Optimization of Rear Signal Pattern for Reduction of Rear-End Accidents during Emergency Braking Maneuvers

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Optimization of Rear Signal Pattern for Reduction of Rear-End Accidents during Emergency Braking Maneuvers

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1 Introduction

For over 30 years, it has been considered whether and, if so, how the intensity of a braking maneuver can be indicated to the traffic behind. The primary objective of all studies performed to date on this subject is to avoid rear-end accidents by allowing hazard situations to be recognized within sufficient time. Moreover, harmonization of the traffic flow in columns would provide a further contribution to increasing traffic safety.

Technical implementation of the initial solution recommendations failed because the systems recommended were technically too complicated or too susceptible to malfunction or their effect was not clear [1]. With further development in the vehicle sector – especially introduction of ABS – the sensor circuitry is now present on most vehicles so that a variety of input data is available which could be used for development of a brake force display. Approval of such systems is not possible with the present regulations from the Vienna Convention, ECE and German Traffic Code (StVZO), on the contrary, reservations were even expressed in the commentary to Section 53 of the German Traffic Code (StVZO).

In this report, it is to be examined which of the present approaches to the solution are practical and feasible and which requirements should be placed on an optimized rear signal pattern. In a further step, it is to be examined whether and how the existing regulations could be changed or supplemented in order to allow approval of a system with optimized rear signal pattern at a European level. The study was accomplished particularly on the basis of the following information sources:

- BASt studies on the subject "Rear signal pattern" in 1999 [2]
- Evaluation of special literature and contributions from the Internet
- Discussions with motor vehicle manufacturers
- Demonstration of two systems on the BASt grounds.

2 Possibilities for Coding Braking Maneuvers with the Rear Light Layout

2.1 Preliminary Considerations From the Viewpoint of Perception Psychology

According to an opinion found very frequently in the literature and widely supported by empirical findings, drivers base their braking reaction on the so-called "Time-To-Collision" (TTC). The TTC is the time remaining before a collision when approaching a stationary or moving object when the vehicle direction and speed remain the same. It is also considered to be proven that drivers perceive this information automatically, i.e. without participation of higher processes for evaluating the information, from the field of vision surrounding them when they are moving with their vehicle [3]. This is based on the speed with which the size of the approaching object increases on the retina [4,5,6,7].
In view of the definition of traffic conflicts, a TTC of 1.5 s is assumed to be the critical limit on which drivers base their braking reaction for avoiding the conflict regardless of the speed driven. According to empirical studies, application of the brakes upon

dropping below this TTC is a "natural" reaction that does not need to be learned and therefore is also independent of variables such as driver experience or individually preferred intervals to the vehicle ahead [8,9].

Naturally, in addition to the TTC, other information is available to the driver from the traffic environment. For example on road surfaces with high traction, the "pitching" of the car when the brakes are applied or squealing of the tires provide further information – however, frequently this information is no longer available today due to the design of the suspension and in the case of low tire traction, for example on icy roads. According to the results from [10], in the dark drivers evaluate the relative motions of vehicles ahead on the basis of changes in the visible angle of the taillights as well as the size and brightness. Limits for the speed at which a motion is recognized were influenced by the initial distance from the vehicle ahead, the time observed and the direction of motion relative to the observer.

Rapid brake reactions in real traffic are required in situations that occur suddenly and unexpectedly for the driver. Expectation of a stimulus requiring a reaction is of decisive importance for the reaction time. Generally, reaction to unexpected stimuli is slower than to expected stimuli [11]. In studies made in field experiments, a value of 0.9 s was determined as the median for the distribution of braking reaction times to unexpected situations [12]. Applying the brakes as a reaction to deceleration of a vehicle ahead assumes that this event has been recognized by the driver. In the vast majority of cases, such events are perceived in the peripheral area of the retina [13]. Since it is generally assumed that actual information processing can only start after the object in question has been fixed in the foveal area of the retina, this would require visual fixation on the object. Burckhardt [13] assumes in his chronological model of an emergency braking maneuver an average value of 0.48 s for such visual fixation. Reduction of this component of the "psychophysical reaction" [13] through improved brake lights could therefore contribute to a significant reduction of the stopping distance for emergency braking maneuvers.

It is well proven by the results of experimental studies that abrupt occurrence of stimuli in the periphery of the field of vision causes involuntary, i.e. spontaneous attraction of visual attention followed by corresponding visual fixation [14]. As a result of the sensory mechanisms responsible for this, significant facilitation of the reaction is measurable beginning with a time interval of 100 ms between onset of a stimulus and a specific target stimulus in the peripheral field of vision [15].

The brake lights of vehicles ahead can therefore be considered to be a very important source of information for the driver of vehicles behind for regulation of his speed and distance to the vehicle ahead. With the present brake lights (2 brake lights and one center high-mounted brake light), the driver receives the information that the vehicle ahead is decelerating. This provides him additional time for planning and action adequate for the situation *before* the TTC reaches a critical value at which he will have to apply his own brakes.

In fact, situations occur in traffic in which only the information that the vehicle ahead is decelerating is not sufficient for a reaction adequate for the situation. As a rule, such situations are emergency braking maneuvers. Starting points for optimizing the brake lights therefore aim primarily at increasing the information provided by offering solution recommendations for providing additional information on *the intensity of the braking maneuver* to the driver in addition.

A number of supplements or modifications to the present signal pattern are described below which could result in better adaptation of the braking maneuver to the traffic situation for vehicles behind. For reasons of completeness, however, it is necessary to note that, in addition to optimization of the rear signal pattern, there are other possibilities for providing driver support for braking maneuvers. These start at a later point in time, i.e. upon application of the brakes themselves. For example, brake assistance systems recognize the intention of the driver by measuring the pedal velocity and provide support for the braking operation. The more effective such systems become and, therefore, create situations with high deceleration rates, the more important becomes situation-adapted information for the drivers of vehicles behind.

2.2 Increasing the Size of the Illuminated Surface

As mentioned at the beginning, approaching an object is associated with an increase in the size of its image on the retina. The resulting impression can be supported by increasing the size of the illuminated surface in stages: The harder the brakes are applied, the larger the illuminated area (Figure 1).

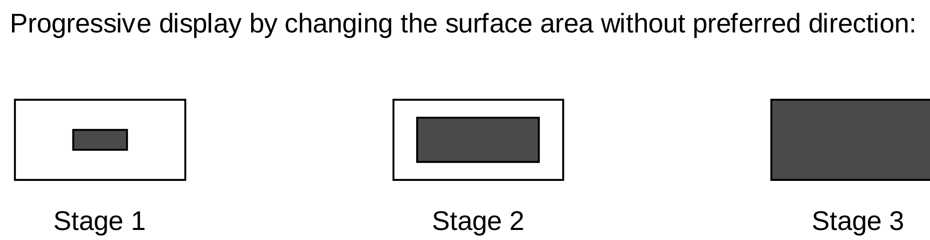


Figure 1: Increase of illuminated area

Since this mechanism is effective regardless of any learning experiences, this form of coding is very good for indicating a change in the braking intensity. According to studies by [16], it is recommendable to at least double the illuminated surface from one stage to another.

2.3 Change in Location of the Illuminated Surface

When approaching a vehicle in front, the horizontal distance between two illuminated surfaces appears to increase. This effect can be supported by moving the brake signal from the inside to the outside depending on the braking intensity (Figure 2).

