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European Commission

Safety assurance of automated driving systems. Defining performance levels

29 October 2020

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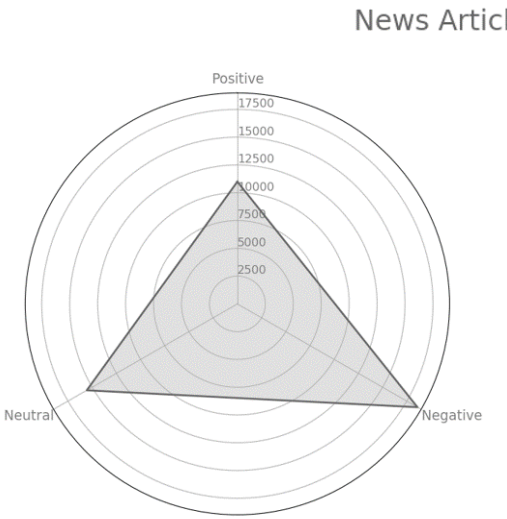
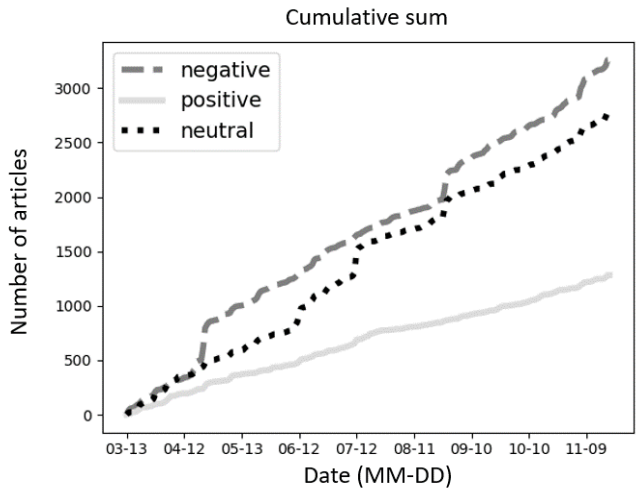
Joint Research Centre

The need for safety assurance

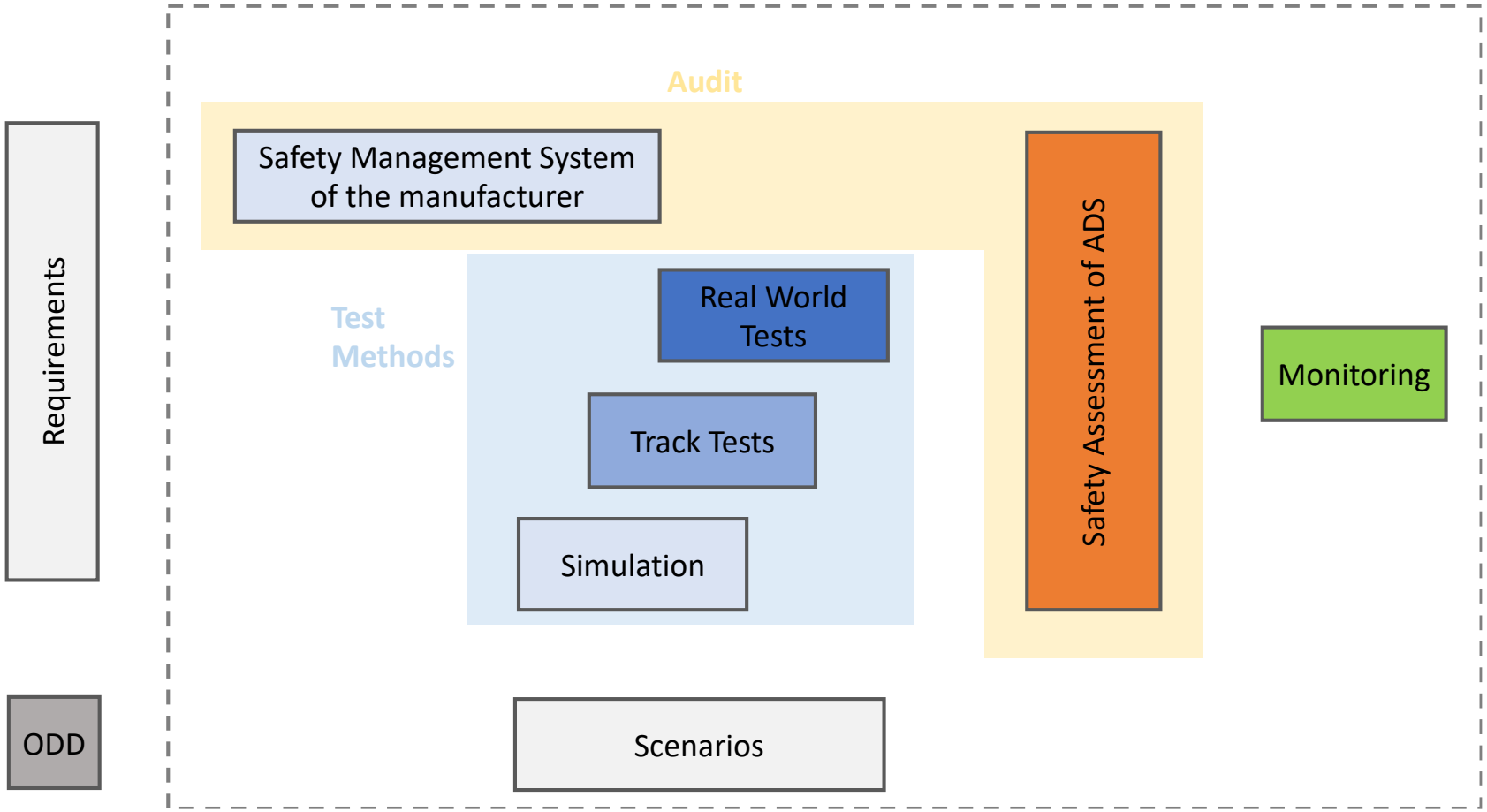
- AVs **promise** to substantially **reduce** the number of **road accidents** (90% of accidents caused by human errors)
- There is **scepticism** in the media and in the public opinion about what AVs will deliver
  - JRC study with European Media Monitor (>45.000 news articles)
  - Eurobarometer survey 496* (>27.000 face to face interviews)





* https://data.europa.eu/euodp/it/data/dataset/S2231_92_1_496_ENG

Assessment of ADS safety in GRVA/VMAD*



* *VMAD-13-03 NATM MASTER DOCUMENT*

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Example: ALKS Regulation 81

- Requirements. The activated system shall:
  - comply with traffic rules
  - not cause any collisions reasonably foreseeable and preventable

Example: ALKS Regulation 81

- Requirements. The activated system shall:
  - comply with traffic rules
  - not cause any collisions reasonably foreseeable and preventable
  - adapt the speed to adjust the distance to a vehicle in front in the same lane to be equal or greater than the minimum following distance.
  - avoid a collision with a cutting in vehicle if the cutting in vehicle is 30 cm inside the lane and

$$TTC > \frac{u_{rel}}{6 * 2} + 0.35\ s$$

Present speed of the ALKS vehicle		*Minimum time gap*	*Minimum following distance*
(km/h)	(m/s)	(s)	(m)
7.2	2.0	1.0	2.0
10	2.78	1.1	3.1
20	5.56	1.2	6.7
30	8.33	1.3	10.8
40	11.11	1.4	15.6
50	13.89	1.5	20.8
60	16.67	1.6	26.7

