Final Report

Camera-Monitor Systems as a Replacement for Exterior Mirrors in Cars and Trucks

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Abstract

Camera-monitor systems (CMS) can be used in motor vehicles to display the driver's rear view on a monitor mounted inside the vehicle. This also offers the possibility of replacing conventional exterior mirrors with suitable CMS and thereby implementing new design concepts with aerodynamic advantages. However, as exterior mirrors are safety-relevant vehicle parts for securing the driver's indirect rear view (requirements specified in UN Regulation No. 46), the question arises whether CMS can provide an equivalent substitute for mirrors.

In the scope of this study, CMS and conventional exterior mirrors were compared and assessed in test drives and static tests under different external conditions. On the one hand, the examination of technical aspects, and on the other hand, issues pertaining to the design of the human-machine interaction, were the objects of the study.

Two vehicles were available for the trials with passenger vehicles: A vehicle, manufactured in small series, which is already equipped with CMS as sole replacement for the exterior mirrors, as well as a compact class vehicle which had a CMS retrofitted by the car manufacturer in addition to conventionally used exterior mirrors. The latter could be covered exclusively for trips with CMS. A tractor unit with semitrailer was available for the truck trials. The driver's cabin was equipped with a CMS system developed by the vehicle manufacturer.

In general, it was shown that it is possible to display the indirect rear view sufficiently for the driver, both for cars and trucks, using CMS which meet specific quality criteria. Depending on the design, it is even possible to receive more information about the rear space from a CMS than is possible with mirror systems. It was also shown that the change from mirrors to CMS requires a certain period of familiarisation. However, this period is relatively short and does not necessarily result in safety-critical situations.

1 Introduction

Camera-monitor systems (CMS) can be used in motor vehicles to display the driver's rear view on a monitor mounted inside the vehicle. This also offers the possibility of replacing conventional exterior mirrors with suitable CMS and thereby implementing new design concepts with aerodynamic advantages. However, as exterior mirrors are safety-relevant vehicle parts for securing the driver's indirect rear view (requirements specified in UN Regulation No. 46), the question arises whether CMS can provide an equivalent substitute for mirrors. Therefore, the Federal Highway Research Institute (BASt) was commissioned by the Federal Ministry of Transport and Digital Infrastructure (BMVI) to carry out corresponding investigations, in which CMS and mirrors are evaluated comparatively. Tests with vehicles equipped with CMS, mirrors or both, were conducted for this purpose. On the one hand, the examination of technical aspects, and on the other hand, issues pertaining to the design of the human-machine interaction, were the objects of the study.

2 Literature Analysis

2.1 Technical background

According to Regulation No. 46 (R 46) of the United Nations Economic Commission for Europe (UNECE), "Uniform provisions concerning the approval of devices for indirect vision and of motor vehicles with regard to the installation of these devices" (UN-R 46, 2010) different mirrors are classified into groups according to their purpose. It is stipulated which of these mirrors must be present in the different vehicle classes.

The UN-R 46 defines exterior mirrors as mirrors mounted on the external surface of a vehicle intended to give the driver a clear view to the rear, side or front of the vehicle within a clearly defined field of vision. Figure 1 shows an example of the prescribed field of vision for indirect vision for cars.

According to UN-R 46, a CMS, i.e. "camera-monitor device for indirect vision", is defined as a device which represents the field of vision obtained by means of a camera-monitor combination to the driver. Camera-monitor systems are used in vehicles in order to provide the driver with information on a specific field of vision (usually the rear view). However, at present it is not permitted to use CMS as a replacement for exterior mirrors. CMS may only be used as an additional source of information for the driver.

Currently, the International Organization for Standardization (ISO) is working on the subject of CMS (ISO standard 16505 “Road vehicles - Ergonomic and performance aspects of Camera-Monitor Systems – Requirements and test procedures”) (ISO, 2012). The standard deals with the requirements and test procedures for CMS in road vehicles, however, it has not been adopted, nor been awarded draft status yet (DIS = Draft International Standard).

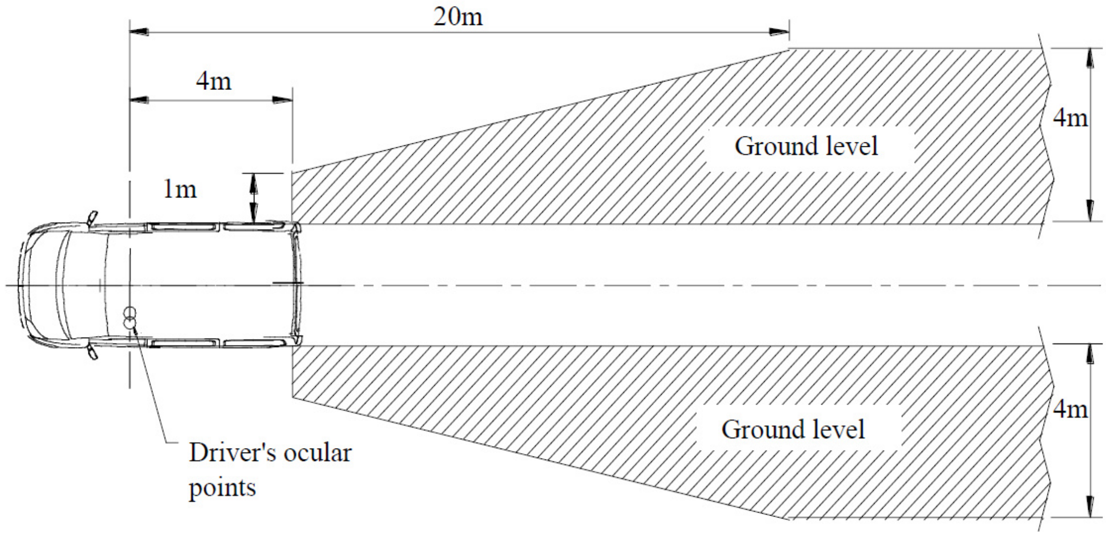

Figure 1: **Prescribed field of vision for Class III (UN-R 46) mirrors, i.e. for small exterior mirrors**

2.2 Human-machine interaction

The first studies on human-machine interaction with regard to CMS were conducted already in 2002. It was concluded that CMS could offer many potential advantages to the driver (Flannagan, 2002). For example, with a CMS the driver is not able to change the indirect vision by moving his/her head, as it is possible with a mirror. In addition, the position of the displayed image is completely different. The position of the exterior mirror is outside of the cabin; whereas the position of the monitor would be inside the cabin and closer to the driver.

2.2.1 Glance behaviour in real traffic situations

According to the regulations of the **A**lliance of **A**utomobile **M**anufacturers (AAM, 2003) for the design of human-machine interfaces in vehicles, glances onto the visual display must not be longer than 2 seconds. A complete secondary task which is performed during driving should not exceed 20 seconds. The maximum time of visual orientation towards a secondary task, which is usually accepted by the driver, is about 1.5 s. Regardless of whether the searched information, was mentally processed, the driver would usually return his/her gaze to the driving task (Rauch, 2009).

If the complexity of the driving task increases, the drivers' frequency of single glances at the display instead of glance duration increases. According to Zwahlen et al. (1988), tasks which require up to three glances and mean glance durations of 1.2 s are acceptable. Tasks which require three to four glances and mean glance durations of 1.2 to 2 s are at the threshold of acceptance. If more than four glances and mean glance durations of more than 2 s are required, the task is considered safety-critical. Thus, the mean glance duration and glance frequency are valid values for the detection of critical gaze patterns.

2.2.2 Glance behaviour during lane-changing

Eye movements and glance movements either occur as an adaptation to body and head movements in order to ensure the continued fixation on a target, or as micro movements of the eyes during fixation in order to maintain sensitivity towards a continuous visual stimulus. These micro movements occur during every fixation. Also eye movements particularly occur as a response to the focus on an interesting target. Here, the continuous eye movement allows for acuteness of vision, because foveal perception is only available in a deviation of approximately 1° to 1.5° from the visual focus.

In addition to foveal perception, other factors play a role while driving a motor vehicle. For example, peripheral objects are perceived by motion stimuli or contrasts and are classified as conspicuous stimuli (Rickheit, Herrmann & Deutsch, 2003). However, peripheral objects are perceived with a lower resolution and colour intensity.

In research, glance and head movements often serve as indicators for imminent lane-changing. According to Henning et al. (2008), lane-changing determines quick glance alternation between the left exterior mirror and the road. Immediately before the driver initiates lane changing, the driver glances over his/her shoulder before he moves the steering wheel. In a study by Bayerl (2012), five subjects performed 650 lane-changes to the left. Regarding to the results, the number of glances into the mirror increased approximately 1 to 5 s prior to the actual lane-changing (see Figure 2).

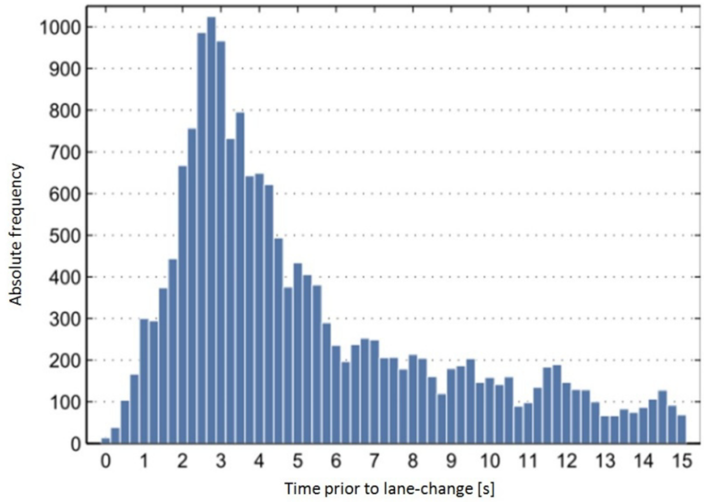

Figure 2: **Temporal distribution and absolute frequency of glances into the left exterior mirror within the last 15 seconds prior to the actual lane-changing. According to Liebner et al. (2010).**

Henning (2009) also examined the earliest indicators for lane-changing and found an increase of glances into the left exterior mirror and a corresponding decrease of glances at other objects. In addition to the glance behaviour, the study shows that the point in time of crossing the lane, as well as the gradual change of the steering angle, was well predictable. However, it was also found that switching on the indicator or a glance over the shoulder are relatively poor indicators for lane-changing (Henning, 2010).

2.2.3 Distance and speed perception in road traffic

In research, the "*last safe gap*" method (see Bowles, 1969; Burger et al., 1980; Fisher & Galer, 1984; Mortimer, 1971; Mortimer & Jorgeson, 1974; Walraven & Michon, 1969) has proven itself for determining the perception of distance and speed via the rear-view mirror. Hereby, the subjective distance and speed perception, which is difficult to determine by humans, is captured indirectly by means of indication of the last safe moment for lane-changing. The subject sits in a static (semi-dynamic design) or dynamic (dynamic design) test vehicle and, by pressing a key button, indicates the last possible moment for him/her to change a lane in view of an approaching vehicle. The approaching vehicle is only observed via the left exterior mirror. It must be noted that in (semi) dynamic tests, it is difficult to differentiate the perception of distance from the perception of speed, because the perception of different speeds of an approaching vehicle occurs as a result of a simultaneous change in distance. The ‘last safe gap’ method (Bach et al., 2006) complies with this assumption.

Due to the curvature of the mirror surface, objects are perceived smaller, which complicates the estimation of speed of approaching vehicles (Mortimer, 1971). In the studies by Mortimer & Jørgensen (1974) and Mortimer (1971), the subjects were also allowed to use the interior mirrors for estimations. Here, it was shown that even by using different types of mirrors (planar; 47 & 29 inch spherical), there were no differences in the estimation of the last safe gap. Accordingly, drivers rely more on the interior mirror when estimating the distance and speed of other road users. If subjects estimated without using the interior mirror, the distance to other vehicles was overestimated. This overestimation of distance was greater in mirrors with a smaller radius of curvature. Previous experience with non planar mirrors can partially reduce the overestimation. De VOS (2000) examined the compensation ability due to previous experience for estimation of distances. Regarding to the results, subjects who were familiar with spherical mirrors compensated the reduction of size of the objects by selecting significantly larger gaps for lane-changing than subjects who had a planar or partially aspherical mirror on their vehicles. Flannagan, Sivak & Traube (1996) also showed that increasing the drivers’ experience with the mirror type, the estimations became more accurate.

Flannagan and Mefford (2005) examined the influence of the displayed object size on distance perception in camera-based monitors in real-traffic conditions. The subjects observed a vehicle, which was preparing to overtake, via the camera-based monitor and responded at which point in time they would still pull out in front of the vehicle. Magnification of the image section by a factor of 1.5 resulted in a significant underestimation of the distance. Whereas, the last possible moment for changing a lane was at a distance of 37.5 m by an image display of 1:1 in relation to the own vehicle, at an image display of 1:2, the distance was only 27.5 m.

2.2.4 Distance and speed perception for exterior mirrors and displays

Distance and speed estimations in road traffic show a significant discrepancy between subjectively perceived and objectively measured values. Hereby, distances in the mirror tend to be more overestimated (de Vos, 2000; Flannagan, 2000). When estimating speeds, an effect of dimension is seen. High speeds are relatively underestimated (Suguira & Kimura, 1978) and slower speeds are overestimated (Henderson, Smith, Burger & Stern, 1983). Likely reasons for different perception of distance and speed using exterior mirrors or camera-monitor systems are due to the limited availability of depth information provided by the CMS. An essential criterion of depth is a result of the eye movement: Both the convergence of the eyes and the curvature of the lens play an important role in the perception of distance and speed of objects: As distant objects are displayed smaller on the eye's retina, humans perceive the movement of distant objects less than those of close objects, which appear larger on the retina (Flannagan, Sivak & Simpson, 2001). With more experience, the brain learns to compensate for these differences. The ability to perceive depth is limited for indirect vision, i.e. a glance into the rear-view mirror during driving. The stronger the curvature of the mirror, the higher the compensation performance of the brain. However, all traffic objects are appear to be on one level on a monitor, irrespective of their actual distance – therefore the image appears flat and remains unchanged in relation to the head and eye movements of the driver.

There is evidence to suggest that depth criteria such as accommodation play a relatively minor role for the driver compared to monocular depth criteria (e.g. relative size, light and shadow effect of an image). In view of the above this is interesting considering the described development towards camera-based monitors as an alternative to exterior mirrors, as CMS eliminate or distort oculomotor, stereoscopic and motion-induced depth criteria due to the two-dimensional representation. However, monitors are very good at reflecting monocular depth criteria such as for example the height in the field of vision (Flannagan & Sivak, 2006). When the driver looks at the monitor, the information from the convergence of the eyes, the accommodation, the motion parallax and the information from the retinal disparity would serve to indicate that the objects in traffic are located at a certain distance to the driver. Consequently, an impression of depth is created as a result of additional information such as monocular depth criteria, light and shadow effects and experience with distance distortion (Flannagan et al., 2001).

3 Technical Aspects

In this study a CMS is compared to a conventional exterior mirror with regard to the technical and road-safety relevant characteristics. In a CMS, the exterior mirrors are each replaced by a small camera. The image recorded by the camera is displayed in the interior on monitors, for the right and left view, in order to present the driver with a rear view.

In this study the technical characteristics and requirements for such a CMS are examined and evaluated. Hereby, the focus is on the comparison to conventional exterior mirrors. Potential problematic conditions when using CMS are examined more closely.

3.1 Test vehicles

3.1.1 Cars

Two vehicles were available for the trials with cars: A vehicle, manufactured in small series, which is already equipped with CMS as sole replacement for the exterior mirrors, as well as a compact class vehicle which had a CMS retrofitted by the car manufacturer in addition to conventionally used exterior mirrors (see Figure 3). The latter could be covered exclusively for trips with CMS. On the vehicle that was equipped for the examination with cameras, the cameras were positioned on the left and right, below the mirror housings.

Figure 3: Left exterior mirror with camera mounted to the mirror housing.

The two monitors of the test vehicle could be mounted variably as they could be fixed on each side in the relevant position by means of three brackets. The monitors on the driver side and close to the passenger door were defined as Position 1 (CMS 1) (Figure 4). Position 2 (CMS 2) (Figure 5) was integrated close to the steering wheel on the air vent grids. Suction feet were mounted on the windscreen, close to the A-pillar of the vehicle for the integration of Position 3 (CMS 3) (Figure 6). Figure 7 shows the locations of the monitors in a schematic overview. During the study, a monitor was always attached to the driver side and passenger side, in accordance with a left and right mirror replacement system.

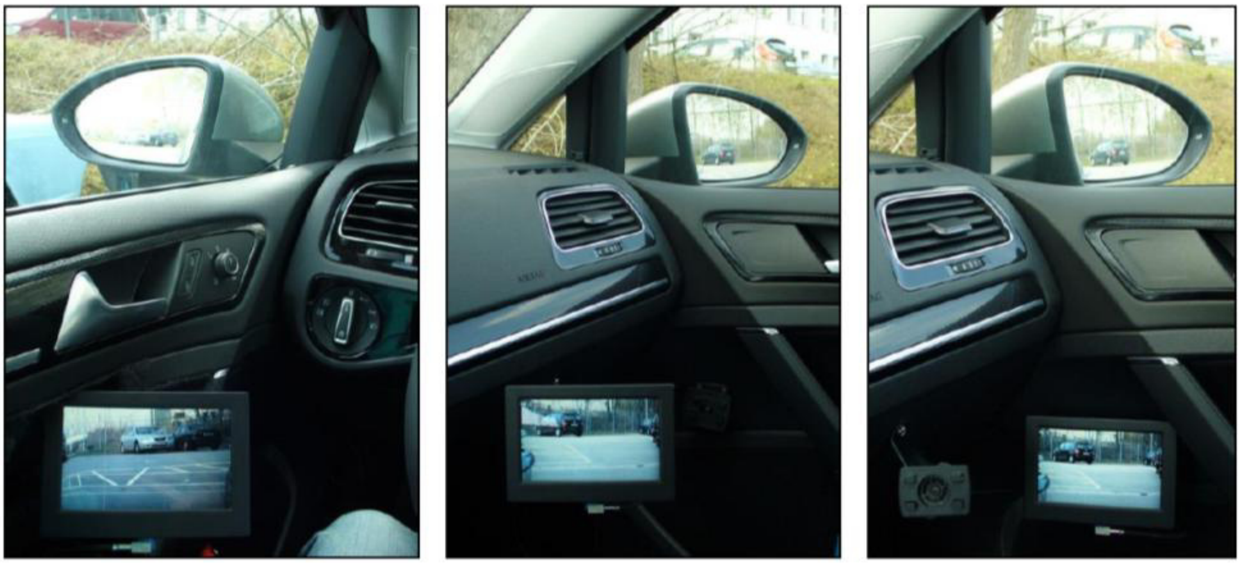

Figure 4: Integration of the monitors in the driver and passenger door (Position CMS 1).

Figure 5: Integration of the monitors on the air vent grids (Position CMS 2).

Figure 6: Integration of the monitors next to the A-pillar (Position CMS 3).

Figure 7: Schematic overview of the location of the positions CMS 1, CMS 2 and CMS 3.

On the monitors used here, one section is represented as a spherical figure and another section as an aspherical figure, in analogy to the mirror. The external aspherical area contained 200 horizontal and 480 vertical pixel. Whereas the spherical area contained 600 horizontal and 480 vertical pixel (KMS Type DASP quoted from TÜV Test Report, 2013). The transition from the main surface to the aspherical area was clearly marked (Figure 8). The camera shot 23.5 images in a dark environment and 33.3 images / s in a light environment. In comparison, from an image frequency of approximately 14 to 16 images / s, the human brain perceives consecutive images as a moving scene (Dube, 2011).

Figure 8: Right-hand monitor with aspherical section.

A driver-side partially aspherical exterior mirror with a curvature radius of 1260 mm (in the spherical section) and a passenger-side cylindrical convex exterior mirror were used as exterior mirrors. There was also a conventional interior mirror.

3.1.2 Trucks

A tractor unit with semitrailer was available for the truck trials. The driver's cabin was equipped with a CMS system developed by the vehicle manufacturer. The cameras were fixed above the main exterior mirrors on the driver and passenger sides. In addition, the vehicle had conventional exterior mirrors, which could also be folded away for trips with the CMS in such a way that the driver was no longer able to use them (see Figure 9).

