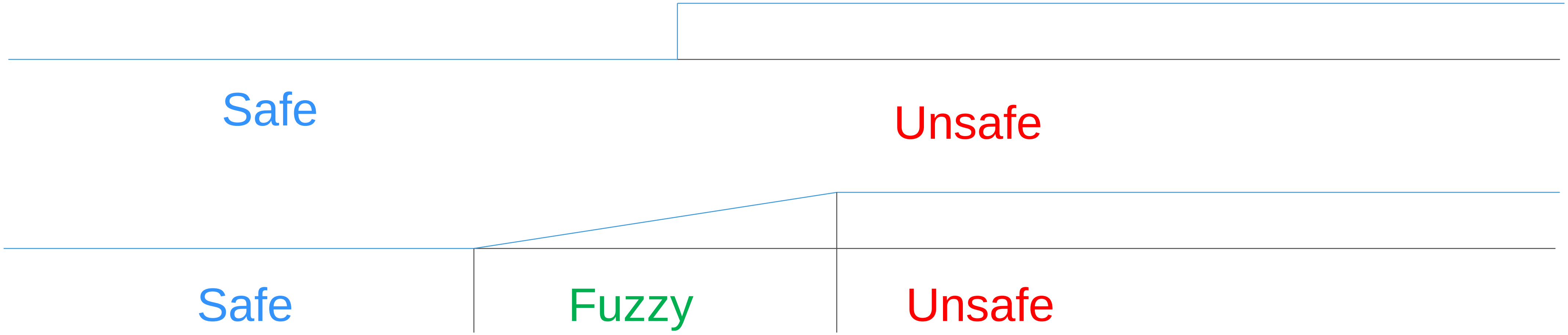
Safe
Do nothing

Unsafe
Decelerate hard

Why Fuzzy logic

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

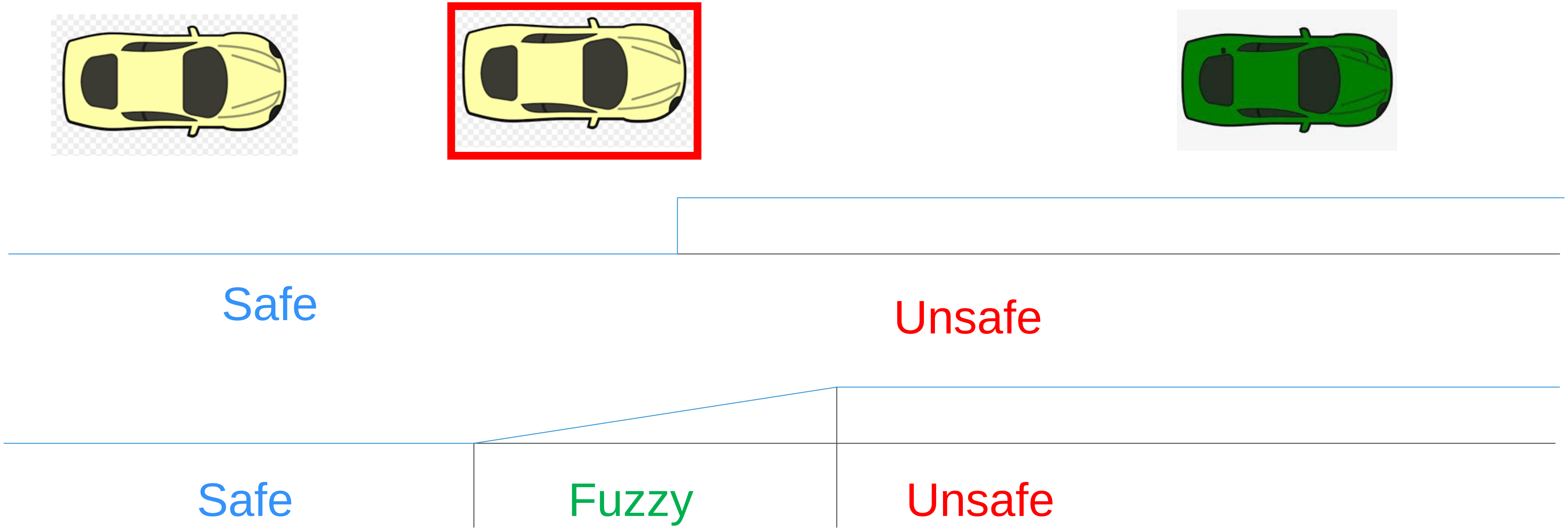




European Commission

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 (cut-in scenario)

