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Pilot Study of Driver Use of A Camera-Based Visibility System Versus Mirrors

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16. Abstract

Camera-based visibility systems, also referred to as camera-monitor systems (CMSs), are systems designed to replace or supplement required vehicle mirrors with small cameras that transmit video images to interior-mounted electronic visual displays. To address research questions outlined in NHTSA's Advance Notice of Proposed Rulemaking regarding whether CMSs provide equivalent information to rearview mirrors, a study utilizing human subjects was performed to examine drivers' eye-gaze behavior and driving performance in a light vehicle with rearview mirrors versus a production-ready prototype CMS. Participants drove an instrumented model year 2018 European-market light vehicle equipped with both the original equipment (OE) outside rearview mirrors and a production-ready prototype CMS on an oval, multi-lane test track. Participants completed drives with each type of rear visibility technology separately in daylight and in darkness for a total of four drives. After each drive, participants completed a post-drive questionnaire to obtain ratings regarding ease of use, image quality, comfort, and perceived safety of the rear visibility technology. Participants were presented with an unexpected obstacle detection event after the last darkness drive. Results of the study suggest that drivers' behavior when using the tested prototype CMS showed differences with respect to the European-specification OE outside mirrors in terms of lane change performance, eye-gaze behavior, head movements, and subjective impressions.

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List of Acronyms

ANPRM	Advance Notice of Proposed Rulemaking
CFR	Code of Federal Regulations
CMSs	camera-monitor systems
FMVSS	Federal Motor Vehicle Safety Standard
I-VT	velocity-threshold identification
OE	original equipment
RMS	root mean square
TRC	Transportation Research Center, Inc.

Executive Summary

Camera-based visibility systems, also referred to as camera-monitor systems, are systems designed to replace or supplement required vehicle mirrors with small cameras that transmit video images to interior-mounted electronic visual displays. Federal Motor Vehicle Safety Standard No. 111 specifies the requirements for rear visibility, including specific requirements for when vehicles must be equipped with driver-side outside and inside rearview mirrors or both driver side and passenger side outside mirrors. FMVSS No. 111 paragraph S5.2 requires that "each passenger car shall have an outside mirror of unit magnification" on the driver's side. FMVSS No. 111 paragraph S5.3 further requires that, if the inside rearview mirror does not meet field of view requirements, then the passenger's side "shall have an outside mirror of unit magnification or a convex mirror installed."

As noted in the 2019 Advance Notice of Proposed Rulemaking, the National Highway Traffic Safety Administration has received two petitions from light and heavy vehicle manufacturers seeking permission to use a camera-based system to meet the visibility requirements currently specified for provision by outside rearview mirrors. The ANPRM also outlines several CMS performance concerns and human factors questions regarding drivers' ability to safely use CMSs for which that ANPRM states data are needed to inform the decision regarding whether to permit CMSs in lieu of required outside mirrors (NHTSA, 2019). For example, while CMSs may have the ability to provide a wider field of view, the displayed image is subject to distortion due to the wider field of view being compressed for presentation on a small display. Questions exist regarding whether CMSs can provide the driver with equivalent visual information as original equipment mirrors as well as similar ease of use. Before the agency considers amending FMVSS No. 111 to allow for CMSs to be installed in place of currently required OE mirrors, it is important to ensure that, at a minimum, camera-based systems would provide the same level of safety as currently required rearview mirrors.

A small-scale research study was conducted to obtain initial information regarding how driving performance is affected when driving with a CMS as compared to mirrors. As camera monitor systems are not currently a permitted means of FMVSS No. 111 compliance with rearview mirror requirements, no U.S. market system was readily available for testing. A U.S. vehicle manufacturer agreed to lease NHTSA their research vehicle that was a European-market compact light vehicle equipped with a production-ready prototype CMS and European-specification OE mirrors that included a convex driver-side outside rearview mirror. The driver-side convex outside rearview mirror of the leased CMS-equipped vehicle did not meet FMVSS No. 111 requirements since the standard requires an outside mirror of unit magnification on the driver's side." Modifying the vehicle to fit it with FMVSS No. 111 compliant mirrors was considered but determined not feasible. As such, the vehicle was tested with the existing mirrors.

The goal of this research was to perform a human subjects experiment to examine drivers' use of CMSs in a light vehicle as compared to use of outside rearview mirrors and to gather information regarding differences in driver behavior and performance. The experiment examined lane-change performance, eye-gaze behavior, detection of an unexpected obstacle, and subjective ratings of ease of use, image quality, comfort, and perceived safety associated with a production-ready prototype CMS compared to European-specification OE outside rearview mirrors in a model year 2018 European-market light vehicle.