The system was based on an embedded FPGA (Field Programmable Analog Array) system (processor with higher graphics operations) and adapted firmware. The displays and cameras consisted of components developed by the manufacturer (two cameras with a resolution of 1.3 mega pixels, manufacturer APTINA; two 12.3 inch monitors with a resolution of 1440 x 540 pixels, visible area 295 mm x 113 mm).

Figure 9: **Exterior mirrors with cameras and monitor integration next to the A-pillar on a truck.**

3.2 Test concept

The direct comparison of the CMS and the mirror is an important factor for the evaluation. To this end, test drives under various conditions as well as static tests were performed (Marandi, 2013). The static and dynamic tests were recorded as video or photo material for analysis. In order to best document the rear view, an additional camera was mounted and aligned in such a way, that both the left rear-view mirror and the left monitor were visible in the recording (see Figure 10). The necessity of the documentation required to reproduce the mirror image or the monitor image, which are actually created in the driver's eye, as an "image of an image" in the report. Therefore, the impression in the test driver's eye is decisive for the assessment of the CMS and mirror. Accordingly, the "images" of the mirror images and monitor images in this report show, in parts, the described effects equally clear, however, in some parts also to a limited extent.

Generally, for static tests a colour and a grey level scheme were used as a background, in order to ensure a good evaluation of the CMS and mirror images. Furthermore, static tests on interference immunity (e.g. with regard to electro-magnetic compatibility (EMC) or glare) were performed.

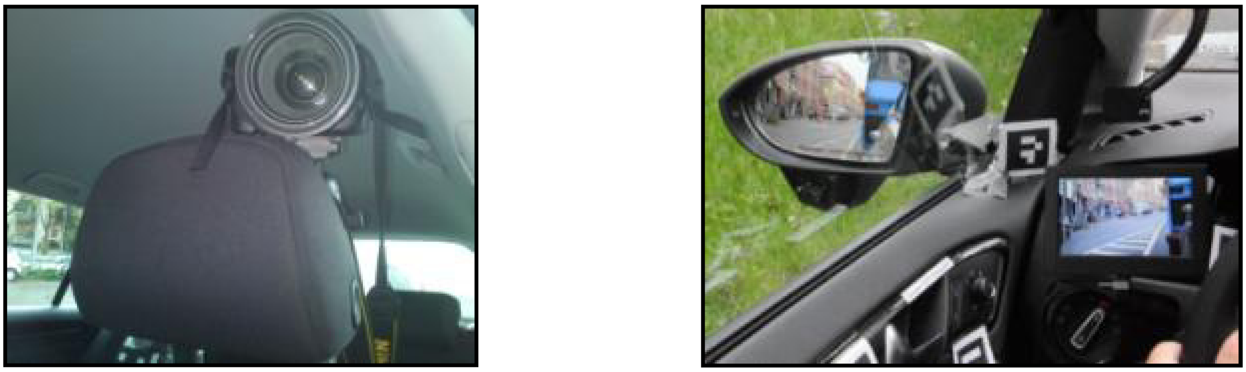

Figure 10: Camera mounting and image for testing the technical aspects of cars.

The CMS was mainly observed for the following technical aspects and situations - always taking differences to the mirrors into account:

- Rear field of vision and, if necessary, restriction of the direct view forward
- General day and night properties
- Image reproduction
- Glare from other head lamps at night
- Reflections and glare (display)
- Adjustability of the camera and display
- Failure safety
- Behaviour under different weather conditions
- Effect of soiling

The technical aspects were examined exclusively in cars, however, the results equally apply to the CMS on the truck.

3.3 Mirror and CMS properties

In principle, mirrors and CMS both have specific advantages and disadvantages, which already allow for a comparison based on technical-physical aspects. Table 1 compares these basic properties of mirrors and camera monitor systems, based on (TÜV Test Report, 2013). The table lists artifacts. Artifacts are image errors (in parts the image does not reflect reality correctly).

Mirror	Camera-monitor system
The law of reflection applies to mirrors. A convex curved mirror provides the viewer with a reduced virtual image of the object. The mirrors can be adjusted to adapt to the user's need. The field of vision can be changed by moving the head.	A camera records a constructively specified field of vision, which is displayed on the monitor. Moving one's head does not alter the displayed field of vision. However, setting options for the camera are conceivable. Also, an adjustable design of the monitor is possible, in order to e.g. ensure a orthogonal line of sight. Deviating from the orthogonal angle of view on to the monitor can result in an altered perception of the depicted objects, contrasts, luminance and colours.
Mirrors depict the object luminance according to its degree of reflection. The object luminance, which is dependent on the degree of reflection, is perceived by the eye, however, diminished by the transmittance of the side window.	The maximum luminance of monitors is limited. Ambient light can diminish the luminance contrast and the colour saturation on the monitor. Also, at night, the monitor has a basic luminance greater than 0 $cd/m^{2.}$
Light on the mirror, e.g. sunlight or light from other vehicles can result in a physiological glare for the driver. Point light sources, e.g. dipped beam head lamps, are reflected as point light sources in the intact mirror. In mirrors with a quality that is standard in the automotive sector artifacts do not appear.	Direct light on the camera can result in artifacts. These artifacts strongly depend on the quality of the camera, especially the lens. Direct light on the monitor can result in a diminishment of the luminance contrast and the colour saturation of the image. Furthermore, direct light reflected on the monitor (simple reflection at the cover glass of the monitor) can cause a physiological glare for the driver. Also, especially at night, the monitor image can reflect in the windows and impair the direct outside view.
Mirrors reflect colours very well.	For CMS the image fidelity is determined by the optical-electrical-optical transfer

Mirror	Camera-monitor system
	function. The colour range of a CMS is limited. Colours can be perceived differently by changing the angle of view on the monitor. Artifacts can affect the depiction and perception of colours.
The resolution of mirrors is higher than the possible resolution of the human eye.	The resolution of CMS is limited and depends on the quality of the components used.
Mirror image changes are reflected in real-time.	Camera image changes are depicted with a minimal time-delay.
The degree of reflection of a mirror can be affected by dirt, condensation, scratches, cracks or rain drops. In addition, viewing the externally mounted mirrors can be affected by dirt, condensation, scratches, cracks or rain drops on the side window.	The camera image can be affected strongly by dirt, condensation, scratches or rain drops on the CMS. However, viewing the internally mounted monitor is not affected by the side window.
A mirror is always operational.	The CMS requires time to boot up.
Mirrors can fail in the form of scratches, cracks, broken glass or dirt.	CMS can fail in the form of missing images (e.g. due to no power or electromagnetic interferences) or an image containing artifacts.

Table 1: Comparison of mirror and CMS properties.

3.4 Fundamentals of optical image effects

Depending on their quality, cameras in CMS have more or less pronounced optical effects, just like other CCD cameras, which affect the representation of visual range. The following describes a few important effects.

Blooming

When photographing extremely light or reflective motifs with a digital camera, blooming effects can occur which let entire surface areas (which are larger than the light motif) appear in a bright white in such a way that contours can no longer be seen. These effects occur, for example, when photographing very bright cloud formations, reflective glass surfaces or mirrored objects.

The blooming effect is caused by an overload of individual photo cells in a CCD sensor. If no light falls on a photodiode, there is virtually no current and the missing current is interpreted as “black”. However, if more light falls on the sensor, there is a higher current, up to a maximum value (white). In case of an “overdose” of light, a single photodiode overloads and emits excess electrons on the neighbouring element. Thus, this also produces a maximum current (for brightest white), although it might be exposed to a lot less light. A range is created, in which all CCD pixel produce a maximum current and thus maximum brightness (Wagner, 2014).

Smear effect

In terms of digital cameras, a smear or smear effect describes white stripes in an image which emanate from particularly bright light sources in the image range. The cause for this is an unwanted influence on pixels which are actually in the dark, caused by a row-type reading process by the CCD camera chips. One cause is that adjacent rows are subjected to stray light. Another cause is the fact that adjacent pixels can also be charged during the transport of the electrical loads which code brightness (translation of German version of Wiki, 2014a).

Lens flare

Visible reflections and light scattering from back lighting in a lens system is referred to as lens flare effect (or “reflection of lens light”). In photographs, lens flare often manifests as star, ring or circular patterns which reduce the colour contrast of the affected areas. The shape of the depicted reflections is also influenced by the aperture blades used: for example an aperture which consists of six elements creates hexagonal patterns (translation of German version of Wiki, 2014b).

<u>Star effect caused by aperture</u>

The smaller the aperture selected (large f-number), the more striking the flare caused by the iris (Figure 11 left). This effect does not occur when using large apertures (small f-number) or a circular pinhole (Figure 11 right).

Figure 11: Flare effect (left small aperture, right large aperture)

3.5 Tests and results

3.5.1 Rear field of vision and direct view forward

For the analysis of the field of vision depicted by the CMS, the field of vision was visualised and measured using traffic cones. The opening angle of the field of vision was delineated both for the spherical and the aspherical part. The displayable areas at a distance of 20.85 m behind the camera (≙ 20 m behind the driver’s eye point) were correlated with the width on the monitor in order to determine the reduction in size of the aspherical part. It is evident that the prescribed field of vision, see Figure 1 in the introduction, was fully captured and thus the requirements for the indirect view are met. The length ratios displayed in Figure 12 and Figure 13, result in a horizontal reduction by a factor of 5.3 for the aspherical section of the monitor compared to the spherical section. Therefore, as with the aspherical section of the mirror, the so-called blind spot can be reduced. However, an estimation of the distance and speed of objects is more difficult in this aspherical section of the monitor.

No influence on the direct view forward was shown in the study. The monitors in the interior were installed in such a way that they did not impair the direct field of vision.

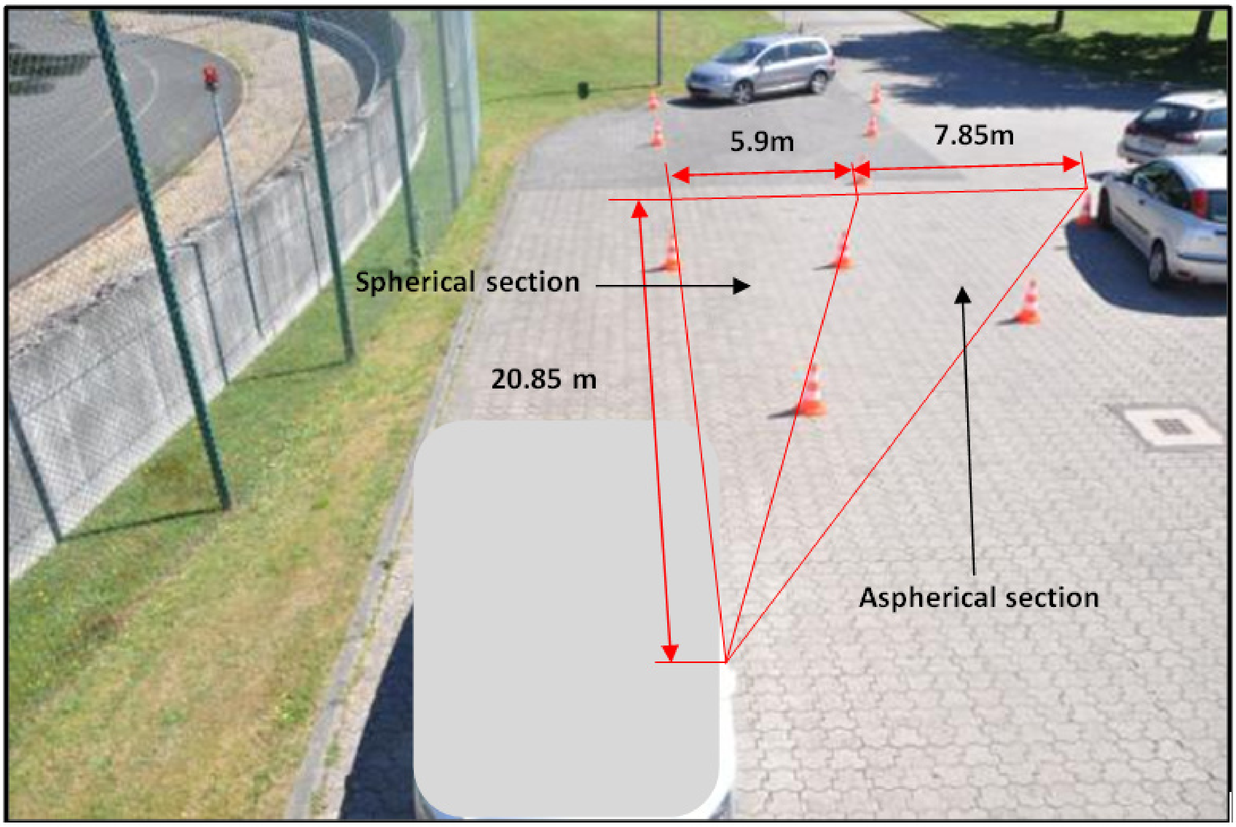

Figure 12: CMS field of vision.

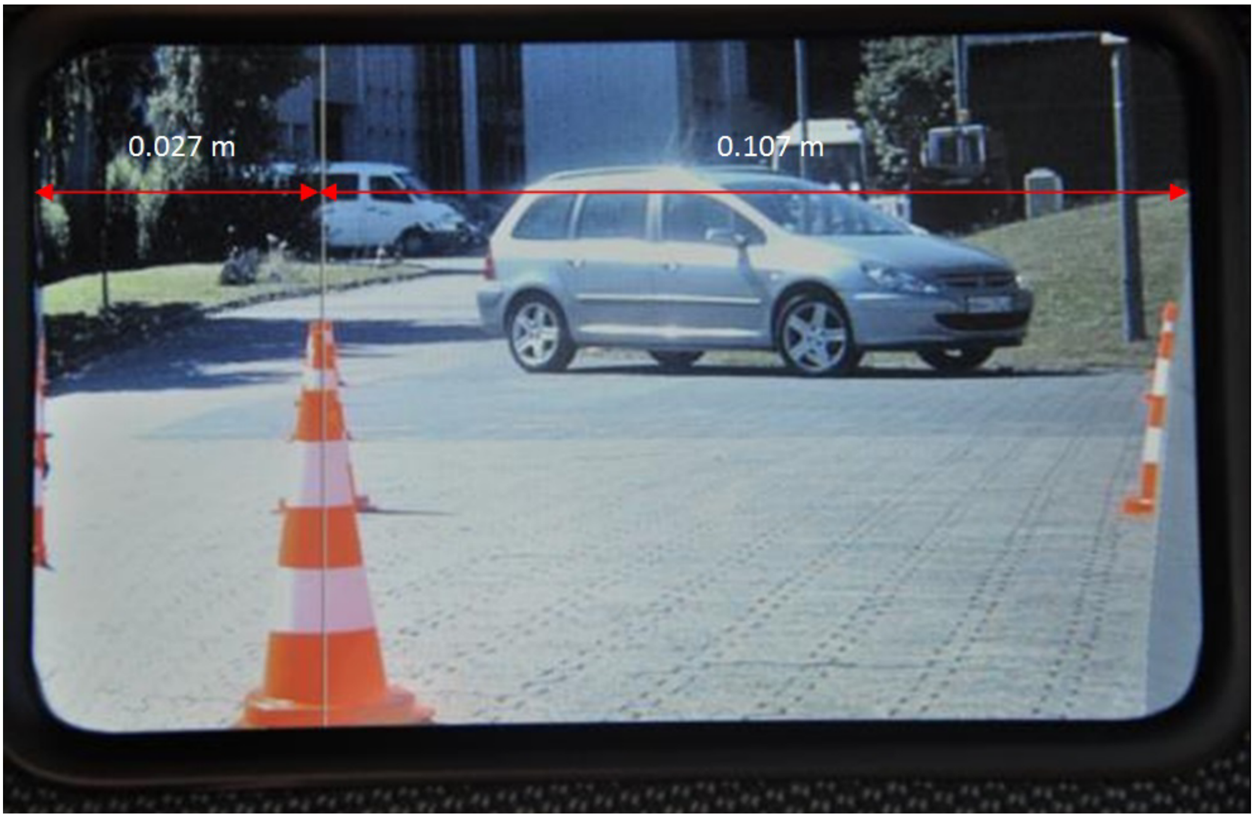

Figure 13: **Monitor view with lateral monitor dimensions.**

3.5.2 General day and night properties

The test drives were performed under different conditions. The drives were performed on the following sections and in the following situations:

- Tunnel (jump in ambient brightness)
- Rural road (fast, periodic change from light to dark)
- Motorway
- Low sun
- Uneven road surfaces
- Rain
- Night drive
- Snow

3.5.2.1 Tunnel (jump in ambient brightness)

How a CMS responds to dynamic changes in the ambient lighting, e.g. when driving through a tunnel, is a subject of the study.

On a bright sunny day the aperture of the camera is only opened slightly before entering a tunnel. When entering the tunnel, the lighting situation changes abruptly (as there is no more sunlight), and the aperture needs to change. On the CMS, the image on the monitor first turns dark, as the camera sensor is underexposed for a moment. Therefore, the image quality decreases in terms of contrast and colour rendering. The camera quickly ($t < 1s$) adjusts to the darker ambient lighting by opening the aperture. In reverse order, when exiting a dark tunnel and entering bright sunlight, the camera chip is exposed to glare as the opening of the aperture is still too great and needs to be regulated by reducing the size of the opening. The initial overexposure results in a blooming effect, as shown in Figure 14: Whereas the vehicle located to the left behind the test vehicle can be seen in the exterior mirror, on the monitor, it disappears for a short moment in a white field. Also, the white van and the lane markings are more difficult to see on the monitor image in comparison to the mirror, which provides a greater contrast and better colour rendering.

At night, this behaviour is reversed, as a blooming effect occurs when entering the (light) tunnel; when exiting the tunnel the aperture is not opened wide enough yet which results in underexposure. However, these artifacts are not as pronounced at night as the difference in lighting is not as great.

Figure 14: Exiting a tunnel during the day.

3.5.2.2 Rural road (fast, periodic change from light to dark)

A country road through a forest on a sunny day presents a challenge. Much like with the tunnel situation light changes occur here in quick succession between the shadows from the trees and the sunny areas. The aperture needs to change constantly. Until the optimal aperture setting is achieved, over or underexposure occurs resulting in the display of the field of vision becoming impaired. For example, Figure 15 shows that the quality of the colour rendering and grey shading on the monitor is significantly reduced in the short and bright driving sections due to overexposure.

Figure 15: Driving on a rural road surrounded by forest.

After entering a wooded area, the generally darker environment and the significantly brighter section in the background (area with no forest) can result in blooming and the associated difficulties in recognition. Figure 16 and Figure 17 show that due to overexposure, a following vehicle can only be seen once it has entered the wooded area. In the mirror, the same vehicle could also be recognised prior entering the dark area.

Figure 16: Entering a forest: The following vehicle is still in the forest-free area.

Figure 17: Entering a forest: The following vehicle is in the wooded area.

3.5.2.3 Motorway

When driving on motorways it is important to detect rear traffic already from a great distance, due to high differences in speed, in order to safely perform driving tasks such as e.g. overtaking.

Early detection requires a good depiction of the traffic. As shown in Figure 18, it is more difficult to perceive the white vehicle and the lane markings on the monitor compared to the mirror. This is due to insufficient grey graduation of the CMS, as the markings and the vehicle are difficult to distinguish on light asphalt or concrete. It is also evident that the colour rendering in the CMS is significantly worse than in the mirror.