Longitudinal safe distance according to Fuzzy SSMs

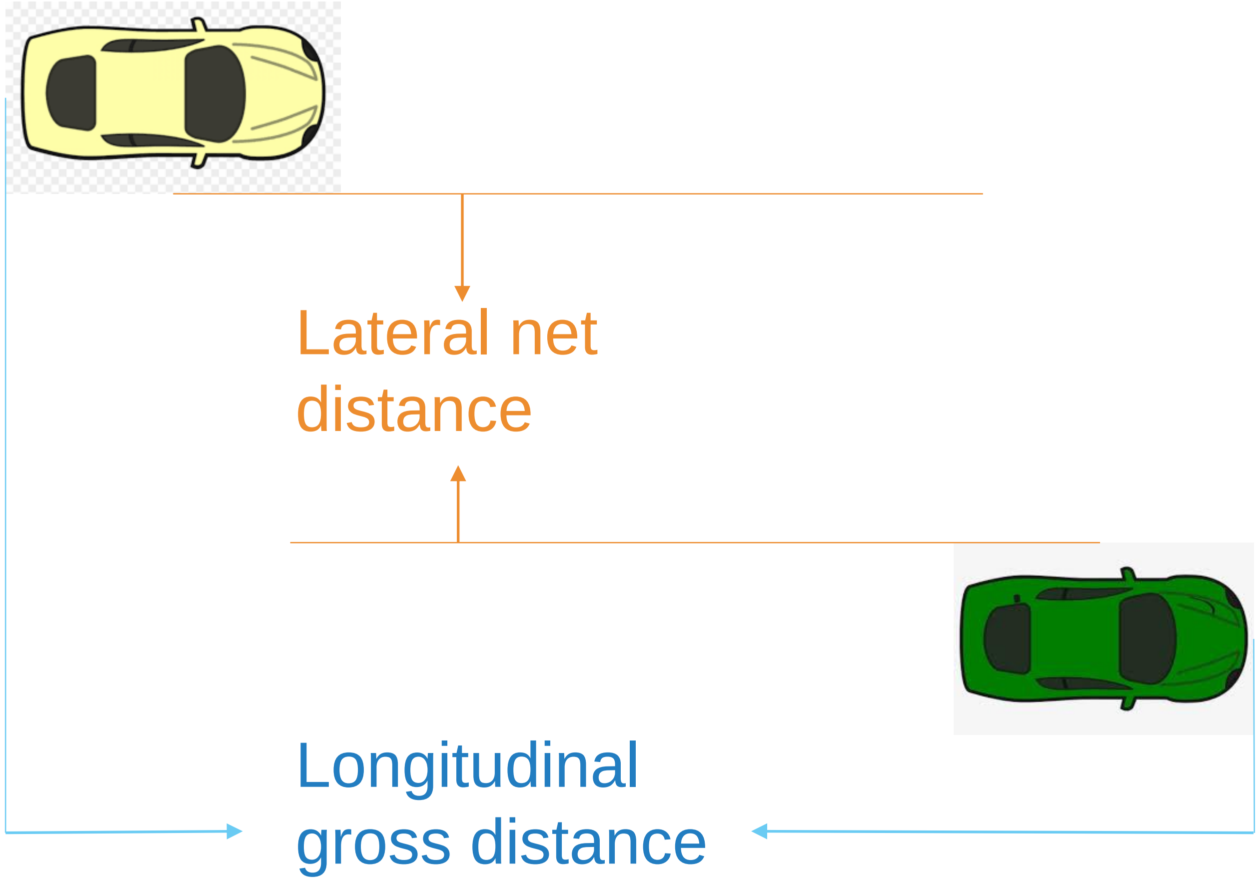
Capacity for calm proactive reaction

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