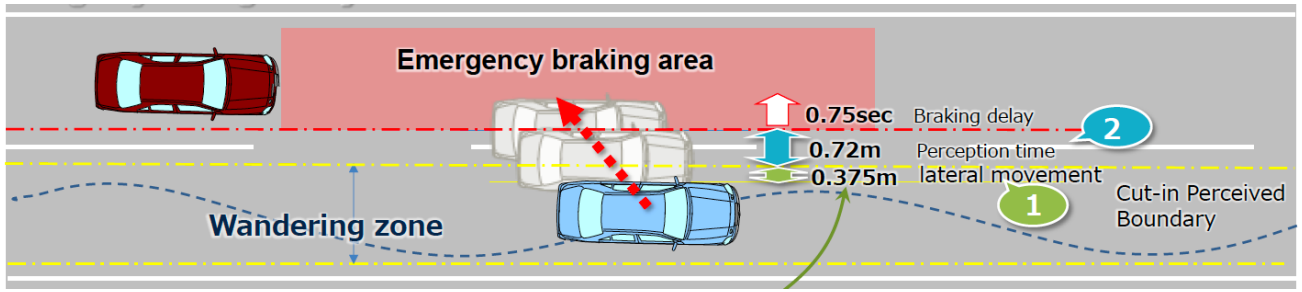
System safety requirements (FRAV*)

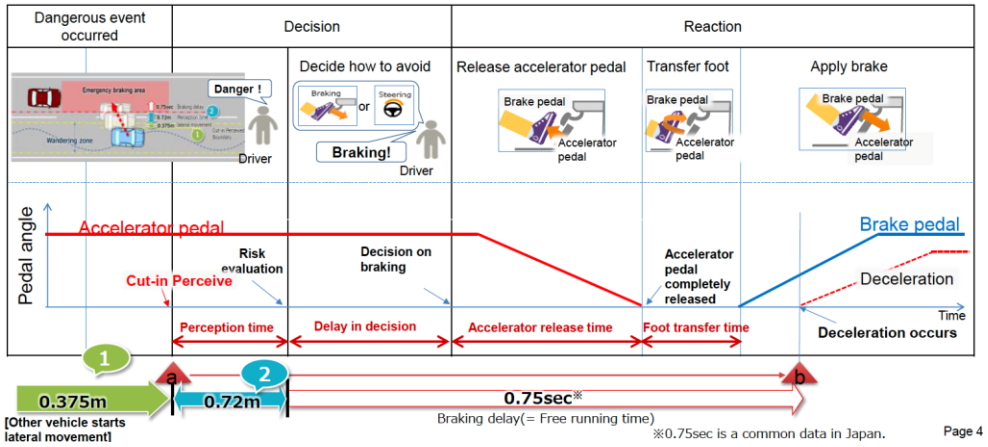
- When in automated mode, the automated/autonomous vehicle should be free of unreasonable safety risks to the driver and other road users and ensure compliance with road traffic regulations. […] (AVs) shall not cause any traffic accidents that were *reasonably foreseeable and preventable*
- [The nominal operation of the ADS shall result in *equal or safer performance than a human driver*. i.e. achieve a neutral or positive risk balance]
- ***How to assess this?***

* *FRAV-02-05-Rev.2*

Proposal from Japan*

- Approach based on the definition of an "**attentive human driver**"*
- Simplified approach to consider a limited number of input parameters to define **preventable scenarios**
- The driver model is built using and extensive database of naturalistic traffic situations and general considerations on drivers' behaviour





* *Draft Appendix on Traffic Disturbance Critical Scenarios (21 February 2020)*

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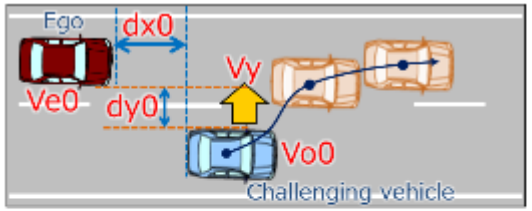
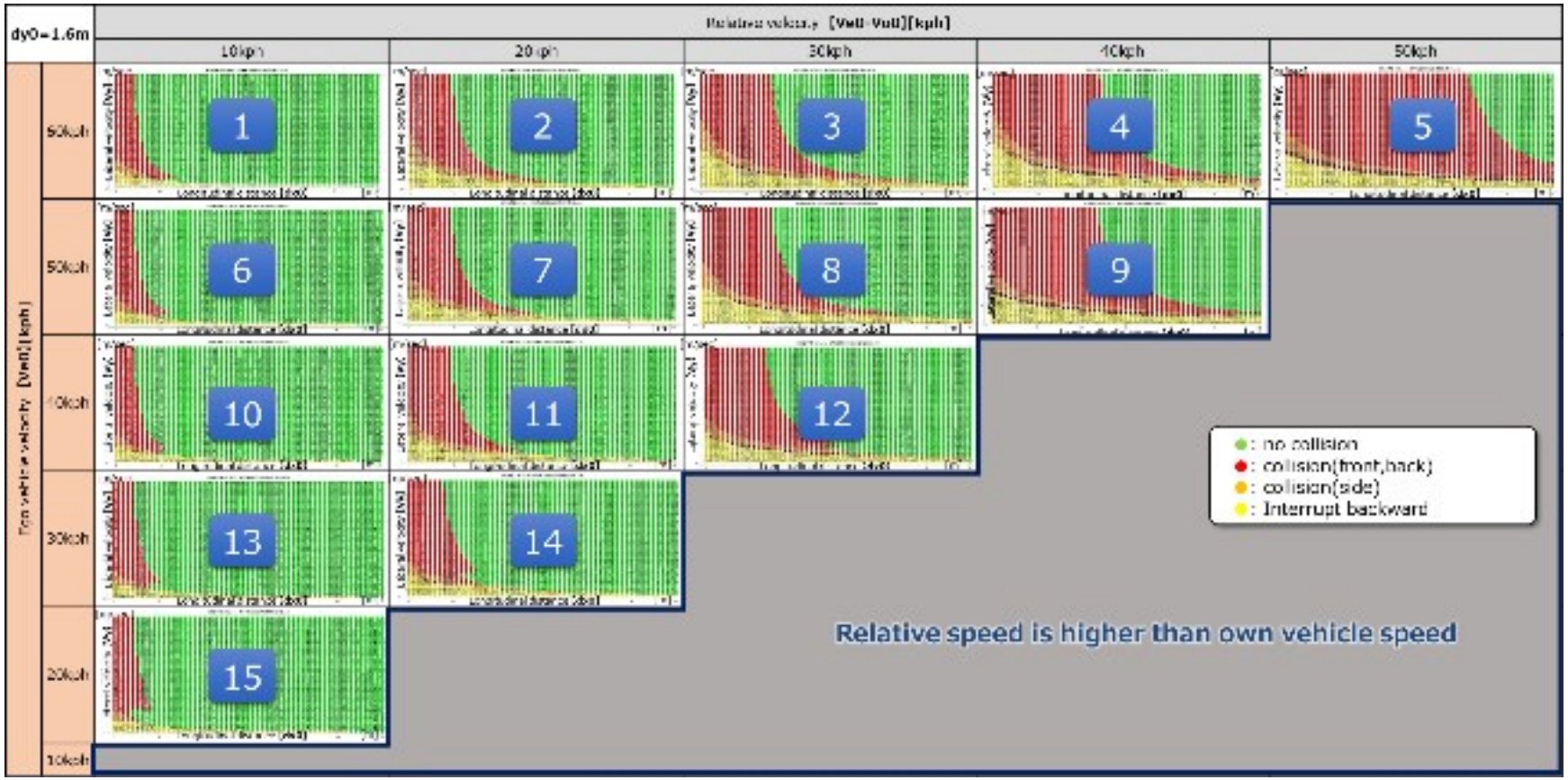
Application of the Japanese approach



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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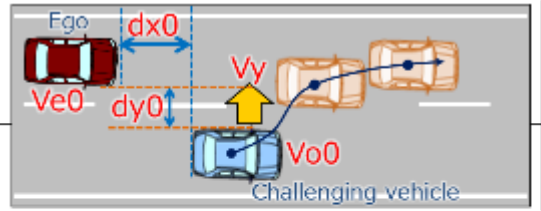
Application of the Japanese Model