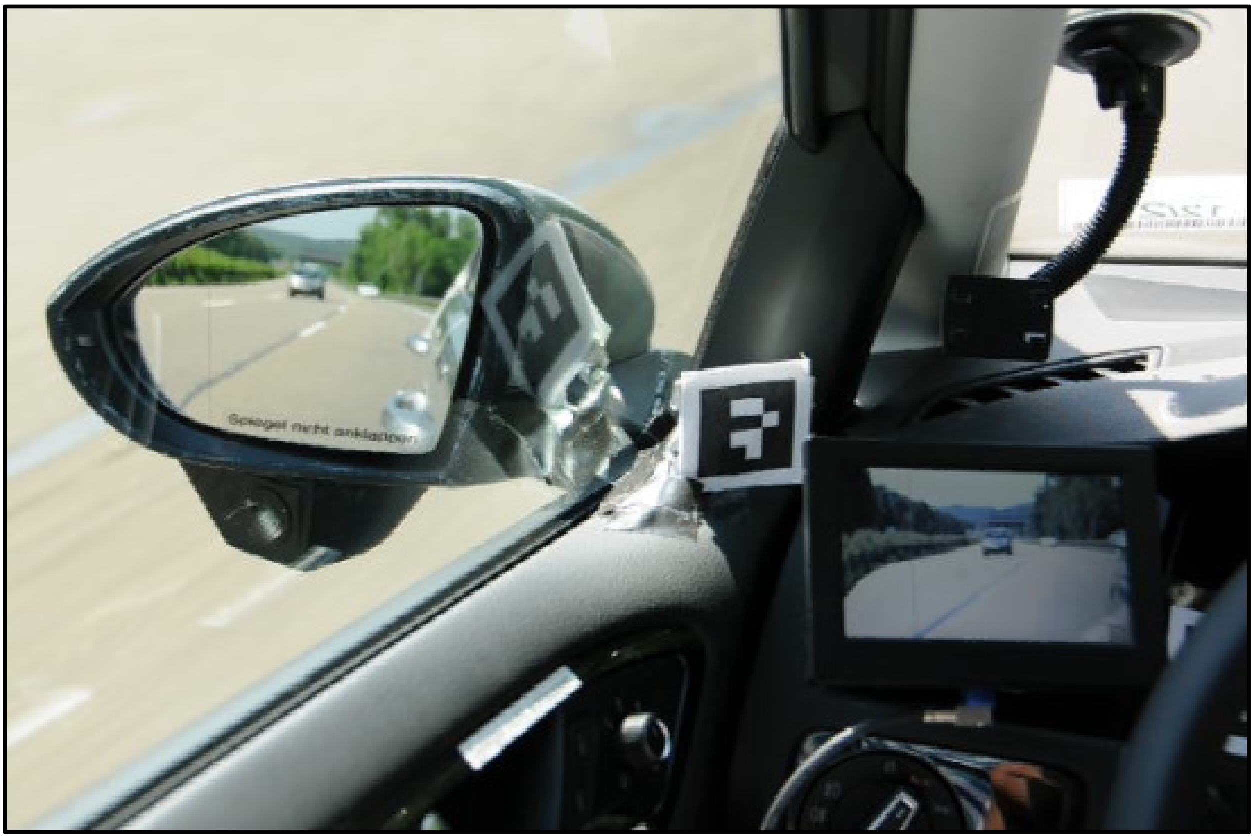

Figure 18: Difficult to detect vehicle in the background (white vehicle on beige concrete carriageway).

3.5.2.4 Low sun

Low sun is considered an extreme lighting situation for driving. When sun rays fall directly onto the camera sensor, the system is subjected to strong glare, which first results in the monitor displaying a complete white image (see Figure 19) caused by the blooming effect. During the test, no image content could be detected for approx. 2 seconds. The aperture had only adapted to the sunlight after this period and the content of the rear field of vision reappeared on the monitor, however, with strong artifacts resulting from the remaining blooming effect and smear effect (see Figure 20).

In this lighting situation the driver does not experience any physiological glare, at any time, from the CMS due to the limited luminance of the monitor. However, exactly this must be noted for the exterior mirror, as due to the law of reflection, the sun rays are steered into the visual field of the driver and cause glare, even if the sun rays do not shine into the driver's eyes directly. Although this causes severe impairment of visibility, almost always additional information can be obtained from the rear area, as the eye can adapt to this physiological glare.

This shows that both mirrors and CMS have advantages and disadvantages at low sun.

Figure 19: Low sun.

Figure 20: Low sun after short adjustment of the camera

3.5.2.5 Uneven road surfaces

Vibrations that occur for example when driving on cobblestones could result in an error in the image display of CMS. Test drives on uneven road surfaces (here cobblestones in Figure 21), however, showed no impairment with regard to image sharpness or blurred images. The monitor always displayed a sharp camera image. Only the relative motion between the driver and the monitor or between the driver and the mirror, that occur when driving on uneven road surfaces, resulted in a blurry perception of the rear field of vision. However, this blurriness was equal in mirrors and monitors and can never be fully avoided on uneven roads.

Figure 21: Driving on cobblestones.

3.5.2.6 Rain

Rain is a weather condition in which the CMS must function faultlessly. On the one side this refers to the criterion of “waterproof”, i.e. the protection against water penetration, and on the other side, to resistance against droplets or formation of water streaking. However, during the corresponding test drives, the need for distinguishing between heavy rain and normal rain became apparent.

Normal rain

During normal rain, rain drops are rarely found on the camera, which generally only influence the image slightly. This is due to the protected installation of the camera.

In the same weather conditions, the view in the mirror is impaired by drops and “water streaking” on the driver’s side window. The additional water layer on the relevant surface causes the image to blur and thus results in a worse situation for the assessment of following traffic, as shown in Figure 22. The monitor view is demonstrably clearer (unaffected) than the mirror view.

Figure 22: Rear view in rain.

Heavy rain

Compared to normal rain, heavy rain causes heavy splashing, which results in more a difficult detection of point light sources in the CMS. This is due to the low brightness of the background (aperture open wide) and the great difference in luminance of the bright head lamps of the following traffic. Point light sources are no longer displayed as such, as shown in Figure 23, resulting in the overexposed vehicle head lamps in the background melting into one large cone of light on the monitor. However, the overall depiction of the scene was good in the CMS in heavy rain.

As is the case with the CMS, the rear mirror view is heavily impaired by splashing and additionally by rain drops, however, the colour rendering is more realistic due to the better contrast ratio. Therefore, individual vehicles can still be distinguished (see Figure 23).

Overall, both mirrors and CMS do not provide a good rear view.

Figure 23: Rear view in heavy rain.

3.5.2.7 Night drive

At night, just like during the day, the rear view must be reflected in accurate detail in the CMS. Here, it is important that individual road users (vehicles) are recognised as such. This means that point light sources of dipped beam or high beam head lamps must be easy to assess (e.g. to distinguish between single and two track vehicles).

During a corresponding test drive (see Figure 24), the individual head lamps of the other vehicles can be recognised well both in the mirror and in the CMS. Only in the CMS, a light flare occurs around the head lamps, however the driver is still able to make out the individual vehicles and to distinguish them.

Additional rain at night causes a merging of the point light sources, in the same way as heavy rain during the day. This makes it a lot more difficult to identify the individual head lamps, which in turn can affect the estimation of speed of the following vehicles. More static tests on glare and point light sources at night are described in Chapter 3.5.4.1.

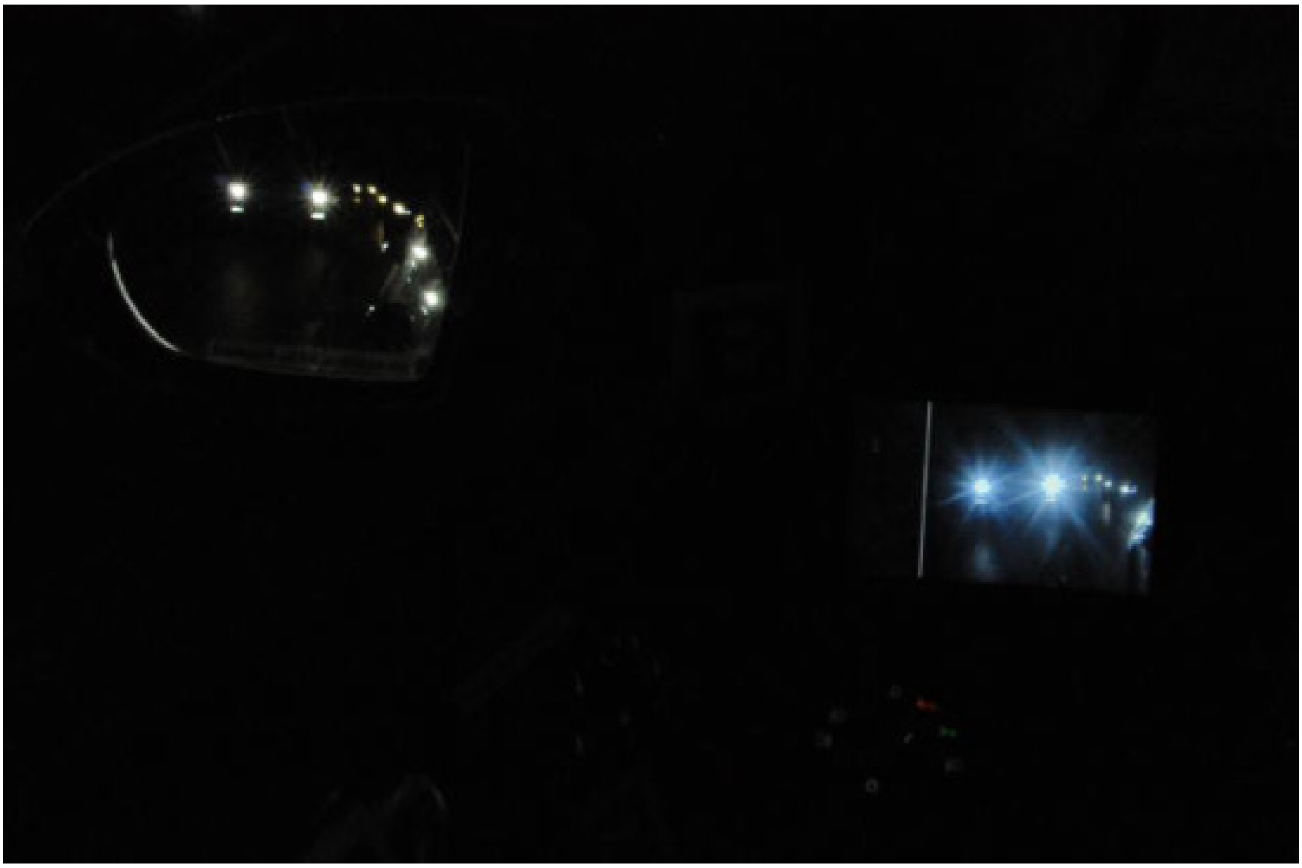

Figure 24: Driving at night.

3.5.2.8 Behaviour in snow and fog

CMS and mirrors must also be available to drivers in snow and fog. Behaviour in snow and fog was therefore tested as well.

At a low ambient luminance including fogged up side windows and / or droplets on the side mirror, the CMS showed an image that was hardly affected by the weather, compared to conventional mirrors (Figure 25). The reflection seen on the monitor is caused by the camera flash. The passing vehicle remains more clearly visible than in a mirror.

Figure 25: Comparison at snow fall and low ambient luminance.

With increased snow fall and higher ambient luminance a vehicle with the dipped headlights turned on, which is close to the camera, merges with the bright background in the CMS. Compared to conventional mirrors the visibility is worse (see Figure 26).

Figure 26: Comparison at snow fall and higher ambient luminance (close vehicle).

A comparison image, at almost the same ambient luminance, however, shows less of a difference between the mirror image and the CMS for vehicles that are further away (Figure 27).

Figure 27: Comparison at snow fall and higher ambient luminance (distant vehicle).

The direct comparison between Figure 26 and Figure 27 shows the influence of a possibly overexposed camera, due to the badly set head lamp of the passing vehicle, on the display of the scene in the CMS. Therefore, the influence of head lamps causing glare on the image reproduction by the CMS is possibly higher than the influence on the conventional mirrors observed for comparison.

3.5.3 Image reproduction

For the evaluation of the image reproduction the following technical properties are examined:

- Contrast and brightness
- Colour rendering

3.5.3.1 Contrast measurement

Contrast refers to the difference in luminance between bright and dark areas of an image or between to image points. Contrast is defined by the ratio of the maximum and minimum luminance. For statements about the contrast representation of the CMS compared to mirrors, evaluations were performed under different ambient conditions.

The contrast measurement tests were performed in the light hall of BASt and under clear skies during daylight (here for maximum lighting).

In order to reduce the ambient brightness to a minimum, as can be the case in night time road conditions, the light hall was completely darkened. A DIN A0 sized test board, which consisted of alternating white and black squares (see Figure 28), was positioned at a distance of 1.40 m behind the vehicle rear, in order to perform the measurement of the luminance (in candela per square metre [cd/m²]) on the individual black or white fields on the monitor and mirror.

The luminance was measured in three different scenarios:

Scenario 1: Turned off vehicle lighting in a dark environment. This scenario represents getting out of an unlit vehicle at night.

Scenario 2: Turned on vehicle lighting in a dark environment - represents a normal drive at night.

Scenario 3: A clear, cloudless day with bright sunshine. This scenario represents a possible drive on a bright day.

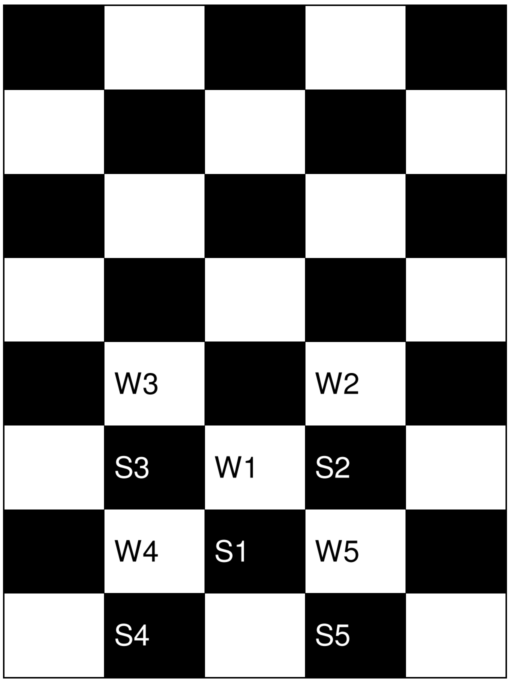

Figure 28: Test board.

For each of the afore mentioned 3 scenarios, the luminance was measured on the test board in five white (W1 to W5) and five black fields (S1 to S5), as marked in Figure 28.This was done once directly on the board as a reference, once in the mirror and once on the monitor, on the latter, once with maximum and once with minimum brightness setting. An LMT L1009 luminance meter (calibrated in December 2012) was used for the examination.

In scenario 1, a contrast of 1.0 was determined for the CMS and the mirror on the test board, i.e. all fields had the same luminance value “black”. The background lighting of the monitor can be determined based on the measurement results from scenario 1 (see Table 2). This has a minimum value of 0.2 cd/m² which is significantly lower than the maximum limit of 2 cd/m² as required by ISO 16505. The low background lighting avoids reflections in the windows and the monitor lighting virtually prevents a physiological glare for the driver during night drives.

Scenario 1: Darkness without vehicle lighting				
	Actual value on test board [cd/m²]	Mirror [cd/m²]	Monitor with max. brightness [cd/m²]	Monitor with min. brightness [cd/m²]
S1	0.1	0.1	0.5	0.2
S2	0.1	0.1	0.5	0.2
S3	0.1	0.1	0.5	0.2
S4	0.1	0.1	0.5	0.2
S5	0.1	0.1	0.5	0.2
Mean of black measuring points	0.1	0.1	0.5	0.2
W1	0.1	0.1	0.5	0.2
W2	0.1	0.1	0.5	0.2
W3	0.1	0.1	0.5	0.2
W4	0.1	0.1	0.5	0.2
W5	0.1	0.1	0.5	0.2
Mean of the white measuring points	0.1	0.1	0.5	0.2
Contrast	1.00	1.00	1.00	1.00

Table 2: Scenario 1.

Scenario 2 describes a night drive with low ambient brightness (from the head lamps). The measurement values (see Table 3) clearly show the high contrast on the monitor (14 or 6) compared to the contrast in the mirror (1.6). An internal amplification in the CMS allows for this high contrast value, which displays a contrast that is double as high than in reality (6.4). Even with maximum dimming, the monitor still approximately reproduces the actual contrast. In contrast, in the light conditions of this scenario, the mirror only reflects a quarter of the actual measured contrast. This means, it reduces the contrast.

Scenario 2: Darkness with vehicle lighting				
	Actual value on test board [cd/m²]	Mirror [cd/m²]	Monitor with max. brightness [cd/m²]	Monitor with min. brightness [cd/m²]
S1	0.1	0.2	0.9	0.3
S2	0.1	0.5	0.8	0.3
S3	0.1	0.2	0.7	0.3
S4	0.1	0.2	1	0.4
S5	0.1	0.2	0.7	0.2
Mean of black measuring points	0.1	0.26	0.82	0.3
W1	0.6	0.4	12	1.9
W2	0.8	0.4	6.2	1.1
W3	0.4	0.4	10.6	1.6
W4	0.5	0.5	19.6	3.2
W5	0.9	0.4	9	1.5
Mean of the white measuring points	0.64	0.42	11.48	1.86
Contrast	6.40	1.62	14.00	6.20

Table 3: Scenario 2.

In scenario 3, the monitor's luminance reaches its limits. The luminance measured on the monitor only has a fractional value of the measurements on the test board. Compared to the CMS, the mirror had a 10 times higher luminance (see Table 4). In the present strong ambient lighting and with the low monitor luminance, the driver's eye needs to adapt more than when looking into the mirror.

In this scenario with maximum ambient lighting, the contrast ratio of the monitor is maximum 50%, whereas the contrast ratio of the mirror still lies at 80%. There can be several reasons for the mirror contrast ratio not corresponding exactly to the value of test board; due to the law of reflection, the contrast in the mirror should be equal to the test board value. These deviations could be the result of transmission losses when the light passes through the mirror glass, in an imperfect mirror (reflection layer), soiling on the surface as well as slightly deviating measurement points.

Scenario 3: Maximum lighting during the day with sunshine and clear skies				
	Actual value on test board [cd/m²]	Mirror [cd/m²]	Monitor with max. brightness [cd/m²]	Monitor with min. brightness [cd/m²]
S1	442	189	23.7	12
S2	437	198	30.7	14.6
S3	462	195	23.7	12.4
S4	443	195	21.2	11.1
S5	429	181	31.1	11.6
Mean of black measuring points	442.6	191.6	26.08	12.34
W1	15840	5440	491	63.7
W2	16400	5650	470	63.6
W3	16300	5640	462	63.3
W4	16240	5620	496	65
W5	16080	5570	512	67.2
Mean of the white measuring points	16172	5584	486.2	64.56
Contrast	36.54	29.14	18.64	5.23

Table 4: **Scenario 3.**

In summary, according to this test, different advantageous conditions could be determined for both versions. The CMS is at advantage for night driving with low ambient lighting based on the internal contrast amplification. In comparison, the contrast ratio in bright daylight is better when using the mirror.

3.5.3.2 Colour rendering

In road traffic, information is also coded via different colours, e.g. traffic lights or vehicle lighting devices. However, as cameras and monitors only detect or reproduce a certain number of colours, it is important to determine whether these limitations result in deficits.

For this purpose, the colour rendering of the image section displaying pencils in 12 different colour shades was evaluated once by the CMS and once using the mirror (see Figure 29).

Figure 29: Colour range in front of mirror and camera.

As shown in Figure 30 and Figure 31, there is hardly any difference with regard to colour rendering between the mirror and monitor. In the mirror image shown here, the colour contrast between the white and orange pencil appears lower than it is in reality, due to the photography of the situation. On the overall, the colour rendering in the CMS is not as high as that of the mirror, however it is sufficient to render the present colours in a recognisable way. However, this has to do with the good ambient lighting condition, in which all colours are clearly visible. In test drives in less bright conditions, the colour rendering was limited, as shown in Figure 15 and Figure 18.

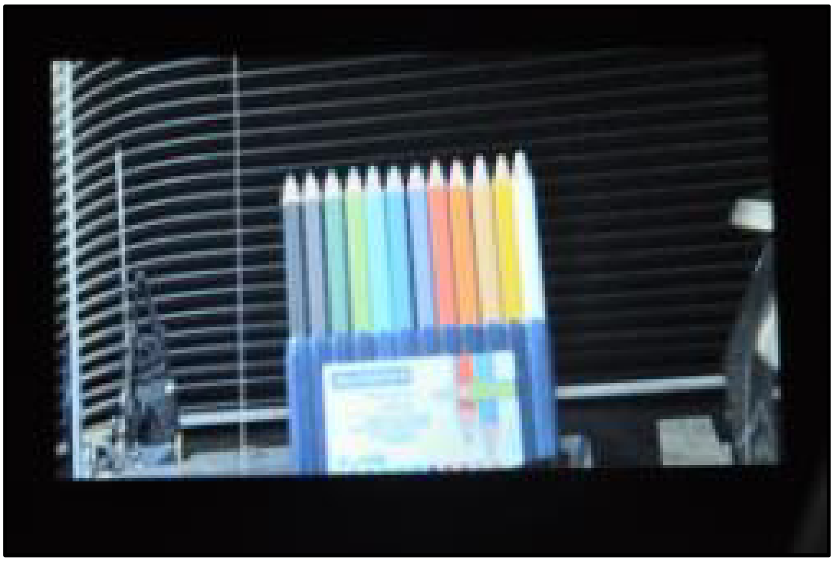

Figure 30: Monitor colour rendering.

