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1 Justification for suppression of warning phase for low relative speeds

UN Regulation No. 131 requires a warning to the driver in order to focus the driver's attention towards a thread, with the assumption that this puts the driver in the position to react in timely manner in order to avoid an accident.

> *"5.5.1. The collision warning referred to in paragraph 5.2.1.1. above shall be provided by at least two modes selected from acoustic, haptic or optical.*
>
> ***The timing of the warning signals shall be such that they provide the possibility for the driver to react to the risk of collision and take control of the situation**, and **shall also avoid nuisance for the driver by too early or too frequent warnings**. This shall be tested in accordance with the provisions of paragraphs 6.4.2. and 6.5.2. of this Regulation."*

Translated to technical requirements, this means:

- A warning shall be given in such a manner that typical drivers - taking into account brake decelerations and reaction time - can avoid an accident when they react after the warning.
- The warning shall not be given when there is no indication that the driver is not in full control of the situation.

Forward collision warning systems are effective because typically, there is a time gap between

- the time when a warning must be given in order to provoke full braking by the driver and
- the time a which typical drivers would initiate a normal brake activation when they are in full control of the situation.

This time gap is longer for higher differential speeds (between target and host vehicle).

This is visualized in Figure 1:

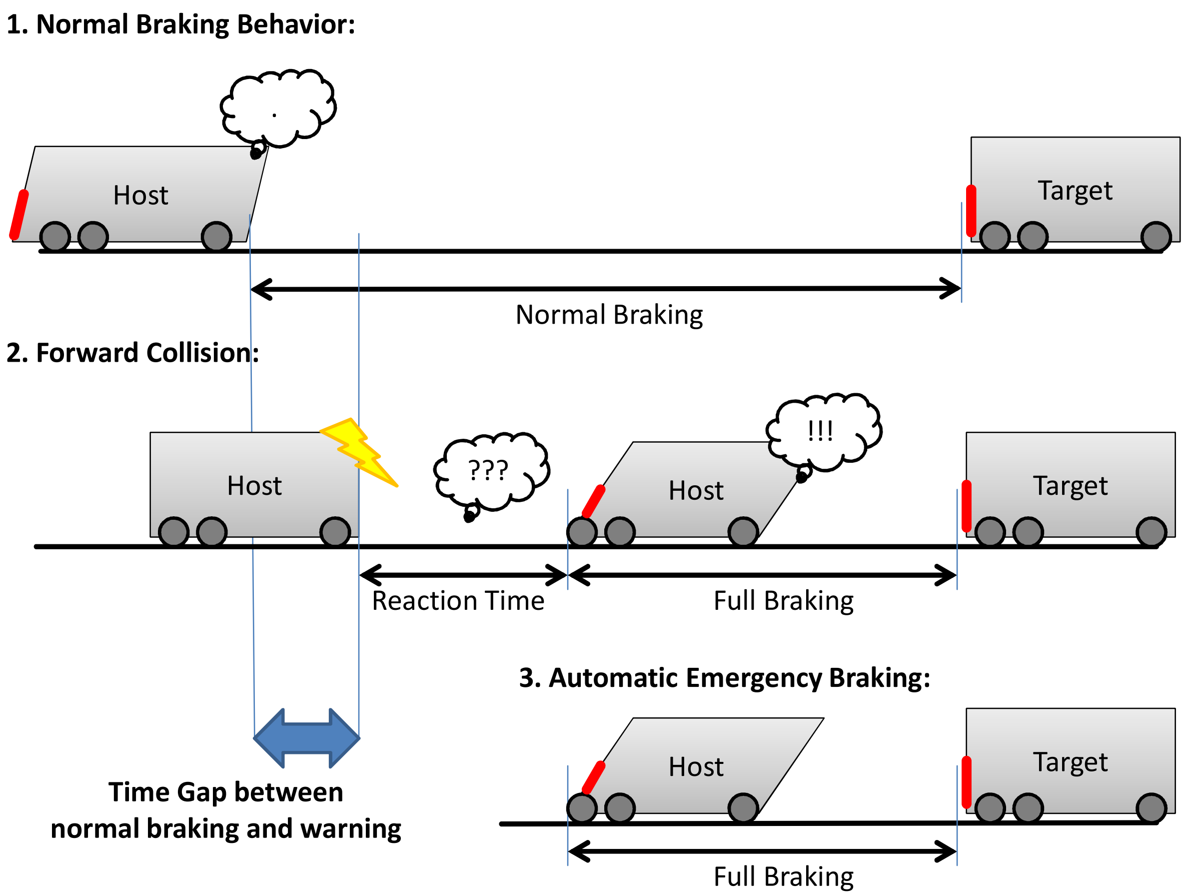

Figure 1: Normal Braking, Forward Collision Warning and Automatic Emergency Braking