Migration of the signal from inside to outside without increasing the illuminated area (for right rear brake light):

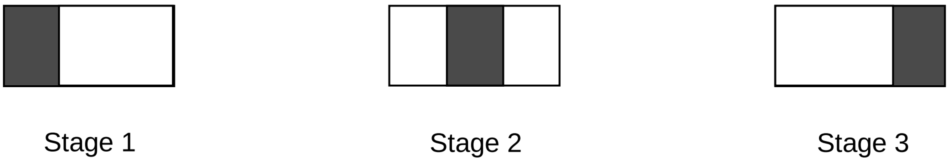


Figure 2: Change in position from inside to outside

Changing the position of the illuminated area from the inside to the outside alone could be misunderstood under certain circumstances for a variety of layout possibilities and therefore should be combined with an increase in the illuminated area [16].

As an alternative, the illuminated area could be moved from bottom to top (Figure 3).

Migration of signal from bottom to top:

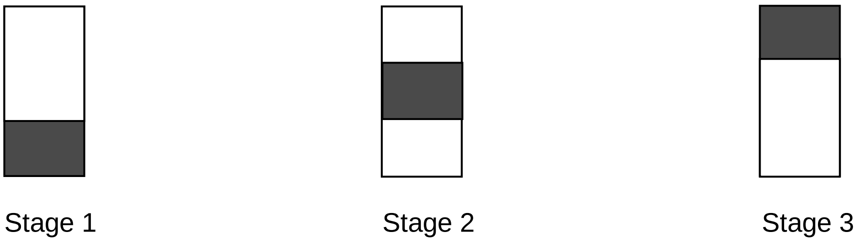


Figure 3: Change in position from bottom to top

2.4 Change in the Luminance

The luminance is the result of the quotient of the luminous intensity to the illuminated area. Therefore, in order to increase the attention while maintaining the illuminated area, it is necessary to vary the luminous intensity. This solution is a possibility when an increase in size or change of position of the brake lights is not possible due to space or design reasons.

However, indication of the braking intensity by increasing the luminance is subject to close limits, because the luminance would have to be increased by at least a factor of five from one stage to the next [1], while simultaneously excluding any dazzling effects, particularly in the dark.

Moreover, it is necessary to consider at this point whether and to what extent a change in the luminance is possible using future lighting technologies (such as luminance adaptation with which the luminance adapts to the ambient conditions making items such as rear fog lights superfluous).

2.5 Flashing Lights

The human eye is particularly sensitive to changes in the brightness in the peripheral area. Flashing is therefore particularly suited for gaining attention. For example, static objects, which are no longer perceived when they are more than 20° outside of the central field of vision, are still recognized when they flash [17]. Flashing lights are therefore a suitable means for coding braking intensity information to obtain quick attention in situations in which the driver is no longer looking directly at the vehicle in front (e.g. looking at something in the vehicle passenger compartment). A flashing frequency of approx. 4 Hz has proven to be the optimum here [2,18]. Flashing signals should, however, be limited to absolute hazard situations to prevent wearing out their warning effect.

A solution with which brake lights with uninterrupted illumination are replaced completely, i.e. over the entire deceleration range, by flashing signals is also imaginable. In this case, minimum deceleration could be indicated by flashing at a low frequency while higher deceleration indicated by faster flashing. Such a brake force display using only modulation of the flashing frequency has not proven to be effective in studies by [16], because association of the perceived flashing frequency with a certain deceleration level is difficult due to the lack of a reference.

2.6 Changing the Light Color

As a matter of principle, the intensity of a braking maneuver could also be signaled by changing the color. In this context, a "Tri-Light" was introduced with which the degree of deceleration was indicated by a change from green (acceleration) transcending to orange (stationary velocity) and finally red (deceleration) [1]. However, here it is necessary to consider that such forms of representation contradict the natural expectations regarding the significance of colors [17,19]. According to stereotyped interpretation, green indicates the state of normal operation and yellow "Caution". Orange indicating a stationary velocity therefore does not correspond to its stereotyped interpretation (“Caution”). The Color-coding of the “Tri-Light” from green to red therefore requires a learning process in any case. Since the differentiation characteristics for color-blind people would not allow recognition or at least not sufficient recognition of such signals, and, moreover, association is difficult under increment weather conditions, the possibility of color coding the braking intensity by changing from one color to another is rejected on a wide basis and therefore not pursued further at this point. Further aspects of switching on lights of different colors in addition to the red brake light are, however, discussed in Chapter 3.6.

2.7 Changing the Contour of the Brake Lights

Indication of the braking intensity by different geometric patterns such as an octagon for "Stop" is also imaginable. However, such changes in the contour are not recognizable to a sufficient extent at greater observation distances or under limited vision conditions and are therefore not considered to be practical for this reason alone.

2.8 Increasing the Number of Brake Lights

The discussion regarding the optimum number of brake lights and their practical arrangement has already been in progress since the introduction of one single rear brake light in 1909. A second brake light became mandatory in 1961. Since then, there have been many recommendations for improving the signal pattern: Systems with up to 10 brake lights in different configurations have been described [1], however, none of these was ever accepted. The next change was made as late as 1980. At this time, two high-mounted brake lights were approved as a supplement to the two conventional lights.

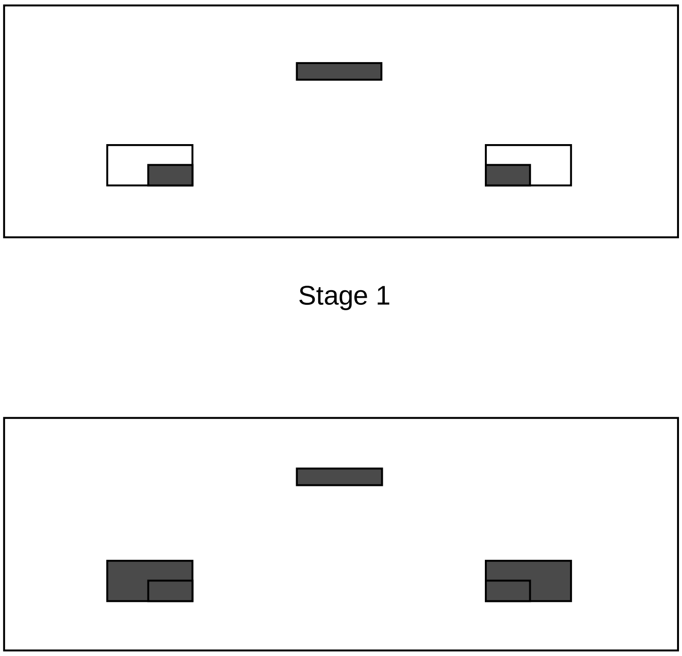
Since 1991, a third center high-mounted brake light has been tolerated in Germany and became mandatory for new vehicles as of 1998 [20]. This improved indication of the braking maneuver was expected to shorten driver reaction times and thereby provide positive effects on the traffic safety. The effects achieved in this manner may have been reduced again in the meantime due to accustomization processes on the part of the drivers. However, the high-mounted brake light does remain an additional safety aspect for drivers of vehicles following several cars behind in a column when the two lower brake lights of the decelerating vehicle are concealed by the vehicle ahead while the high-mounted brake light remains visible through the vehicle ahead.

In the literature, the term "Conventional Brake Lights “ also indicates cars equipped with only two brake lights on the rear of the vehicle. This designation is somewhat unclear when we consider that the major portion of the present vehicle fleet consists of vehicles with high-mounted brake lights. Since, however, – as already discussed – the third high-mounted brake light is mandatory in Germany in the meantime, the configuration with only two brake lights will continue to be designated as "conventional brake lights" in the present report and the configuration with a third high-mounted brake light as "present brake lights".

2.9 Combination of Various Stimulus Factors

The described coding possibilities can, naturally, also be combined with one another in a number of ways. As a matter of principle, the number of signals as well as their differentiation can be increased by multiple coding, i.e. combining at least two coding dimensions (e.g. luminance and position). Sanders and McCormick [11] recommend, however, not combining more than two dimensions with one another for multiple coding in the interest of rapid interpretation and moreover to note that not all dimensions can be combined with one another as desired. This includes, for example, the combination of the dimensions "Flashing rate" and "Brightness".