Figure 31: Mirror colour rendering.

3.5.4 Behaviour in glare

3.5.4.1 Camera glare caused by a second vehicle from the back with dipped beam and high beam head lamps

In order to clearly capture vehicles in the rear field of vision during night drives, the head lamps must be recognised as point light sources. To what extent this is the case for CMS and mirrors with high differences in brightness (head lamps vs. dark background) was shown in a static investigation with the test vehicle in the completely darkened light hall of BASt and with a second vehicle which represented the following traffic. For this, the latter (Mercedes E-class, 1999) was positioned at distances of 50 m, 25 m and 5 m, once with turned on Xenon dipped beam head lamps and once with halogen high beam head lamps (see Figure 32). This scenario was evaluated both with the CMS and the mirror.

Figure 32: Test set-up: The following vehicle at a distance of 50 m with turned on dipped beam head lights.

In the CMS representation, the turned on dipped beam head lights at a distance of 50 m, were displayed with artifacts, however, as shown in Figure 33, point light sources can be clearly recognised. However, a very limited colour rendering of the CMS was shown here under the given lighting conditions. Compared to Figure 34, in which the same scenario was observed using the mirror, the different coloured traffic signs appearing at the edge of the roadway could be recognised. The dipped beam head light did not cause a physiological glare for the driver in both the CMS or the mirror.

This was followed by the examination of a turned on high beam head light, again at a distance of 50 m. Figure 35 shows that the head lights merge based on the blooming and smear effects which makes the detection of point light sources more difficult. In the same set-up, both high beam head lights could be differentiated in the mirror (Figure 36), however, the driver experienced glare and thus a strong impairment of view.

Similar perceptions were determined for both distances of 25 m and 5 m, however the intensity of the artifacts decreased: Already at a distance of 25 m, the high beam head lights were displayed clearly as point light sources on the monitor. With regard to the examined conditions it must be stated that the scenario of turned on high beam head lights is unusual in road traffic.

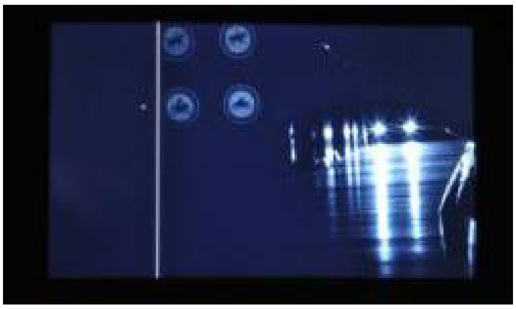

Figure 33: Monitor at a distance of 50 m and turned on dipped beam head lights.

Figure 34: Mirror at a distance of 50 m and turned on dipped beam head lights.

Figure 35: Monitor at a distance of 50 m and turned on high beam head lights.

Figure 36: Mirror at a distance of 50 m and turned on high beam head light.

3.5.4.2 Camera glare caused by infra-red

A combination of infra-red lights and special cameras is used in driver-assistance systems such as for example “Night Vision” systems, for the improvement of the recognition of objects and persons during night driving and thus for increasing safety. To this end, infra-red light in the wavelength range of 700 -1000 nm is emitted, reflections are detected by an optimised camera and are provided to the driver in an appropriate representation. Whereas infra-red light is not perceived by the human eye, and other road users are not affected (Robert Bosch GmbH, 2007), the question arises whether the CMS is sensitive for infra-red radiation and to which extent it is potentially impaired by this.

For the examination, an infra-red light emitting remote control was aligned to the camera, by pressing any key, a signal was sent by the infra-red emitter. The infra-red signal was clearly represented on the monitor as a light point.

It was shown that the camera of the CMS is generally sensitive to infra-red light. However, an evaluation with regard to the impact of a driver-assistance system with active infra-red lighting could not be performed, as no suitable system was available. It appears that this type of wave length light could cause glaring - similar to low sun. It still needs to be examined whether glaring through infra-red light can occur and which technical possibilities (e.g. filters) could be used to prevent this.

3.5.5 Reflection on the display and screen glare

3.5.5.1 Glare through reflections on the display

In some test drives reflections could be observed on the monitor of the CMS. These were so severe that the view out of the window of the driver's door could be seen on the passenger side display due to the reflections. As a result the image content of the monitor could hardly be seen (see Figure 37). When, for example, turning off to right, this could result in the driver overlooking other road users. Comparable reflections did not occur in mirrors.

Figure 37: Reflections on the passenger side display.

3.5.5.2 Screen glare

Screen glare means direct light falling on the screen of the display and the consequences thereof. This incidence of light on the screen of the display is usually caused by the sun. As the monitor has a limited maximum luminance, the luminance caused by sunlight on the display can be greater. This results in a reduction of contrast and colour perception for the driver.

The effects caused by screen glare due to direct light incidence are shown in Figure 38. The image clearly shows the difference between the part of the monitor exposed to sunlight and the shadow of the A-pillar. The colours in the shaded part and the contrast are clearly much stronger. As a consequence, road side vegetation appears more green and differences between bright and dark are more pronounced. In order to minimise the impact of glare due to direct light incidence, the display could be equipped with a shield or set back in the housing.

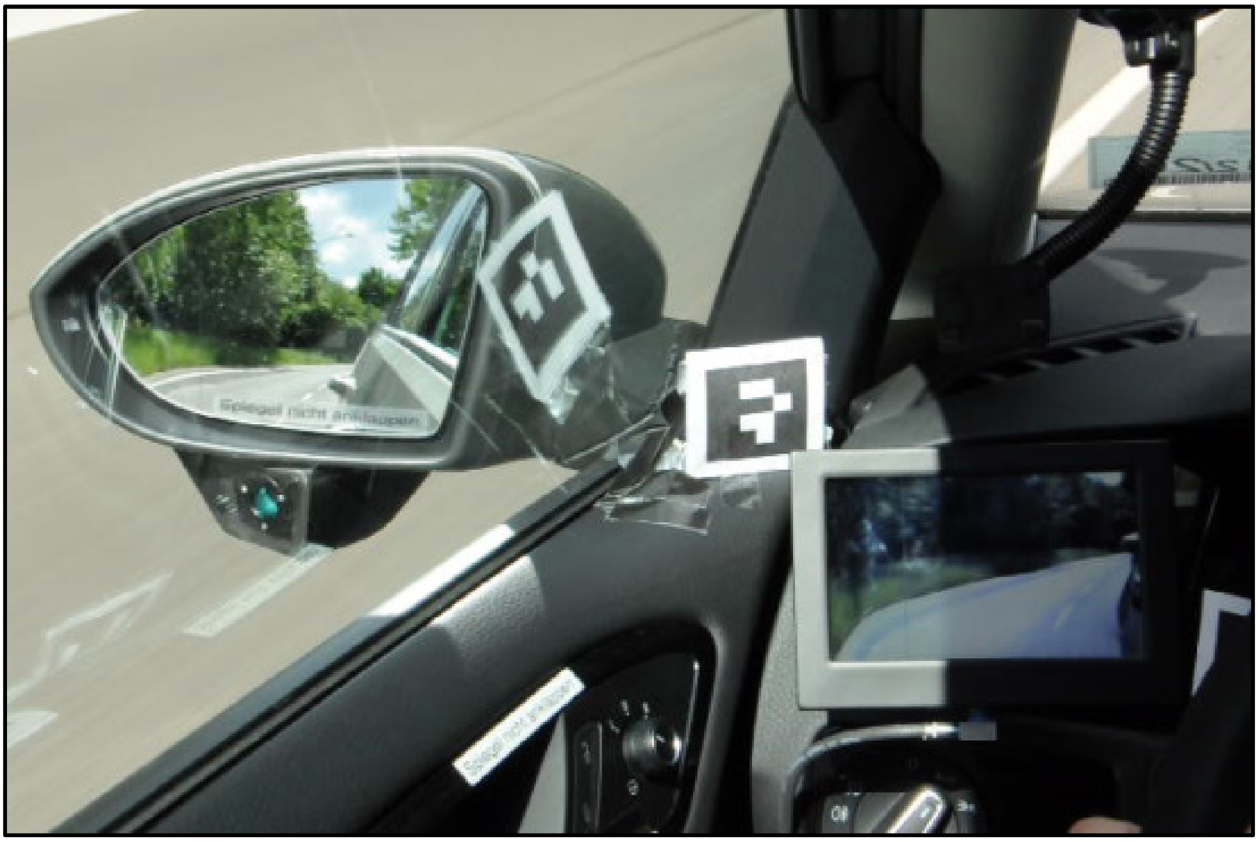

Figure 38: Screen glare.

3.5.6 Adjustability of the camera and display

The examined CMS in the small series vehicle could be changed in the two parameters of zoom and brightness. For the image angle, the adjustment was performed automatically, as soon as the vehicle was put into reverse gear. In this case, the view changed to a wide-angle mode across the entire screen, which previously was divided into a spherical and aspherical section (see Figure 13). The wide-angle mode which is optimised for reverse driving - symbolised by a displayed "R" on the top outer edge – expands the field of vision in such a way that far objects are represented on the monitor, albeit smaller. However, objects which are located closer to the vehicle, which are not in the field of vision during normal mode, are displayed. The zoom factor of both views (for reverse or forward driving) is non-adjustable, this ensures that the statutory prescribed field of vision for normal driving (no gear or forward gear) is covered at all times. An adjustment of the monitor to adapt to the eye positions of the different drivers for a orthogonal view on to the display is desirable, however, this was not possible in the tested case.

The monitor brightness in the examined CMS could be reduced, by holding down the turn on button. If the driver perceived the monitor image as too bright, despite the automatic brightness adjustment, the background lighting of the monitor image could be dimmed with this button. The automatic control adjusted the set brightness point according to the changing ambient conditions. Restarting the vehicle or briefly tapping the power button reset the original brightness level.

If adjustments are necessary must be evaluated carefully. Adjustments allow for the individual adaption to the driver's requirements. However, this carries the risk that mirrors or CMS are adjusted by drivers in such a way that the indirect view is no longer optimal. The advantage of the CMS is that the optimal (and prescribed) field of vision can always be preset with the default settings. However, depending on the driving situation, a manual adjustment of the image section can be useful. This particularly applies to trucks. (For mirrors, the image can be adjusted both by head movements or adjustment devices). Adjustability of the monitor to the body size of the driver would also be beneficial, in order to ensure the best possible orthogonal view on to the display.

In terms of brightness and contrast, automatic adjustment to the ambient conditions should be standard, additional manual adjustment options were considered as useful.

3.5.7 Failure safety

During the CMS investigation, occasional outages of the monitor occurred. For approximately 1 second, an error message as shown in Figure 39, was displayed instead of the camera signal.

These outages occurred both on the left and the right side, however never on both sides at the same time. In normal test drives these outages could not be correlated with any specific events or surroundings. The cause could not be established. However, the facts show the importance of failure safety in safety-relevant systems.

Figure 39: Image loss.

3.5.7.1 Electromagnetic radiation

The impact of electric and electromagnetic effects or electromagnetic radiation on technical devices are examined for electromagnetic compatibility (EMC). To determine whether unwanted interactions occur in a CMS, tests involving electromagnetic radiation in the wavelength range of data transmission were conducted. As the CMS is a safety-relevant device on a vehicle, functional outages due to electromagnetic radiation are unwanted.

For the assessment of the effects, a test board was positioned behind the test vehicle in the field of vision of the CMS and mirror in order to receive a comparable and defined image. Two radio units of the brand Topcom with a frequency of 446 MHz were used as the source of the electromagnetic radiation, which sent out a “call” close to the camera, monitor and control device. In addition, a mobile phone (Sony Experia Sola) receiving a call, was placed in the same position.

Interferences of the CMS were observed in the form of image errors on the monitor when the radio devices sent out a call in the vicinity of the control device. The image errors are shown in Figure 40 and Figure 41 and range from flickering including distortion of the image to a complete loss of image where the monitor displays a red X. However, the radiation from the mobile phone did not trigger any image errors.

Image errors only became apparent when the radio device was located closer than 5 cm to the CMS controls while simultaneously sending a call. Even if this combination of events is not very likely and needs not to be considered very often in everyday life, it is shown that it is very important to design the individual components of the CMS with appropriate measures that ensure compatibility with electromagnetic influences.

Figure 40: Error in image caused by electromagnetic radiation.

Figure 41: Loss of image caused by electromagnetic radiation.

3.5.8 Behaviour in extreme cold and heat

3.5.8.1 Behaviour in extreme cold

The CMS monitors are based on LCD technology (liquid crystal display). This means that they contain liquid crystals in the displays which operate with severe limitations in cold temperatures as the liquid crystals become sluggish due to the cold, which in turn results in the image loading more slowly. To test the CMS in extreme cold, the test vehicle was cooled in a climate chamber to a temperature of -20°C and conditioned for one night. A test board was positioned as a reference on to a presentation wall, in order to receive a comparable and defined image.

At the beginning of the evaluation, the ignition was started in the climate chamber to start the CMS. Thereafter, a slow movement of the hand was performed at a distance of one metre, thus generating a moving image. The CMS displayed a blurred image of this movement (see Figure 42), whereas the movement could be observed in the mirror in real-time (see Figure 43).

In the second part of this test the vehicle engine was started, the mirror heating was activated and the test vehicle was driven out of the hall due to the exhaust emissions. In order to determine the full functionality of the CMS, the time was measured from starting the engine. After driving out of the hall, condensation formed and accumulated both on the camera and the mirrors (see Figure 44). After two minutes the mirror heating had cleared the mirror surface. However, the camera still showed condensation and was not ready for operation (see Figure 45).

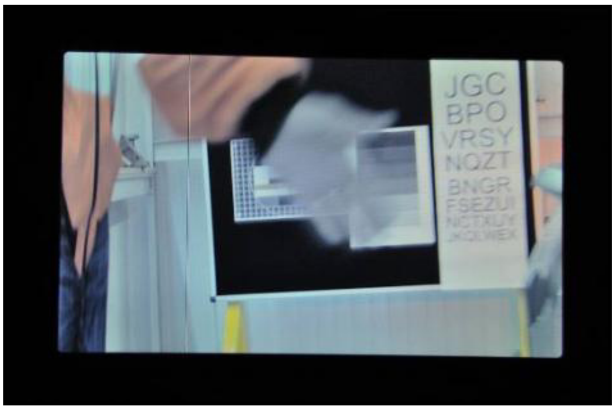

Figure 42: Monitor view.

Figure 43: Mirror view

Figure 44: **Camera and mirror fogged up.**

Figure 45: **Mirror is clear, camera still shows condensation.**

Only after approx. six minutes, rough outlines of the test board, which was positioned behind it, could be recognised (see Figure 46). At this time the camera was still fogged up and no clear statement could be made about whether the monitor was fully operational and the image was no longer blurred. Even after 13 minutes the condensation on the camera lens was still present, therefore it was now cleaned manually (wiped clear) with the result of the image sequences displaying in undisturbed quality.

Figure 46: Monitor view after approx. 6 minutes.

Due to the fogged up camera lens, it cannot be accurately established from which point in time the monitor works without error or delay. The climate scenario used is rather untypical: The test vehicle was driven out of the climate chamber (- 20 °C) on to an open site (15 °C, shade) and humidity precipitated. Such a rapid climate change might occur in cold regions with road tunnels (e.g. the Alps).

However, the test showed that mirrors allow for a complete rear view after two minutes and the CMS camera was still fogged up after 13 minutes. A heated CMS, in which both the camera and the monitor are headed, could alleviate this problem. This type of heating could significantly reduce the time up to full operational readiness and thus increase road safety.

3.5.8.2 Behaviour in extreme heat

On the sensor chip in cameras, photodiodes convert light into electric power. The heat alone, together with the base voltage in the sensor, discharges electrons. This creates a so-called basic noise of the sensor chips. During normal operation this noise floor is masked by the high number of electron discharges based on the exposure. However, if the sensor heats up strongly, the colour noise can be amplified and impact on the monitor image. The behaviour of the CMS in heat was examined in a test, more exactly the impact of heat on the camera. For this, the test vehicle was placed in the test hall with the CMS turned on. As a comparison motif, a test board was placed behind the vehicle. The camera was heated with a hot air blower on the driver's side (Figure 47).

At the beginning of the test, the monitor image was viewed, photographed, the temperature on the camera housing measured (20°C) and thereafter the hot air blower turned on. The distance between the heat source and the camera was reduced under continuous temperature control until the temperature of the housing reached a stable level of 83 °C. To ensure that the camera chip inside the housing reached this temperature, the test conditions were maintained for 15 minutes. Finally, a re-evaluation and photographic documentation of the image reproduction was conducted. The result showed that after heating no visual changes could be recorded (see Figure 48 and Figure 49).

Figure 47: Test set-up for behaviour in extreme heat.

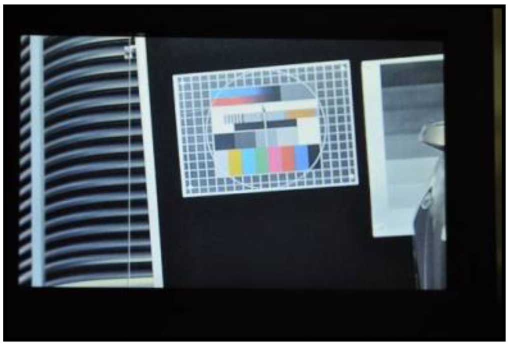

Figure 48: Monitor image before heating

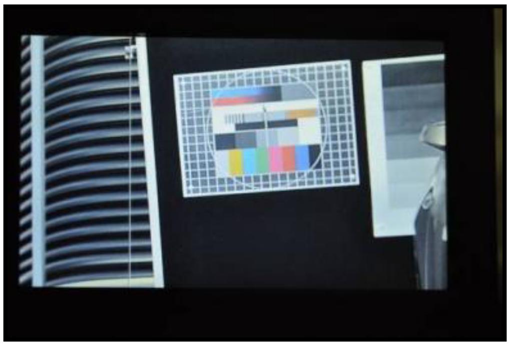

Figure 49: Monitor image after heating

3.5.9 Effects of soiling

CMS cameras mounted on the outside of the vehicle as well as mirrors are generally subject to soiling. The type of soiling can have different causes: e.g. pollens, dust, dirt in water or salt. The effects of soiling on mirrors and cameras were analysed in a test series. For this, a test board was placed behind the CMS vehicle and assessed using mirrors and CMS, see Figure 50 and Figure 51. First, a defined dirt film was applied on the camera and exterior mirror on the driver's side. To create the dirt film, the camera lens or mirror was sprayed with one spray of a saturated salt solution. This was left to dry completely. After assessment and photographic documentation the next step of application was performed. In each of the three soiling stages, the image quality of the CMS must be classified as better, compared to the mirror, as shown in Figure 52 to Figure 57. The contrast representation and colour representation is higher in the CMS.

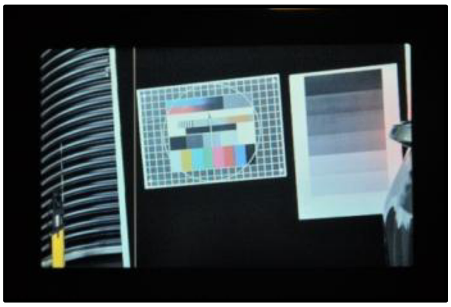

Figure 50: Monitor image without soiling

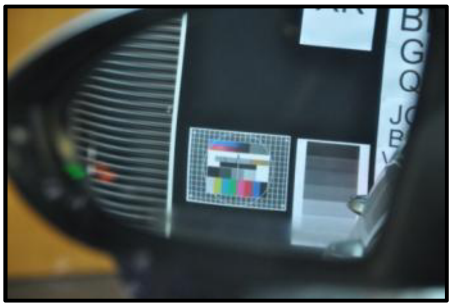

Figure 51: Mirror image without soiling.