But at a certain speed, this time gap reduces to zero, meaning that a warning (*taking into account reaction time and assuming full braking after the reaction time has ellapsed*) needs to be given exactly at the time when drivers that are in full control of the situation would initiate a braking action (*meaning they would brake comfortably, but without reaction time*).

For lower speeds, the warning must be given at a time when drivers in their normal behaviour would not have started braking. As a consequence, the probability for nuisance due to too early/often warnings increases. A better choice for this kind of situation is to only apply automatic braking and suppress the warning for small differential speeds.

This is because coming to a full stop takes only a small time at low speeds. The time required is much smaller than for instance the reaction time required for drivers to understand and react appropriately to a warning.

1.1 Concept and Methodology

The goal of this document is to identify the threshold for the speed difference between host vehicle and target vehicle below which warnings would need to be given at a time when the driver is still in full control of the situation.

This can be done by calculating the stopping distance (as function of speed difference) for a driver that is in full control of the situation, and by calculating the stopping distance (as function of speed difference) with full braking but including reaction time (= the distance at which a warning must be given).

The minimum differential speed for which a warning can be given without nuisance is then calculated as the speed where both stopping distances are equal, as a function of speed difference and including parameters describing "normal" brake behaviour and brake system characteristics for emergency braking.

1.2 Definitions, basic equations

TTC is the relative distance divided by the relative speeds for two objects moving in the same direction, on the same path, and with constant speed:

$$TTC = \frac{x_2 - x_1}{v_2 - v_1} = \frac{x_{rel}}{v_{rel}}.$$

The braking distance in the inertial system of the front vehicle by braking of the rear vehicle (index 2) is given by

$$x_{rel} = \frac{v_{rel}^2}{2 \cdot a_2}.$$

TTC can be expressed as relative distance:

$$x_{rel} = TTC \cdot v_{rel}.$$

The TTC for which avoidance of a specific relative speed and for a given deceleration value is achieved can be calculated:

$$TTC \cdot v_{rel} = \frac{v_{rel}^2}{2 \cdot a_2},$$

$$\Leftrightarrow TTC = \frac{v_{rel}}{2 \cdot a_2}.$$

Therefore, the TTC for start of braking as function of relative speed in order to reduce the speed to zero is given by

$$TTC = \frac{v_{rel}}{2a}.$$

To simplify the equations: $v_{rel} := v$.

1.3 Braking in regular driving situations

Brake deceleration cannot be built up immediately. An exact solution requires numeric integration; the error is neglectable if half the time required for buildup is added

$$TTC = \frac{v}{2a} + \frac{1}{2} t_{buildup}.$$

The TTC at which regular drivers initiate a regular braking event in normal driving situations therefore is given by

$$TTC_{Brake,regular} = \frac{v}{2a_{regular}} + \frac{1}{2} t_{builup,regular}.$$

1.4 Braking in emergency situations

In emergency situations, the TTC at which emergency braking needs to start is given by

$$TTC_{Brake,emergency} = \frac{v}{2a_{emergency}} + \frac{1}{2} t_{builup,emergency}.$$

If a forward collision warning system is used, a reaction time needs to be taken into account. The warning needs to be given at least so much earlier that the driver can initiate emergency braking after his reaction time.

$$TTC_{Warn,emergency} = \frac{v}{2a_{emergency}} + \frac{1}{2} t_{builup,emergency} + t_{react}.$$

1.5 Identification of relative speed below which warnings should not be required

The speed below which forward collision warning systems will not contribute to accident avoidance without causing nuisance to the driver by warning during regular brake application is the speed at which the warning timing and the regular brake application timing are equal:

$$TTC_{Brake,regular} = TTC_{Warn,emergency} .$$

This is calculated by:

$$\frac{v}{2a_{regular}} + \frac{1}{2} t_{builup,regular} = \frac{v}{2a_{emergency}} + \frac{1}{2} t_{builup,emergency} + t_{react} .$$

