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Approach to Derive Verifiable Performance Requirements for Accident Avoidance

Despite the fact that behavioural competencies will help the automated vehicle to not cause accidents or drive defensively to stay away from conflicts, there are situations where automated vehicles have to react to unexpected situations, e.g. where other traffic participants cause situations which can end up in accidents. It is the task of the automated driving system – like it is the task for human drivers – to perform evasive actions, whether it is *possible and reasonable in order to minimize any human harm*.

One important question is – to what extent and depending on what circumstances is collision avoidance *possible*? This question will have to be answered when developing concrete new regulations (UN regulations and/or Global Technical Regulations) for automated driving systems.

For this, simple logic models, the so-called safety models, are introduced. They provide assumptions how traffic rule violations and misbehaviour by other traffic participants could be dealt with and use physical properties and fundamental driving dynamics to further detail conditions for accident avoidance.

The purpose of this document (which could be annexed to FRAV's final result, or could possibly be integrated into another annex to that final result document) is to define a process as to how concrete performance criteria for future ADS regulations could be developed.

The set of safety models described in this document should be regarded as a *set of tools, whereas selecting the right tool (the right safety model) depends on the boundary conditions* and should be the task of groups dedicated to writing concrete regulations. Hence in this document, there exists no preference for any of the safety models being depictured.

Two important points to consider: safety models are a methodology to derive a threshold vector to separate between collisions that have to be avoided and those where only mitigation is required. The aim is NOT to prescribe a specific behaviour of the ADS in any given critical situation. This is only about the expected outcome. However, the safety model selected need to fit the use case. E.g. a steer-around model cannot be selected for cases without a second lane.

Also, the characteristics for typical / generic vehicles given below should not be used to calculate accident avoidance for the specific vehicle in the approval process, but for typical / generic vehicles. The reason for this is that low required accident avoidance capabilities could be a wrong incentive in the vehicle design process.

1 Introduction and Definition of Safety Models

In a mathematical & logical sense, for any given situation, there will be a function depending on variables that partly describe a scenario, delivering a Boolean “true” or “false” for whether the collision needs to be avoided, and vice versa for whether mitigation is acceptable:

$$Avoidance[0;1] = f_{safetymodel}(scenario\ variable\ 1, scenario\ variable\ 2, \dots),$$

$$Mitigation[0;1] = 1 - f_{safetymodel}(scenario\ variable\ 1, scenario\ variable\ 2, \dots).$$

It is envisioned that concrete ADS regulations, (being) built by using the guidelines as specified here, may contain either a concrete scalar threshold (example: avoid accidents for a driving speed below 42 km/h, see UN R152), or formulate a concrete $f_{\text{safetymodel}}$ where all parameters are specified (simplified example from UN R157: when cut-ins of other vehicles occur before a specific TTC, the collision needs to be avoided, the resulting function as given in the regulation would be:

$f_{\text{safetymodel}}$ = [1 for $TTC_{LaneIntrusion} > (v_{rel}/(2 \cdot 6\text{m/s}^2) + 0.35s)$; 0 otherwise].

Choosing appropriate model(s) depends, amongst others, on:

- the balance between risk to the ADS itself vs. risk towards the accident partner (e.g. for pedestrians, it would very likely be acceptable to have a slightly increased risk for the typically belted ADS occupants when the risk for the pedestrian would be significantly reduced, e.g. by earlier or stronger brake intervention; for unmanned ADS similar risk balance considerations have to be done),
- the assumed anticipation level (e.g. is it feasible to anticipate actions of other traffic parameters and start countermeasures earlier, or will it be a simple reaction to faults),
- the environmental condition parameters. (e.g. what level of friction is typically available where the ADS are travelling),

- the balance between efficiency and acceptable remaining risk (e.g. passing a pedestrian with no acceptable risk would be possible only with very low speeds, which would render the current sidewalk close to streets infrastructure useless for automation).

These factors will be different for different situations, or in other words: there would be different $f_{\text{safetymodel},i}$ for different critical situations anticipated to occur in the operational domain of the concrete ADS regulation in pseudo-code:

Example Regulation XXX =

{Situation / parameter range 1, avoidance = $f_{\text{safetymodel},1}$(parameters a,b,c);

address pedestrian accidents in urban areas

Situation / parameter range 2, avoidance = $f_{\text{safetymodel},2}$(parameters d,e,f);

address car-car accidents with cut-in on motorways…}.

The following paragraphs summarize the safety performance models that can be used to assess the behavioural competency of an ADS based on the scenario.

2 Detailed Description of Safety Models

This section describes the structure of safety models and their general characteristics, but not the parameters to be used with them – parameters are found in section 3.

The safety models can be grouped into models for the performance in accident avoidance and behaviour models for conflict avoidance, see Table 1. The difference between those two is that the accident avoidance models can be used to understand to what extent accident situations – caused by other traffic - are unavoidable, while conflict avoidance models formalize strategies for the behaviour of an ADS to not come into conflict. Conflict avoidance models are better suited being integrated into the document on the dynamic driving task.

Table 1: Overview of Safety Models

Model	*Explanation*
Performance Requirements for Accident Avoidance	
Last Point to Steer	Estimate avoidance and mitigation in longitudinal traffic, typically used for driver assistance & active safety
Safety Zone	Estimate avoidance and mitigation in cross-traffic accidents with VRU

Careful and Competent Human Driver	Estimate avoidance and mitigation in longitudinal traffic cut-in situations, using reaction characteristics of good human driver
Fuzzy Safety Model	Estimate avoidance and mitigation in longitudinal traffic cut-in situations, taking anticipation of other vehicle behaviour into account
Performance Requirements for Conflict Avoidance (not included in this document)	
Responsibility Sensitive Safety	A general approach on safety distances both longitudinally and laterally that can prevent accidents based on assumptions for parameters of other vehicles
Safety Force Field	A general approach on safety distances both longitudinally and laterally that can prevent accidents when all actors obey the concept

2.1 Last-Point-to-Steer (LPS, Ref.: AEBS HDV 03.03).

When to use this model? This model assumes an emergency braking intervention in longitudinal traffic is justified at the latest as soon as a collision cannot be avoided by steering anymore and can be used to calculate the expected speed reduction by braking, given the relative speeds between both traffic participants. It is applicable to longitudinal traffic conflict situations, however in most cases, the automated vehicle will be required to avoid all longitudinal accidents. For rare cases with obstacles that are detectable really late, this process could still be used.

Verifiable performance requirements are derived with the following steps:

1. Calculate the time to collision or distance up to which it is possible to steer around the other vehicle.
2. Calculate the possible speed reduction by braking, when braking starts at that time.

A typical traffic situation is shown in Figure 1 below.