For example, a combination of increasing the area and changing the position is very effective for coding the braking intensity. The best version has proven to be an increase in the size from the lower inside to upper outside [16] (Figure 4).



Stage 1

Stage 2

<u>Figure 4:</u> Increase in size of both lower brake lights from lower inside to upper outside

3 Present Solution Approaches for Optimization of Rear Signal Pattern for Emergency Braking Maneuvers

As already mentioned, ideas have been present for some time as to how the intensity of a braking maneuver could be indicated to the traffic behind. These also include a few "exotic" suggestions. For example, one recommendation was to introduce a speed indicator on the rear [1]. One "enthusiast" offers a circuit especially for the Fiat Uno in the Internet that simultaneously activates the rear-fog light when the brake pedal is depressed [21]. Even though it is certainly not necessary to discuss such recommendations seriously, this does show that many drivers obviously feel a necessity for greater support here. A few practical solution recommendations have already been completely developed. These recommendations are introduced and evaluated below.

3.1 Indication of Braking Intensity by Means of Increase in Luminance and Area

During the years 1994 – 1999, BMW completed comprehensive tests on the effectivity of brake force displays. The following studies were performed:

- **Literature Analysis**

- **Tests in Driving Simulator**
  20 test persons were requested to follow a vehicle at a distance of 40-50 m. At a speed of 100 km/h, light (1.3 m/s²), medium (2.5 m/s²) and hard braking

maneuvers (6.0 m/s²) were performed. The influence of different stimuli (increase in size, change in position, number of stages, high-mounted brake light, frequency), effects on the driver behavior (vehicle interval, reaction behavior, acceptance) and the influence of limited visibility conditions were studied [16].

- **Scale Consideration on Model Road at Technical University in Darmstadt**
  Test persons were requested to evaluate the changes in the area size and position as well as lumimance on a scale of 1-9 on the model road [1:10] at the Technical University of Darmstadt. Since this study was performed primarily to determine the peripheral perception, the test persons were also requested to observe a monitor at an angle of 7° [16].

- **Studies in Light Tunnel**
  The visibility of the brake force display was tested in the light tunnel under conditions at night and in rain. The 25 test persons were requested to reconstruct and subjectively evaluate the braking intensity of a signal vehicle at a distance of 40 m by applying corresponding pressure on the brake pedal. Here, a diversion was also present in the form of maintaining a specified speed with the gas pedal [16].

- **Traffic Flow Simulation with the Program "Pelops" at RWTH in Aachen**
  Here, the driver behavior of a column of 10 vehicles was tested at a speed of 100 km/h with an initial distance between individual vehicles of 40 m. A conventional brake indicator with 2 rear lights was compared with a 3-stage brake force display [16].

- **Field Studies on a Test Track by VTI**
  Three series of studies were performed with limited extraneous traffic on a closed test track [22].

  Series1: In the first step, a total of 12 test persons drove without previous instruction behind a vehicle with 3-stage brake force display. They were then informed of the purpose and function of the brake force display and the test was repeated in order to check whether the brake force display could be learned intuitively and easily.

  Series 2: Here, four alternatives for brake force displays including and not including the high-mounted brake light were compared. Eight test persons were requested to evaluate the different versions.

  Series 3: While driving at night, four test persons were requested to evaluate two different luminance levels.

- **Field Tests on Freeways by TRL**
  In order to obtain comprehensive information on the effectivity of a brake force display in real traffic situations, 30 test persons drove behind a test vehicle with conventional brake lights (only the two break lights) as well as behind a vehicle with 3-stage brake force display. On the one hand, the braking maneuvers associated with normal traffic were registered and, on the other, braking maneuvers were provoked artificially. For safety reasons, emergency braking maneuvers were not made [22].

Based on the results of the first studies, a 3-stage brake light (Brake Force Display, BFD) was favored which was laid out as follows (Figure 5):

Braking stage	Brake light	High-mounted brake light
Stage 1 (light)	Illumination of standard brake light at medium luminance	without
Stage 2 (medium)	Increase in luminance, increase in illuminated area	Standard light illuminated
Stage 3 (hard)	Increase in illuminated area	Increase in width of light

Each next higher stage was switched on 200 ms after illumination of the initial stage

Figure 5: 3-stage brake force display [22]

Differentiation was made between light, medium and hard braking maneuvers based on the distribution of the brake pedal forces while driving on a freeway with dry pavement (Figure 6). The effects of the BFD were not studied inside of city limits.

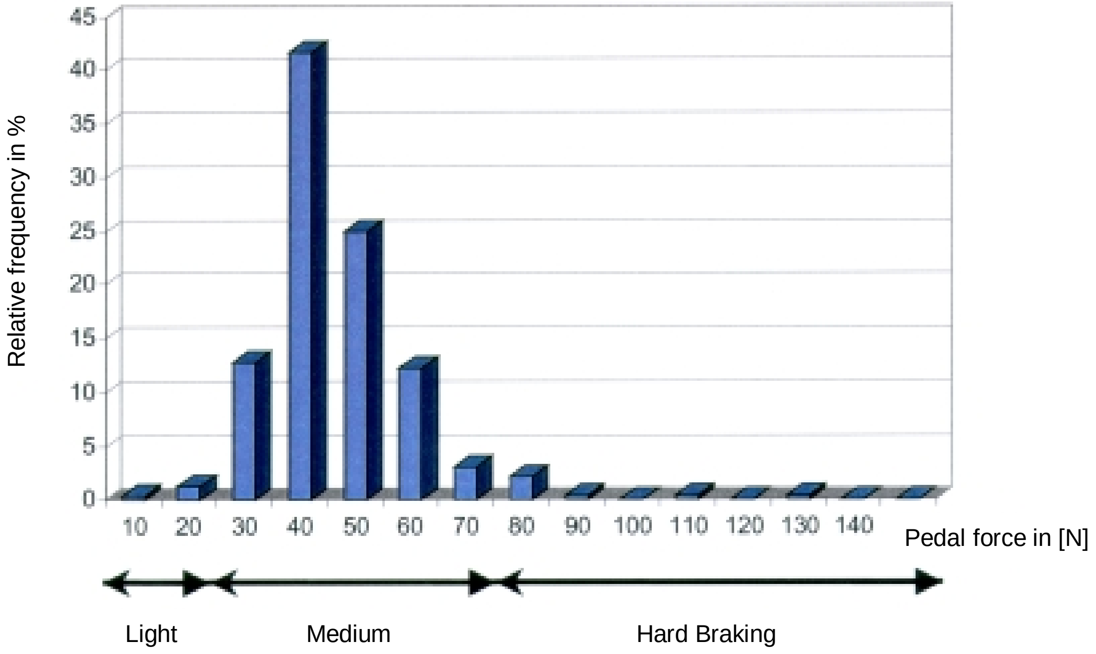


Figure 6: Distribution of brake pedal force [N] while driving on a freeway [23]

The following results were specified by BMW:

For light braking maneuvers the reaction time of the drivers was greater, i.e. the drivers took their foot from the gas pedal and were ready to apply the brakes, however, waited to see if it was really necessary to apply the brakes. This is also reflected by a significant reduction in the number of brake pedal actuations. When it was necessary to apply the brakes, the delayed reaction time was compensated by slightly higher brake pedal pressure, so that an increased hazard potential did not result here. As simulation of the traffic flow showed, this braking stage is a suitable instrument for harmonizing traffic flow.