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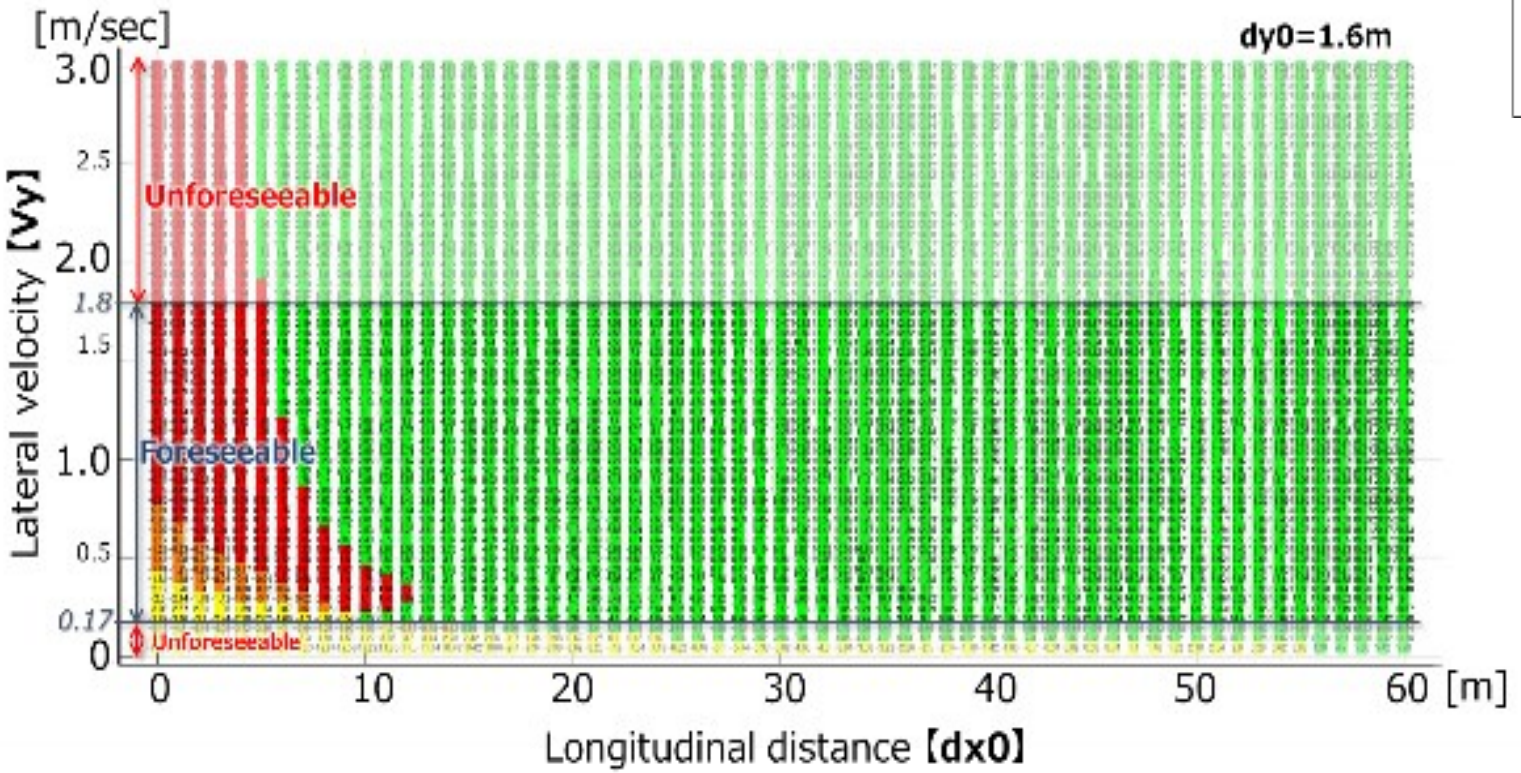
※Latteral distance

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

1 Ego vehicle velocity【Ve0】 : 60[kph]
Relative velocity【Ve0-Vo0】 : 10[kph]



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Preventable scenarios – limitations

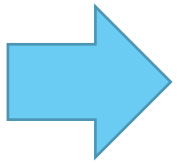
- The proposed methodology is extremely interesting as it defines in a transparent, simple and analytical way the preventable scenarios
- Given its fundamental role in the definition of the tests that an ADS would be subject to* the JRC has expressed its concerns about a number of limitations inherent of the approach
  - Lack of proper validation of the results.
  - Limited scalability of the approach
  - Limited representativeness of the attentive driver concept
  - **Lack of additional contribution to safety by state-of-the-art technologies**

** The method also defines the conditions where ADS **should not be tested** because would lead to an accident for an attentive human driver*

Safety envelope as behavioural requirement

- An alternative approach to comparing the performance of an ADS with that of human drivers is the introduction of a safety envelope as system requirement

- **Safety envelope**
  - If the vehicle controller is able to keep other traffic **objects away** from this space
  - If the **parameters** used to derive it **are correct**



The vehicle will **not be responsible to cause** an accident

- Common sense rules and kinematic laws are used to derive a mathematical formulation of a **safe "envelope"**

Safety-envelope formulation

- Recent developments in ADAS/ADS has led to the development of a few mathematical formulations formalizing the duty of care
  - **Advaced surrogate safety metrics**
  - **NVIDIA's Safety Force Field (SFF)**
  - **Intel's Mobileye Responsibility-Sensitive Safety (RSS)**
  - **Fuzzy-logic based frameworks**
  - **…**

Example: RSS

- **No absolute safety:** The developers assume that there could not be a perfectly safe vehicle

- **Statistical approach is not viable:** A LOT of driving hours are required, this must be repeated for every change

- **Responsibility:** RSS claims that **a vehicle abiding by those rules will not be responsible for an accident** (without taking sensor failure into account)

RSS – 4 “common sense” rules

- Keep **a safe distance from the car in front of you**, so that if it will brake abruptly you will be able to stop in time
- Keep **a safe distance from cars on your side**, and when performing lateral manoeuvres and cutting-in to another car’s trajectory, you must leave the other car enough space to respond
- You should respect “right-of-way” rules, **but “right-of-way” is given not taken**
- **Be cautious of occluded areas,** for example, a little kid might be occluded behind a parked car

RSS – 5 “common sense” rules (updated)

- Do not hit someone from behind.
- Do not cut-in recklessly.
- Right-of-way is given, not taken.
- Be careful of areas with limited visibility
- **If you can avoid an accident without causing another one, you must do it.**

RSS – Cases

- **Longitudinal**
- **Multiple lanes**
- Multiple Geometry and Right-of-Way Rules
- Unconstructed road
- Pedestrians
- Cautiousness with respect to Occlusion

Example. RSS for longitudinal interaction*

$$d_{min} = \left[u_r \rho + \frac{1}{2} a_{max,accel} \rho^2 + \frac{\left(u_r + \rho a_{max,accel}\right)^2}{2 a_{min,brake}} - \frac{u_f^2}{2 a_{max,brake}} \right]$$

d_{min}: the minimum safe distance

u_r: the ego vehicle speed

u_f: the front vehicle speed

ρ: the ego vehicle reaction time

$a_{max,accel}$: the ego vehicle maximum acceleration

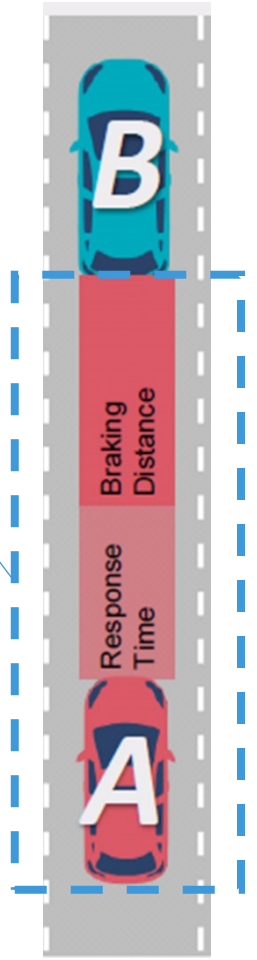
$a_{min,brake}$: the ego vehicle maximum deceleration