This research sought to answer the following questions.

1. Does lane-change performance differ when driving with the tested CMS compared to European-specification OE outside rearview mirrors?
2. Does driving with the tested CMS result in differences in distance judgments when passing a slower lead vehicle compared to European-specification OE outside rearview mirrors?
3. Does driver eye-gaze behavior during lane change and passing maneuvers differ with the tested CMS compared to European-specification OE outside rearview mirrors?
4. Does driver head movement during lane change and passing maneuvers differ with the tested CMS compared to European-specification OE outside rearview mirrors?
5. Does illumination from the tested CMS visual displays hinder drivers' ability to detect forward obstacles in darkness?
6. Do drivers' subjective impressions of general use, comfort, and visibility differ for the tested CMS compared to European-specification OE outside rearview mirrors?

Results showed differences in driving performance, eye-gaze behavior, head movements, and subjective impressions between the tested CMS and European-specification OE outside rearview mirrors. Analysis results are summarized below according to the previously listed numbered objectives.

1. **Findings regarding whether lane-change performance differs when driving with the CMS compared to European-specification OE outside rearview mirrors**

   Individual lane change completion times did not differ when driving with the tested CMS compared to the European-specification OE outside rearview mirrors. Participants were slower to complete lane changes in darkness compared to daylight, but there was no difference in lane change completion times between the tested CMS and the European-specification OE outside rearview mirrors. However, with the tested CMS, participants did take longer to complete an entire passing maneuver (i.e., two lane changes) as compared to the European-specification OE outside rearview mirrors.

2. **Findings regarding whether driving with the CMS results in differences in distance judgments when passing a slower lead vehicle compared to European-specification OE outside rearview mirrors**

   Results found that participants maintained a greater overtake distance (i.e., the distance between the subject vehicle and the scenario vehicle being passed) when passing a slower moving vehicle while driving with the tested CMS in daylight compared to driving with the European-specification OE outside rearview mirrors in daylight. Additionally, participants maintained a greater overtake distance with the tested CMS when making a left lane change back in front of the slower moving vehicle (i.e., passing on the right) compared to making a left lane change with the European-specification OE outside rearview mirrors.

3. **Findings regarding whether driving with the CMS leads to differences in eye-gaze behavior compared to European-specification OE outside rearview mirrors**

   Analysis of participants' eye-gaze fixations showed that participants made a greater number of fixations in daylight to the tested CMS displays compared to the European-specification OE outside rearview mirrors. There was no difference in the number of fixations between rear visibility technologies in darkness. The number of fixations did not differ when comparing the driver-side CMS display to the driver-side European-specification OE outside rearview mirror, the inside rearview mirror between rear visibility technology conditions, or the passenger-side CMS display to the passenger-side European-specification OE outside rearview mirror.

   Analysis of participants' average fixation durations showed that participants fixated for a longer average duration in darkness to the tested CMS displays compared to the European-specification OE outside rearview mirrors. There was no difference in the average fixation duration between rear visibility technologies in daylight. Additionally, in darkness, participants fixated for a longer average duration to the driver-side CMS display compared to the driver-side European-specification OE outside rearview mirror. Average fixation durations did not differ between the driver-side CMS display and driver-side European-specification OE outside rearview mirror in daylight or between the passenger-side CMS display and passenger-side European-specification OE outside rearview mirror in either lighting condition. The average fixation duration to the inside rearview mirror did not differ between rear visibility technologies in daylight or darkness.

   Analysis of participant total fixation durations showed that participants fixated for a longer total duration to the tested CMS displays compared to the European-specification OE outside rearview mirrors, specifically to the tested CMS displays when making a left lane change in darkness compared to the European-specification OE outside rearview mirrors when making a left lane change in darkness. Total fixation durations did not differ when comparing the driver-side CMS display to the driver-side European-specification OE outside rearview mirror, the inside rearview mirror between rear visibility technology conditions, or the passenger-side CMS display to the passenger-side European-specification OE outside rearview mirror.

   Overall, participants did not make many long duration fixations to either the tested CMS displays or European-specification OE outside rearview mirrors.

4. **Findings regarding whether head movements differed for CMS compared to European-specification OE outside rearview mirrors**

   Participants' head movements observed during lane change maneuvers differed between the tested CMS and the European-specification OE outside rearview mirrors in the heading and pitch directions. Overall, participants made more movements in the heading and pitch directions when driving with the European-specification OE outside rearview mirrors compared to the tested CMS. Additionally, there was an interaction whereby for left lane changes, head movement in the heading direction was greater for European-specification OE outside rearview mirrors compared to the tested CMS.