For medium braking maneuvers, which occurred most frequently while driving on the freeway, a significantly shorter reaction time was noted for the vehicles driving with a minimum safety interval. When the safety interval is increased, a tendency to longer reaction times was noted in field tests indicating that the drivers also "wait" in this case to see how the situation develops. When the brake force curve is considered, we note that the maximum value is reached considerably quicker. Here, we also see a tendency to improve the distance behavior to the car in front even for medium braking maneuvers.

For safety reasons it was not possible to perform any tests for hard braking maneuvers under actual traffic conditions. It was therefore not possible to clearly define whether the reaction time of a driver is reduced by the brake force display. However, the brake force curves in the driving simulator and on the test track are significantly better than without display. The maximum value is reached more quickly and the entire braking curve is more harmonious (Figure 7, Figure 8).

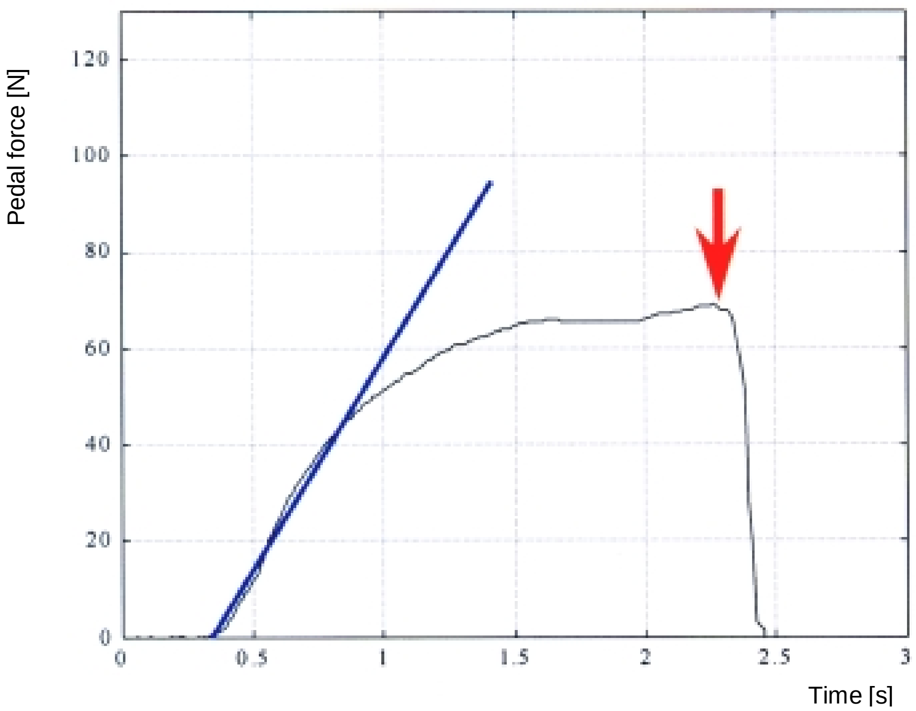


Figure 7: Brake pedal force curve with conventional display [23]

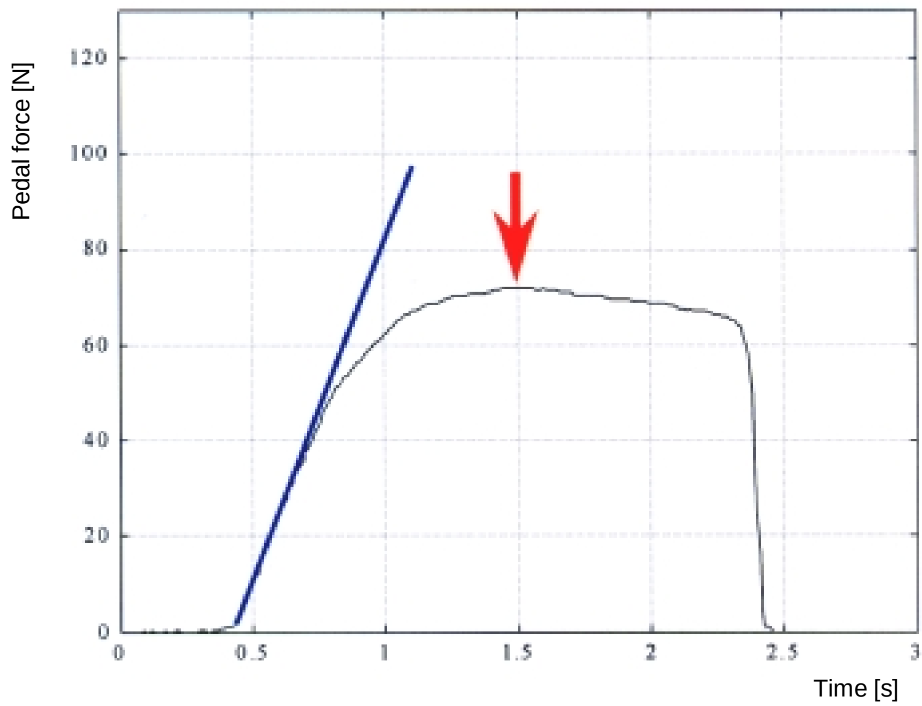


Figure 8: Brake pedal force curve with brake force display [23]

An improved interval behavior to the vehicle in front was noted even for hard braking maneuvers. This is shown when we observe the maximum speed difference of the two vehicles during the braking maneuver (Figure 9).

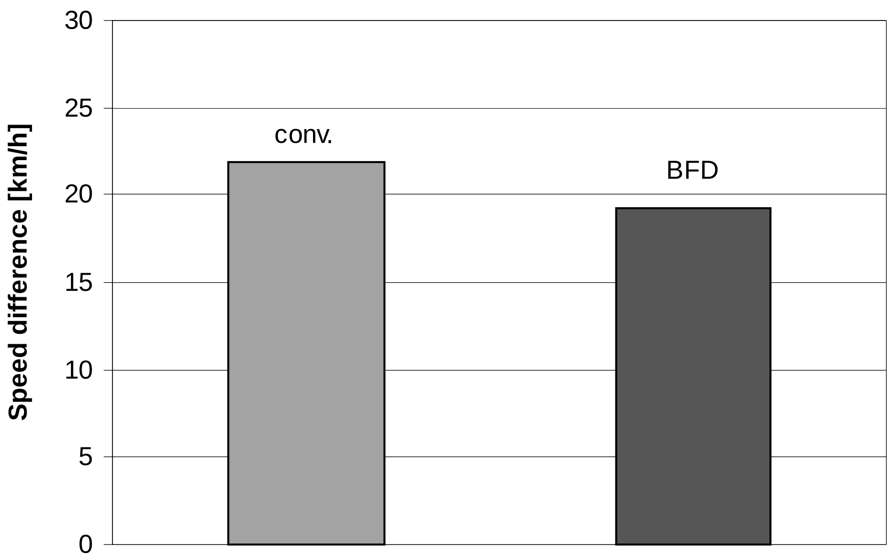


Figure 9: Maximum speed difference [km/h] during hard braking maneuvers [22]

Practical implementation of a 3-stage brake force display is contradicted by the enormous space requirement (doubling of area from one stage to next). For this reason, BMW has presented a 2-stage BFD as an alternative (Figure 10).

Braking stage	Brake light	High-mounted brake ligt
Stage 1 a < 4-5 m/s²	Illumination of standard brake lights	with
Stage 2 a > 4-5 m/s² or actuation of ABS	Increase in luminance Increase in size of illuminated area to side or upward	Possible increase in width of light

Figure 10: 2-stage Break Force Display

While the 3-stage version differentiates between light, medium and hard braking maneuvers, the simpler 2-stage version differentiates between standard and hard braking maneuvers. The field studies performed to date are limited to the 3-stage version.