$a_{max,brake}$: the front vehicle's maximum deceleration

State variables

Technological parameters

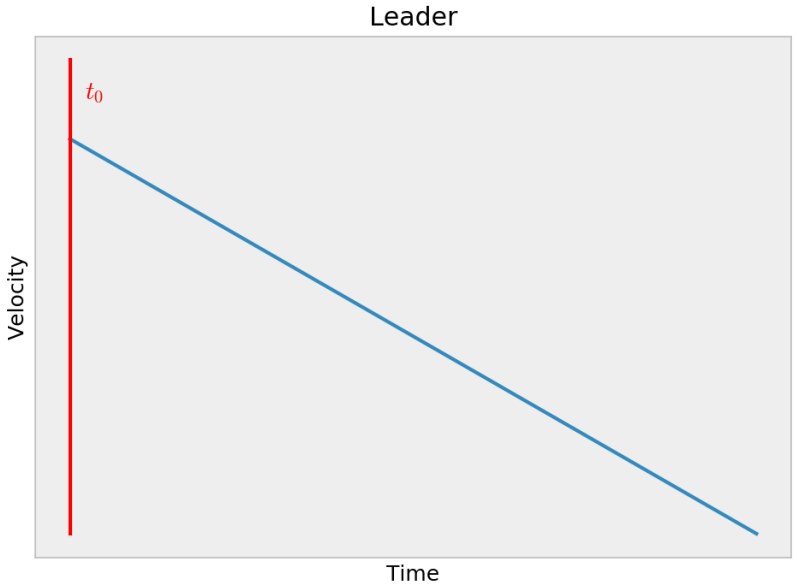
Leader's parameters

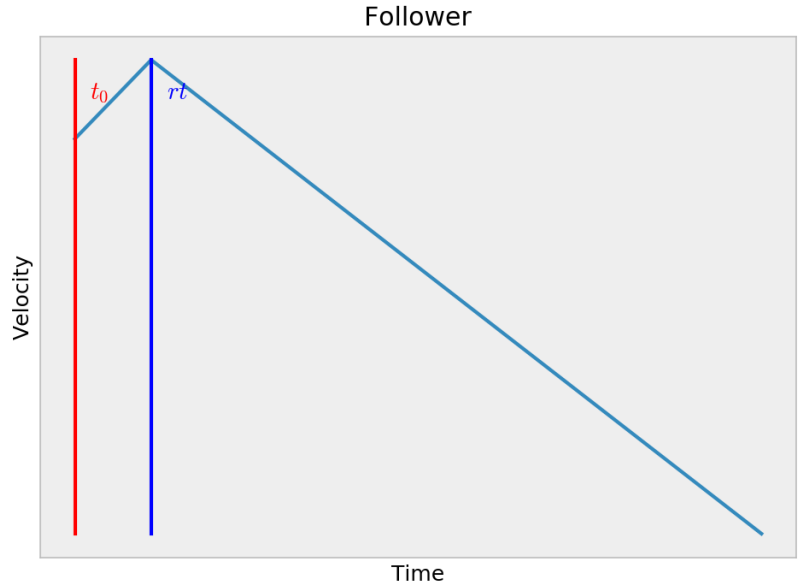


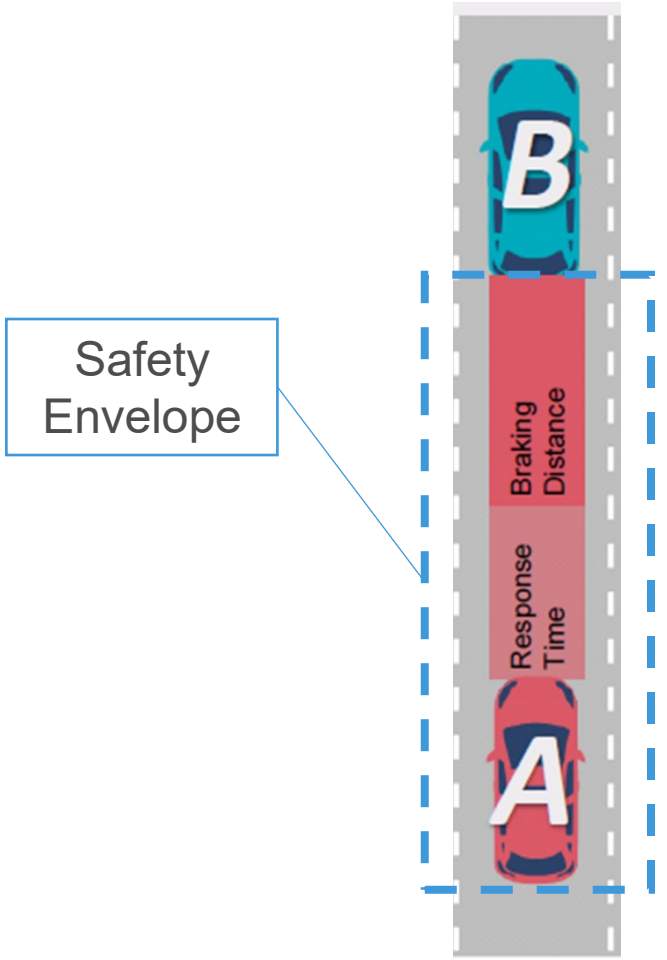
*Shalev-Shwartz, S., S. Shammah, and A. Shashua. On a Formal Model of Safe and Scalable Self-Driving Cars. *arXiv:1708.06374 [cs, stat]*, 2017.

RSS for longitudinal interaction*

$$d_{min} = \left[u_r \rho + \frac{1}{2} a_{max,accel} \rho^2 + \frac{\left(u_r + \rho a_{max,accel}\right)^2}{2 a_{min,brake}} - \frac{u_f^2}{2 a_{max,brake}} \right]$$







Example. RSS for lateral interaction

Lateral safety distance

$$d_{min} = \mu + \frac{2u_1 + \rho a^{lateral}{}_{max,accel}}{2}\rho + \frac{\left(u_1 + \rho a^{lateral}{}_{max,accel}\right)^2}{2a^{lateral}{}_{min,brake,correct}} - \frac{2u_2 + \rho a^{lateral}{}_{max,accel}}{2}\rho + \frac{\left(u_2 + \rho a^{lateral}{}_{max,accel}\right)^2}{2a^{lateral}{}_{min,brake,correct}}$$

d_{min}	the minimum safe distance
μ	minimum lateral distance (parameter)
u_i	the lateral speed of vehicle i
ρ	the vehicles' reaction time
$a_{max,accel}$	the vehicle's maximum lateral acceleration (high)
$a_{min,brake}$	the vehicle's minimum lateral acceleration (low)