5. **Findings regarding whether illumination from the tested CMS visual displays hinders drivers' ability to detect forward obstacles in darkness**

   Results found no rear visibility technology-based difference in performance in the unexpected obstacle detection event. All participants saw the object and stopped before hitting it. Additionally, there was no difference between the European-specification OE outside rearview mirrors and the tested CMS for the distance from the vehicle's stopped location to the object.

6. **Findings regarding whether drivers' subjective impressions of general use, comfort, and visibility differ for the CMS compared to European-specification OE outside rearview mirrors**

   Participants subjectively rated the European-specification OE outside rearview mirrors as easier to use, more comfortable, and providing better image quality than the tested CMS. The European-specification OE outside rearview mirror's field of view size was rated to be more acceptable compared to that of the tested CMS. Especially in daylight, participants found they were less able to judge distances to either the left or the right with the tested CMS compared to the European-specification OE outside rearview mirrors. When asked to choose which rear visibility technology they would prefer to use in everyday driving, most participants chose the European-specification OE outside rearview mirrors over only the tested CMS or having both systems.

Results showed differences in driver behavior and performance observed between the tested CMS and the European-specification OE outside rearview mirrors. Participants took longer to complete a passing maneuver in daylight and maintained a greater overtake distance with the tested CMS compared to European-specification OE outside rearview mirrors. Separately, participants also maintained a greater overtake distance with the tested CMS when making a left lane change compared to making a left lane change with the European-specification OE outside rearview mirrors.

Participants' visual behavior also differed between the tested CMS compared to the European-specification OE outside rearview mirrors. In daylight, participants made a greater number of fixations to the tested CMS displays compared to the European-specification OE outside rearview mirrors. The number of fixations did not differ between rear visibility technologies in darkness. However, in darkness, average fixation durations were longer to the tested CMS displays compared to the European-specification OE outside rearview mirrors, specifically to the driver-side CMS display in darkness compared to the driver-side European-specification OE outside rearview mirror in darkness. Total fixation durations were also longer to the tested CMS displays, specifically the tested CMS displays when making a left lane change in darkness compared to the driver-side European-specification OE outside rearview mirror when making a left lane change in darkness.

Participants subjectively rated the European-specification OE outside rearview mirrors to be easier to use, more comfortable, and providing better visibility as compared to the tested CMS. When asked to choose which rear visibility technology they would prefer to use in everyday driving, most participants chose the European-specification OE outside rearview mirrors over only the tested CMS or having both systems.

Results of this small, preliminary study suggest that drivers' behavior in using the tested production-ready prototype CMS in a model year 2018 European-market light vehicle was different in terms of lane change performance, eye-gaze behavior, head movements, and subjective impressions compared to European-specification OE outside rearview mirrors. Results showed differences in overtake distance, passing maneuver completion time, number of fixations, average fixation durations, and total fixation durations when comparing the tested CMS to European-specification OE outside rearview mirrors. This study is part of a larger research program that will gather additional data on drivers' use of CMSs to assess whether these trends are consistent with a larger sample size, other systems, and the implications for driving safety.

1.0 Introduction

1.1 Background Regarding Camera-Based Visibility Systems

Camera-based visibility systems, also referred to as camera-monitor systems, are systems designed to replace or supplement required vehicle mirrors with small cameras that transmit video images to interior-mounted electronic visual displays. FMVSS No. 111 specifies the requirements for rear visibility, including specific requirements for when vehicles must have driver-side outside and inside rearview mirrors or both driver side and passenger side outside mirrors. FMVSS No. 111 paragraph S5.2 requires that "each passenger car shall have an outside mirror of unit magnification" on the driver's side. FMVSS No. 111 paragraph S5.3 further requires that, if the inside rearview mirror does not meet field of view requirements, then the passenger's side "shall have an outside mirror of unit magnification or a convex mirror installed."

As noted in the 2019 ANPRM, NHTSA has received two petitions from light and heavy vehicle manufacturers seeking permission to use a camera-based system to meet the visibility requirements currently specified for provision by outside rearview mirrors (NHTSA, 2019). The ANPRM also outlines several CMS performance concerns and human factors questions regarding drivers' ability to safely use CMSs for which that ANPRM states data are needed to inform the decision regarding whether to permit CMSs in lieu of required outside mirrors. For example, while CMSs may have the ability to provide a wider field of view, the displayed image is subject to distortion due to the wider field of view being compressed for presentation on a small display area. Questions exist regarding whether CMSs can provide the driver with equivalent visual information as OE mirrors as well as similar ease of use. Before the agency considers amending FMVSS No. 111 to allow for CMSs to be installed in place of currently required OE mirrors, it is important to ensure that, at a minimum, camera-based systems would provide the same level of safety as currently required rearview mirrors.