3.2 Integral Brake Light (IBL)

An integral brake light was developed by Gerhaher, Wermuth and Barske [24]. Display of the brake force is accomplished here by the third high-mounted brake light consisting of 2 x 15 LEDs arranged in strip form. These are initially actuated in 15 stages from the outside to the inside depending on a continually sensed "hazard value", so that at the conclusion the strip of light is closed. If the brake deceleration increases beyond this, the lights flash with increasing frequency in four additional warning stages. The hazard value G is calculated by the ABS control module and takes the duration of the deceleration maneuver into consideration in addition to the momentary deceleration.

$$G = \int_{t_0}^{t_1} a^3 \, dt$$

A subsequent warning time going beyond the time the vehicle comes to a standstill is intended to signal the speed difference still existing at the end of the braking maneuver. The effectivity of the IBL was studied in driving tests on a test track operated by the Forschungsgesellschaft Kraftfahrwesen in Aachen [24]: Eight test persons went through 30 typical braking situations once with the present brake lights and once with IBL. During the first run, the test persons were not informed, then the function of the IBL was explained to them and the tests were repeated. Evaluation of the IBL by the test persons was positive. The measured values also showed improved reaction and braking behavior.

3.3 Optimization of Rear Signal Pattern by Means of Flashing Lights

At the request of the Daimler-Benz AG as it was known at that time, studies on optimization of the rear signal pattern for passenger cars were performed in 1992 [18].

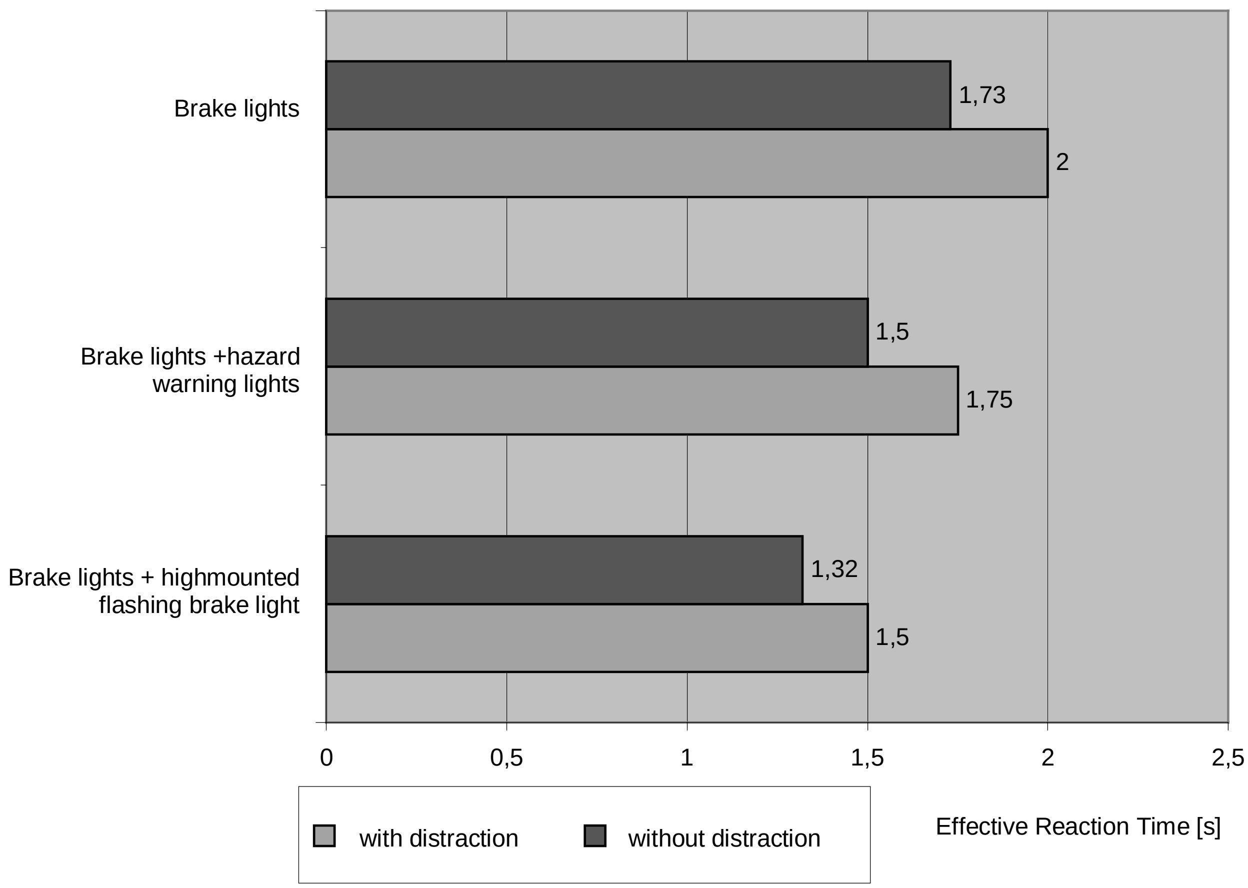
Based on initial theoretical considerations, the conclusion was also reached here that indication of the deceleration should be accomplished with a maximum of two to three stages. A chronological change in the signal pattern was preferred in the form of an intermittent display.

Studies using a driving simulator were intended to indicate whether the reaction time of the driver in the event of an emergency braking situation could be reduced by flashing lights and which type of signal pattern would be best suited for this. The 40 test persons were informed in detail of the various solution recommendations before starting the tests. They were requested to follow a vehicle at an interval of 50 m and a speed of 130 km/h and react properly to different braking maneuvers. In the first run, the test drives were accomplished without distraction, in the second run, the test persons were requested to look at a red light in between.

The studies concentrated primarily on the following versions:

- Conventional brake lights
- Conventional brake lights and hazard warning lights
- Conventional brake lights and high-mounted flashing brake light

The test results are illustrated in Figure 11:



<u>Figure 11:</u> Effective reaction times with and without distraction [25]

For both versions, improved reaction times resulted when flashing lights were used, whereby the solution with the high-mounted flashing brake light was more effective.

Tests on a computer measuring station indicated that the best frequency for indicating a hazard value is 4 Hz [18]. This also ensures clear differentiation from the flashing of the indicators (1.5 Hz $\pm$ 0.5 Hz). For signaling an emergency braking maneuver, the frequency should therefore not be selected too low, because a time of more than one period is required to identify flashing as such. Technical implementation of such a high frequency appeared possible only when LEDs were used in the third high-mounted brake light at that time. On the basis of such considerations, it was not evaluated how the reaction time of the driver would improve if all of the brake lights flash simultaneously, although this version was considered to be the solution with the highest safety factor as a matter of principle. In the meantime, advancements have been made in this area allowing a test vehicle to be equipped with the corresponding devices. A demonstration of this vehicle at the Federal Highway Research Institute confirmed the positive effect of this configuration.

The data available from the ABS and brake assistant which was already available, was used as the input data by Daimler Chrysler.

3.4 Solution Recommendation with Activated Hazard Warning Lights

PSA was the first to realize a display for hazard values at major deceleration rates with the development of the Peugeot 607: At speeds greater than 50 km/h, deceleration values greater than 7 m/s² over a period of longer than 0.3 s activate the hazard warning lights [28]. As shown in the diagram in Chapter 3.3, such displays are suitable in principle for reducing the driver's reaction time.

3.5 Continuous Illumination of Rear Indicators

The "Motor vehicle brake light" [30] is a recommendation from a private person who developed a simple 2-stage brake force display (Figure 12):

Braking stage	Brake light	High-mounted brake light
Stage 1 $a < 4$ m/s²	Illumination of standard brake lights	with
Stage 2 $a > 4$ m/s² or actuation of ABS	Additional illumination of rear indicators (continuous yellow light)	no change

Figure 12: 2-stage "Motor vehicle brake light"

Studies on the effectivity of the "Motor vehicle brake light" are not available. However, similar tests with a combination of conventional brake lights and red taillights did not show any significant improvement [18].