State variable

Technological parameters

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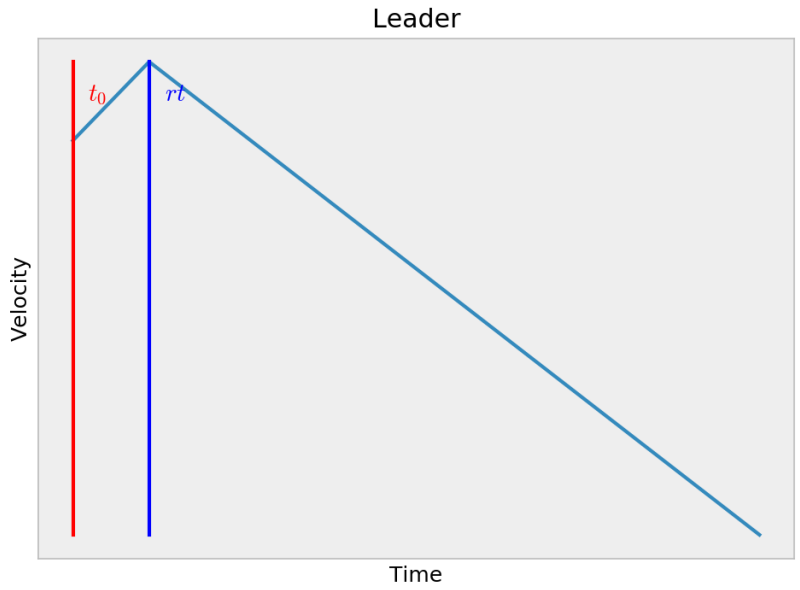
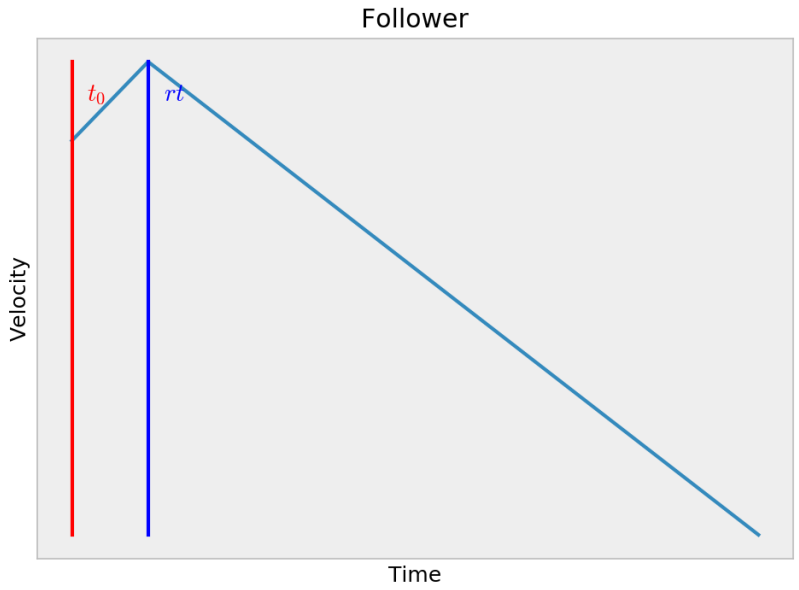
Example. RSS for lateral interaction

Lateral safety distance

$$d_{min} = \mu + \frac{2u_1 + \rho a^{lateral}{}_{max,accel}}{2}\rho + \frac{\left(u_1 + \rho a^{lateral}{}_{max,accel}\right)^2}{2a^{lateral}{}_{min,brake,correct}} - \frac{2u_2 + \rho a^{lateral}{}_{max,accel}}{2}\rho + \frac{\left(u_2 + \rho a^{lateral}{}_{max,accel}\right)^2}{2a^{lateral}{}_{min,brake,correct}}$$





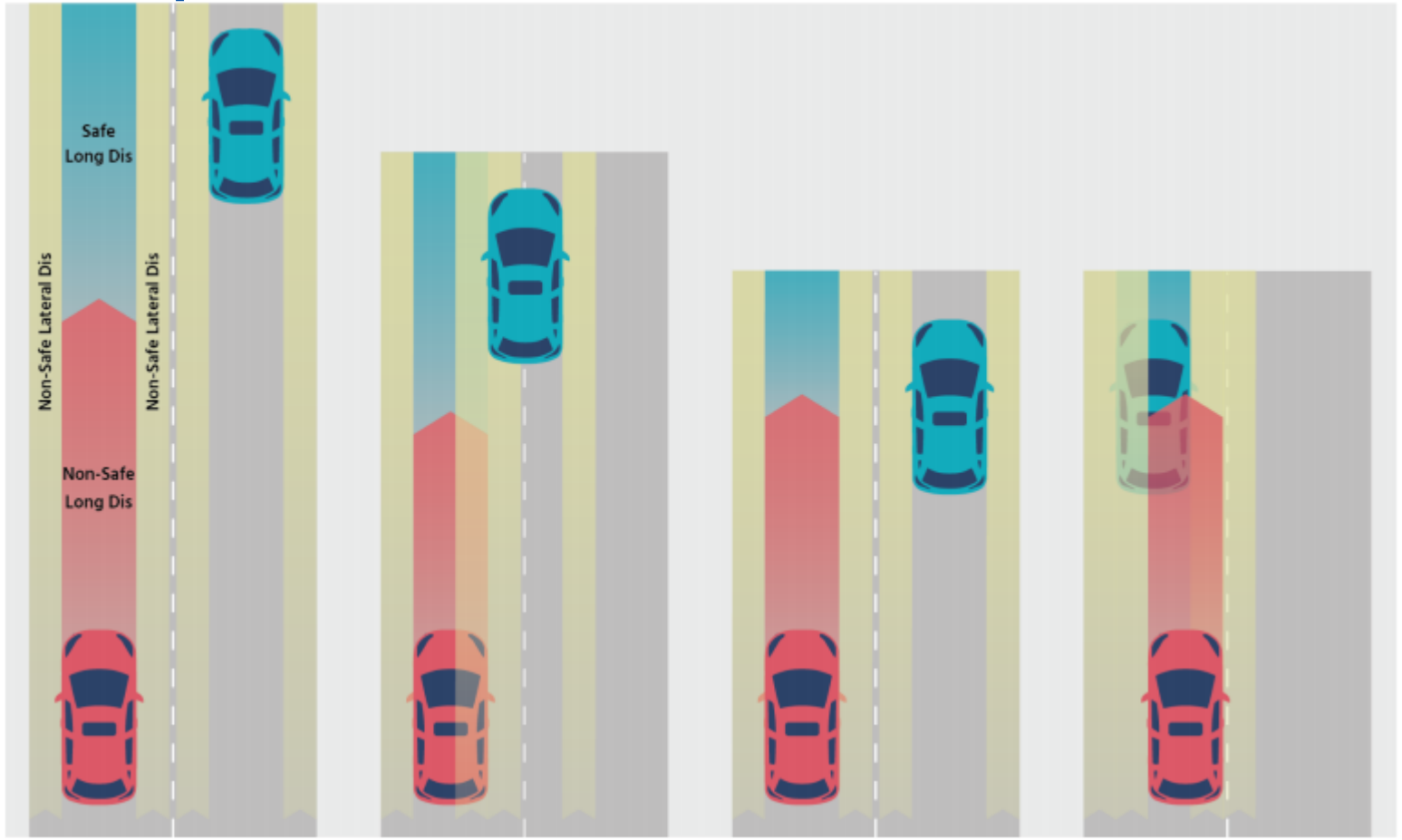
Interactions in multiple lanes

A situation is unsafe only if both safety distances are not respected.

Responsibility:

- Keep safe longitudinal distance with vehicles in front.
- Keep safe lateral distance with the vehicles aside.

While performing a lane change in front of another vehicle, an RSS vehicle is **responsible to keep safe longitudinal distance with the new follower.**



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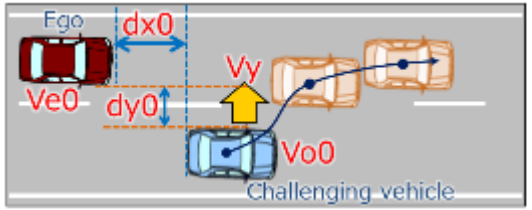
Safety envelope as behavioural requirement

- Pros:
  - **Transparent and coherent** definition of safety conditions
  - Based on ***physical laws and technological properties***
  - Possibility to amend the parameters of the model as technology improves
- Cons:
  - **Limits OEMs' choices** in setting vehicles' operational strategy
  - If it comes with fixed values of the parameters it may hinder innovation

Safety envelope as performance requirement

- In order to combine the positive aspects of the different approaches our proposal is to use s**afety envelope concept as performance requirement, i.e. to define which scenarios are preventable**
- Pros:
  - The parameters of the safety envelope do not depend from any assumption on the performance of a human driver
  - Not used as a requirement it does not directly affect vehicles' operation strategy
- Cons:
  - It does not allow to assess whether ADSs will be statistically better than human drivers