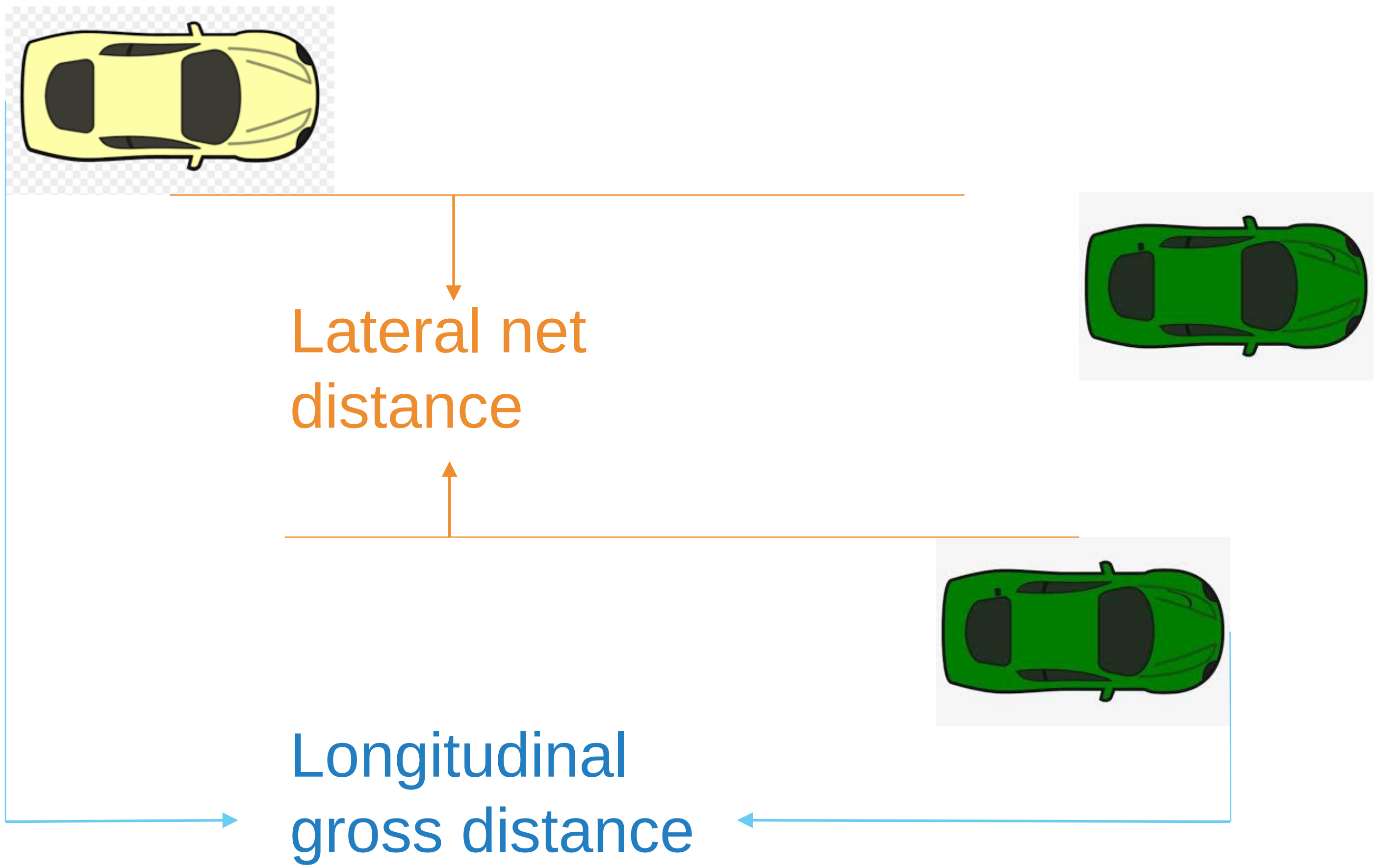
If all three restrictions apply, then we have to check the situation for the longitudinal safe distance