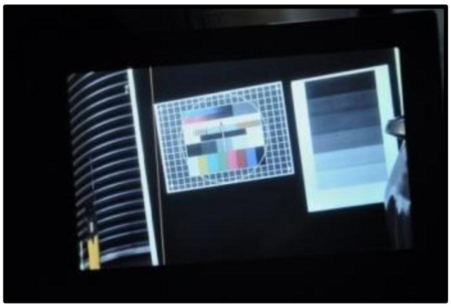

Figure 52: Monitor image with soiling, step 1.

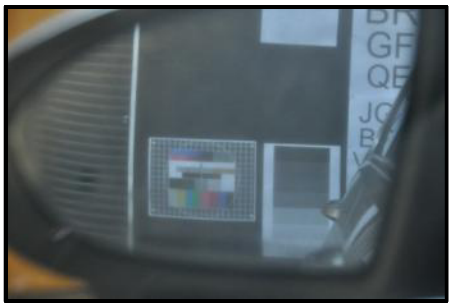

Figure 53: Mirror image, soiling, step 1.

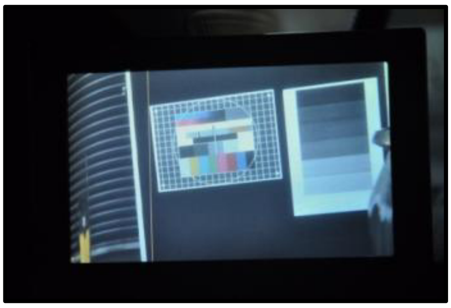

Figure 54: Monitor image with soiling, step 2.

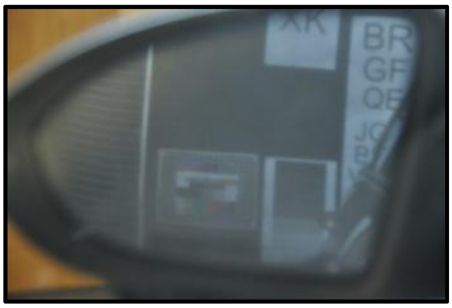

Figure 55: Mirror image with soiling, step 2.

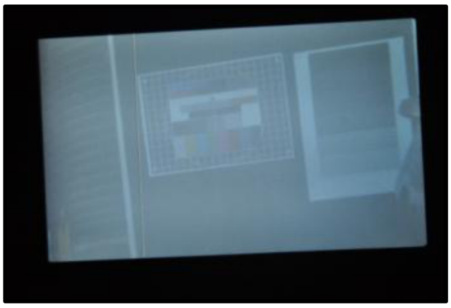

Figure 56: Monitor image with soiling, step 3.

Figure 57: Mirror image with soiling, step 3.

4 Aspects of Human-Machine Interaction

Two studies were performed in order to investigate aspects of human-machine interaction during the use of the CMS / exterior mirrors, one study each for the vehicle classes cars and trucks. The underlying research question was, whether the replacement of exterior mirrors with CMS is possible from a HMI perspective. The car study focussed on the estimation of distance, analysis of glance behaviour, and subjective assessment using acceptance criteria. The truck study used estimation of distance and subjective evaluation.

4.1 Car study

The car study approached the question whether the driver-vehicle interaction changes in case of replacing mirrors with a camera-monitor system (Denson, 2013). The focus of interest, on the one hand, was on the visual support which the driver received by the system during driving manoeuvres which demand for watching the rear traffic (e.g. pulling out for overtaking). For this, subjective measures (questionnaire) and objective measures (glance behaviour) were taken into account. On the other hand, it was of interest whether changes in distance and speed perception of an approaching vehicle may occur, if the driver solely uses a camera-based monitor. In this case, the assessment of the CMS had to be performed in comparison with conventional exterior mirrors. Furthermore, the question arose whether the driver's ability to appropriately use such a system in road traffic benefits from the driver's previous experience with such a system. Therefore, the sample of the study was divided into two driver groups: (a) *Experts,* who were allowed to exercise the use of the CMS in real traffic before they performed the tests, and (b) *Novices,* who were unfamiliar with the CMS. It was hypothesized that existing experiences affect the driver's ability in such a way that distances are estimated more reasonably (compensation) because of the skills acquired in the learning phase (see, for mirrors: de Vos, 2000; Flannagan et al. 1996). Accordingly, it was expected that the quality of distance estimation via the CMS converges to the reference values attained via the exterior mirrors over time. Two experiments were performed in the car study. Experiment I focused on distance and speed perception. Experiment II investigated glance behaviour during real drives.

4.1.1 Sample

A total of 42 subjects took part in the study. The total sample was comprised of 18 female subjects and 24 male subjects. The average age of the total sample was 47.8 years with a standard error (*SE)* of 2.7. The youngest subject was 25 years old and the oldest subject was 78 years old.

The sample was first divided into two experimental groups, i.e. an experts group and a novices group. The experts group consisted of eleven subjects, of which 5 subjects were females and 6 subjects were males. The subjects of the experts group were required to pass through a training phase by making use of the CMS in real traffic over a period of at least 60 minutes up to 2 days at the maximum. The average age of the experts group was 38.4 years ($SE = 2.7$).

The second group was made up of novices. This group consisted of 31 external subjects who did not have any previous experience with the CMS. The novices group only received a short oral instruction on how to use the CMS and a pre-test run.

With regard to visual capabilities, 81.8 % of the experts and 87.5 % of the novices stated that they had no impairments. All subjects could be classified as active drivers (average mileage > 12,000 km/year).

4.1.2 Test procedure

The data was collected on five days per week. Each day two subjects performed their tests, one subject at 9.00 am and the other at 1.30 pm. Maximum duration of the tests per subject was three hours. The subjects received a consent form which informed them about the course of the study and data protection rules. Thereafter, the participants received a questionnaire for the collection of demographic data. The procedures of the main tests are described in the following sections.

4.1.3 Experiment I: Distance and speed perception

The first experiment examined changes in the driver’s estimates of distance to and speed of a vehicle which approached from behind. Data both during using the CMS and during using a conventional exterior mirror was collected. The estimation using a conventional exterior mirror was used as a reference value. It was of particular interest to determine whether the experts group estimated distance and speed significantly different to the novices group.

The “*last safe gap*” method was applied for the estimation of distance and speed. For this, the driver, while sitting in a static test vehicle, observed the approaching object vehicle by using the left monitor of the CMS or the left exterior mirror of the static vehicle, respectively. Neither the interior mirror nor a glance over the shoulder was permitted for the estimation. The subject had to press a button to indicate the last safe gap before he/she would pull out the vehicle for over-taking (see Bach et al., 2006).

4.1.3.1 Experimental set-up

The static test vehicle was parked alongside a test lane at the test facility of BASt (see Figure 58). Markings were affixed on the ground in order to ensure a consistent rear field of vision.

The object vehicle passed the test vehicle in 12 runs per subject. The number of runs resulted from the number of factor combinations: 3 levels of speed of the object vehicle, in randomised order (20 km/h, 35 km/h, 50 km/h) x 2 types of devices (monitor, exterior mirror) x 2 trials per speed/device combination. The levels of speed were not given to the subject, but were only known to the test managers. As shown in Figure 58, the lane on which the object vehicle passed the static test vehicle was divided into a), an acceleration section (length 50 m), and b), a target speed section (length 100 m). The driver of the object vehicle was instructed to reach the given speed at the end of the acceleration section and to maintain speed when driving in the target speed section. In order to appropriately interpret the time when the button was pressed, light barriers and reflectors were attached to both vehicles. An additional reflector was located at the 50 m mark of the test lane.

The reflector at the end of the acceleration section triggered the light barrier attached to the object vehicle and was used for the control of the speed conditions. When the object vehicle passed the test vehicle, the light barrier responded to the reflector on the test vehicle and was triggered a second time. The triggering of the light barrier on the test vehicle served to achieve a real-time synchronisation of the point in time the button was pressed and the point in time the object vehicle passed the test vehicle (*point in time when passing the vehicle - point in time the button is pressed = period used to calculate the distance of the last safe gap).*

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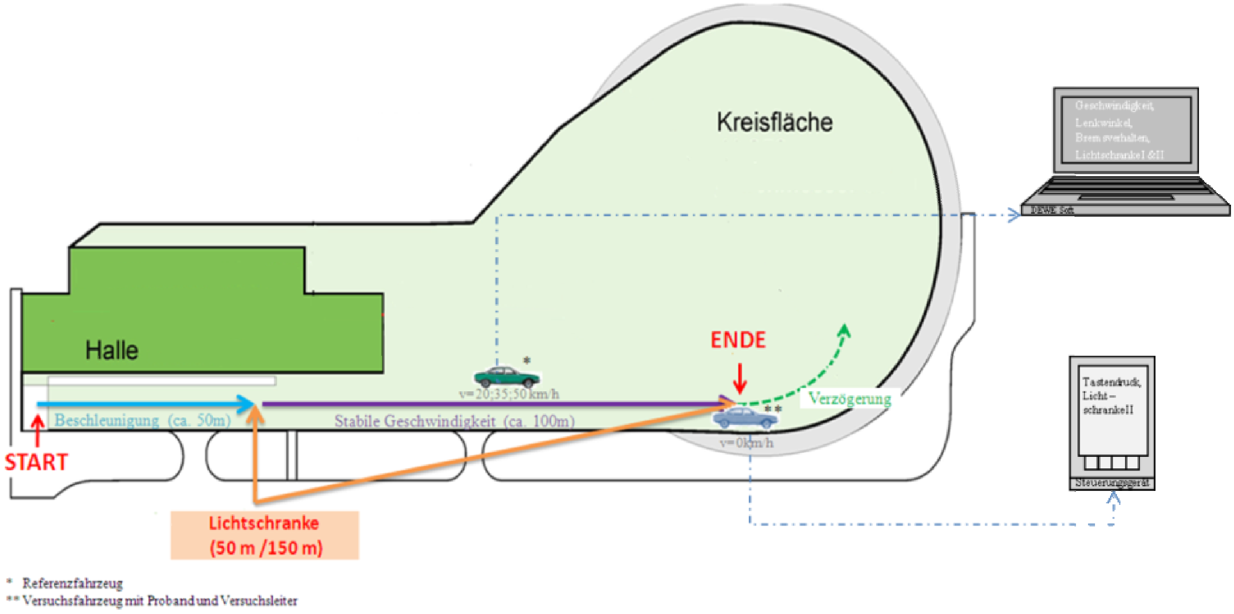


Figure 58: **Schematic test set-up for distance and speed estimation of an approaching object vehicle at the test facilities of BASt**

4.1.3.2 Test procedure

At the beginning, the test manager explained the task to the subject and handed over the button (Figure 59a). The test manager checked the function of both the light barrier (by means of a reflector film) and the button (response signal) at the control device. Upon arrival of the object vehicle at the start position, the data recording software was launched. The data recording software recorded the following defined channels: speed, angle of the steering wheel, brake actuation and light barrier. The driver of the object vehicle received a list containing the given speeds he/she needed to drive at. A signal (flashing warning lights) was given to the object vehicle driver when to start the next run (Figure 59b). After six rounds, the object vehicle parked behind the test vehicle and the test manager double checked the correct recording of the data. Thereafter, the object vehicle returned to the start position. The test manager changed the system (mirror, monitor) which was to be used for the next runs. In case the exterior mirror had to be used for estimation, the monitors where turned off manually. If the monitors were used for estimation, the exterior mirrors were covered with adhesive tape. The test manager noted any comments in an observation form as well as the weather conditions, light conditions and subjectively perceived glaring or reflections.

(a) Inside of the test vehicle: Test participant (left-hand side) with button, test manager (right-hand side) with observation form

(b) Outside of the test vehicle: Object vehicle approaching from behind at a consistent speed.

Figure 59: Static test vehicle at the test facilities of BASt.

4.1.4 Experiment II: Glance behaviour during real drives

The second experiment examined the driver's glance behaviour in real drives on a motorway (Bundesautobahn). Data were collected both during drives when using the new CMS and drives when using the conventional exterior mirrors. For capturing glance behaviour, an eye-tracking system was used. Particular attention was paid to age-related effects in the novices group.

4.1.4.1 Experimental set-up

The drives were conducted between exit *Refrath* and exit *Overath* on the motorway A4. The motorway was travelled on in both directions for this test series. This allowed testing the four considered monitor/mirror positions (CMS 1, CMS 2, CMS 3, exterior mirror, see Figure 7) on the same route and under similar traffic conditions. The test route one-way from Refrath to Overath was about 14.7 km in length and took a driving time of ca. 12 minutes.

To exclude sequence effects, the order of the considered monitor/mirror positions were permuted over the subjects. The test event “Overtaking” should occur at least three times and should not exceed five times. The start of the test event “Overtaking” was defined as the moment when the vehicle had completely changed to the left lane. The end of the test event was defined as the moment when the vehicle had completely changed to the right lane.

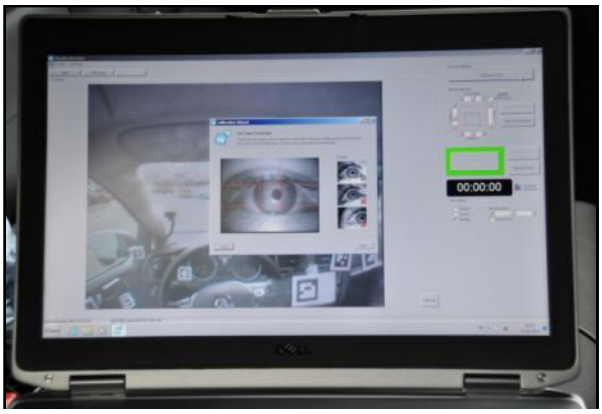
4.1.4.2 Test procedure

After a subject had completed the tests in experiment I, the subject continued with the tests of experiment II. The test manager handed the head unit of the eye-tracking system to the subject. When fastening the head unit on the subject's head, it was ensured that the test participant still had enough space to turn his/her head to the side and glance over his/her shoulder. A calibration device was used in order to align the eye camera to the field camera. The field camera was directed in viewing direction. The eye camera was horizontally and vertically adjusted to the left eye centre of the subject (Figure 60a).

Thereafter, the line of sight was synchronised to the surroundings (Figure 60b). For the final check, the subject was asked to glance at the exterior mirrors, the interior mirror and the brackets of the monitors. This procedure was repeated with each change in monitor/mirror position (Figure 60c).

The subjects drove from BASt facilities to exit Refrath on the motorway A4, followed the motorway towards Olpe until exit Overath, and then returned to exit Refrath. During each drive, the “Overtaking” test events (Figure 60: Measuring glance behaviour by using an eye-tracking system.

d) were marked in the logfile by the test manager. The test route was driven several times. After each run the vehicles parked in a parking area at the motorway, where the next monitor/mirror position was set and the subjects completed questionnaires which contained questions about situational awareness. After finalization of all runs the vehicle returned to BASt facilities.



(a) Calibration of the eye-tracking system.

(b) Alignment of the eye camera to the field camera.

(c) Monitor mounted on position CMS 2. Test vehicle arriving at the parking area

(d) Test event "Overtaking". Preparing for lane change to the left.

Figure 60: Measuring glance behaviour by using an eye-tracking system.

4.1.4.3 Analysis of the distance and speed perception

The recorded raw data from the eye-tracking system was prepared for statistical calculation by using special analysis programs. Eight subjects had to be excluded from the analysis because of lacking or faulty data. Thus, data records of 34 subjects were included in the calculations.

In order to prepare data for statistical analysis, the signals of the two light barriers and the button needed to be temporally synchronised. This way it was possible to calculate the distance between the object vehicle and the test vehicle at the time the button was pressed.

A multivariate analysis of variance (MANOVA) was calculated in order to determine whether the factors “System type” (2 levels: exterior mirror, CMS) and “Speed” (3 levels: 20 km/h, 35 km/h, 50 km/h) had an impact on the point in time when the button was pressed. As differences between the measures of the experts group and the novices group were expected, previous experience was defined as sub-subject factor in a further MANOVA with repeated measurements. The *F*-statistic (*Greenhouse-Geisser*) was used in the statistical analysis ($\alpha < .05$).

4.1.4.4 Analysis of the glance behaviour

The glance data was validated by checking and manually post-processing pupil detection data for all relevant time lines. The cross-hair marker was readjusted in the centre of the pupil and eye leaps due to incorrect pupil detection were excluded. The images of the field camera were superimposed on the images of the eye camera and examined. Periods which were to be considered for analysis were checked in order to ensure that the glances fell into the defined areas of interest (AOIs). Due to the large volume of data records, only data in time periods needed for analysis were recalibrated. The glance data from the following periods were to be analyzed, because it was known from pre-tests that glances are mainly bound forward when reaching the target lane: a) periods which lasted 10 s until the start of the “Overtaking” event was reached, and b) periods which lasted 10 s until the end of the “Overtaking” event was reached. Selecting a sufficient time period of 10 s ensured that the glances relevant to the changing of lanes could be included in the predefined AOIs of the analysis (see Bayerl, 2012). Thus, the overtaking process was divided into two test events (pulling out, pulling in) for which the following start and end points were defined:

(1) Start “pulling out” = -10s before the test vehicle had completely changed to the left lane

(2) End “pulling out” = test vehicle had completely changed to the left lane

(3) Start “pulling in” = -10s before the test vehicle had completely changed to the right lane

(4) End “pulling in” = test vehicle had completely changed to the right lane

The detection of the AOIs and the subsequent calculation of the glances related to the AOIs were coupled to reference points (markers) in the vehicle. The recognition of the markers was performed in an automated process across all glance videos. The glance videos which showed an insufficient detection rate after this automated process were manually processed.

19 subjects were excluded from the analysis, because the data was not usable or the subjects belonged to the experts group. Thus, data records of 24 subjects were included in the calculations. The following glance parameters were considered:

(i.) *Number of Glances*: Number of glances to the left monitor / left exterior mirror (AOI) (ii.) *Maximal Glance Duration*: Maximal duration of glances to the left monitor / left exterior mirror (AOI), in seconds.

The calculation was performed over all “pulling out” and “pulling in” events for each of the four monitor/mirror positions.

For the further statistical analysis of the data, a univariate analysis of variance (ANOVA) with the factor monitor/mirror positions (AOI) (4 levels: exterior mirrors, CMS1, CMS2, CMS3) was calculated. Here again the F-statistic (*Greenhouse-Geisser*) was used ($\alpha < .05$). If the null hypothesis was rejected, the partial η^2 was reported.

4.1.5 Results

4.1.5.1 Descriptive statistics

Table 5 shows the results of the subjects’ statements on how they usually use of the exterior mirrors in different traffic scenarios. All subjects stated that they mostly used the exterior mirrors for ‘turning’, ‘merging into moving traffic’, ‘monitoring rear traffic’, and ‘before getting out of the vehicle’.

"How often do you use the exterior mirror ... ?"	Group *	Never	Rarely	Some-times	Mostly	(Nearly) always
... for turning	E	.	18.2	9.1	45.5	27.3
	N	12.5	6.3	.	37.5	43.8
... for merging into moving traffic	E	.	9.1	.	27.3	63.6
	N	.	.	.	18.8	81.3
... for monitoring rear traffic	E	.	.	36.4	9.1	54.5
	N	.	.	31.3	31.3	37.5
... before getting out of your car	E	18.2	18.2	.	18.2	45.5
	N	.	6.3	6.3	56.3	31.3

** E = Experts; N = Novices*

Table 5: Results of the subjects' statements on their traditional use of exterior mirrors in different traffic situations, in percentage (N=42).

The results of the training phase which the experts group passed in order to gain some experience with the CMS is shown in Table 6. On average the experts used the CMS for 158 minutes in real traffic. The standard deviation of 96 minutes indicated a high variance of duration of use. The minimum duration of use was 1 hour, the maximum duration was 5.5 hours. The average distance driven was 161 km ($SD =$ 135 km). The use of the CMS differed over road types. The percentage of distance driven with the CMS was highest for road type "Motorway" (57 %). The percentages for the other road types were much lower ($\bar{x}(City)$ $=$ 19 %); $\bar{x}(Rural\,road)$ $=$ 24 %).

	M	*SD*	Min	Max	Σ
Total duration (min)	158	96	60	330	1740
Distance driven (km)	161	134	32	523	1772
Inner-city road (%)	19	16	5	50	
Rural road (%)	24	14	5	60	
Motorway (%)	57	20	30	85	

Table 6: Duration, distance, and percentage of distance driven by the experts when exercising the CMS during the training phase (*N* = 11).