Application



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※Latteral distance

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

- Scenario: **cut-in for ALKS**
- Models used: **Japan driver model, Reguation 81 based on TTC, and RSS**
- Scenario characterization approach: **same as Japan**
- Simulation framework: in-house developed using Python

The “vehicle” class

- For any vehicle, a predefined desired trajectory is defined using its position and speed in the 2D space for each simulation step. The position corresponds to the centre of gravity of the vehicle
- Basic parameters for each vehicle:
  - Width
  - Length
  - Maximum longitudinal acceleration
  - Maximum longitudinal deceleration
  - Maximum lateral acceleration
- Additional parameters are needed by the different models

Parameter values

- Unless stated otherwise by one of the models, the parameter values used are:
  - Width = 1.9 [m]
  - Length = 5 [m]
  - Maximum longitudinal acceleration = 3 [m/s^2]
  - Maximum longitudinal deceleration = 6 [m/s^2] (0.774 g for the JP model)
  - Maximum lateral acceleration = 1 [m/s^2]

Vehicle movement

- Each vehicle has a predefined trajectory
- Only for the ego vehicle, for each simulation step, it is checked whether there is reason for avoidance manoeuvres.
- If yes, the avoidance maneuverer is forced
- Otherwise, if the vehicle was never unsafe, it continues with the predefined trajectory
- If it has used avoidance maneuverer, but it is safe now, it continues with constant speed
- The simulation step is set to 0.1 sec

Application of the Japan Driver model

- Specific parameters:
  - Maximum longitudinal deceleration = 0.774 g [m/s^2]
  - Reaction time = 0.75 [s]
  - Maximum absolute jerk = 12.65 [m/s^3]
  - Idling deceleration = 0.4 [m/s^2]

- If the ego vehicle is behind the cutting in vehicle with TTC < 2 sec:
  - Decelerate with Idling deceleration for Reaction time, and then increase deceleration according to the Maximum absolute jerk until reaching the Maximum longitudinal deceleration

Application of the driver model implicitly defined in Regulation 81

- The analysis also includes the approach used in the recently approved ALKS regulation and based on the TTC surrogate safety metric. It has been recently showed that its results are not substantially different from the Japanese model*
- Specific parameters:
  - Maximum longitudinal deceleration = 6 m/s^2
  - Reaction time = 0.35 [s]
- If the cutting in vehicle is 30 cm inside the lane and

$$TTC \leq \frac{u_{rel}}{6 * 2} + 0.35\ sec$$

  - Keep constant speed for Reaction time, and then decelerate with Maximum longitudinal deceleration

* *Informal document ACSF-25-18 from Japan submitted to the ACSF 25th session*

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Application of the RSS model

- Specific parameters:
  - Maximum longitudinal deceleration RSS param = 6 [m/s^2]
  - Actual maximum longitudinal deceleration = 0.774 g [m/s^2]
  - Reaction time = 1 [s]*
  - Maximum absolute jerk = 12.65 [m/s^3]
  - μ = 0.3 [m]

* Value defined following the exchanges in VMAD SG1a

Application of the RSS model

The RSS safety rules consider the lateral movement of the other vehicles before the cutting in happens.

Thus, the simulation starts with the cutting in vehicle having 0 lateral speed.

For comparison with the VMAD Driver method, the simulation is extended backwards, so the cutting in vehicle achieves the chosen lateral speed at the chosen lateral and longitudinal distance.

The initial positions of both vehicles change, assuming constant longitudinal speed and maximum lateral acceleration for the cutting in vehicle.

Application of the RSS model (1/2)

- In every simulation step safe lateral and longitudinal distances are calculated using the RSS formulation.
- If both the lateral and longitudinal distances are less than safe, longitudinal evasive maneuverers start. No lateral evasive manoeuvres are considered in line with the approach proposed by VMAD-SG1 driver model

- For time equal to Reaction time, the speed of the ego vehicle is constant.

$$u_{ego}(t) = u_{ego}(t - i)$$

Application of the RSS model (2/2)

- After Reaction time, the deceleration decreases according to the Maximum absolute jerk.

$$acceleration_{ego}(t) = acceleration_{ego}(t - i) - jerk * i$$

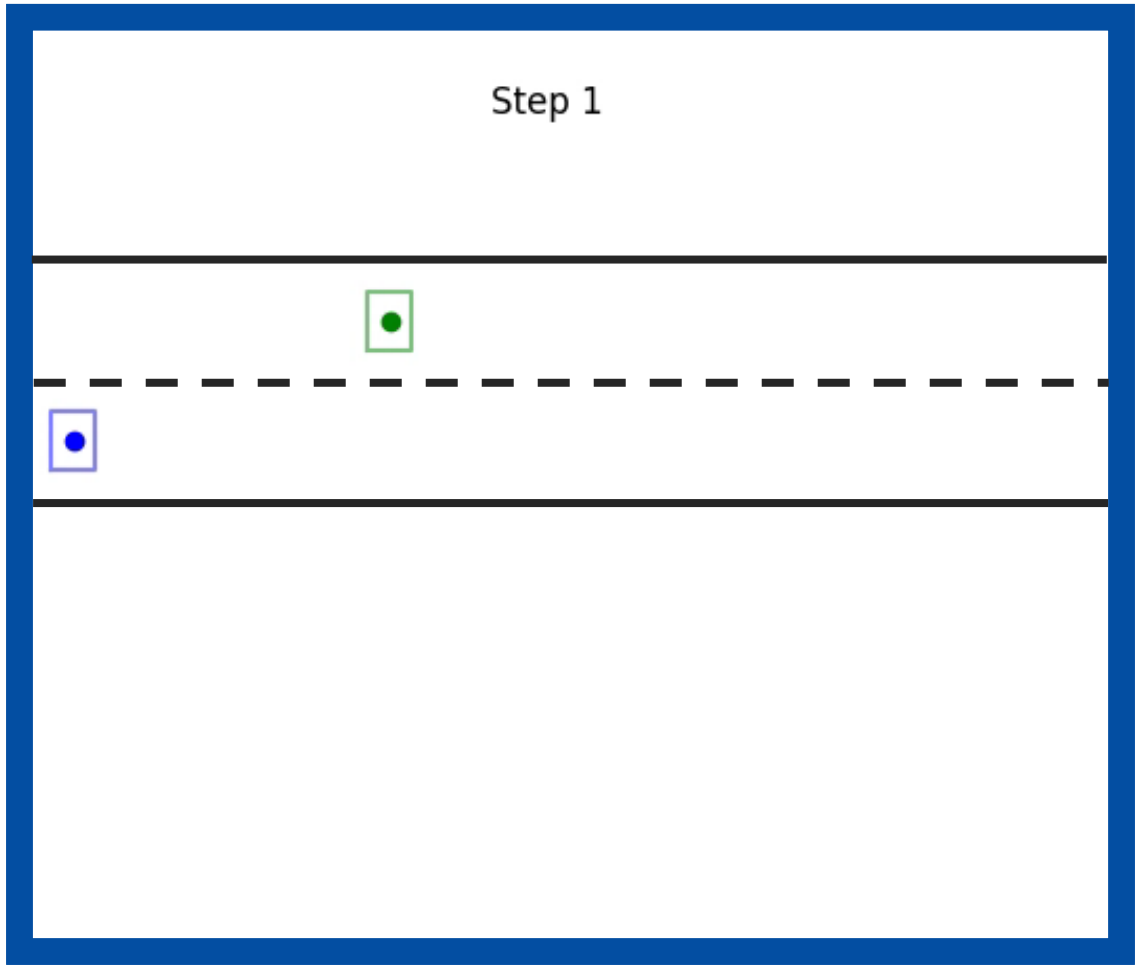
$$u_{ego}(t) = u_{ego}(t - i) - acceleration_{ego}(t) * i$$

- When the Actual maximum longitudinal deceleration is achieved the vehicle continuous with constant deceleration until it is again safe.