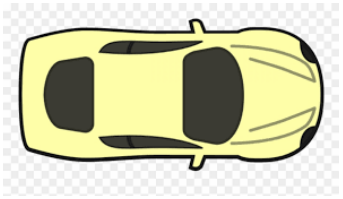
Different calculation of lateral safe distance



- 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

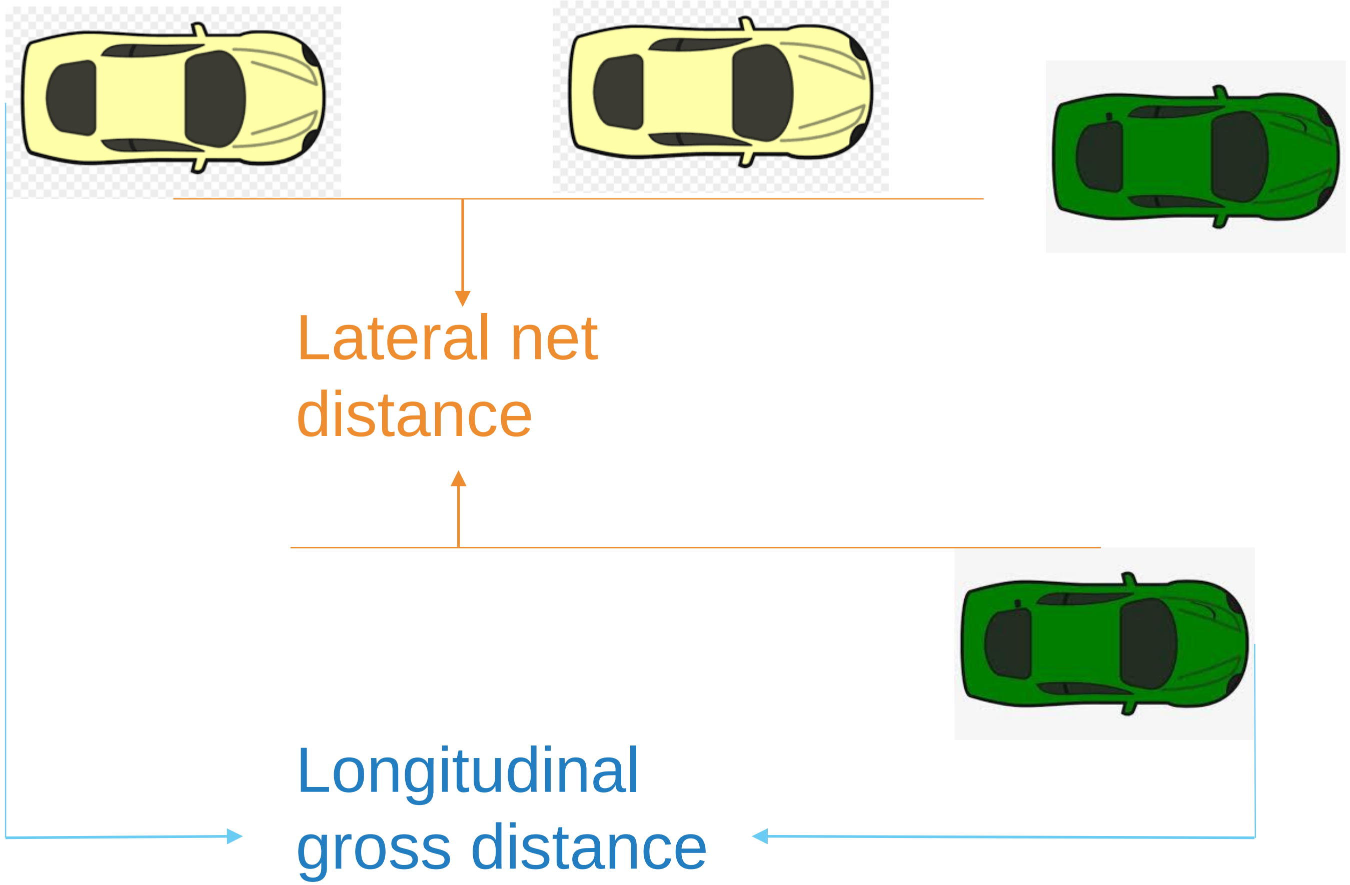
Different calculation of lateral safe distance