3.6 Assessment of the Solution Approaches from BASt's Point of View

Increase in luminance and illuminated surface area

The multiple-stage brake force displays described can be comprehended intuitively in our opinion. The changing position, increase in the area and increase in the luminance represent processes, which can also be observed when naturally approaching an object. For this reason, a learning process is not required as indicated in the field tests on the test track [22]. Demonstrations for employees of the Federal Highway Research Institute also confirm this impression.

When the eyes are fixed on the signal pattern generated by the vehicle in front, changes in the brake force display are easily perceptible. This also applies in the dark or under poor visibility conditions. A change in the brake force display is also recognizable in the peripheral field of vision as a motion by the brake signal so that the driver can react properly in this case as well. In our opinion, problems can occur only when the switchover between two brake stages is not perceived due to major diversion of the eyes. With the many different vehicle models, it would then be necessary to differentiate whether the brake lights are just particularly large or whether the brake force display has already switched to the next higher stage. However, particularly in emergency braking situations, it is important to obtain the attention of the driver under all circumstances. For this reason, an increase in the area or luminance alone for signaling an emergency-braking maneuver appears insufficient. On the other hand, in the opinion of the Federal Highway Research Institute, the brake force display is well suited for providing the driver with additional information relevant for safety even at deceleration rates of 4-5 m/s^2, which do not yet correspond to an extreme emergency braking maneuver.

If the multistage brake force display is approved, the question remains open whether the warning function of the rear signal pattern will be reduced in the long term due to accustomization processes. In contrast to the present version of high-mounted brake light, indication of the higher braking stages is accomplished with an offset in time. Moreover, in comparison to simple additional illumination of a third high-mounted brake light, this provides a true coding of the brake force. Since various signal patterns are offered depending on the intensity of the braking operation in the place of the conventional pattern which always remains the same, a reduction in the warning effect as is suspected with the third high-mounted brake light is not expected.

Due to the additional space requirement for the lights, retrofitting old vehicles with the brake force display described with increasing area is difficult. In addition, it will be necessary for all rear-end carriers to be equipped with new lights. Moreover, making an area increase mandatory would represent a significant intervention in the manufacturer's design freedom. For these reasons, the possibility of increasing the area for signaling an emergency braking operation should be optional and not mandatory.

Integral Brake Light

The intention of the Integral Brake Light (IBL) is completely different than with the two-stage system with increase in area and luminance described previously. This has primarily a warning function: "Caution, this car is decelerating rapidly", indicating to the driver of the vehicle behind to also apply his brakes hard and find an evasion possibility if necessary. The intention is to increase the attention suddenly. With the IBL, the driver is animated to "emulate" the braking force of the vehicle ahead. In our opinion, this requires concentrated visual fixation of the high-mounted brake light and under certain circumstances may therefore limit the angle of vision for evaluation of the overall situation.

In evaluating multiple stage brake systems, however, a system with 2-3 stages is preferred [1,16,18,33]. The 19 brake force stages used by the IBL overtax the driver according to the literature.

Flashing Brake Light

General approval of flashing brake lights is prohibited according to a term in the Vienna Convention from 1968 specifying that red illumination devices must not flash [26]. In highway traffic and on highway equipment, red flashing lights – to date reserved exclusively for indicating a hazard at railroad crossings without barriers – are quite controversial, because the significance of the signal "Continuous red light = Stop" could be reduced by a flashing display [27]. However, flashing brake lights on a vehicle have a different function. They are intended to attract the attention of the driver to the high deceleration of the vehicle ahead. Flashing lights are best suited for such purposes. Since this is a dynamic braking maneuver, the coding "Brakes applied = Red light" should be maintained. It will be necessary for drivers to learn that flashing brake lights indicate an emergency braking situation. If flashing is restricted to the third high-mounted brake light, the lower brake lights continue to show the familiar pattern of continuously illuminated brake lights preventing any irritation that could arise from three flashing brake lights.

A red flashing display on vehicles is already used in the USA, where the indicators are red.

<u>Activation of the Hazard Warning Lights</u>
In the type of situations that usually occur, the hazard warning lights are activated today by the driver and not automatically. According to the commentaries to Section 53a of the German Traffic Code (StVZO), there are basically no legal traffic regulations that preclude a hazard warning light that is switched on in relation to the deceleration rate, however, automatic switch-on is only permissible for extremely high deceleration rates between 1.5 g and 10 g [29]. In the case of an emergency braking maneuver with deceleration significantly less than 1.5 g, automatic switch-on of the hazard warning lights is not permissible to date according to the German Traffic Code (StVZO).

In our opinion, the hazard warning lights are not predestined for indicating a braking maneuver or the brake force due to the signaling function to the front as well as the rear. Moreover, illumination of the hazard warning lights in highway traffic is not necessarily associated with a braking maneuver, but rather serves for warning of highly differing hazards according to the German Traffic Code. As a rule, these are not highly dynamic situations but more frequently semi-static events such as vehicle breakdown. The previous coding "Brakes applied = Red light" should be maintained to prevent incorrect interpretation of the signal in the event of hard braking.

Moreover, in our opinion, the third high-mounted brake light should be included in signaling an emergency braking maneuver due to the better visibility in columns of traffic, which is not the case if the hazard warning lights were used alone.

<u>Continuous Illumination of Rear Indicators</u>
To avoid irritation, the indicators should not be "misused" for indicating the brake force. Continuous yellow light is not provided in the present signal pattern. Its introduction would require a learning process. The coding “Brakes applied = Red light” should be maintained to indicate a braking maneuver.

4 Requirements for a Brake Light Configuration with Optimum Effect

Based on the theoretical and practical knowledge regarding the effectivity of individual measures for improving the rear brake signal discussed in the previous studies, in our opinion, it is necessary for an optimized brake light to fulfill the following requirements in the event of an emergency-braking maneuver:

1) It should be possible for the signals to also be perceived quickly by drivers whose vision is distracted in order to shorten their reaction times.
2) The signal should be perceived and understood intuitively, i.e. the type of information coding selected should correspond to the natural expectations of drivers without previous learning.
3) The signal offered should be subdivided into a minimum number of stages to keep the requirements placed on human differentiation capabilities as low as possible [13].
4) The stages selected for an optimized brake light should be derived from the distribution of brake forces occurring in actual highway traffic.
5) The intention of an emergency-braking maneuver should also be indicated even on surfaces with less traction (ice).
6) The warning effect of a display for emergency braking should be as insensitive as possible to the effects of accustomization.
7) The signal should be clear and must not confuse other drivers.
8) Technical realization of the signal pattern should be possible for all vehicle models. Therefore, retrofitting possibilities should also be available.

A significant reduction in the reaction time and optimum reaction-demanding character are achieved by rapidly flashing lights (4 Hz) [2,18]. Rapidly flashing lights in the peripheral field of perception obtain visual attention and therefore attract the attention to the traffic situation particularly when the driver does not have his eyes fixed on this situation. Here, the coding "Brakes applied = Red light" should be maintained.

The optimized rear signal pattern requires changes in relation to previous practice for new developments as well as any retrofit solutions to be developed. Display of an emergency-braking maneuver flashing at a frequency of 4 Hz requires the use of LEDs, because the actuation characteristics of incandescent bulbs are too sluggish to reproduce this frequency of individual pulses that can be clearly separated visually. Additional control signals would be required for the lights in order to activate the higher stage of the brake signal pattern. A frequency between 3 Hz and 5 Hz should be prescribed in order to allow an economical retrofit solution with which display of the emergency braking maneuver could also be realized with incandescent bulbs.