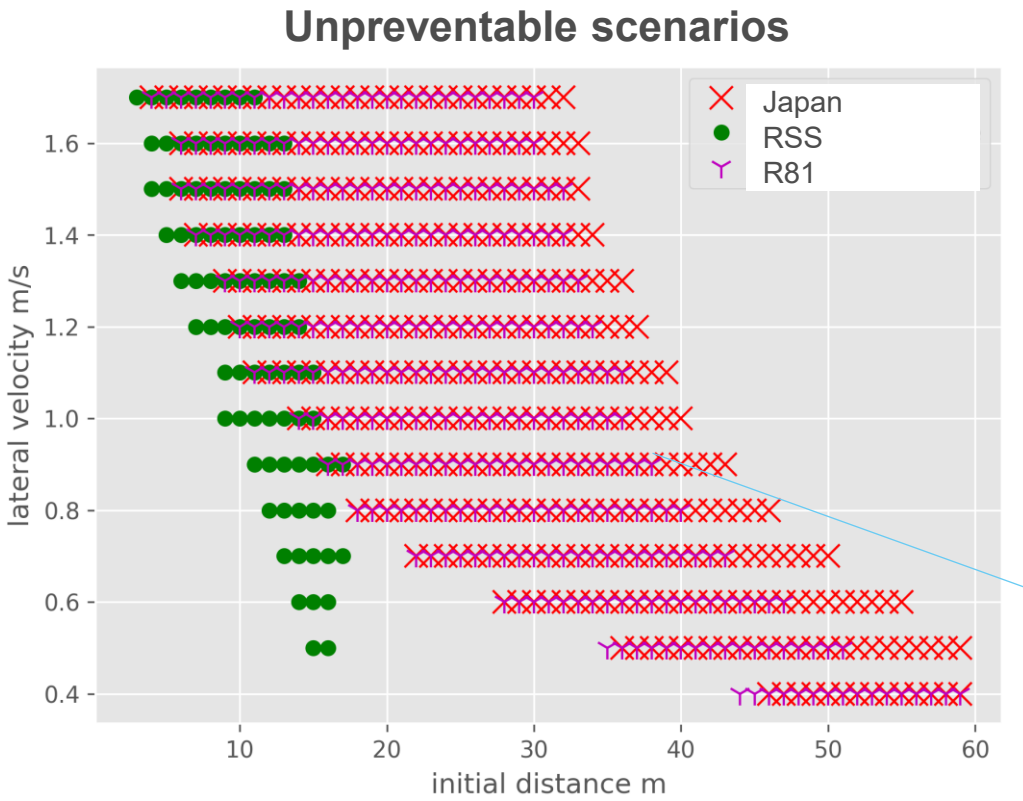
$$u_{ego}(t) = u_{ego}(t - i) - deceleration_{max,ego} * i$$

- In the notation, i is the simulation step, equal to 0.1 sec

Application of the RSS model



Results



- dy = 1.6 m
- Ego velocity = 60 km/h
- Relative velocity = 50 km/h

- **Calculations confirm that JP and DE models can be considered equivalent (JP model with fewer preventable scenarios)**
- **RSS significantly more ambitious in terms of ADS capabilities than the other two**

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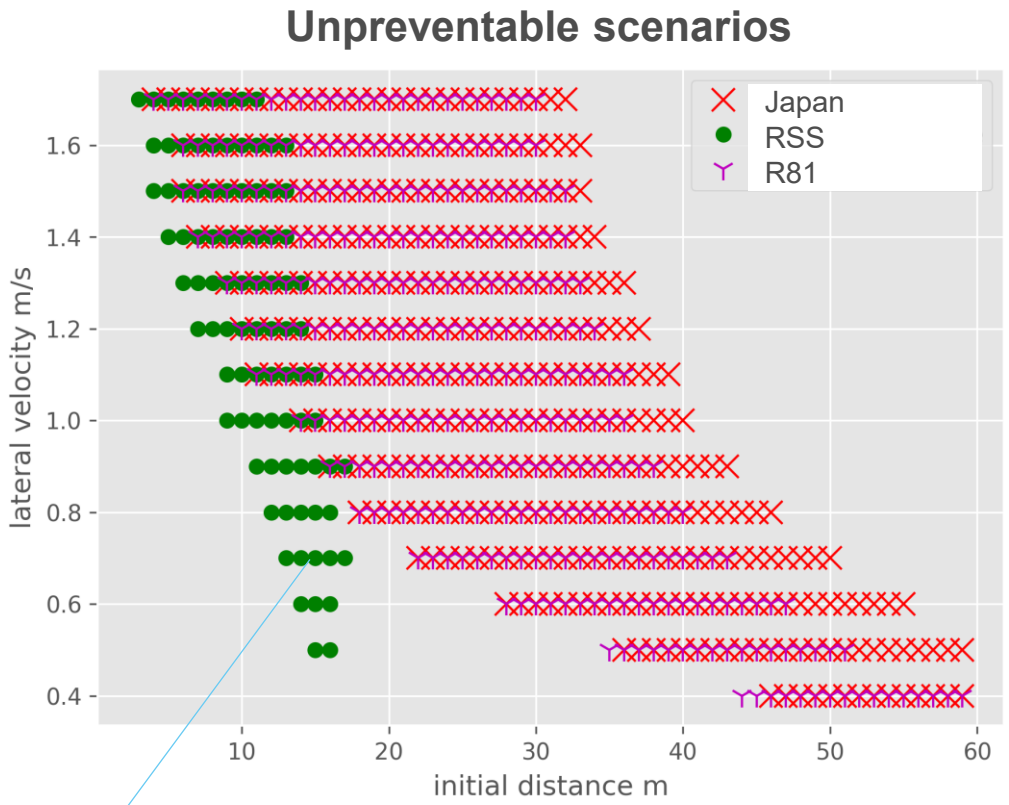
Results



- dy = 1.6 m
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- Relative velocity = 50 km/h

In these cases, in the JP model, since the ego vehicle does not decelerate (unrealistic situation), the cut-in ends behind it. The RSS instead assumes that the vehicle starts decelerating thus producing an accident.