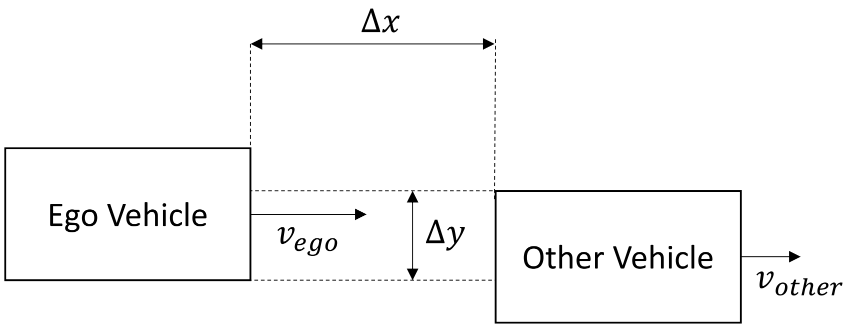


Figure 1: Configuration

Step 1 – calculate the last point to steer

Assuming a constant and maximum lateral acceleration, the process of laterally shifting the ego vehicle is given by

$$y(t) = \iint \ddot{y}_{max} \mathrm{d}t^2 = \left[\frac{1}{2}\ddot{y}t^2\right]_{t=0}^{t=t_{required}}.$$

This leads to the following t_{required} required to shift the ego vehicle's lateral position by Δy:

$$t_{required} = \sqrt{\frac{2\Delta y}{\ddot{y}_{max}}}.$$

Note that this equation describes a turn as shown in Figure 2 below.

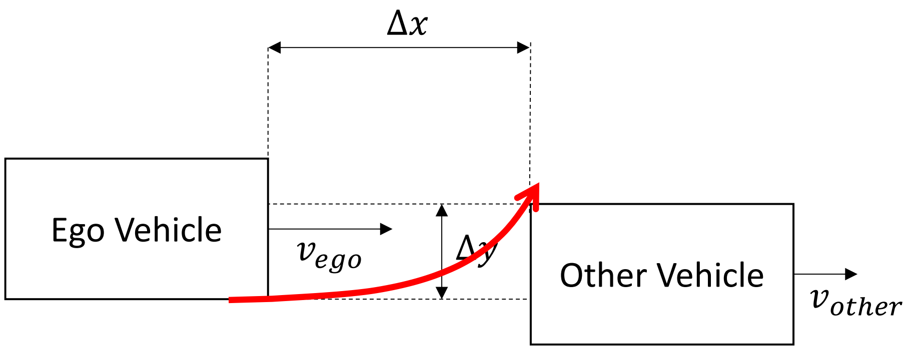


Figure 2: Trajectory for steering around another vehicle

A trajectory that would be more suitable for traffic situations with less space results in the following time to steer:

$$t_{required,same\ direction} = 2\sqrt{\frac{\Delta y}{\ddot{y}_{max}}}.$$

This is a trajectory where the ego vehicle is pointing in the same direction as before the shift, as shown in Figure 3 below.

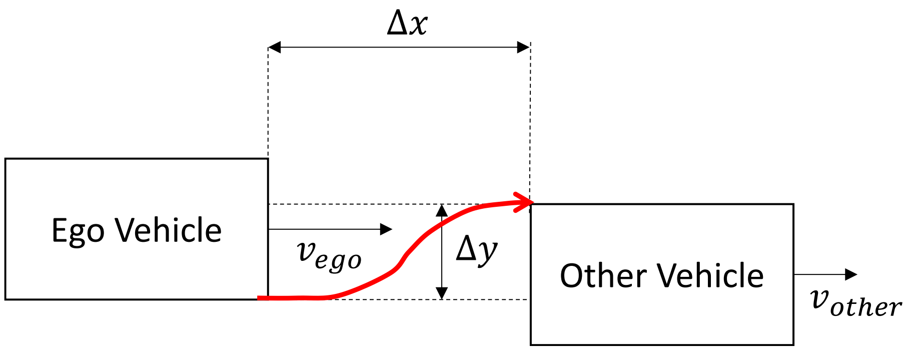


Figure 3: Trajectory for steering around and maintaining direction, thus being efficient

Note that for most vehicles, the maximum absolute accelerations depend on the tire-road-friction, but there might be limitations due to center of gravity, see below.

<u>Step 2 – calculate the resulting impact speed, if any</u>

When the time to collision or distance at the start of brake intervention is known, it is possible to calculate the resulting speed reduction. For this, the TTC to steer needs to be slightly modified to account for the brake force build-up time:

$$TTC_{Brake,effective} = TTC_{steer} + \frac{1}{2} \cdot t_{buildup}$$

The relative impact speed then depends on the relative speed $v_{rel,0}$, the minimum possible acceleration $\ddot{x}_{min}$ (which by convention is always negative for braking! The maximum possible deceleration would by convention always be positive) and the effective TTC at brake onset.

The $TTC_{\text{Brake,effective}}$ is sufficient for avoidance in this case:

$$TTC_{Brake,effective} \geq \frac{v_{rel}}{2 \cdot (-\ddot{x}_{min})}.$$

In this case, the resulting relative impact speed is 0. If not, the relative impact speed is:

$$v_{rel,impact} = \sqrt{v_{rel,0}^2 - 2 \cdot TTC_{Brake,effective} \cdot v_{rel,0} \cdot (-\ddot{x}_{min})}.$$

<u>Summary of the process</u>

It is possible to derive concrete performance requirements from the assumption that a brake intervention is justified when steering around the obstacle is not possible anymore. In the course of this, there are certain parameters that need to be specified:

1. The <u>maximum lateral</u> and <u>longitudinal accelerations</u>, depending on the road surface condition (dry / wet / snow / ice).

2. If the regulation applies to heavy vehicles, there could be a limitation of lateral acceleration by typically high centre of gravity.
3. It needs to be decided whether the vehicle should typically be pointing in the same direction as before (which results in higher times to steer around, hence earlier brake intervention and lower impact speeds), or whether a last possible steering avoidance should be taken into account (hence lower times to steer around and higher impact speeds).
4. Finally, the characteristics of a typical brake system need to be defined, mainly the assumed brake force build-up time.

When these four decisions have been made, an equation for the allowed relative impact speed as function of the relative speed and of the required lateral shift exists. Note that from a regulatory point of view, the requirements should be applicable to all vehicles in the scope, so they should not take specific values of a concrete vehicle into account.

A final equation could look like this and needs to be filled with as much parameters as possible.

$$v_{rel,impact} = \sqrt{v_{rel,0}^2 - 2 \cdot (2\sqrt{\frac{\Delta y}{\ddot{y}}} + \frac{1}{2} \cdot t_{buildup}) \cdot v_{rel,0} \cdot (-\ddot{x}_{min})}.$$

2.2 Safety Zone (SZ, Ref.: AEBS HDV 03.03).

When to use this model? This model assumes an emergency braking intervention with cross-traffic is justified as soon as the collision partner is no longer able to not enter the path of the ego vehicle AND a collision will occur.

Verifiable performance requirements are derived with the following steps:

1. Calculate the time to collision when the pedestrian enters the safety zone.
2. Calculate the possible speed reduction by braking, when braking starts at that time.

Step 1 – calculate the time to collision when the pedestrian enters the safety zone

The general configuration for cross-traffic VRU accidents is as shown in Figure 4 below.