4.1.5.2 Experiment I – Results of the distance and speed estimation

No significant difference, in terms of distance at the last safe gap, could be demonstrated between the system types CMS and exterior mirror (F(1,33) = 3.646, p = .065). A significant main effect could be shown for the factor speed of the object vehicle (F (2.66) = 39.752, p = .000). The interaction of system type and speed (F(2,66) = 1.187, p = .310) showed no significant effect.

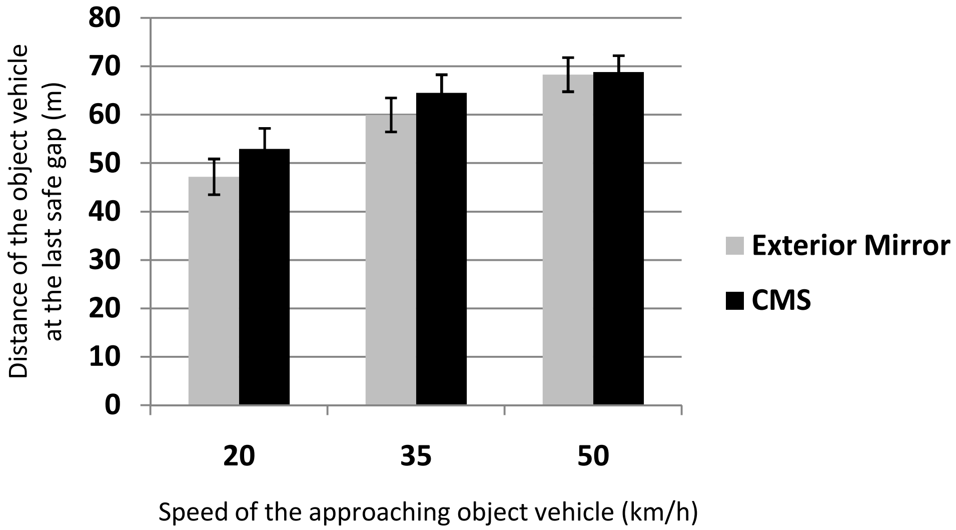


Figure 61: Last safe gap estimated by the subjects for the two system types. The distance between the moving object vehicle and the static test vehicle was measured at the time the button was pressed (N = 34).

The last safe gap is slightly larger with CMS than with exterior mirrors. The results suggest that subjects would not pull out for overtaking at an earlier point in time when using the CMS (see Figure 61). At speeds of 20 km/h, subjects pressed the button at $\bar{x}$ = 47.2 m (SE = 3.7) when the exterior mirror was used. In contrast, when watching the object vehicle on the monitor, the button was pressed at a distance of $\bar{x}$ = 52.9 m (SE = 4.3). When the object vehicle approached at a speed of 35 km/h, the distance was $\bar{x}$ = 59.9 m (SE = 3.5) for the exterior mirror and $\bar{x}$ = 64.5 m (SE = 3.8) for the CMS. The results showed nearly the same distances in the 50 km/h scenario, i.e. $\bar{x}$ = 68.3 m for the exterior mirror and $\bar{x}$ = 68.8 m for the CMS. It seems that the distances estimated for the two system types converge with higher speeds.

The results shown in Figure 61 describe the main effect of the object vehicle's speed on the estimated distance of the last safe gap. Correspondingly, distance increased for higher speeds.

Figure 62 shows the results for the subjects' estimations of distances to a stationary object vehicle (distances: 5 m, 12.5 m, 20 m). Significant main effects could be shown for both the factor real distance ($F(2,14) = 182.3$; $p = .000$) and the factor system type ($F(1,39) = 5.203$; $p = .028$).

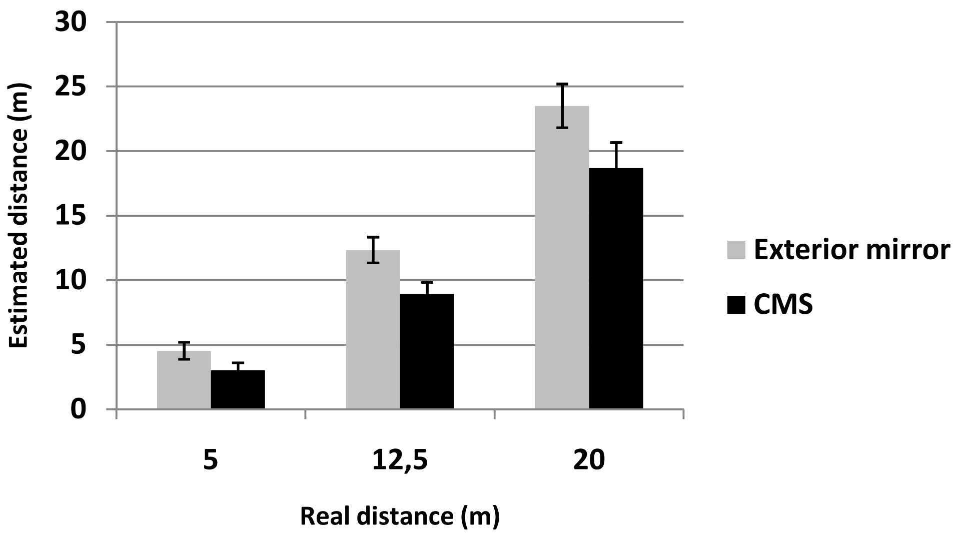


Figure 62: Estimated distances to a stationary object vehicle using the exterior mirror and the CMS.

The estimated distance to the stationary object vehicle was smaller when using the CMS than when using the exterior mirror. At the maximum of the given distances (20 m), the subjects overestimated the distance to the object vehicle when using the exterior mirror.

4.1.5.3 Experiment II – Results of the glance behaviour tests on motorway

Due to poor raw data quality the data of only 24 subjects (12 females, 12 males), from a total of 42 subjects, could be used for the analysis of glance behaviour. The average age was 51.6 years (*SD* = *16.6).*

<u>Merging into moving traffic</u>

Figure 63 and Figure 64 show the results of glance behaviour during merging into moving traffic. System type showed a significant effect on the number of glances ($F(3,19) = 5.87$; $p = .005$) as well as on glance duration of ($F(3,19) = 5.87$; $p = .019$).

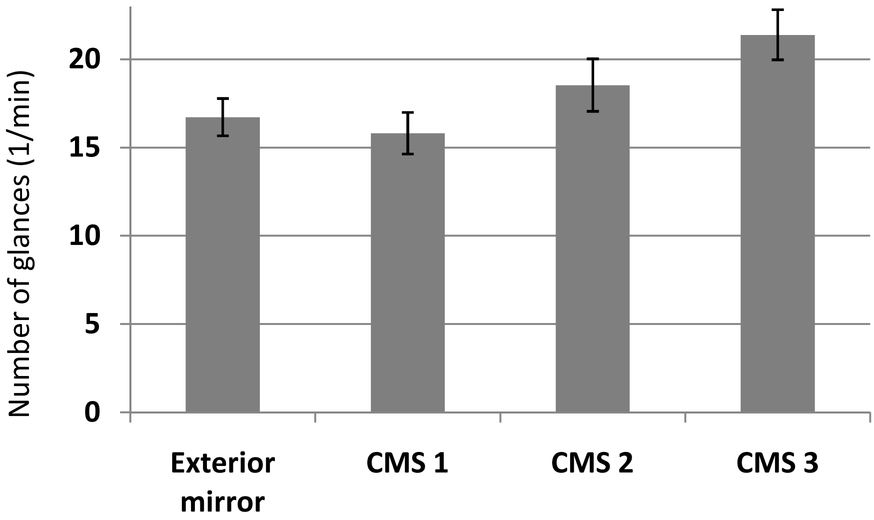


Figure 63: Number of glances per minute when merging into moving traffic, for different monitor/mirror positions

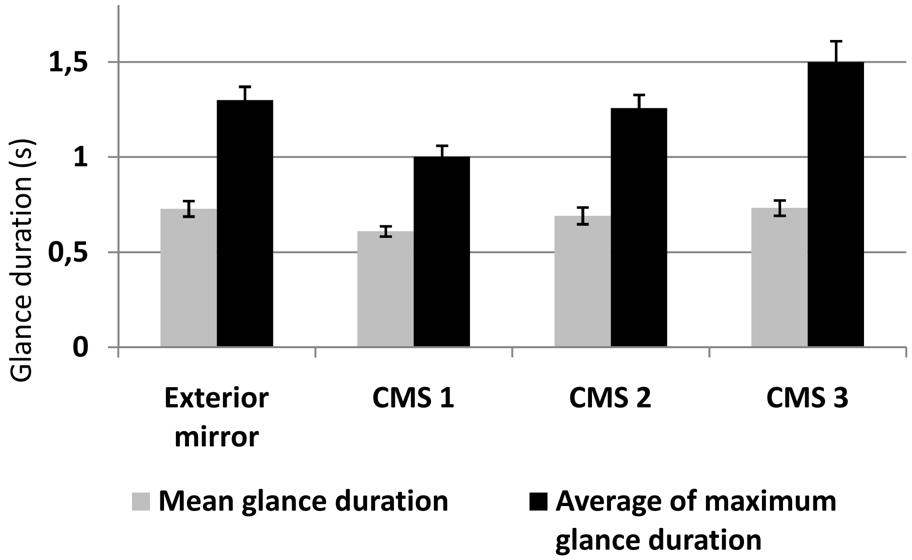


Figure 64: Duration of glances when merging into moving traffic, for different monitor/mirror positions

Overtaking (left lane change)

The mean duration of the overtaking task (time period between pulling out and pulling in again) was 16 s. It did not differ between the two system types (exterior mirrors, CMS). The results of the statistical analysis (Figure 65 and Figure 66) did not show a significant effect of the system types, neither in terms of glance frequency ($F(3,19) = 2.92$; $p = .06$) nor in terms of glance duration ($F(3,19) = 1.65$; $p = .214$).

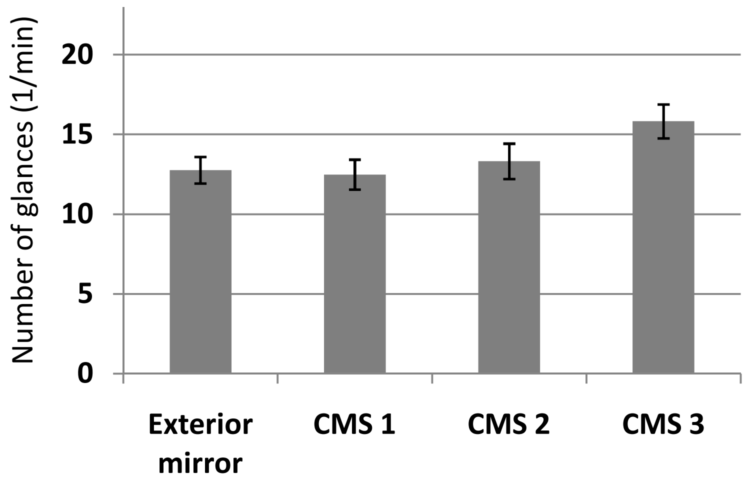


Figure 65: Number of glances per minute during overtaking, for different monitor/mirror positions.

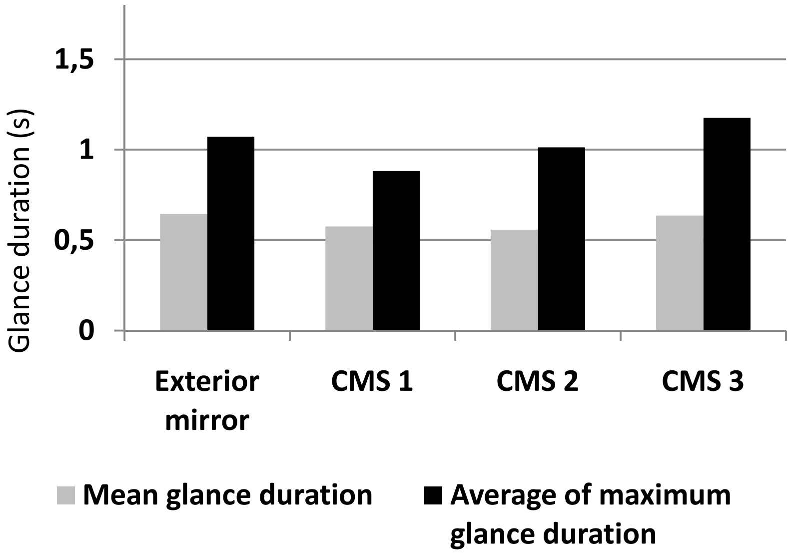


Figure 66: Duration of glances during overtaking, for different monitor/mirror positions

The number of glances was higher with the CMS than with the exterior mirrors, if the monitors of the CMS were located at the A-pillar (CMS 3). This position was close to the position of the left and right exterior mirror. A larger quantity of information on the monitor, due to the wide aspherical area displayed, may be the reason why the subjects needed more glances when using the monitor than when using the exterior mirrors. Glance duration was shortest for the monitor position CMS 1, where both monitors were located at the height of the door panel (see Figure 7). This means that the monitors which are located below the normal field of view are less taken into account by the subjects. The results show a tendency towards decreased glance duration, if the monitor's position required the subjects to avert the eyes from the vehicle environment and the moving traffic. This suggests that subjects felt more unsafe in this case and, therefore, reduced glance duration.

The analysis of the frequency distribution of the maximum glance duration across all subjects showed that three of 24 subjects exceeded the critical glance duration (2 s) at CMS 2 and CMS 3. At the start of overtaking (left lane change), only two subjects exceeded the critical glance duration during glances at the mirror and at the monitor in position CMS 2. At the end of overtaking (right lane change) the subjects did not exceed the critical glance duration.

Monitor position and acceptance of the CMS

Figure 67 shows the subjects' preferences with regard to monitor position. The most preferred positions were CMS 3 and CMS 2. More than half of the subjects (22 subjects) preferred CMS 3 and 38 % (15 subjects) preferred CMS 2. Only one subject chose CMS 1. Two subjects gave preference to CMS 3 on the left-hand side in combination with CMS 2 on the right-hand side. The analysis of the acceptance ratings of the CMS showed that acceptance is unrelated to experience gained by the subjects, i.e. the acceptance did not depend on whether and how long the CMS was used by the subjects.

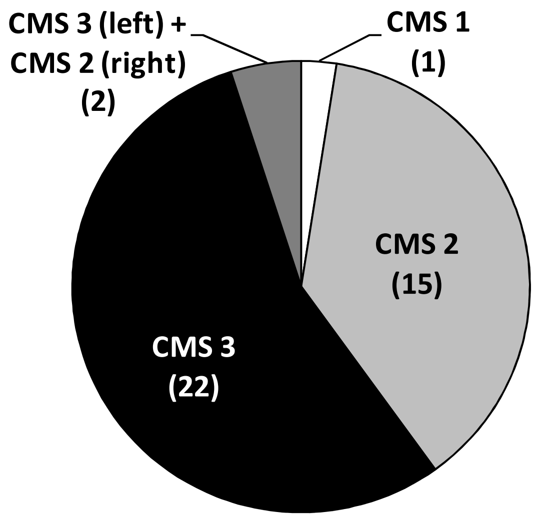


Figure 67: Monitor position preferences of the subjects (subjective measure).

4.1.5.4 Subjective assessment of the CMS by the subjects

The subjective assessment aimed at investigating the subjects' opinion on whether the use of the CMS affected their driver-vehicle interaction. Subjects received questionnaires which were used to collect their statements. The assessment criteria mainly covered the use of the CMS in specific driving manoeuvres and environmental conditions such as parking, lane changing, driving in tunnels, multi-lane roundabout traffic, low sun, night/darkness, contrast/colour. In sum, the subjective assessment showed the following results:

<u>Opinion of the experts group:</u>

Prior to the experiment, the experts group had the opportunity to get used to the CMS. The evaluation of the questionnaires yielded the following results:

- Five of ten experts stated that estimating the distance and speed of vehicles which approach from behind was difficult during changing lanes on the motorway.
- Four of six experts found it difficult to use the CMS during passing through a multi-lane roundabout or driving in curves, as the image representation on the monitor was distorted because of the wide aspherical area displayed.
- Four of nine experts experienced difficulties in estimating the distance during parking.
- Four of seven experts stated that they could not sufficiently recognise the information represented on the monitor when passing through a tunnel, because the vehicle head lights strongly lit up and flashed the environment. In addition, it was hardly possible to recognise anything on the monitor in low background luminance (e.g. lane markings, distance of approaching vehicles from behind).

<u>Opinion of the total sample</u>

The CMS received negative ratings with regard to the criteria of distance/speed estimation and spatial perception. Here, 18 of 20 subjects stated that it was very difficult to estimate different vehicle speeds due to a lack of spatial depth of image representation. Furthermore, 14 of 20 subjects experienced driving in rain as being more disturbing when using the CMS due to the reflections caused by the vehicle lights on the road surface. The majority of the subjects evaluated the CMS positively with regard to the reduced blind spot and the enlarged field of vision to the rear area of the vehicle.

4.2 Truck study

Following the car CMS study, the CMS properties as well as psychological questions with regard to human-machine interaction (MMI) in trucks were examined.

4.2.1 Sample

A total of 10 male subjects took part in the experiment. All subjects were employees of the BASt. The average age was 51.1 years (*SE* = *2.4).* Eight of ten subjects had not driven a truck for an average of 11.4 years. 50% of the subjects had experience with the camera-monitor system due to their participation in the CMS car study.

Prior to the experiment, all subjects received a demographic questionnaire which contained questions about visual aids, their last consultation to an ophthalmologist, their truck driving experience and routine use of exterior mirrors. All subjects were active car users and hold a class C or class CE driver’s licence. With regard to visual function, all participants fulfilled the minimum requirements for visual performance according to Annex 6 of the German Driver Licensing Regulations.

4.2.2 Test procedure

Before starting the experiment all subjects received the relevant information about the test procedure and data protection regulations. The subjects signed consent forms for participation in the experiment.

4.2.2.1 Test procedure

For the evaluation of the CMS, all subjects carried out a test drive at the BASt test facilities as well as in real traffic. The subjects evaluated the CMS based on specified criteria by means of spontaneous statements and questionnaires.

To get used to both systems, the subjects first completed an exercise drive at the BASt test facilities (see Figure 68). The exercise drive lasted approximately 20 minutes and included scenarios such as straight driving, curves and straight reversing.

Figure 68: Subjects during the test drive on the BASt test facility.

Before the test drive started, the subjects received explanations about the test procedure, an introduction of the truck operation system as well as information about the camera-monitor system. The total experiment took about 2 hours per subject. In nine of ten drives the sun was shining with clear shadow formation. During one of the drives, weather was misty with little sunshine.

4.2.3 Experiment I: Distance estimation

The distance estimation was performed at the BASt test facility by means of rear approach to two pylons to the right and left of the end of the trailer (see Figure 69 and Figure 70). A distance of 4 m was selected for the distance estimation.

Figure 69: Rear approach to two pylons for distance estimation.

Figure 70: Distance of the trailer to the pylons.

The pylons had a height of one metre and the distance between both pylons was 3.20 m. For the distance estimation, half of the subjects first started the rear approach to the pylons using the mirrors and then using the CMS; the other half of the subjects first started with the CMS and then continued with the mirror system. For rear driving using the CMS, the exterior mirrors were folded back.

4.2.4 Experiment II: Commented drives in real traffic

After the exercise drive and experiment I the subjects felt secure enough to drive in real traffic. No subject had aborted a test drive or mentioned that they needed the exterior mirrors as an additional aid for driving.

The first drive in real traffic was performed on the motorway / rural road and served as another exercise for the subjects to get used to the truck and the CMS, because the majority of the subjects had not driven a truck for several years. The first drive was therefore accompanied by a technician, who instructed the subjects in the use of the operating elements and the CMS. This made it easier for the subjects to concentrate on the CMS during the second real drive.

The second drive in real traffic was accompanied by the project manager (a psychologist) who noted any spontaneous statements about the CMS given by the subjects and posed questions to the subjects based on specified criteria (perception of different speeds, driving in roundabouts / urban areas, recognition of distant objects) and documented the answers. At the end of the real drives the subjects received another questionnaire. The total length of route was 57 km, of which 29 km were on the motorway and 28 km on rural roads (see Figure 71). The route stretched from the Heumarer Mauspfad - direction Cologne/Bonn airport – motorway A 59 direction Bonn/ Frankfurt – motorway A 560 direction Frankfurt/Siegburg - rural road 56 direction Much – motorway A 3 direction Cologne - exit Königsforst – rural road towards Bergisch Gladbach-Bensberg.