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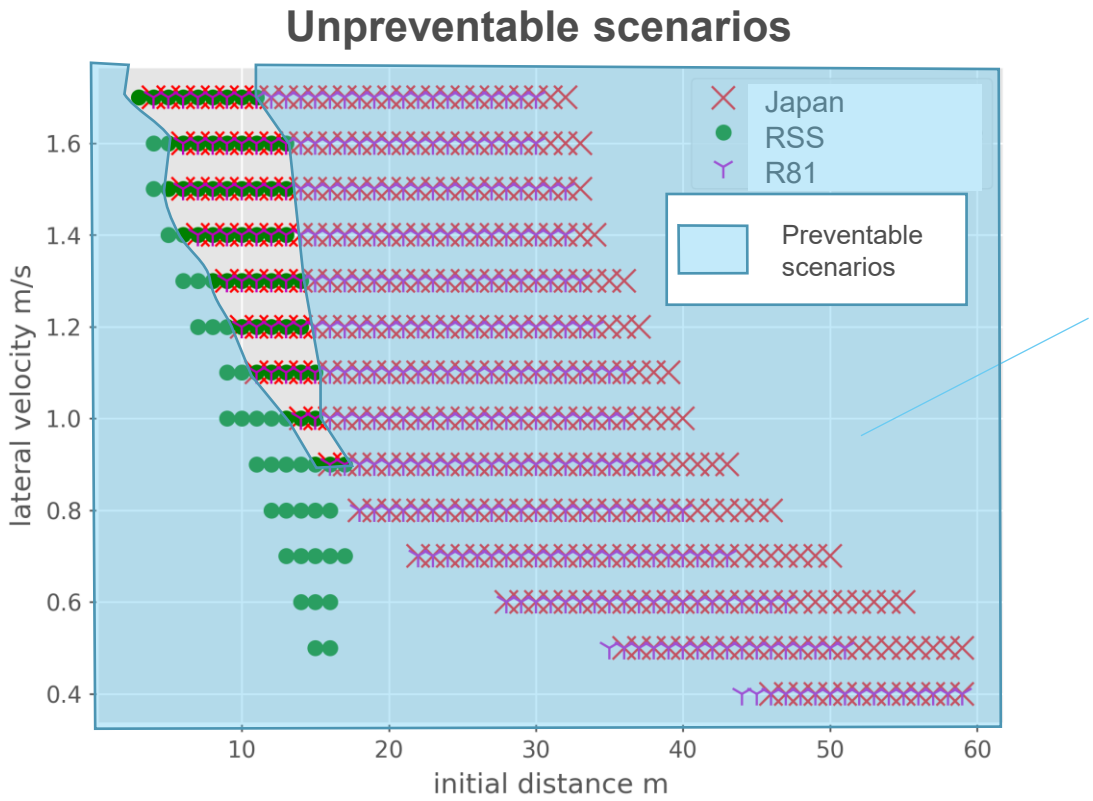
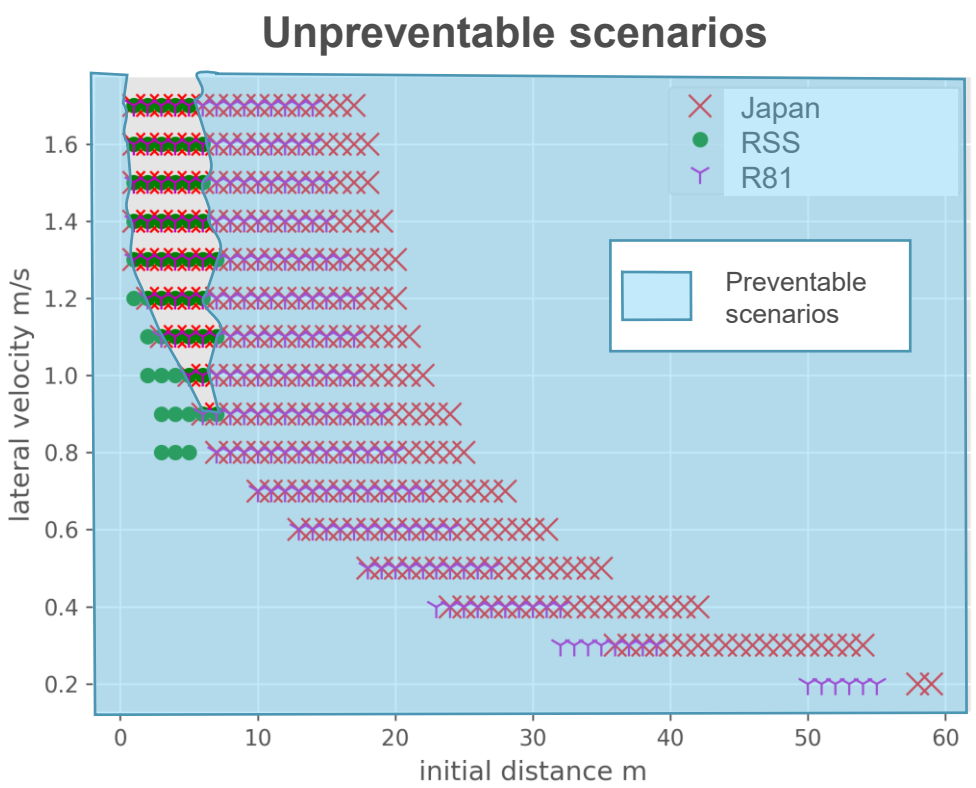
A combined approach



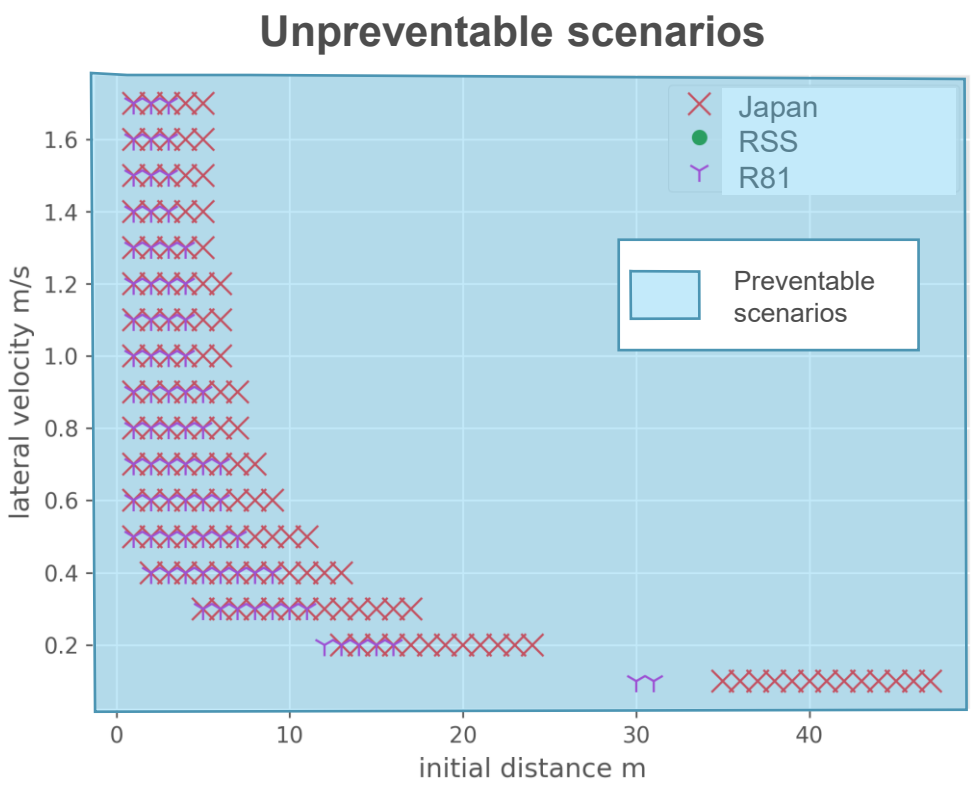
- **Unpreventable scenario are those where both the validated driver model and the safety envelope approach produce an accident**
- **An ADS cannot be less safe than a human and shall take advantage of the available technologies**

A combined approach



- dy = 1.6 m
- Ego velocity = 60 km/h
- Relative velocity = 30 km/h

A combined approach



- dy = 1.6 m
- Ego velocity = 60 km/h
- Relative velocity = 10 km/h

Positive Risk Balance – Industry

- Similarly to the Japanese one, industry proposal focuses on the definition of a complex **driver model** explicitly taking into account the interaction between the driver and the vehicle
- The driver model is calibrated so that in the simulations the rate of accidents is close to the **rate of accidents on German** motorways
- Differently from the Japanese method the approach does not focus on the definition of preventable scenarios
- The approach is based on the concept of **Positive Risk Balance**
- If from all the simulations carried out the **accident rate of the simulated ADS is lower than that of the human driver model, the ADS is safe enough**

Next steps

- Finalize and validate the **driver model**
- Select/fine tune the **safety envelope** and agree on its parameters to set performance requirements
- Define the **assessment approach** (preventable scenarios region VS positive risk balance)

Conclusions

- Japan has proposed a **driver model** to define **traffic scenarios** with preventable accidents that should be used to test the capability of automated driving systems.
- The approach is very interesting but presents a **number of limitations** that could limit the scope of its application
- A possible way forward is to combine/replace it by a **technology-based model** developed on the basis of the safety envelope concept
- Even with **not ambitious assumptions** on the performance of first generation ADSs the model would consider a larger number of preventable scenarios
- In order to cope with the possible limitations of both approaches a **combination of the two** is suggested in which only the accidents resulting by the application of both models are considered

Conclusions

- The combination of the two approaches can **increase the validity** of both.
- **Validation and representativeness** remain however two issues worth of additional research especially when considering more complex scenarios than the simple ALKS
- Once the first ADS will be on the market, the **technology-based approach can fully replace** the driver model for assessing the safety of future and more advanced systems

Thank you

European Commission