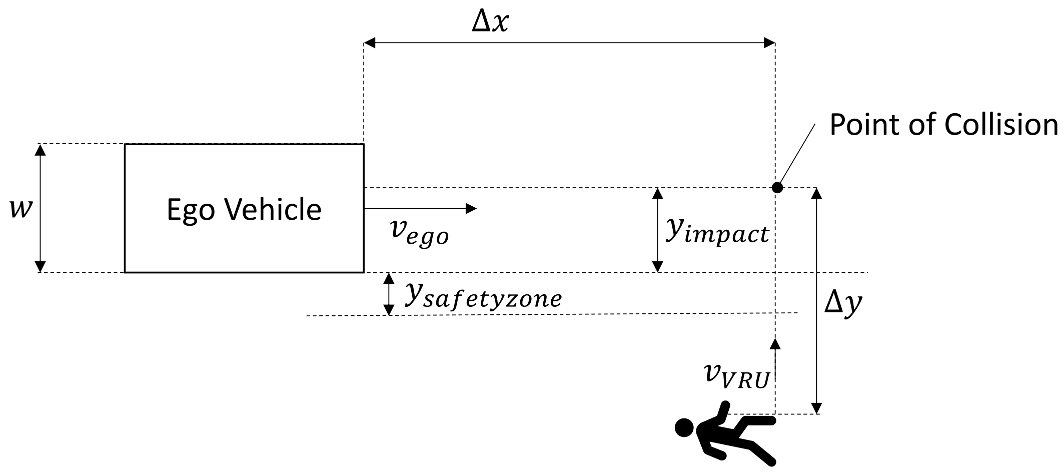


Figure 4: Configuration for safety zone model

If no brake intervention occurs, both collision participants will reach the point of collision at the same time. Thus, the Time To Collision can be calculated independently by assessing the time needed for each participant to reach the point of collision:

$$TTC = \frac{\Delta y}{v_{VRU}} \; and \; TTC = \frac{\Delta x}{v_{ego}}.$$

The TTC (valid for both the vehicle and the vulnerable road user) when the vulnerable road user has reached the safety zone is then

$$TTC_{Entry,SafetyZone} = \frac{y_{impact}}{v_{VRU}} + \frac{y_{safetyzone}}{v_{VRU}}.$$

Note that the result of this equation is very sensitive to the impact position. The current Regulation (UN) No. 152 defines the impact position as the center of the vehicle:

$$y_{impact} = \frac{w}{2},$$

however accidentology suggests that there is no preferred impact position in vehicle-VRU-accidents.

<u>Step 2 – calculate the resulting impact speed, if any (copied from last point to steer model, above)</u>

When the time to collision or distance at the start of brake intervention is known, it is possible to calculate the resulting speed reduction. For this, the TTC to steer needs to be slightly modified to account for the brake force build-up time:

$$TTC_{Brake,effective} = TTC_{Entry,SafetyZone} + \frac{1}{2} \cdot t_{buildup}.$$

The impact speed then depends on the speed v_0, longitudinal friction μ and the effective TTC at brake onset:

$$v_{impact} = \sqrt{v_0^2 - 2 \cdot TTC_{Brake,effective} \cdot v_0 \cdot \mu \cdot g}.$$

Summary of the process

It is possible to derive concrete performance requirements from the assumption that a brake intervention is justified when steering around the obstacle is not possible anymore. In the course of this, there are certain parameters that need to be specified:

- The width of the safety zone, the impact position of the vulnerable road user on the vehicle front and typical VRU speed for each kind of VRU needs to be selected.
- The typical width of vehicles needs to be defined.
- Finally, the characteristics of a typical brake system need to be defined, mainly the assumed brake force build-up time.

When these three decisions have been made, an equation for the allowed impact speed as function of the speed exists. Note that from a regulatory point of view, the requirements should be applicable to all vehicles in the scope, so they should not take specific values of a concrete vehicle into account.

A final equation, in this case for center impacts, could look like this:

$$v_{impact} = \sqrt{v_0^2 - 2 \cdot ((\frac{y_{safetyzone}}{v_{VRU}} + \frac{y_{impact}}{v_{VRU}}) + \frac{1}{2} \cdot t_{buildup}) \cdot v_0 \cdot \mu \cdot g}.$$

2.3 Fuzzy Safety Model (FSM, Ref.. UNECE Reg. 157 Annex 3 §3.4).

When to use this model? In this model, it is assumed that the driver can anticipate the risk of a collision and apply proportionate braking to avoid the need for harsh and imminent reactions later. Such an anticipatory reaction can make collisions preventable, while they would not be preventable only by a last-second reaction. The model considers only the longitudinal braking reaction, and is not suitable, as it is, for situations in which the optimal strategy would include steering.

The model is set up in a simulation framework, recreating specific scenarios, and simulating the behaviour of a human driver using a fuzzy model. In the current implementation, the types of scenarios that can be tested include the ego vehicle receiving a cut-in, following a decelerating vehicle, or following a vehicle that cuts-out, to reveal a static obstacle. For the latter two, while an automated driving system would be required to avoid almost all longitudinal accidents, the safety model can be used also to classify the difficulty of each specific situation.

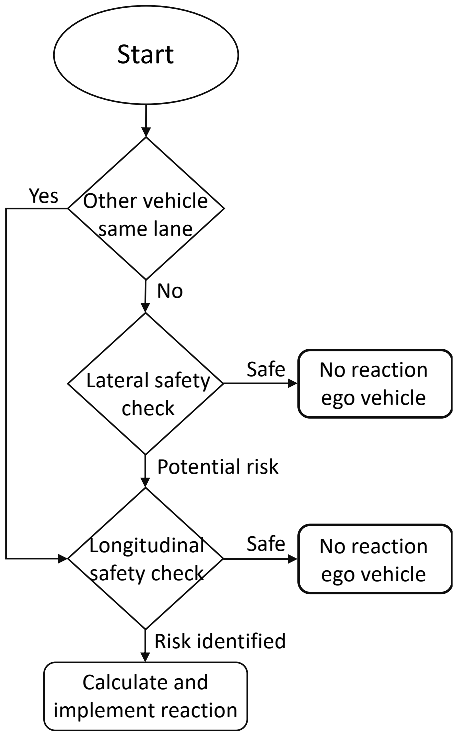
Verifiable performance requirements are derived with the following steps:

1. Set up the simulation for a specific case.
2. Run the simulation using the simulated behaviour of the ego vehicle.

3. Evaluate the case based on the results of the simulation, preventable if an accident was avoided in the simulation, or not.

In each simulation step, there are three actions from the ego vehicle:

1. Other Vehicle Lane Status Check
2. Lateral Safety Check.
3. Longitudinal Safety Check
4. Calculate and Implement Reaction



Step 1- Other Vehicle Lane Status Check

Firstly, the ego vehicle checks the other vehicle lane. The lateral safety check is ignored in case the ego vehicle and the target vehicle are in the same lane. In such cases, the process continues to step three directly. Otherwise, i.e. the other vehicle is in an adjacent lane, the lateral safety check is executed.

Step 2 – Lateral Safety Check

The Lateral Safety Check identifies a potential risk of collision if the following conditions hold true:

a) the rear of the 'other vehicle' is ahead of the front of the ego vehicle along the longitudinal direction of motion;

b) the other vehicle is moving towards the ego vehicle's path;

c) the longitudinal speed of the ego vehicle is greater than the longitudinal speed of the other vehicle

d) the following equation is satisfied

$$\left|\frac{dist_{lat}}{u_{other,lat}}\right| < \frac{dist_{lon} + length_{ego} + length_{other}}{u_{ego,lon} - u_{other,lon}} + 0.1$$

where:

$dist_{lat}$ instantaneous lateral distance between the two vehicles

$dist_{lon}$ instantaneous longitudinal bumper to bumper distance between the two vehicles

$length_{ego}$ length of the ego vehicle

$length_{other}$ length of the other vehicle

$u_{other,lat}$ instantaneous lateral speed of the other vehicle

$u_{other,lon}$ instantaneous longitudinal speed of the ego vehicle

$u_{other,lon}$ instantaneous longitudinal speed of the other vehicle.