Reordering leads to

$$\Leftrightarrow \frac{v}{2a_{regular}} - \frac{v}{2a_{emergency}} = \frac{1}{2} t_{builup,emergency} + t_{React} - \frac{1}{2} t_{builup,regular}$$

Further resorting:

$$\Leftrightarrow v\left(\frac{1}{2a_{regular}} - \frac{1}{2a_{emergency}}\right) = \frac{1}{2} t_{builup,emergency} + t_{React} - \frac{1}{2} t_{builup,regular}$$

$$\Leftrightarrow v\left(\frac{a_{emergency} - a_{regular}}{2a_{regular}\, a_{emergency}}\right) = \frac{1}{2} t_{builup,emergency} + t_{react} - \frac{1}{2} t_{builup,regular}$$

$$\Leftrightarrow v\left(\frac{a_{emergency} - a_{regular}}{2a_{regular}\, a_{emergency}}\right) = \left(\frac{1}{2} t_{builup,emergency} + t_{react} - \frac{1}{2} t_{builup,regular}\right)$$

$$\Leftrightarrow v = \frac{2a_{regular} \cdot a_{emergency}}{a_{emergency} - a_{regular}} \left(\frac{1}{2} t_{builup,emergency} + t_{react} - \frac{1}{2} t_{builup,regular} \right)$$

This equation can be read in the following way:

- Quicker "normal" brake application (lower $t_{\text{buildup,regular}}$ and/or higher a_{regular}) will increase the threshold speed, since it will become clear that a driver is not in control LATER in the course of the accident.
- Quicker "emergency" brake application (higher $a_{\text{emergency}}$ and/or lower $t_{\text{buildup,emergency}}$) will decrease the threshold speed, because accident avoidance as a consequence of warning and emergency application is still possible
- Lower assumed reaction times will decrease the threshold speed, because later warnings would still lead to accident avoidance.

2 Characterization of regular driving brake application

Data from real traffic drives with a 18-ton truck was available for evaluation with regard to typical brake behavior. The test drives were conducted by two different truck drivers over a total distance of 1372.2 km and covered a large section of the western part of Germany with a mixture of rural roads, city traffic and highways (see Figure 2).

The truck which was used was empty and equipped with a combined GPS and inertial measurement unit. No critical driving situations that required immediate brake application to prevent an accident are included in the data.

Research question: what is the maximum deceleration that the drivers applied in these uncritical driving situations, and what is the brake deceleration rate or increase time for this that the drivers applied.

An evaluation of all brake event (meaning all situations where a brake deceleration higher than 0.5 m/s^2 was observed to exclude data noise) shows the following:

- In 95% of the time when braking was observed, the brake deceleration is lower than 2.5872 m/s^2 (see Figure 3)
- In 90% of all times when braking was observed, the brake deceleration is lower than 1.9992 m/s^2 (see Figure 3)
- In 95% of the time when braking was observed, the acceleration rate is higher than -4.2323 m/s^3 (see Figure 4)
- In 90% of the time when braking was observed, the deceleration rate is higher than -3.0206 m/s^3 (see Figure 4)

Taking these values into account, the times required to reach these values in real driving can be calculated:

- It takes 0.6 seconds to reach 2.58 m/s^2 with a deceleration rate of 4.23 m/s^3.
- It takes 0.66 seconds to reach 2 m/s^2 with a deceleration rate of 3.02 m/s^3.

Taking this numbers, the following brake behavior is assumed to be a normal behavior:

> **Typical drivers apply the brake in such a way that they reach a deceleration of not more than 2.58 m/s^2 within a time of not less than 0.6 seconds, in case the situation is not a critical driving situation.**