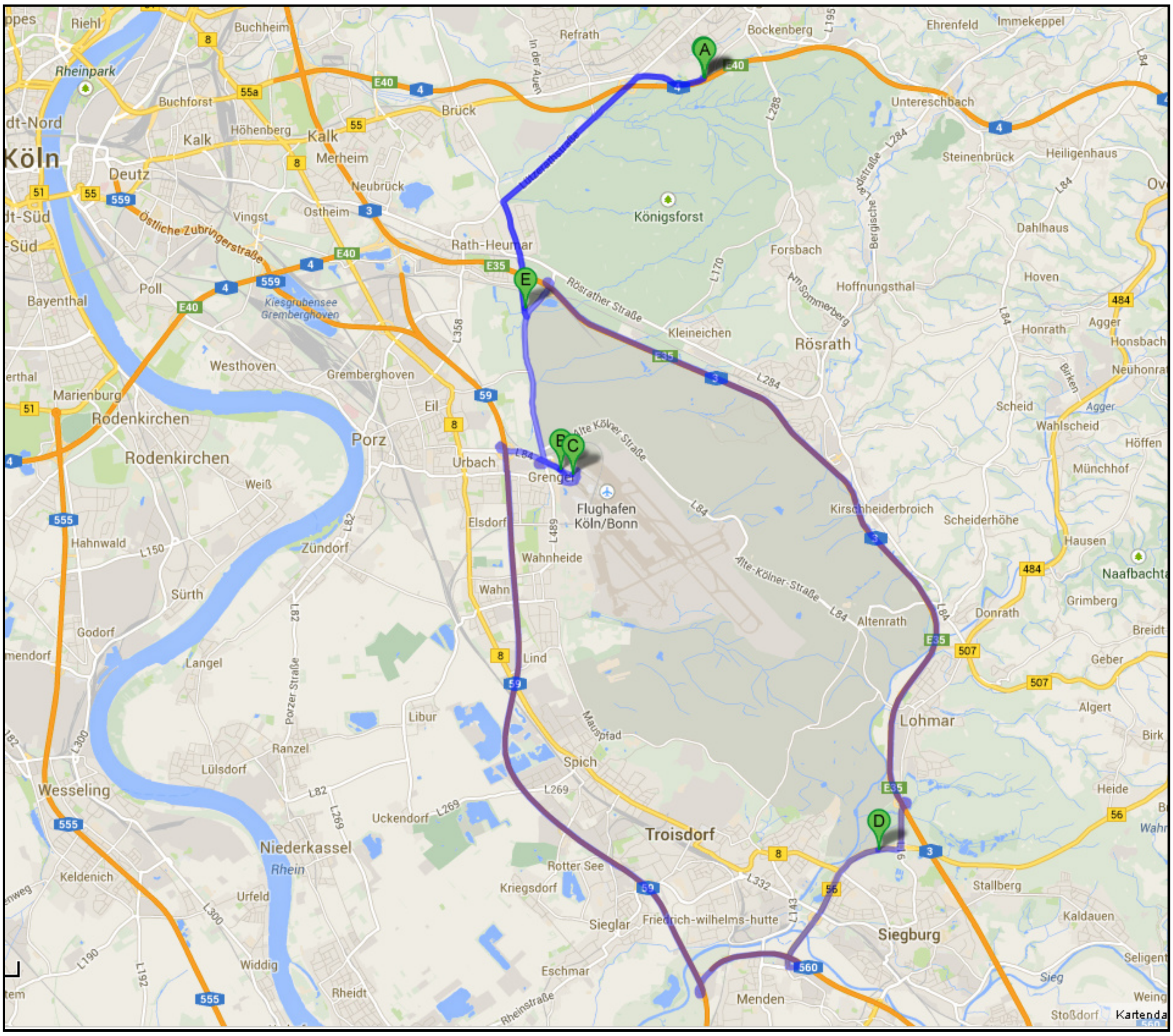


Figure 71: Test route taken by each subject.

4.2.5 Results

The qualitative evaluation of the questionnaires was performed taking the number of positive and negative comments about the CMS and frequency calculations into account. For the analysis of the distance estimation, a paired t - test was calculated.

4.2.5.1 Analysis of particularities mentioned by the subjects

Positive comments

- The system is unfamiliar, however one can get used to it (10 subjects)
- Less soiling (2)
- Disadvantages of the wide angle mirror (distorted image, strong curvature) is compensated by the CMS (1)
- Aerodynamics (1)
- Better direct view out of the windows due to no exterior mirrow mirrors (3)
- Fuel savings (1)
- Front of the trailer clearly visible on the monitor (1)
- No head movement required (1)

Negative comments

- Contrast and colour reproduction too poor; in parts, colours are not realistic (8)
- Shadow formation too strong; road users, objects (kerbs) and distances in the shadow of the trailer are not clearly visible or difficult to estimate (too dark) (7)
- Objects are displayed smaller on the screen (7)
- Display could be larger, especially the right monitor (5)
- Flickering / jittering of the image especially during engine start and turns (3)
- The position of the left monitor is too close, for drivers which are long-sighted and don’t wear multifocal glasses; the monitor should be placed closer to the windshield, so that the distance to the eyes is greater (3)
- Position of the right monitor is too far; objects are even more difficult to recognise (3)
- Reduced feeling of safety in comparison to mirrors (3)
- Driving in roundabouts is (rather) difficult (3)
- Dust and finger prints visible and distracting (3)

Subjects’ wishes

- Manual adjustment for improving contrast, colour and size of objects (2)
- Covers on top and at the side of the monitor to prevent glaring (1)

4.2.5.2 Experiment I - Results of the distance estimation

The subjects were asked to reverse up to 4 m to the pylons by using the exterior mirrors and the camera-monitor system. When using the camera-monitor systems, the exterior mirrors were folded back.

Figure 72 demonstrates that short distances (here 4 m) are clearly overestimated when using the exterior mirrors, i.e. a further distance than 4 m is kept to the pylons ($M = 7.5$ m; *t*-test vs. 4: $p < .01$). This is not the case for the CMS ($M = 5.5$ m; *t*-test vs. 4: $p = .13$). For one subject (subjec no. 5) only the estimated value by means of the exterior mirrors could be used for the analysis. The difference between the exterior mirrors and the CMS is not significant, however a clear tendency was shown (paired *t*-test: $p = .062$).

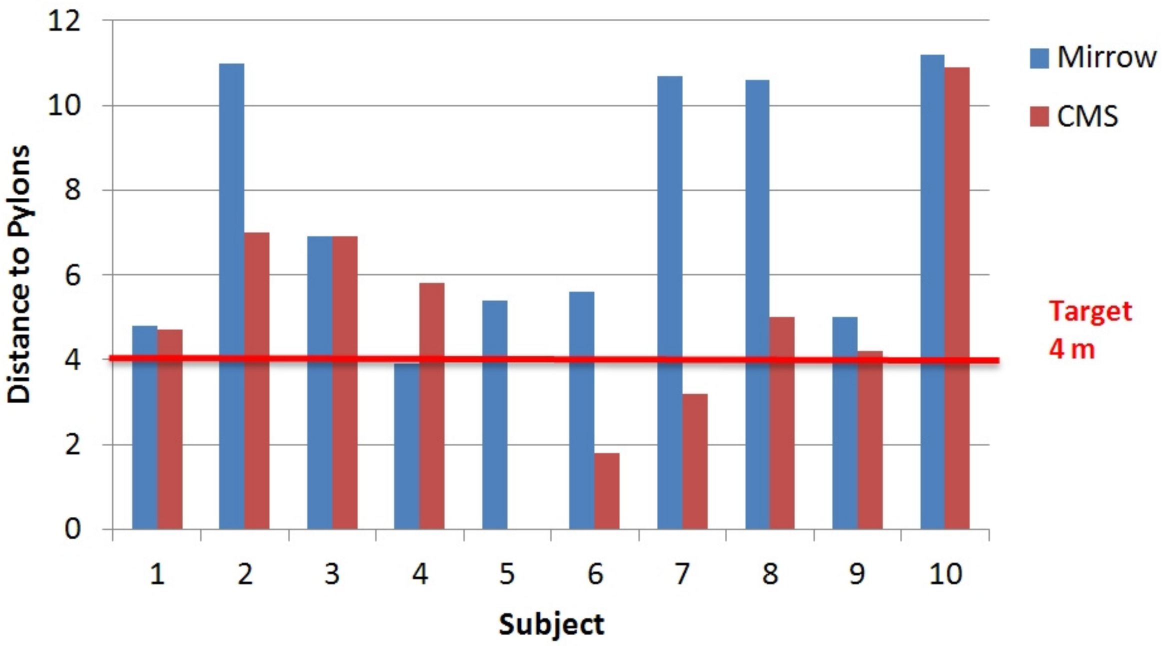


Figure 72: Estimation of the distance to the pylons.

4.2.5.3 Experiment II – Results of the drives in real traffic

In the following the results of the evaluation criteria of recognisability, colour and image quality, monitor position, driving situation and distance estimation are illustrated graphically.

Recognisability:

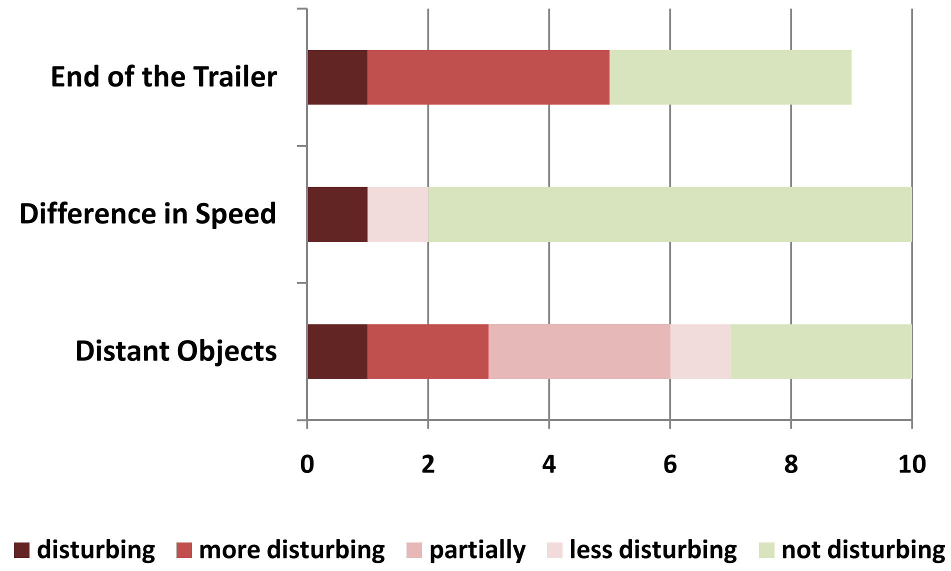


Figure 73: Estimation of the degree of disturbance on recognisability.

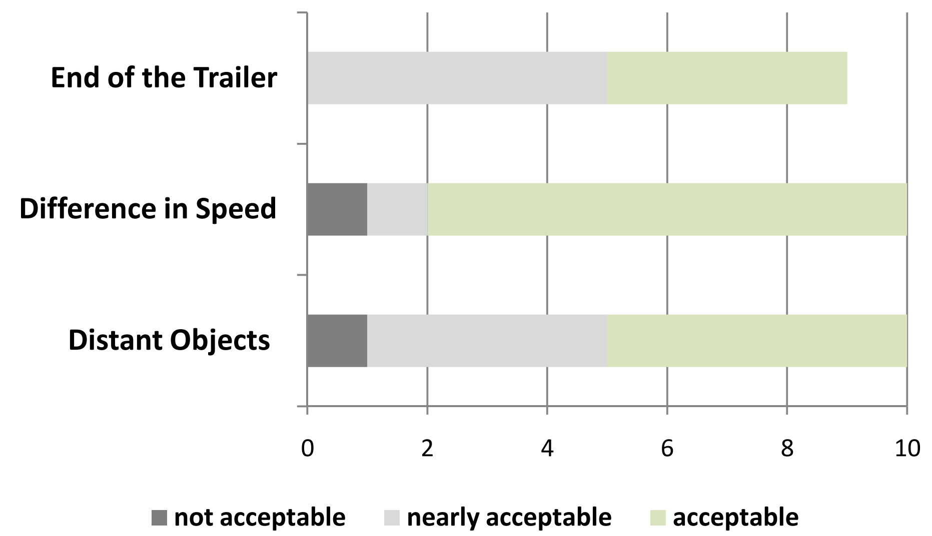


Figure 74: Level of acceptance of recognisability.

Figure 73 shows that the differential speed was better recognised by the subjects than objects which were located further away or than the back of the trailer. This limited recognisability was perceived as disturbing by the subjects (see Figure 74). One subject gave no statement for the point “Recognisability of the end of the trailer”.

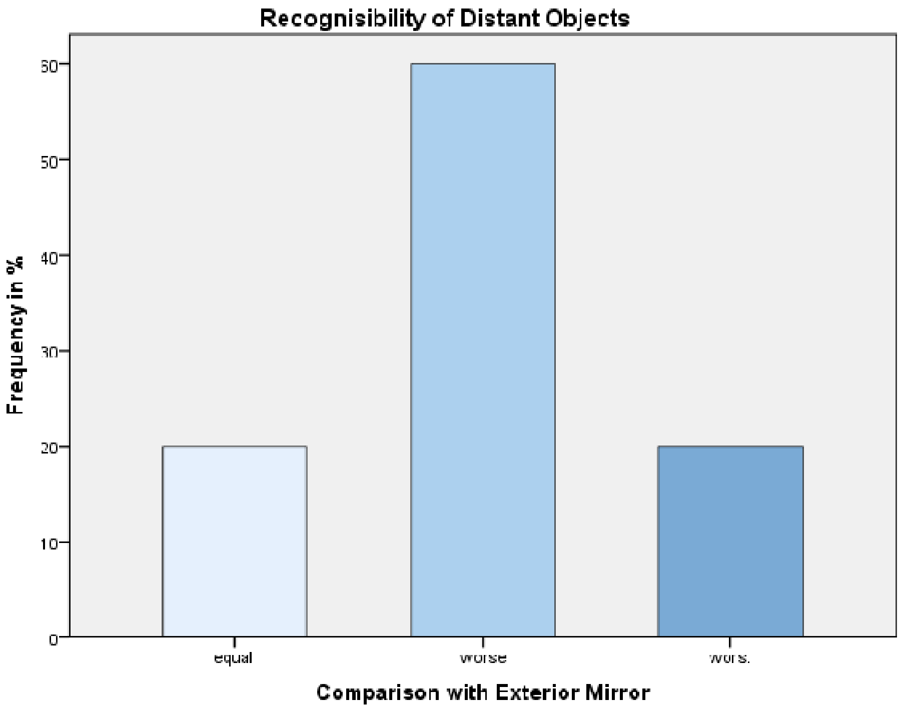


Figure 75: Comparison between CMS and exterior mirror with regard to recognisability of distant objects.

As shown in Figure 75, nearly 60% of the subjects mentioned that the recognisability of distant objects was poorer when using the CMS compared to when using the exterior mirrors.

<u>Evaluation of the driving situation:</u>

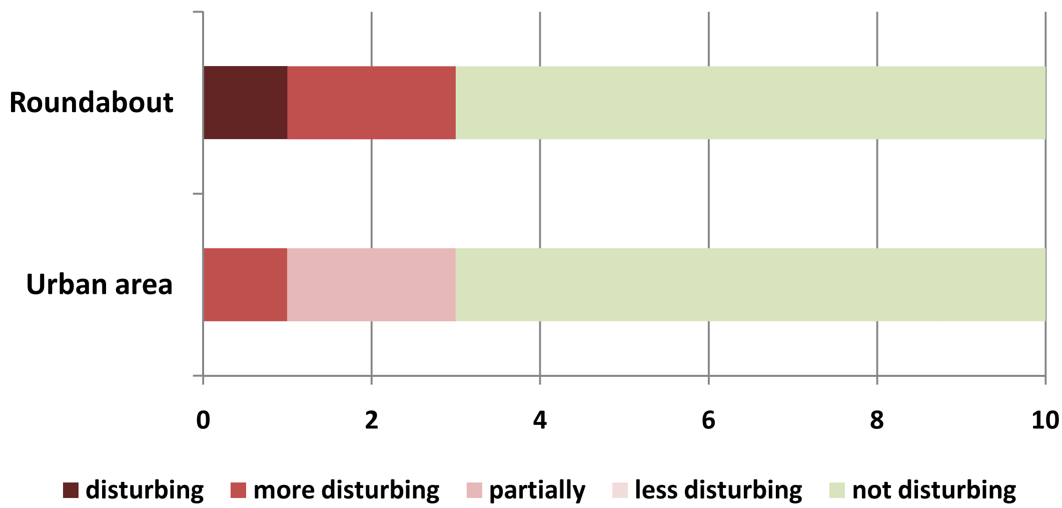


Figure 76: Evaluation of the degree of disturbance on the driving situation.

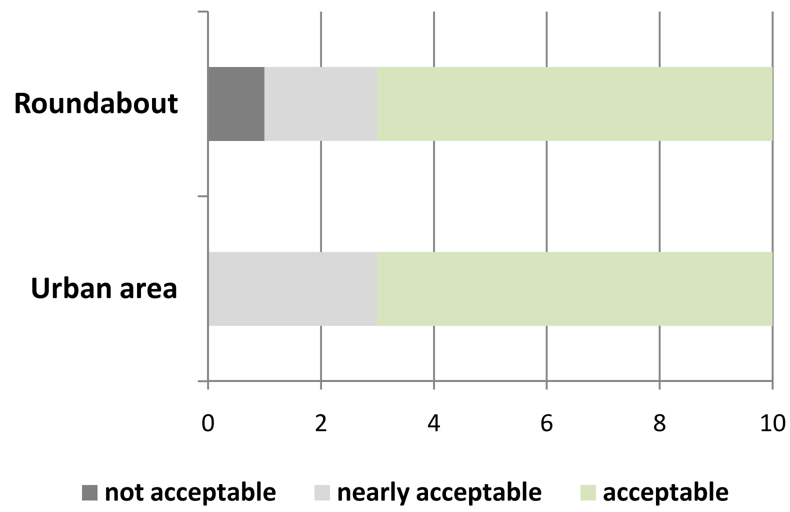


Figure 77: **Degree of acceptance of the driving situation.**

The majority of the subjects evaluated the use of the CMS in roundabouts or on urban roads as being acceptable. Driving in a roundabout was perceived as difficult by three subjects (see Figure 76 and Figure 77).

<u>Statement on image quality (brightness / contrast, colour rendering, image sharpness):</u>

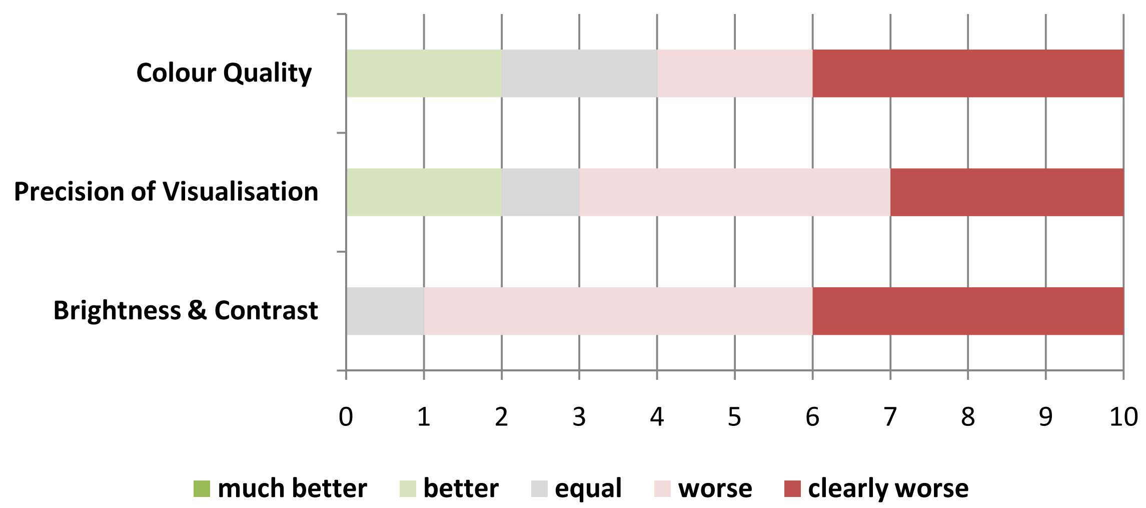


Figure 78: **Comparison between CMS with exterior mirrors with regard to image quality.**

Most of the subjects assessed the image quality of the CMS as being poorer than the quality of the exterior mirrors (see Figure 78).