The lateral safety check is ignored in case the ego vehicle and the target vehicle are in the same lane. In such cases, the process continues to step two directly. If the lateral safety check finds no potential conflict, then step three is ignored and there is no reaction.

Step 3 – Longitudinal Safety Check

The Longitudinal Safety Check requires the assessment of two Fuzzy Surrogate Safety Metrics, the Proactive Fuzzy Surrogate Safety Metric (PFS), and the Critical Fuzzy Surrogate Safety Metric (CFS).

The PFS is defined by the following equation:

$$PFS(dist_{lon}) = \begin{cases} 1 & \text{if } 0 < dist_{lon} - d_1 \leq d_{unsafe} \\ 0 & \text{if } dist_{lon} - d_1 > d_{safe} \\ \frac{dist_{lon} - d_{safe} - d_1}{d_{unsafe} - d_{safe}} & \text{if } d_{unsafe} < dist_{lon} - d_1 \leq d_{safe} \end{cases}$$

where:

d_1 is the safety distance when the two vehicles reach a complete stop

$$d_{safe} = u_{ego,lon}\tau + \frac{u_{ego,lon}^2}{2b_{ego,comf}} - \frac{u_{other,lon}^2}{2b_{other,max}} + d_1$$

$$d_{unsafe} = u_{ego,lon}\tau + \frac{u_{ego,lon}^2}{2b_{ego,max}} - \frac{u_{other,lon}^2}{2b_{other,max}}$$

where:

τ the reaction time of the ego vehicle defined as the total time from the moment in which the need for a reaction is identified until it starts to be implemented

$b_{ego,comf}$ the comfortable deceleration of the ego vehicle

$b_{ego,max}$ the maximum deceleration of the ego vehicle

$b_{other,max}$ the maximum deceleration of the other vehicle

The CFS is defined by the following equation:

$$CFS(dist_{lon}) = \begin{cases} 1 & \text{if } 0 < dist_{lon} < d_{unsafe} \\ 0 & \text{if } dist_{lon} \geq d_{safe} \\ \frac{dist_{lon} - d_{safe}}{d_{unsafe} - d_{safe}} & \text{if } d_{unsafe} \leq dist_{lon} < d_{safe} \end{cases}$$

Where:

$$d_{safe} = \begin{cases} \frac{(u_{ego,lon} - u_{other,lon})^2}{2a_{ego}^{'}} & \text{if } u_{ego,lon,NEXT} \leq u_{cut-in,lon} \\ d_{new} + \frac{(u_{ego,lon,NEXT} - u_{other,lon})^2}{2b_{ego,comf}} & \text{if } u_{ego,lon,NEXT} > u_{cut-in,lon} \end{cases}$$

$$d_{unsafe} = \begin{cases} \frac{(u_{ego,lon} - u_{other,lon})^2}{2a_{ego}^{'}} & \text{if } u_{ego,lon,NEXT} \leq u_{cut-in,lon} \\ d_{new} + \frac{(u_{ego,lon,NEXT} - u_{other,lon})^2}{2b_{ego,max}} & \text{if } u_{ego,lon,NEXT} > u_{cut-in,lon} \end{cases}$$

in which:

$$a_{ego}^{'} = max\,(a_{ego}, -b_{ego,comf})$$

$$u_{ego,lon,NEXT} = u_{ego,lon} + a_{ego}^{'}\tau$$

$$d_{new} = \left(\frac{(u_{ego,lon} + u_{ego,lon,NEXT})}{2} - u_{cut-in,lon}\right)\tau$$

where:

a_{ego} the instantaneous longitudinal acceleration of the ego vehicle

$a_{ego}^{'}$ a modified instantaneous acceleration which assume that ego vehicle cannot decelerate by more than $b_{ego,comf}$

$u_{ego,lon,NEXT}$ the expected longitudinal speed of the ego vehicle after the reaction time assuming constant acceleration

d_{new} the expected longitudinal change in distance between the ego vehicle and the other vehicle after the reaction time

The Longitudinal Safety Check identifies a potential risk if either PFS or CFS are greater than 0.

Step 4 Calculate and Implement Reaction

If a risk is identified the ego vehicle is assumed to plan and implement a reaction by decelerating according to the following equation:

$$b_{reaction} = \begin{cases} CFS \cdot \left(b_{ego,max} - b_{ego,comf}\right) + b_{ego,comf} & \text{if } CFS > 0 \\ PFS \cdot b_{ego,comf} & \text{if } CFS = 0 \end{cases}$$

The deceleration is implemented after a time equal to $\boldsymbol{\tau}$ when it starts to increase with a constant rate equal to the maximum jerk. If a risk is not identified, there is no deceleration applied. In the case the reaction is not able to prevent the vehicle from colliding with the cutting-in vehicle, the scenario is classified as unpreventable, otherwise, it is classified as preventable.

Summary of the process

It is possible to derive concrete performance requirements from the assumption that a human driver can anticipate certain conflicts and use a proportional braking intervention in advance. In the course of this, there are certain parameters that need to be specified:

- The typical width and length of vehicles need to be defined.
- The Reaction time of the ego vehicle
- The jerking limits of the ego vehicles braking system.
- The Comfortable deceleration of the ego vehicle.
- The Maximum deceleration of the ego vehicle.
- The Maximum deceleration of the ego vehicle.

Additionally, the challenge level of cases of preventable accidents can be determined, based on the values of PFS and CFS reached during the simulation. An example result for a combination of parameter values is shown in the Figure 5, where the “x” markers represent the unpreventable collisions, and the three different colour dots, green, yellow, and red represent three classifications of difficulty, easy, medium, and hard, respectively.