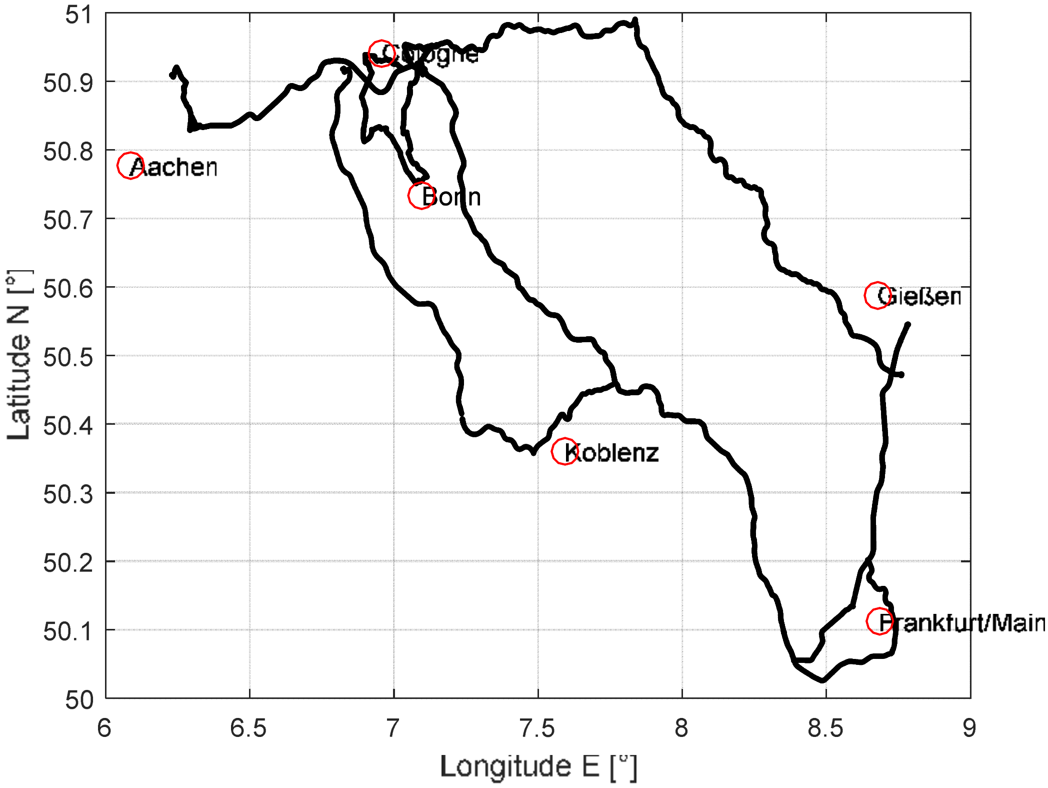

Figure 2: Locations where real traffic driving data was recorded

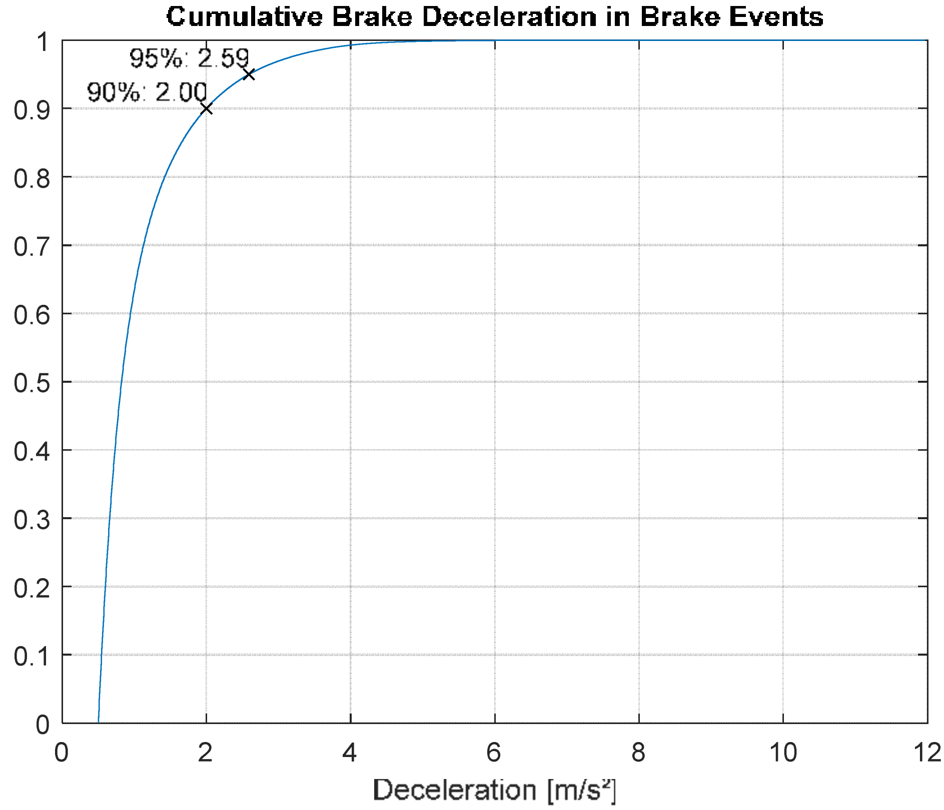

Figure 3: Brake deceleration in brake events

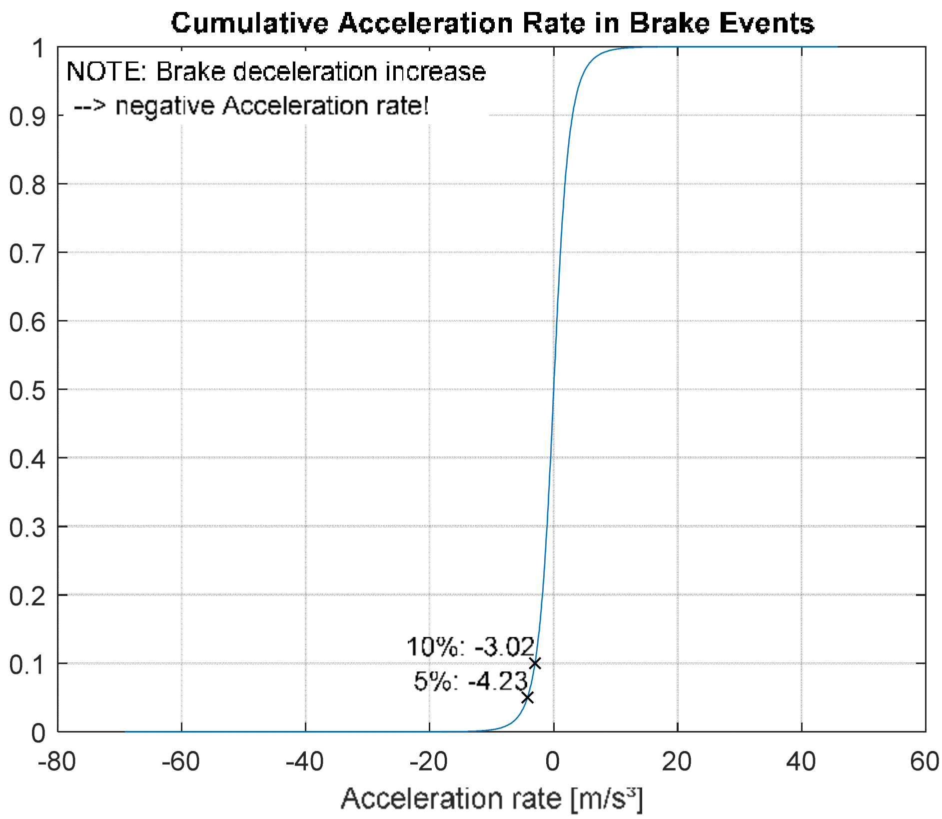

Figure 4: Change of acceleration per time. 5% value corresponds to 95% value of deceleration (=negative acceleration).

3 Brake deceleration rate for AEB interventions

Figure 5 shows that the empty vehicle was able to achieve an average jerk (acceleration rate) of approximately -16 m/s³ (see Figure) during an automatic brake activation. It is assumed this value is limited by the energy storage in the brake system. For a fully laden vehicle, this value needs to be corrected to take the higher mass into account.