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:

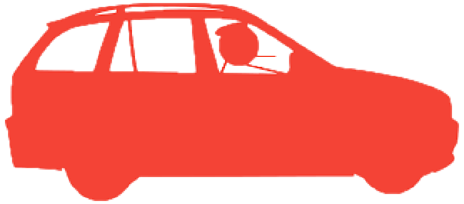
If the leader vehicle decelerates, the follower vehicle cannot avoid an accident (Vienna Convention on Road Traffic)

If nothing changes, there will be a collision in x sec (TTC)

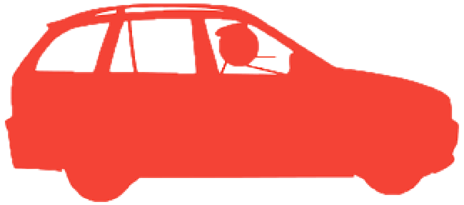
We calculated the Proactive Fuzzy SSM (PFS) and the Critical Fuzzy SSM (CFS)

Longitudinal safe distance according to Fuzzy SSMs

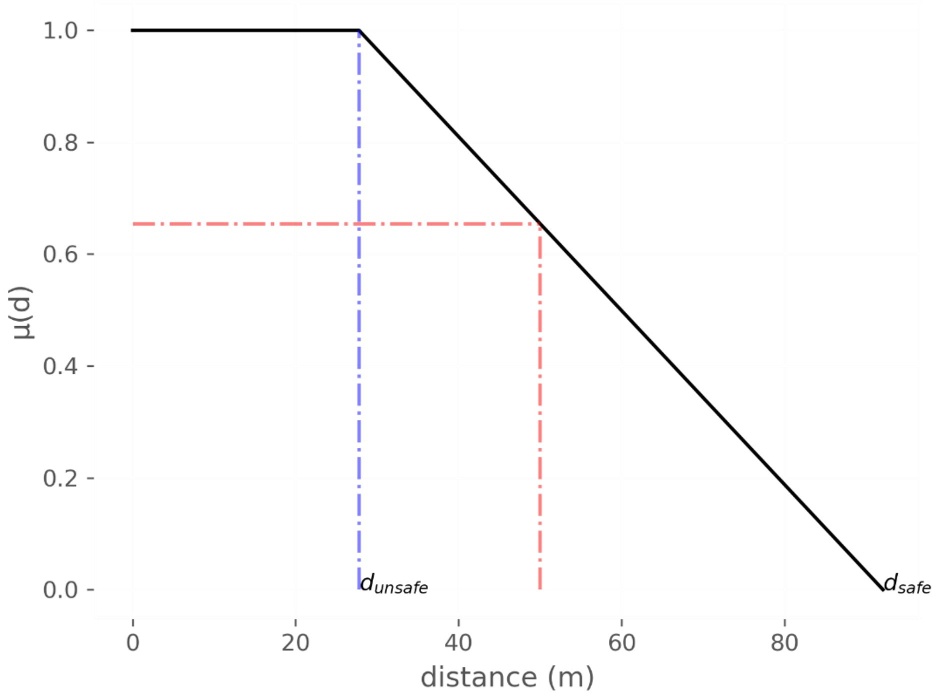
Maximum Unsafe distance



Minimum Safe distance



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

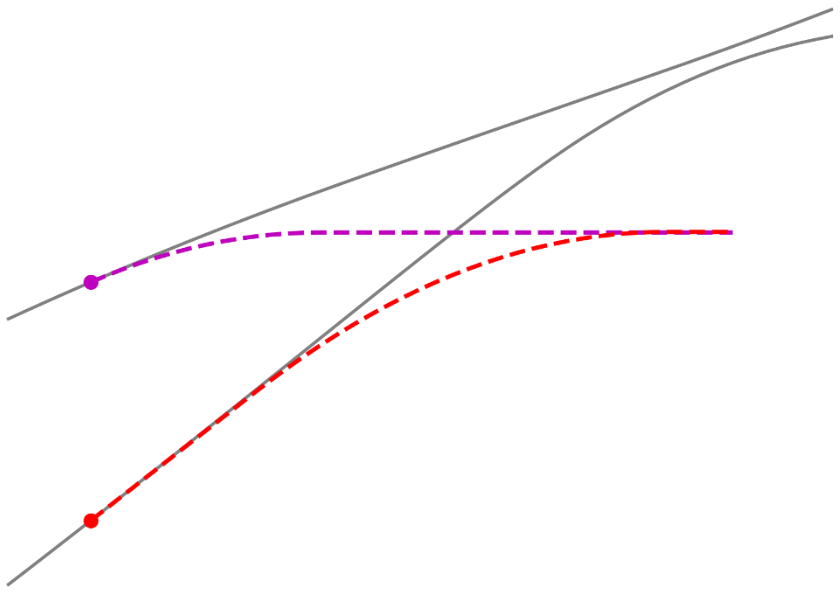


Longitudinal safe distance according to Fuzzy SSMs