Information on the display position:

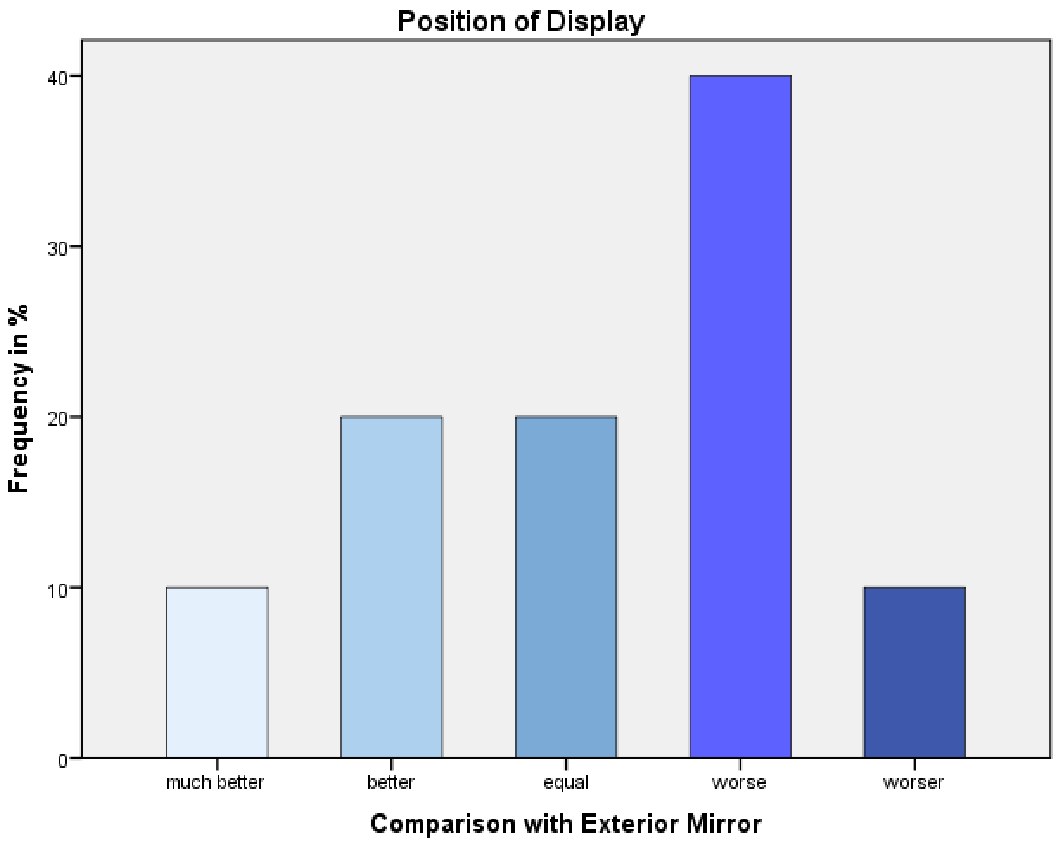


Figure 79: Comparison of the CMS to the exterior mirrors with regard to display position.

Nearly 40 % of the subjects mentioned that the display position of the monitors was poorer than that of the exterior mirrors (see Figure 79). 40% of the subjects would have preferred a left monitor position at a greater distance to the driver; however, this could be corrected by wearing bifocal spectacles. 30% of the subjects stated that the right monitor was positioned to far away from the driver. The recognisability of distant objects seemed to decline with the CMS, due to the fact that images of objects were displayed smaller on the monitor than on the mirror.

Evaluation of the CMS (support for distance estimation, conveying of a feeling of safety, recommendation):

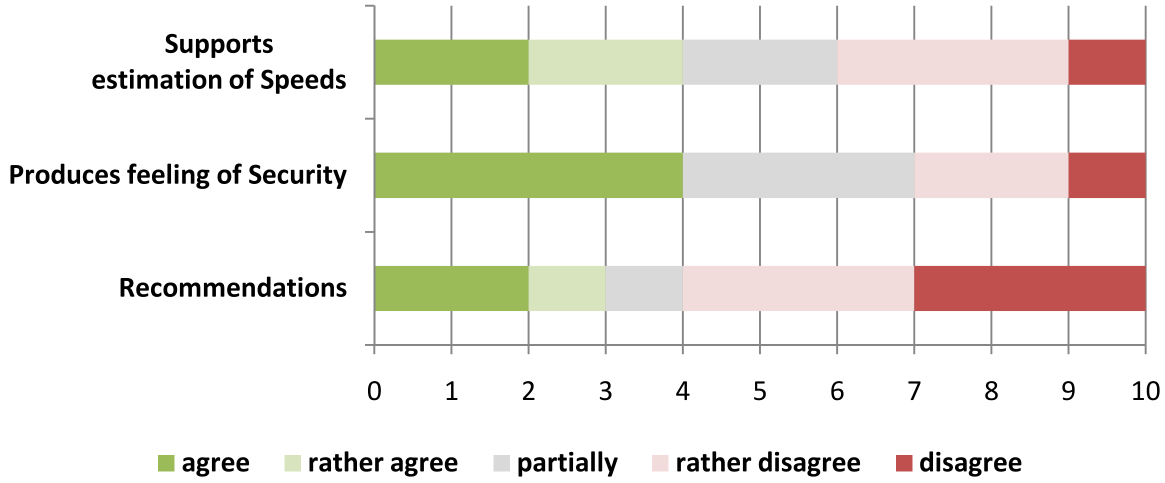


Figure 80: Assessment of the CMS by the subjects

The green zone in Figure 80 shows that four of ten subjects stated that the CMS supports the estimation of speed and in total conveys a feeling of safety. Four people at least partially would recommend the CMS in its present form.

5 Discussion of the results

5.1 Technical aspects

The analysis of the technical properties of the CMS showed advantages and disadvantages of the CMS as compared to conventional exterior mirrors.

With regard to the rear field of vision the CMS covered all required areas and even reduced the blind spot. These are positive features in terms of safety. However, the increased horizontal distortion in the aspherical section of the image displayed on the monitor made it difficult to assess the distance and the speed of the following traffic. It seems to be advisable, in order to shape the transition from conventional mirrors to CMS as smoothly as possible, to design the position of the display of the CMS and its image according to commonly used positions and display formats.

Positions of the cameras and monitors must be chosen in such a way that the all-round view is not impaired and ergonomic requirements are taken into account. It makes sense that the driver does not view the monitor in a skewed manner and that adjustment options allow for an optimal image quality in terms of colour rendering, contrast and luminance.

During operation, a CMS must be able to reliably present information in different and partially changing environmental conditions. Compared to mirrors, there are situations in which the recognisability of the rear field of vision was improved, and in other cases were less good using the CMS.

The prevention of physiological glaring in low sun or turned on high beam head lights of the following traffic, as can occur in a mirror, was assessed as positive. Furthermore, a CMS shows less vulnerability in normal rain with regard to impairment due to water droplets or smearing or soiling.

A dynamic change in lighting, which can occur for example in tunnel entry or exit or in shade from tree-lined roads, is a challenge for CMS. As a result of the interaction of multiple components the optimal display of the CMS in such situations is sometimes only achieved after a certain response time (up to approximately two seconds).

Due to the limited display option of colour nuances and differences in luminance, the study showed situations in which important image details were not recognised or were only difficult to recognise. Here, an improved and more realistic rendering of colour and grey values is desired.

With regard to the displayable contrast, the CMS showed a better reproduction in a dark environment in the tests. In contrast, the mirrors showed a stronger contrast during the day in a brighter environment. Here, the possibility of contrast enhancement for monitors was shown for poor light conditions, and the limitations of the monitor luminance in very bright light conditions.

The reflections caused by light on the covering glass of the monitor were evaluated as negative, as in these situations the image content was not or hardly recognisable. Especially on the passenger side reflections occurred, which could result in overlooking other road users when turning to the right. Remedies are required here, through a different installation location, shielding against sunlight or a reflex-reducing sight protection. In reverse, these measures could contribute to the prevention of the monitor image in the vehicle interior being reflected on other surfaces.

Because a CMS replacing mirrors would be a safety-relevant feature on the vehicle, it is of upmost importance to design it in a way that excludes any outages. It must be ensured that the operational readiness is guaranteed after turning on the system, and that the CMS is operational at all times. This applies to both the power supply and the electrical protection (e.g. fuse). One needs to consider to which extent status monitoring with corresponding signalling for the driver and eventual redundancy needs to be provided. The individual components of the CMS must be designed in an electromagnetic radiation compatible manner.

Within the framework of the experiments, the CMS proved resistant to heat (e.g. by exposure to sun light). However, the sensitivity to cold climate conditions such as thawing, condensation or icing was problematic. Therefore, a CMS heating makes sense.

In order to avoid optical artifacts in image processing, components (lens, camera chip etc.) of quality beeing as high as possible should be used. This also applies to the resolution of the system for a good reproduction of details.

Quick and precise adjustment of the camera to changing ambient lighting and also the aperture is important for optimal functioning. Furthermore, in terms of brightness and contrast an automatic adjustment to the ambient conditions should be standard; additional manual adjustment options were considered as meaningful.

The minimum level of the sampling rate and reproduction frequency for a CMS in order to reproduce timed light signals (e.g. variable message signs or police signs) without loss, was not clarified. It is important the CMS displays the situation without time delay.

If fuel-savings need to be achieved by the CMS, it must be ensured that the energy consumption of the CMS is less than the energy saving due to aerodynamic optimisation.

5.2 Aspects of human-machine interaction

In the present study, aspects of safety-relevant perception using a camera-monitor system as a replacement for exterior mirrors were determined. The subjects' estimation of the last safe gap which they would accept for changing the lane was intended to provide insights on the perception of distances displayed on the monitor.

There was no statistical evidence to confirm the assumption that lane-changes with the CMS, which occur at an earlier point in time than lane changes with the mirror, are assessed as not being safe anymore by the drivers. No significant difference in terms of the used system could be demonstrated. In case of pulling out the car at low speeds, mean distance for the CMS showed a tendency towards an increased safe gap compared to the mean distance for exterior mirror. This result indicates a non-critical misjudgement of speed of and distance to the approaching object vehicle.

Furthermore a highly significant main effect of the object vehicle's speed on the distance at the last safe gap was shown. The distance increased with increasing speed of the object vehicle. The main effect suggests that different speeds can be perceived on the monitors.

As camera-based monitors only provide monocular depth criteria to the driver, they appear to create an impression of depth. Otherwise, the subject always would have to press the button at the same time. Flannagan et al. (2001) examined the role of binocular depth information when estimating a relative distance of two vehicles which were viewed in the rear-view mirror. The subject had to provide two estimations, one with one eye and the other with both eyes. It was shown that viewing with both eyes showed no advantage at a distance between 20 m and 80 m. The distances at which the subjects of the present study would still perform lane changes fall in this critical range. Accordingly, based on these results, it must be assumed that the oculomotor, stereoscopic and motion induced depth criteria are not of central significance for drivers in most traffic situations. Consequently, the results of the present study and those of Flannagan et al. (2001) suggest that no negative effect for the use of camera-monitor systems is to be expected for the analysed distances.

The overestimation of speed and the underestimation of distance when using the CMS seem to have a positive effect on road safety. As the vehicles are perceived as being closer than they actual are, larger gaps for lane changing were chosen. Possible effects of different traffic densities (congestion, slow moving traffic) could not be conclusively established and need to be considered in further research. If an interior mirror is available to the driver, it can be expected that the additional information available in the interior mirror supports the driver to realistically estimate speed and distance. This may contribute to correct erroneous estimations (see Mortimer, 1971; Mortimer & Jørgensen, 1974).

The results for the CMS and the exterior mirror show that the distances of the last safe gap converge at speed level 50 km/h. It seems to be of great importance to explore the distance estimation for speeds higher than 50 km/h. The critical question is whether the tendency to underestimate the distance reverses at a certain (high) speed level and turns to an overestimation of the distance. This would have a negative impact on road safety, because vehicles would be perceived as more distant than they actually are. As the recommended speed on German motorways is 130 km/h, a distance and speed perception study according to the applied method is recommended up to this speed level.

There is no statistical evidence for the assumption that distances are estimated more realistically with increasing experience of using the CMS. However, a main effect of experience could be shown irrespective of the implemented system type ($F(1,21) = 14.673$, $p = .001$). The “Experts” pull out later than the “Novices”. It is recommended to investigate training effects of using the CMS in further research.

The results of the glance analysis during overtaking (pull out, pull in events) could be summarised as follows: Compared to conventional exterior mirrors, an increased number of glances occurred on CMS 3 only. This position was close to the position of the exterior mirror. A larger quantity of information on the monitor, due to the wide aspherical area displayed, may be the reason why the subjects needed more glances when using the monitor than when using the exterior mirrors. However, the monitors at CMS 1 and CMS 2 did not show that high number of glances, although they displayed the same information. A possible reason for this result can be found when additionally taking the glance duration into account. Maximum glance duration for the CMS 1 and CMS2 (low area of the field of view) was shorter as compared to CMS 3. This can be interpreted as an indicator for lower preference of the CMS 1 and CMS 2 positions due to reduced visual-spatial attention, which is relevant for safe driving. Former studies (e.g. Hoffman, Wipking, Blanke & Falkenstein, 2013) already verified that visual attention decreases with an increasing distance from the central field of view. It can be concluded that the low preference of CMS 1 and CMS 2 also resulted in a decreased number of glances for CMS 1 and CMS 2.

On the other hand, glance frequency and glance duration for CMS 3 indicate that the monitor located at this position is highly accepted by the drivers. The statements given by the drivers confirm this conclusion.

The truck drives with using the CMS in real traffic proved to be unproblematic for all subjects, i.e. no subject aborted the drive or required the exterior mirrors. Comparing the positive and negative statements, the subjects’ majority assessed the system negatively. However, all subjects stated that the driver has to get some experience to the CMS. The drivers got familiarized with the CMS, so that the small monitor size, the position of the monitors and the changed light conditions for example were perceived as less disturbing. However, several subjects stated that they perceived some risks in terms of road safety during using the CMS:

- Objects were perceived smaller on the display. This issue was criticised by all subjects. It is of great importance, especially for manoeuvring, that the displayed image supports the driver in estimating the real object size.
- Contrast and colour intensity change depending on sunlight. The contrast between the trailer and road is hardly perceivable. Shadows on the display appear very dark during strong sun exposure, so that objects in the shade of the trailer are not clearly visible. Thus, subjects are not able to estimate the distance to the kerb accurately.
- Images on the monitors differ in terms of their colour in case of sun exposure. This resulted in increase glance durations towards the monitor in order to recognize objects on the display. Bright vehicles as well as outlines of distant objects (e.g. head lights of other vehicles) are only poorly or not at all recognisable .
- Driving in a roundabout was assessed as “rather disturbing”. In the subjects’ perception the image jiggled on the monitor and the contrast ratio was so low that it was only possible to estimate the distance between the wheels and the traffic island by close observation.

Nine of ten subjects mentioned that the present weaknesses of the CMS have to be eliminated before the system can be used by customers. With regard to spatial depth perception, the majority of the subjects indicated that they perceived the spatial depth as limited due to the reduction in size of the objects, but the measurement of speed distances would be still possible.

The less positive assessment of the image quality by the subjects in the present study is probably the result of incident solar radiation during the performance of the tests which yielded different levels of glare effects on both monitors. Furthermore, due to the strong shadow formation on the monitors the recognisability of (distant) traffic objects was strongly restricted. Travelling through urban scenarios as well as the estimation of different speeds on motorways was assessed as positive. Besides that, the distance to the pylons was also evaluated as more detailed in CMS than in exterior mirrors.

In addition to technical investigations (avoidance of glare and shadows), further tests should be performed in order to allow for a more comprehensive assessment of the suitability of CMS in trucks. Tests should include a broad range of weather conditions (rain, fog, snow and at night) and investigate the effect of familiarization with the CMS. This test would help to confirm the present statements of the subjects, e.g. with regard to the size and position of the monitors.

6 Conclusions and Recommendations

In general, it was shown that CMS, which meet specific quality criteria, are able to adequately display the indirect rear view to the driver, both for cars and trucks. Depending on the design, it is even possible to receive more information about the rear space from a CMS than is possible with mirror systems. Nevertheless, both solutions show fundamental differences. For example, depth information or a spatial impression of the image is always present in mirrors, however with the CMS this is not possible due to the two-dimensional representation. Furthermore, the field of vision in mirrors can be changed slightly through head movements, this is not possible with the CMS.

In general, the CMS is more resistant to soil and rain drops than the mirror, because the camera is small and the display is installed in the interior. The small camera size is also an advantage with regard to aerodynamics. However, frost, cold and electromagnetic interferences can lead to problems with the CMS. The CMS does not function without power; whereas a mirror is always ready for use. In direct sun exposure the CMS is superior, as it avoids the driver being exposed to direct physical glare. Furthermore, unlike mirrors, it offers the possibility of enhancing or weakening contrasts - depending on the ambient brightness - resulting in an increased comfort of viewing and information content of the image - especially at night. However, the adaptability of the CMS (required time to adapt to differences in brightness and ability to display a large range of brightness levels) is of importance here. Depending on the location of the monitor of the CMS, reflections or glaring can occur on the display. Covers or housings installed at the monitors could remedy this disadvantages. Furthermore, the possibility of artifacts such as “blooming” or “smear” is typical in CMS. This may result in images which do not clearly depict the real conditions, especially when artificial light sources are displayed. On the overall, there is no clear preference for CMS or exterior mirrors, because both systems show advantages and disadvantages. However, the CMS has to meet certain requirements in order to ensure equivalence with the mirrors:

- The electromagnetic compatibility must be ensured
- Good colour and contrast reproduction, minimisation of artefacts
- Quick adaption to changes in ambient brightness
- Representation with no time delay
- Detection and immediate display of image losses or, even better, ensuring that image losses do not occur
- Frost and condensation protection

The test drives with subjects showed that the change from mirrors to CMS does not necessarily result in safety-critical situations, but CMS require a certain period of familiarization. However, the time needed for familiarization seems to be rather short. For cars, with regard to speed and distance estimations, it was found that these are carried out more conservatively with the CMS than with mirrors, i.e. subjects waited for slightly larger gaps before pulling out. As for the trucks, images displayed on the wide-angle mirrors were distorted and represented in relatively small size due to the concavity of the mirror. In comparison to the mirrors the CMS displayed the image more clearly. The reverse driving task was performed more easily with the CMS than when using exterior mirrors. However, distant objects were more difficult to estimate using the CMS due to the lack of depth information. The exact location of the rear part of the vehicle is particularly important when manoeuvring. Here, an additional close-up view of the rear part of the vehicle would be desirable for both mirrors and CMS.

With regard to the positions of the monitors, some subjects stated that information about the left side should always be displayed on the left-hand side. The same applies to the right side. They stated that information does not necessarily have to be displayed close to the A-pillar, but can also be displayed closer to the steering wheel. This was considered positive for truck drivers, because the number of head movements of the driver would be reduced and the details of the images displayed on the monitor would be better recognizable. The area available for direct view increases, if the mirror can be omitted. This was seen as another benefit of the CMS. An installation of the monitors at a location far below the central field of view was considered as undesirable. A sufficiently large representation of the objects must be ensured for recognising distant objects on the monitor. The subjects also found it important that the resolution on the monitor is sufficiently high and comes close to the resolution of the mirrors. A high quality of the colours (especially the white) is also desired. For trucks it was noted that the display should be as large as possible. Far-sighted people should wear glasses when using the CMS, because the monitor of the CMS is positioned closer to the driver than the mirror.

A subject survey showed a medium level of acceptance of the CMS, which did not change when the CMS was used for a longer period of time. It can therefore be assumed that the average expectations of the road users on the CMS were met during the test use.

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