The rear signal pattern must be clear and differentiated from other signals in road traffic, however, should simultaneously not cause over-taxation with visual stimuli and its effects should be influenced as little as possible by accustomization. Based on these requirements, flashing displays should be limited to absolute hazard situations requiring a high deceleration rate (> 7 m/s^2) as switch-on criterion.

Only the third high-mounted brake light should flash in the event of an emergency braking maneuver and the two lower brake lights should maintain their previous, familiar continuous illumination during braking maneuvers to avoid confusion. An additional safety improvement can be achieved by increasing the area and luminance of the two lower brake lights (see Chapter 2.9). In particular, the intuitive perception and application of the brakes as required for the situation with the greatest possible deceleration are ensured optimally in this manner. Here, the increase in the area should be accomplished upward and outward adjacent to the initial area. If the area is increased without additional increase in the luminance, the areas should be at least doubled, if the luminance alone is increased it should be increased by at least a factor of 5. Combined increase in the luminance and area should be laid out so that they achieve at least the same effect as increasing the area alone by a factor of 2 or increasing the luminance alone by a factor of 5. If adjacent taillights are included in the increase in the area, the luminance of the areas switched on in addition must be adapted to the brake lights. Unfortunately, a change in the area and luminance cannot be implemented on all presently common vehicle models and can therefore only be offered as an option. In some cases, the space required for increasing the area is not available. Moreover, the overall image of a vehicle is also characterized by the design of the lights so that a change in the light configuration would contradict the development of many vehicle manufacturers and could only be realized in future vehicles.

These considerations lead to the following design for the rear signal pattern for improving the signaling of emergency braking maneuvers and reduction of rear-end accidents:

4.1 Signal Patterns for Optimized Brake Light Configuration

The present signal pattern should be maintained for braking maneuvers in the deceleration range up to 7 m/s² (Figure 13):

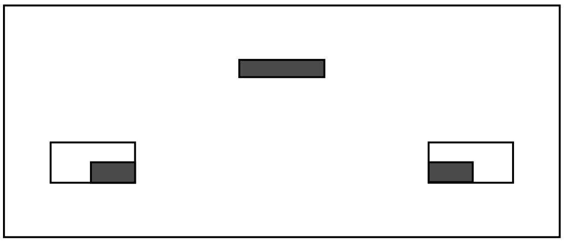


Figure 13: Retention of present signal pattern for brake deceleration rates up to 7 m/s²

In emergency braking situations with deceleration rates > 7 m/s², drivers should react within the shortest possible time even when their attention is diverted and apply the brakes with the highest possible pedal force. This can be achieved more simply and effectively by the third high-mounted brake light flashing at a frequency of 3 to 5 Hz (Figure 14).

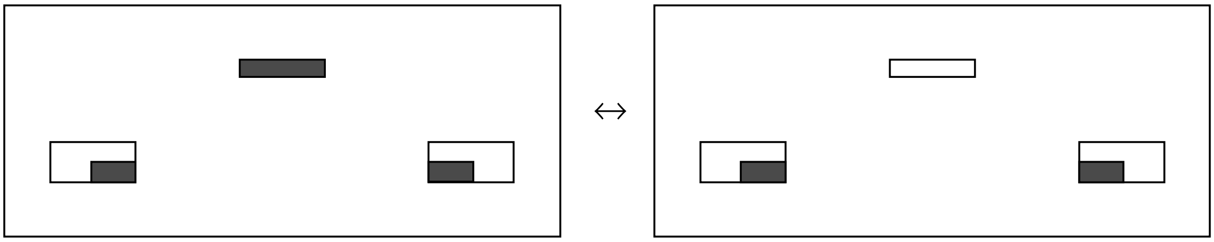


Figure 14: **Third high-mounted brake light flashes at frequency of 3-5 Hz in emergency braking situations (>7 m/s²)**

This signal pattern should be supplemented optionally by an increase in the area and luminance of the two lower brake lights (Figure 15).

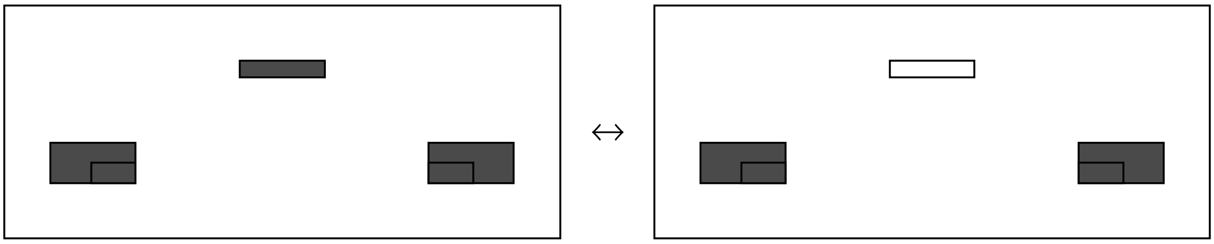


Figure 15: **Increase in area and luminance of the two lower brake lights in addition to the third high-mounted brake light flashing in emergency braking situations (>7 m/s²)**

Implementation of the entire vehicle fleet with the possibility for signaling an emergency braking situation would be a process requiring a number of years. During this period of time, vehicles with and without brake force display would exist next to one another. To date the problem of "mixed traffic" has not been studied. For example, it is not clear whether following a vehicle without such a display would be perceived only as an inconvenience or if this could result in erroneous reactions. The display of a present brake light configuration on a vehicle not equipped with emergency braking display could, for example, be interpreted incorrectly as a "light braking" because the emergency braking maneuver that is actually occurring is not emphasized particularly.

As a matter of principle, the following should be noted: If a multiple stage brake force display is recognized as a suitable instrument for avoiding rear-end accidents, the positive benefit should be evaluated higher in the long run, particularly when a higher degree of equipment is achieved rapidly by a retrofit possibility. Introduction of the third high-mounted brake light resulted in a similar situation. The increase in safety associated with this was certainly not questioned by anyone even though irritations may have occurred under certain circumstances during the transition phase. No mentionable effects were noted for the mixed traffic. If the vehicle ahead is not equipped with such a display, the previous signal pattern would be visible when the brakes are applied regardless of the intensity. Reaction to an emergency braking maneuver would then have to be based on additional visual information regarding the approach rate to the vehicle in front, as is presently the case, so that although the reaction time would be longer than with a brake force display, it would not be any longer than in present traffic. It can therefore be assumed that mixed traffic will not have any significant negative effects on traffic safety (as in the past for many new types of equipment).

4.2 Technical Execution of Optimized Signal Pattern

The deceleration rates specified for the brake signal patterns described are based on braking maneuvers on dry roads. If present, various other input variables could be used in place of the deceleration values mentioned here for determining the deceleration rate desired by the driver. This is practical and easily realizable particularly on vehicles equipped with ABS (Antilock Brake System) or brake assistant systems. If one of these systems actuates, an emergency braking maneuver can be assumed and the higher stage of the signal pattern is activated. Other suitable input variables instead of the actual vehicle deceleration rate would allow recognition of intended hard braking maneuvers and signal these accordingly via the brake lights even on road surfaces with low traction.