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

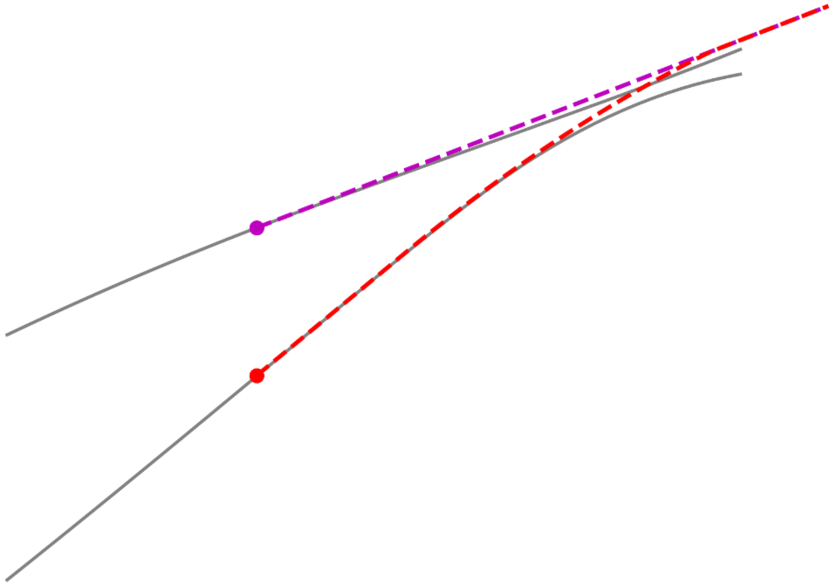
$$d_{safe}(t) \;=\; d_{unsafe}(t) = \frac{\left(u_2(t) - u_1(t)\right)^2}{2a_2'(t)}$$

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

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

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

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



European Commission

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

Keep in touch

EU Science Hub
joint-research-centre.ec.europa.eu

@EU_ScienceHub

EU Science Hub – Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

@eu_science

Biagio.CIUFFO@ec.europa.eu

European Commission

Thank you

European Commission