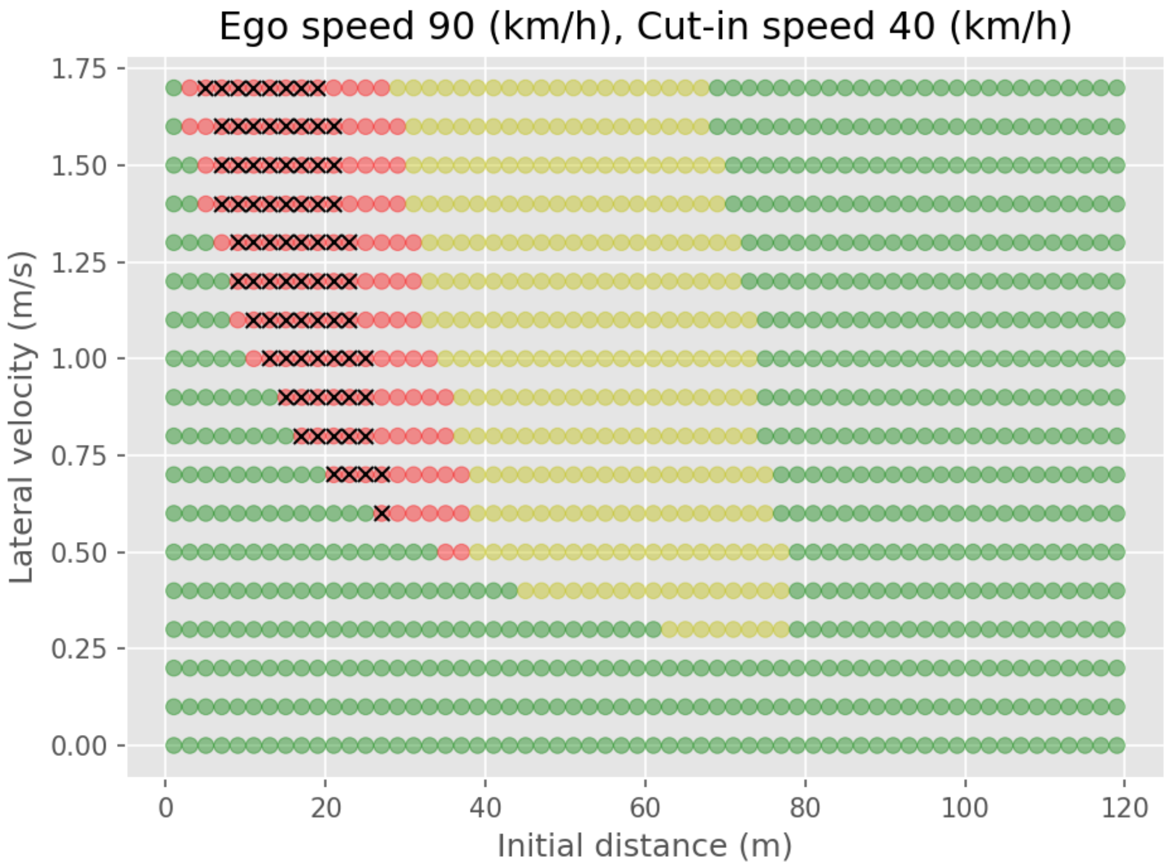


Figure 5: Example results, "x" markers represent the unpreventable collisions, and the three different colour dots, green, yellow, and red represent three classifications of difficulty, easy, medium, and hard, respectively

A software implementation of the safety model to derive the scenario classification from simulation applied to the three traffic critical scenarios is openly available at: https://github.com/ec-jrc/JRC-FSM

2.4 Careful & Competent human driver (CC, Ref.: UNECE Reg. 157 Annex 3 §3.3).

This C&C Human driver Model is coming from the concept that ADS should be at least safer than level of C&C human driver. When we think about purpose of promoting ADS, safety is one of the most important aspects. To achieve safer traffic by ADS, ADS should be safer than conventional vehicles, which are driven by human driver.

When there are clear requirement by taking into account existing function in our market, ADS should meet such requirement. However even if there are no such requirement, ADS should be safer than C&C human driver.

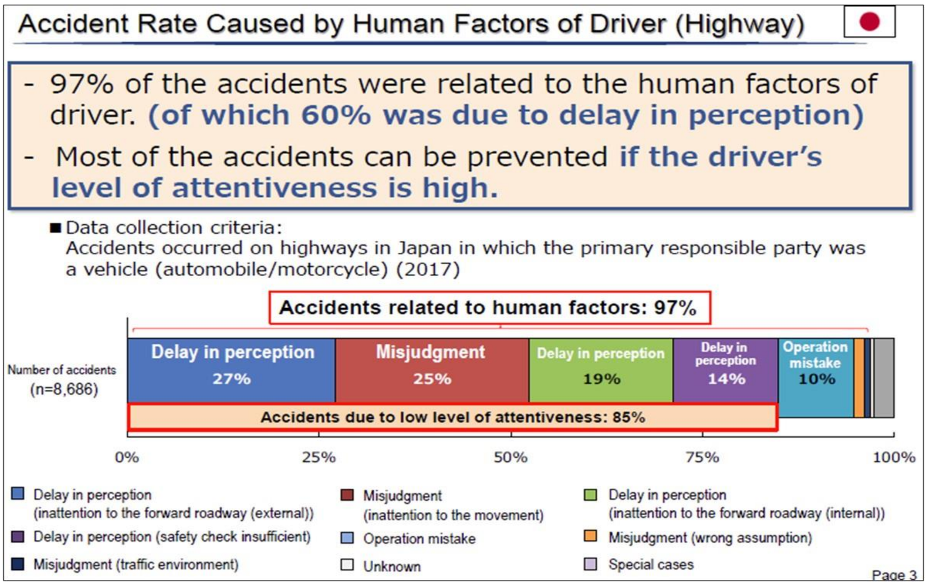
Based on the above concept, this C&C human driver model presents a method for obtaining rationally foreseeable and preventable performance requirements for C&C human drivers as specific numerical conditions in each traffic scenarios.

Justification

The following two points can be considered as justification for setting criteria equal to or higher than Careful & Competent human driver performance:

- Social acceptance; Many countries consider critical the driving competency of the driver in judging liability for traffic accidents. There is no rational reason to apply different criteria only for Automated Driving vehicles.
- Social benefit; 97% of traffic accidents is caused by errors by human drivers.

Setting Careful & Competent Human Driver as the minimum level of safety performance for ADS, hence a Safety Criteria, shall mean lower risk of human errors and contribution to safer traffic environment with less accidents.



2.4.1 Example; C&C Human Driver model (ref; UNECE Reg. 157 Annex 3 §3.3)

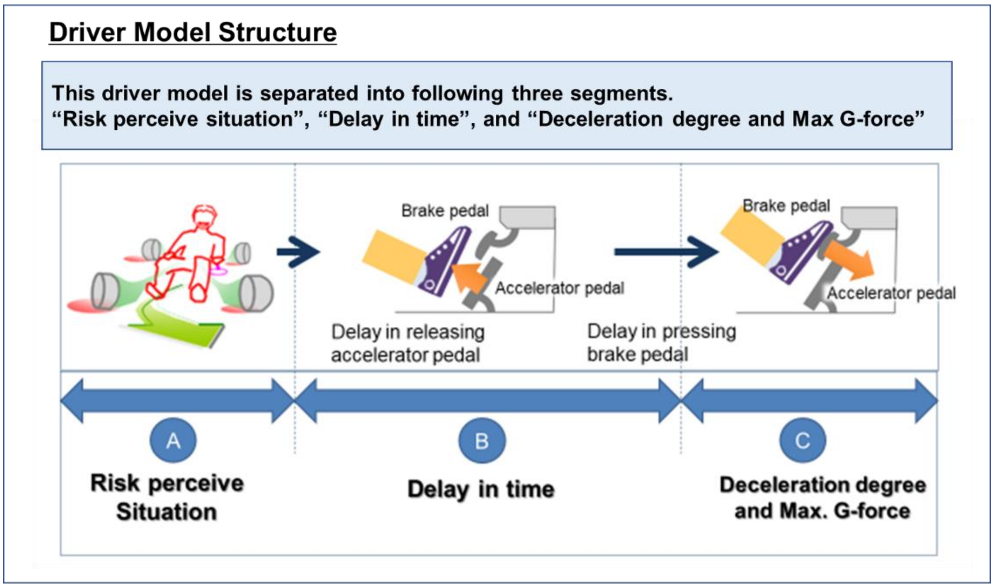
In order to develop safety models based on C&C concept, define under the specific scenario 1) delay in recognition and reaction time by C&C Human Drivers, 2) timing to start recognizing by C&C Human Drivers. A Cut-in case scenario is shown below as a specific example of C&C model, and 3) anticipation capability or behavior shift of human drivers as reaction to the situation.