Input variables
The reference variable for display of the brake force is the deceleration desire of the driver. Physically, this intention of the driver is first indicated by motion of the foot (moving the foot from the gas to the brake pedal). Conclusions regarding the intended deceleration rate can be made from the speed of the foot movement alone. This is utilized by so-called brake early warning systems, with which the braking maneuver is indicated even before the foot has made contact with the brake pedal. Other systems such as the brake assistant conclude whether an emergency braking maneuver is desired from the speed at which the brake pedal is actuated and then ensure that the maximum brake force is achieved as quickly as possible without the driver first having to press the pedal hard enough. The data from such brake assistant systems is therefore predestined for use as an input variable for signaling an emergency-braking maneuver. On vehicles without brake assistant, actuation of the ABS, which is present today on nearly all new vehicles, can be used for identification of an emergency braking situation, whereby signaling should be accomplished only when at least two wheels are in the actuation range simultaneously. The brake force and brake pedal force can also serve as input variables in conjunction with the vehicle speed. If none of these values is available, the only remaining input variable is the deceleration determined by a deceleration sensor or from the change in the vehicle speed. The actual deceleration can, however, be slight in the face of low traction, even in an emergency braking situation. Or when driving downhill on a steep grade it is possible for the vehicle deceleration measured by a deceleration sensor to be high even when an emergency braking situation is not present. For this reason, it would be most practical to use the input variables mentioned first if possible.

Switch-on and switch-off criteria
The next higher stage of a display for an emergency-braking maneuver should be switched on after vehicle-internal evaluation of the input variables described above. Flashing or additional increase in the area and luminance can then be accomplished directly without a time delay. When the brake pedal is released, when the vehicle comes to a standstill or after recognition of termination of the emergency braking situation by the brake assistant or ABS, the next higher stage should then be switched off immediately. In addition, it could also be considered at this point whether

the brake lights should generally be switched off when the vehicle comes to a stop – eventually with a short-time delay, because at this moment, the deceleration process is completed. If extreme deceleration rates occur as a result of an accident, the hazard warning lights should be activated automatically instead as mentioned previously.

Frequently, signaling devices on the vehicle are misused for purposes other than that intended and can therefore lead to a danger for traffic in extreme cases. Of mention here are for example, "Greeting others" with the horn, switching on the hazard warning lights for short-term parking on the roadway, trying to force one's way in the passing lane using the headlight flashers, unnecessary actuation of the brakes on the freeway, momentarily switching on the lights to simulate a braking maneuver for the driver behind. Such possibilities for misuse should be excluded to the greatest possible extent for the brake force display. The layout of the signal pattern with increasing deceleration should depend on vehicle-internal values alone providing information on the braking maneuver and vehicle motion. If the brake pressure or brake pedal pressure is used as an input variable for the brake force display, it is necessary to exclude the possibility of the driver actuating a higher stage when the vehicle is standing still, e.g. at a stoplight, by pressing the brake pedal down hard. To avoid erroneous illumination of the brake force display, it may be necessary to ensure that the brake force display illuminates only above a minimum speed (e.g. walking speed of approx. 5 km/h). In city traffic, a positive effect from the emergency braking signal is also expected, so that the minimum speed should not be too high (close to walking speed).

5 Necessary Changes in Existing Regulations

Although introduction of a signaling feature for emergency braking maneuvers should require the least possible changes to the existing regulations, it must be considered that introduction of new technical possibilities should be advanced regardless of the regulation situation, when they are accompanied by a significant improvement in safety and in such a manner that further improvements can be supplemented easily. In order to approve a multiple stage brake force display at the European level, it will be necessary to reconsider and correspondingly change the following regulations:

<u>Definition of brake actuation</u>
ECE Regulation No.7 [31] and No.48 [20] define that the brake lights indicate that the driver has actuated the service brake. However, switch-on of a second stage in a brake force display would be actuated by the vehicle itself (as a reaction to the actuation of the brakes by the vehicle driver). Illumination of the brake light configuration going beyond the conventional pattern should therefore not be coupled explicitly to switching on or actuation by the driver. Actuation of the brakes should only be a basic prerequisite for all possible brake signal patterns with various additional switch-on criteria.

<u>Dynamic change in brake lights during braking maneuver</u>
Points 2.7.12 and 6.7.7 of ECE Regulation No.48 [20] should allow the brake lights to be illuminated subsequently in two stages, i.e. allow a change in the signal pattern during the course of a braking operation. Here, changes in the area and luminance

as well as flashing should be provided. Moreover, the switch-on and switch-off criteria should be defined.

Number of lights
More than three lights must be permissible for the brake light signal for the special case of an emergency braking maneuver for realization of an increase in the area by changing the number of lights. This would have to be specified in Point 6.7.2 of ECE Regulation No.48.

Luminous intensity
The limits for the luminous intensity level specified in ECE Regulation No.7 should be maintained, also to avoid the danger of dazzling other traffic. However, within these limits, it should be possible to vary the luminous intensity even during a braking maneuver.

Flashing of third high-mounted brake light
Section 53, Para. 2 of the German Traffic Code (StVZO) [29] should allow the use of flashing light for the third high-mounted brake light. This also applies for ECE Regulation No.48, Point 5.9.
Appendix 5, Para. 42 of the Vienna Convention on Highway Traffic from 1968 [26] should allow flashing of red lights.

Distance from rear fog lights
According to ECE Regulation No.48, Point 6.11.9 and Section 53 d of the German Traffic Code (StVZO), the light emitting surfaces of brake lights and rear fog lights must be at least 100 mm apart. In order to realize an increase in the area of the brake lights in a simple manner, this minimum distance should be eliminated for signaling emergency braking maneuvers. Short-term signaling of an emergency braking maneuver or hard braking has a significantly higher priority than the rear fog light. Recognizability of the vehicle even in thick fog is still possible even when the brake signal illuminates directly next to the rear fog light. The minimum interval should be maintained for light braking maneuvers with the previous signal pattern.

6 Conclusion

With the present brake signal pattern, drivers following are provided only with the information that the brakes have been applied on the vehicle in front, however, not how hard they are applied. The purpose of this report was to work out on the basis of a study of the literature, which requirements should be placed on an optimized rear signal pattern and provide a solution or recommendation for signaling emergency braking maneuvers. For this purpose, the following signal patterns were analyzed individually and compared:

- Increase in area and luminance of brake lights
- 19-stage integral brake light with switch-on of LEDs and flashing of third high-mounted brake light
- Flashing of the brake lights
- Flashing of the two rear indicators
- Continuous illumination of both rear indicators.

The primary result of the comparison is that both principles (increase in the area and luminance as well as flashing of the lights) have their respective advantages, i.e. reduction of the driver reaction time and quickly achieving a suitable deceleration rate in various hazard situations, because both provide information in different forms to the driver of the vehicle behind: For example, an increase in the area and luminance intuitively provide the driver with an impression of quickly approaching the vehicle in front, while flashing attracts the attention of the driver to the car in front particularly when the driver behind is not looking directly at it at the moment.

Moreover, it was found that only two, up to a maximum of three, display stages are suited for differentiation of the signal pattern and correct interpretation by the drivers behind. More stages pose the hazard of confusing the driver.

In order to maintain a uniform color-coding and thereby avoid unnecessary learning requirements as well as mix-ups, the brake information should always be connected with red light.

Based on these results, the following version was recommended as a possible solution: When the brake assistant or ABS actuates or at a vehicle deceleration rate greater than 7 m/s^2, the emergency braking maneuver is signaled by flashing of the third, high-mounted brake light at a rate of 3-5 Hz. As an option, the area and luminance of the two lower brake lights could be increased in addition.

Introduction of such types of signaling for an emergency-braking maneuver would require changes to ECE Regulations No. 7 and No. 48 as well as to the Vienna Convention. This affects the points which couple the brake light with actuation of the brakes, a change in the brake signal during the course of a braking maneuver, increase in the area and luminance and flashing of the brake lights as well as switch-on and switch-off criteria.

It is expected that the described advancement in the rear signal pattern with special representation of the emergency braking maneuver will be accompanied by an increase in the traffic safety and a reduction in the number of severe rear-end accidents.

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