An approximation for this would be to assume linear dependency of the average brake jerk from the vehicle loading conditions:

$$\dddot{x}_{laden} = \dddot{x}_{empty} \cdot \frac{m_{empty}}{m_{laden}}.$$

The assumed brake deceleration rate for a fully laden vehicle then is

$$\dddot{x}_{laden} \approx \frac{16\text{m}}{s^3} \cdot \frac{9.5t}{18t} = 8.4\text{m/s}^3.$$

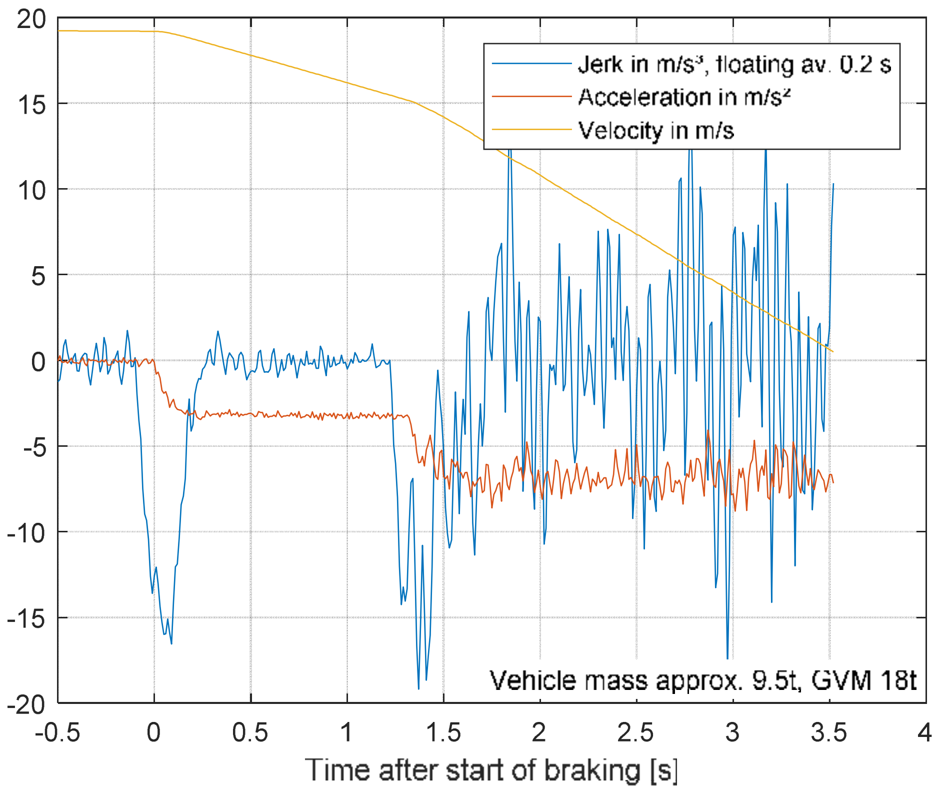

Figure 5: Example measurement, automatic emergency braking from 70 km/h to standstill

4 Calculation of warning threshold speed

4.1 Assumptions

- Deceleration $a_{\text{emergency}}$ [m/s²] available by typical trucks for emergency braking (by driver), 7 m/s², several measurements available.
- Time required to reach this deceleration $t_{\text{Buildup,emergency}}$, 0.83 s, assuming a brake jerk of 8.4 m/s³.
- Deceleration a_{regular} as applied by typical drivers in regular driving situation, 2.58 m/s², 5% of all brake decelerations in regular traffic higher than this value.
- Time required to reach this deceleration in regular driving situation $t_{\text{buildup,regular}}$, 0.6 s (brake jerk higher than 4.23 m/s³ in 5% of all brake times, combined with 2.58 m/² this leads to 0.6 s time required to reach 2.58 m/s² in typical driving situations).
- Driver reaction time, t_{react}, 1.4 s, taken from duration of AEBS warning phase in Regulation No. 131 for N3 and M3 vehicles.

4.2 Results

With the given examples, the speed can be calculated:

$$v = \frac{(2 \cdot 2.58 \cdot 7)\text{m}^2 \cdot \text{s}^2}{(7 - 2.58)\text{m} \cdot \text{s}^4} \left(\frac{1}{2} \cdot 0.84\text{ s} + 1.4\text{s} - \frac{1}{2} \cdot 0.6\text{s} \right)$$

$$v = \frac{36{,}12}{4.42} \cdot 1.52\text{m/s} = 12.42\text{ m/s} = 44{,}71\text{ km/h}$$

These calculations, given the values as specified, show that a collision warning phase should not be required below **44.71 km/h (rounded 45 km/h)**, since below these speeds the forward collision warning needs to be given earlier than the brake application by typical drivers occurs.