In a generalized form, it would be appropriate to present human drivers with a situation corresponding to (all of the relevant) specific accident scenarios, but not with clear instructions e.g. as to what speed or lateral position they should follow, since these behavioral changes are expected to have a significant potential to change the situations risk (i.e.: giving more reaction time by slightly shifting the vehicle position in the ego lane away from the threat or by reducing relative speed towards threats). Only then will the behavior of typical drivers be reflected.

Checking whether there was an accident (fail) or not (pass) as function of the initial parameters (e.g.: relative speed to target, lateral speed, lane change timing etc.) would then allow to identify concrete performance criteria.

The following model reflects driver’s behavior to the extent possible. At the same time, there could be more room to improve by defining parameters for human driver competencies including anticipation.

Analyzing the human driver's “perception”, “judgment”, and “control” behavior in each traffic scenario, and specifics of the driver's reaction time and control amount (deceleration ramp up time/maximum deceleration) in each cross section (perception/judgment/control). It is a model that quantifies such numerical values and reflects them in avoidance maneuver.



2.4.2 Cut-in scenario

1. Performance model – Braking model

1.1. The driver model is separated into the following three segments: "Perception"; "Decision"; and, "Reaction".

The diagram in Figure 1 is a visual representation of these segments.:

1.2. Performance model factors for these three segments in Table 1 should be used as the driver performance model.

Which is considering attentive human drivers’ behaviors with ADAS(AEBS).

Figure 1
Competent and careful human driver performance model

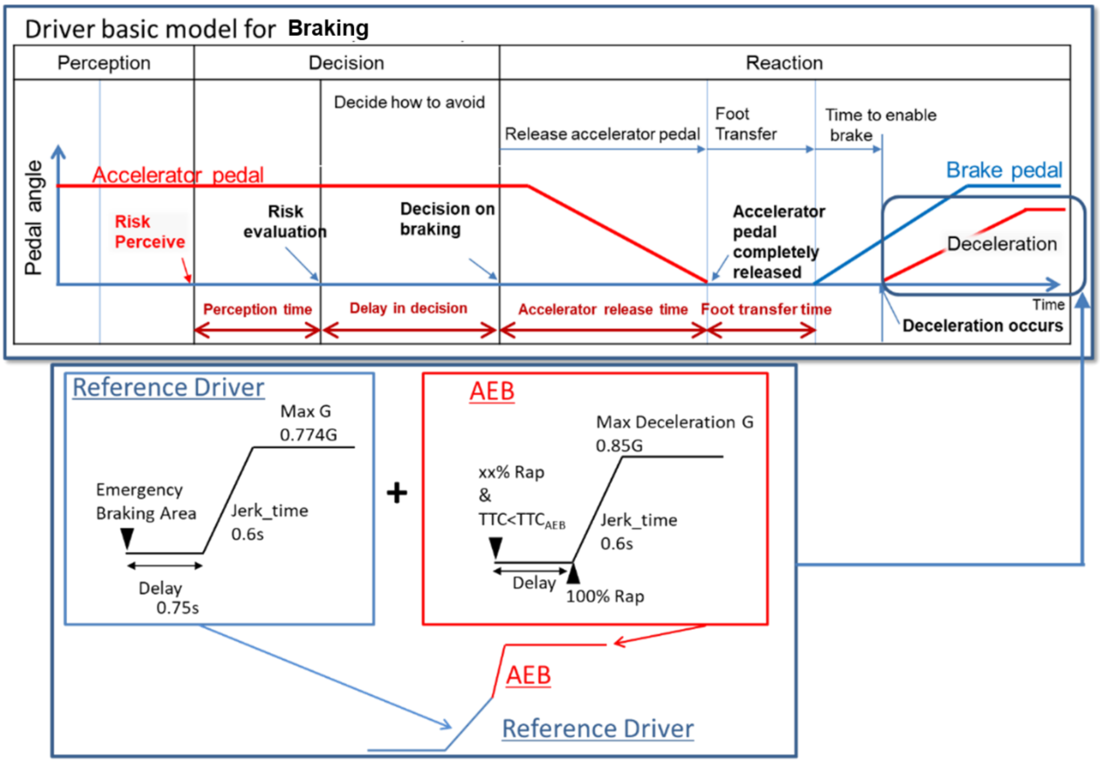


Table 1

Performance model factors for vehicles

		Factors
Risk perception point	Lane change (cutting in)	Deviation of the centre of a vehicle over 0.375m from the centre of the driving lane
Risk evaluation time (Risk perception time)		0.4 seconds
Time duration from having finished perception until starting deceleration		0.75 seconds
Jerking time to full deceleration (road friction 1.0)- Human driver characteristics		0.6 seconds to 0.774g
Jerking time to full deceleration (after full wrap of ego vehicle and cut-in vehicle, road friction 1.0)- AEBS characteristics		0.6 seconds to 0.85g

1.3. Apply to “Cut in scenario”

The lateral wandering distance the vehicle will normally wander within the lane is 0.375m. (Based-on real

traffic flow observation)

The perceived boundary for cut-in occurs when the vehicle exceeds the normal lateral wandering distance

(possibly prior to actual lane change)

The distance a. is the perception distance based on the perception time **(a)**. It defines the lateral distance required to

perceive that a vehicle is executing a cut-in manoeuvre a. is obtained from the following formula;

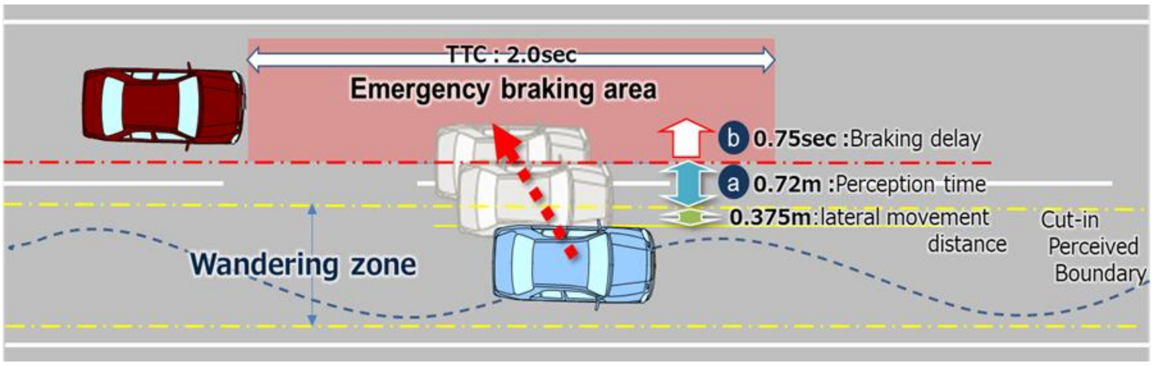
a.= lateral movement speed x Risk perception time **(a)** 0.4sec

The risk perception time begins when the leading vehicle exceeds the cut-in boundary threshold.

2sec* is specified as the maximum Time To Collision (TTC) below which it was concluded that there is a danger of

collision in the longitudinal direction.

Figure 2
Driver model for the cut-in scenario



3 Physical parameters

3.1 Environment parameters and basic driving dynamics

One of the most important parameters regarding the environment is the friction coefficient, a placeholder for the complex force behaviour of tires. Every change of motion of any vehicle requires forces between the vehicle and the surrounding. For the large majority of all vehicles, aerodynamic effects[1] and active changes in wheel load[2] can be excluded for influencing dynamic movement.

[1] There will always be an aerodynamic resistance, called drag, but this drag belongs to the driving resistance factors (compensated by the engine to maintain a constant speed) and is not used for dynamic control of the vehicle, except for race cars.
[2] Changes in wheel loads by control of active or semi-active suspension change wheel loads only for a short duration, with the opposite effect after that.

Actual tire behaviour is typically modelled using longitudinal and lateral tire slip and camber angle, all three generating horizontal forces. The dynamics of forces typically is constrained more due to the actor dynamics (speed of brake force increase, change in wheel sideslip), so it is justified to use scalar values for longitudinal and lateral friction instead, for the sake of simplicity they can be considered equal:

$$\mu_0 = \mu_{lateral} = \mu_{longitudinal} \ .$$

Assuming an ideal distribution of the forces between all wheels (something taken care of by driving dynamics control systems ABS and ESC nowadays), the maximum lateral and longitudinal accelerations, if not limited the location of the center of gravity, are given by multiplying the corresponding μ with g:

$$|\ddot{x}| \leq \mu \cdot g,$$

$$|\ddot{y}| \leq \mu \cdot g.$$

If acceleration in two directions is combined, longitudinal and lateral acceleration needs to follow the following equation:

$$\sqrt{\ddot{x}^2 + \ddot{y}^2} \leq \mu.$$

Typical values and sources are given in Table 2 below.

Table 2: tire-road-friction parameters

Parameter	**Typical Quantity**
μ, M1 and motorcycles	1.0
Maximum longitudinal or lateral acceleration, M1	10 m/s²
μ, other vehicles	0.6…0.7
Maximum longitudinal acceleration, other	6…7 m/s²
μ lateral, other	6…7 m/s² if center of gravity permits
μ on wet roads	0.6
μ on snow	0.3
μ on ice	0.1
Maximum acceleration on wet roads	6 m/s²
Maximum acceleration on snow	3 m/s²

Maximum acceleration on ice	1 m/s²

3.1.1 Limits for achievable acceleration

There might be cases when the lateral of longitudinal accelerations are limited by the centre of gravity in such a way that high decelerations would lead to lift-off of the rear wheel (as can be seen in motorcycles) or high lateral accelerations would lead to tipping of the vehicle.

First, a vehicle starts to tip over or capsize when one of the wheel loads becomes zero. This can easily be calculated when evaluating the equilibrium of torques around the "other" wheel, see Figure 6.

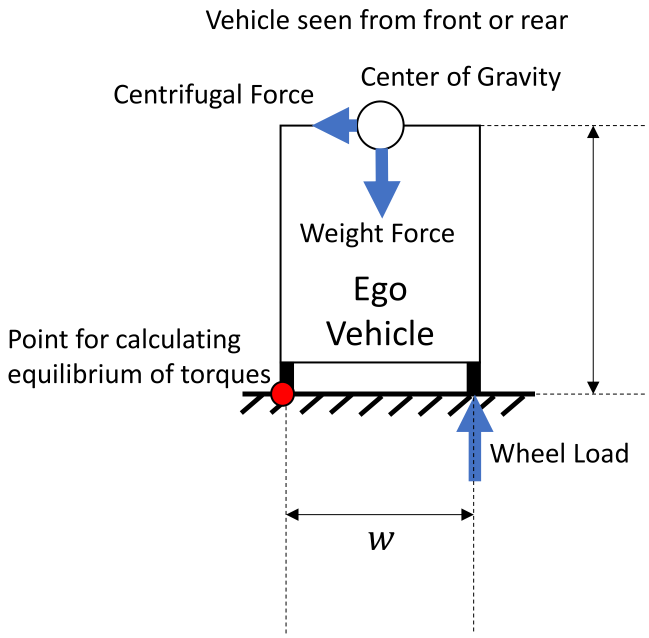


Figure 6: Lateral acceleration limit due to tipping

The maximum lateral acceleration, assuming a center of gravity in the central symmetry plane, then becomes

$$\ddot{y}_{max,tipping} = \frac{w}{2 \cdot h_{CoG}} g,$$

with the wheel base w.

Another, quite comparable, situation is braking, when the inertia force counteracting the brake force is possibly able to pitch the vehicle, see Figure 7.

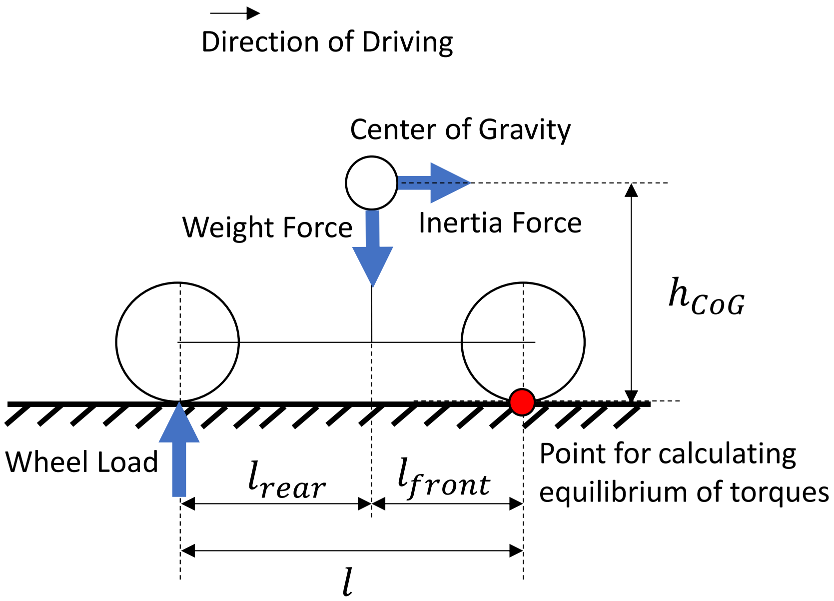


Figure 7: Pitching of a braking vehicle

In this situation, the maximum possible deceleration before pitch occurs (which happens when the rear wheel load becomes zero) is given by

$\ddot{x}_{min,pitching} = -\frac{l_{front}}{h_{CoG}}$ (negative since for deceleration, the acceleration is negative).

3.2 Other road user and vehicle characteristics

When using safety models, characteristics for the typical behaviour of other road users is relevant as well. The quantities can be found in Table 3 below.

Table 3: other road user and vehicle characteristics

Parameter	**Typical quantity**
Pedestrian walking speed	5 km/h
Pedestrian running speed	8…10 km/h
Pedestrian acceleration	10 m/s² in all directions
Bicycle cycling speed	15…25 km/h
Bicycle longitudinal acceleration	5…6 m/s²
Bicycle lateral acceleration	6…7 m/s²
Stopping distance for pedestrian	0.3 m
Stopping distance bicycle	1.5. … 4.8 m

Impact position pedestrian	Center for typical regulations; equally spread in accidontology

3.3 Component characteristics

The build-up time is typically 0.1 to 0.5 seconds (the lower value corresponding to linearly actuated brake pumps, the higher value for conventional ESC pumps) for reaching 10 m/s²; it can be linearly scaled down for lower decelerations.