Given the fact that these values have been taken from measurements of one specific vehicle, the robustness of the calculated speed needs to be checked.

Higher-performing vehicles

In case the brake jerk possible by the AEBS system is 50% increased (effectively the system is able to reach its maximum deceleration after 0.56 s), the threshold speed reduces to **40.6 km/h**.

$$v = \frac{(2 \cdot 2.58 \cdot 7)\text{m}^2 \cdot \text{s}^2}{(7 - 2.58)\text{m} \cdot \text{s}^4} \left(\frac{1}{2} \cdot 0.56\text{ s} + 1.4\text{s} - \frac{1}{2} \cdot 0.6\text{s} \right)$$

$$v = \frac{36{,}12}{4.42} \cdot 1.38\text{m/s} = 11.28\ \text{m/s}\text{=40,6 km/h}$$

This means that if a vehicle is able to brake quicker (and consequently later) while still being able to avoid an accident, a warning is effective even at lower speeds.

<u>Lower driver deceleration rate</u>

In case typical drivers would apply brake deceleration not in 0.6 seconds as assumed but in 0.9 seconds (50% slower), while maintaining the other parameters, the threshold speed will be **34.7 km/h**.

$$v = \frac{(2 \cdot 2.58 \cdot 7)\text{m}^2 \cdot \text{s}^2}{(7 - 2.58)\text{m} \cdot \text{s}^4}\left(\frac{1}{2} \cdot 0.84\ \text{s} +\ 1.4\text{s} - \frac{1}{2} \cdot 1\text{s}\right)$$

$$v = \frac{36{,}12}{4.42} \cdot 1.18\text{m/s} = 9.64\ \text{m/s}\text{=34.7 km/h}$$

This means that slower "normal" driver behavior will help in earlier understanding that a driver is not in full control of the situation, thus making warnings effective down to approximatey 35 km/h.

In case the assumed driver reaction time is reduced to 1 second (not possible with current regulation 131), while maintaining the other parameters at their original value, the threshold speed reduces to **28.83 km/h.**

$$v = \frac{(2 \cdot 2.58 \cdot 7)\text{m}^2 \cdot \text{s}^2}{(7 - 2.58)\text{m} \cdot \text{s}^4}\left(\frac{1}{2} \cdot 0.84\ \text{s} +\ 1\text{s} - \frac{1}{2} \cdot 0.6\text{s}\right)$$

$$v = \frac{36{,}12}{4.42} \cdot 0.98\text{m/s} = 8\ \text{m/s}\text{=28.83 km/h}$$

4.3 Discussion

These calculations show that in principle, a forward collision warning is not effective for accident avoidance below a specific threshold speed.

When selecting parameters appropriate for typical drivers and current AEBS systems on the market, the speed threshold is approximately 45 km/h. Future/quicker AEBS systems have only a small influence; with a 50% quicker AEBS system, the speed reduces to approximately 40 km/h.

A larger influence is the normal driver braking characteristic. In case typical drivers would set their desired deceleration in 0.9 instead of 0.6 seconds, the speed threshold reduces to approximately 35 km/h; for drivers with an estimated reaction time of 1 second instead of 1.4 seconds, warnings might still be effective just below 30 km/h. This, on the other hand, is not allowed by the current regulation 131, which requires a warning phase with a duration of 1.4 seconds (for N3 vehicles).

5 Conclusion

It has been shown that a warning to the driver, with the goal of avoiding an accident, is not suitable for speeds below a specific threshold speed.

The threshold speed depends on various influence factors, but taking the regular brake application that typical drivers use (this was measured for > 1300 km on regular roads) and a brake system that is able to achieve an automatic brake deceleration of 7 m/s^2 within 0.84 seconds (measured on the test track), a warning would not contribute to accident avoidance or be too early below **44.71 km/h**.

For quicker brake systems (=better performing vehicles), this speed could be reduced to **40.6 km/h**, and for slower "normal" driver brake application, a warning could be useful for speeds above **34.7 km/h**.

A case not consistent with the current mandatory warning phase (duration 1.4 s for N3 vehicles) is an assumed reaction time of 1 seconds. In this case, a warning could still contribute to accident avoidance while not generating nuisance down to **28.83 km/h**.