There is typically no limitation for the minimum possible acceleration (=the maximum possible deceleration) due to the brakes itself, all modern brake systems are built to reach the maximum possible deceleration and maintain that at least for the duration of a full braking event.

4 Example for the Application of Safety Models to Define Concrete, Verifiable Performance Criteria

Defining a guideline, outlining what ADS regulations should include, is a necessary and important first step, however it should not be the end of the FRAV process: The more concrete the criteria will become, the more harmonized ADS regulations around the world will become.

As detailed in Document FRAV-26-07, Germany believes that an intermediate step should be chosen before detailing exact performance criteria: proposing a process to come to these criteria using safety models. To show what exactly could be the outcome (result) of the proposed process, the following is the set of (to a small extent simplified for better explainability, see yellow notes) critical situation requirements from the EU regulation on automated driving, Regulation (EU) No. 2022/1426, formalized in pseudo-code.

Regulation (EU) No.2022/1426 =

{

<u># General</u>

Do not cause accidents &

Follow traffic regulations &

(no collision for $f_{safetymodel,i}$=1) &

$f_{behaviourmodel,i}$=1)

Requirements are fulfilled if the ADS does follow all relevant traffic regulations, does not cause accidents, does not have any collisions when the safety models require collision avoidance (however, when collisions are deemed unavoidable, e.g. due to violation of rules by others, collision avoidance is not required), and finally matches the requirements from the behaviour models.

Flexibility: Note that Regulation (EU) No. 2022/1426 allows vehicle manufacturers to use different performance requirements in case there is proof that they would lead to comparable safety.

Scenario dependency: Note that the requirements as shown below are stated in combination with possible scenarios.

Collision avoidance required for cutting in of other vehicles:

In a mathematical & logical sense, for any given situation, there will be a function depending on variables that partly describe scenario, delivering a Boolean "true" (1) or "false" (0) for whether the collision needs to be avoided, and vice versa for whether mitigation is acceptable:

$f_{\text{safetymodel,LaneChange from other vehicle}}$ = [1 for $TTC_{LaneIntrusion}$ > (v_{rel}/(2·2.4m/s²) + 0.16s) & standing passengers; 0 otherwise]

$f_{\text{safetymodel,LaneChange from other vehicle}}$ = [1 for $TTC_{LaneIntrusion}$ > (v_{rel}/(2·6m/s²) + 0.25s) & not standing passengers; 0 otherwise]

/* This is oversimplified for the sake of clarity, since Regulation (UN) No. 157 defines additional parameters like e.g. the violating traffic must have been visible for a time of 0.72 seconds and others.

The concrete values for the above equations were derived from the safety model "Last Point to Brake" [1], assuming that a deceleration level of 2.4 m/s² can be achieved after a delay of 0.1 s and a ramp up time of 0.12 s after the lane intrusion of the other vehicle (standing passengers are considered to be able to cope with decelerations of 2.4 m/s²), or 6 m/s² after a delay of 0.1 s and a ramp up time of 0.3 s. Note that since during the ramp up time, the brake deceleration increases, thus it is counted half [1] .

The time to collision for start of braking in order to avoid an accident in general is the following:

$TTC_{Avoid} = \frac{v_{rel}}{2 \cdot d} + t_{delay} + \frac{1}{2} t_{ramp-up}$ (1)

with the relative velocity between two objects travelling longitudinally in the same direction v_{rel}, the deceleration d and the ramp-up time to achieve this deceleration $t_{ramp-up}$, assuming linear increase of the deceleration, and a delay before brake intervention t_{delay}. */

Collision avoidance required for leading vehicle slower / braking / standing:

$f_{safetymodel,leading\ traffic}$ **= [1 for collision avoidance; 0 otherwise]**

/* The assumption here is that the automated vehicle, travelling behind a general vehicle, shall be able to avoid all collisions with slower, braking or standing vehicles or traffic participants ahead simply by controlling its own speed in an appropriate manner. */

Collision avoidance required for VRU crossing:

$f_{safetymodel,crossing\ pedestrian,\ urban/rural}$ **= [1 for collision avoidance &** v_{veh} **<= 60 km/h &** v_{vru} **<= 5 km/h ; 0 otherwise]**

$f_{safetymodel,crossing\ bicycle,\ urban/rural}$ **= [1 for collision avoidance &** v_{veh} **<= 60 km/h &** v_{vru} **<= 15 km/h ; 0 otherwise]**

/* The parameters for the equations above are derived from the safety model "Safety Zone" [3] as applied during the development of Regulation (UN) No. 152, assuming a safety zone of 0.65 meters for the pedestrian and a vehicle total width of 2 m (meaning: the vehicle starts to brake when the pedestrian is 0.65 m from the vehicle path), or 3.95 m for the bicycle, which leads to an assumed brake intervention of the ADS at 1.19 s (during which the VRU travels from the beginning of its safety zone to the center of the vehicle path), with a deceleration of 9 m/s² and a ramp-up time to achieve this value of 0.54 s, those brake characteristics are in line with the assumptions from Regulation (UN) No. 152. The resulting avoidance speed for these brake characteristics, following equation (1), is then 60 km/h. */

$f_{safetymodel,crossing\ obscured\ pedestrian,\ urban/rural}$ **= [1 for** $v_{collision}$**-**$v_{initial}$ **>= 20 km/h &** v_{veh} **> 60 km/h |** v_{vru} **> 5 km/h ; 0 otherwise]**

$f_{safetymodel,crossing\ obscured\ bicycle,\ urban/rural}$ **= [1 for** $v_{collision}$**-**$v_{initial}$ **>= 20 km/h &** v_{veh} **> 60 km/h |** v_{vru} **> 15 km/h ; 0 otherwise]**

/* Following the same considerations as stated above, the speeds are above the calculated avoidance speeds, so avoidance by the ADS cannot be expected. However, a speed reduction of 20 km/h for the ADS is expected, which is pragmatically taken from Euro NCAP pedestrian test requirements. */

Behaviour for merging into traffic:

Comparable to the discussions above, in a mathematical & logical sense, for some situations, there could be a function depending on variables that partly describe scenario, delivering a Boolean "true" (1) or "false" (0) for whether the behaviour of the ADS was acceptable. Regulation (EU) No. 2022/1426 explicitly defines the clearance between the ADS and crossing traffic or traffic:

$f_{\text{behaviourmodel,merging into privileged traffic}}$ = [1 for $TTC_{\text{dyn}} > (v_e + v_a)/(2 \cdot 3\text{m/s}^2) + 1.5s$); 0 otherwise]

/* The concrete values for the above equations were derived in principle from the safety model "Careful and Competent Human Driver" [2], assuming that a comfortable deceleration level of 3 m/s² can be achieved without ramp-up of the deceleration, but within a reaction time of the careful and competent human driver of 1.5 s. These braking considerations are valid for the other vehicle, already traveling in the lane where the automated vehicle merges into. */

Behaviour for crossing traffic:

$f_{\text{behaviourmodel,crossing privileged traffic}}$ = [1 for $TTC_{\text{dyn}} > (v_c)/(2 \cdot 3\text{m/s}^2) + 1.5s$); 0 otherwise]

/* The considerations here are the same as above: The manual driver of the other vehicle needs to be able to comfortably brake for the crossing vehicle (reaching 3 m/s² with a reaction time delay of 1.5 seconds), thus the time to collision between both vehicles shall never fall below the value as given above. */

}