A small-scale research study was conducted to obtain initial information regarding how driving performance is affected when driving with a CMS as compared to mirrors. As camera monitor systems are not currently a permitted means of FMVSS No. 111 compliance with rearview mirror requirements, no U.S. market system was readily available for testing. A U.S. vehicle manufacturer agreed to lease NHTSA their research vehicle that was a European-market compact light vehicle equipped with a production-ready prototype CMS and European-specification OE mirrors that included a convex driver-side outside rearview mirror. The driver-side convex outside rearview mirror of the leased CMS-equipped vehicle did not meet FMVSS No. 111 requirements since the standard requires an outside mirror of unit magnification on the driver's side." Modifying the vehicle to fit it with FMVSS No. 111 compliant mirrors was considered but determined not feasible. As such, the vehicle was tested with the existing mirrors.

The objective of this research was to perform a human subjects experiment to examine drivers' use of a CMS in a light vehicle as compared to the outside rearview mirrors and to gather information regarding differences in driver behavior and performance. The experiment examined lane-change performance, eye-gaze behavior, detection of an unexpected obstacle, and subjective ratings of ease of use, image quality, comfort, and perceived safety associated with a production-ready prototype CMS compared to European-specification OE outside rearview mirrors in a model year 2018 European-market light vehicle.

1.1.1 Field of View

A specific question laid out in the ANPRM was whether a CMS can provide a "clear and reasonably unobstructed view" equivalent to that of rearview mirrors. FMVSS No. 111 specifies requirements regarding mounting specifications and a minimum field of view. CMSs have the potential to offer an expanded field of view, potentially eliminating the blind spots seen with rearview mirrors. However, a wider field of view also has the potential to cause minification of objects, rendering objects narrower and more difficult to discern (Mazzae et al., 2018). Additionally, unlike with rearview mirrors, drivers cannot move their head to alter the view provided by CMSs. While this may mean participants ultimately do not have to make as many head movements while driving as seen by research from Ali and Bazilah (2014), it also means evaluating the field of view must take into consideration that any differences in field of view cannot be compensated for by the driver.

1.1.2 Depth Perception

A component of answering the ANPRM's question regarding whether CMSs provide a clear and unobstructed view concerns distinguishing if the CMS provides similar visual cues as rearview mirrors. Rearview mirrors allow for retention of the distance cues afforded by stereoscopic vision allowing for the processing of depth. When viewing an object, the two eyes point inward to focus on one object in an action called convergence. Stereoscopic vision allows the retina of each eye to produce a slightly different image of the scene before it because each eye is a slightly different distance from the objects in a viewing scene. When the brain assembles both images together, depth can be extrapolated using the disparity of each eye. If another object is in front of or behind the first object, the image of the second object will fall on a slightly different relative position on each of the two retinas (Flannagan et al., 2001a). Planar mirrors reflect light at the same angle that the mirror received the light, allowing for perfect mapping between the object and the image reflected by a planar mirror and retaining the distance cues the eyes need to perceive depth.

However, because an electronic visual display is not reflecting light, the mapping available with planar mirrors is not seen. With an electronic visual display, all objects appear to be on the same level, irrespective of the actual distance and do not provide all the visual distance cues that are available to drivers with direct vision (or that are available with planar, but not convex, rearview mirrors) (Flannagan et al., 2001b). This affects how drivers can accurately perceive depth with CMSs.

The ability to accurately perceive depth when driving is important, particularly for judging distances to other vehicles and objects along the road. Research with heavy trucks has shown that a CMS may help drivers more accurately judge whether there is clearance between the trailer and an adjacent vehicle (Fitch et al., 2008; Wierwille et al., 2011), but that this may also lead to shorter cut-in distances when making a lane change in front of a slower moving vehicle (Fitch et al., 2008; Fitch et al., 2011). However, research with light vehicles has shown that participants left longer distances when indicating the least acceptable gap distance for pulling out in front of another vehicle (Flannagan & Mefford, 2005; Schmidt et al., 2016). Research with heavy trucks has also shown that drivers' mean glance time may be shorter to CMS displays (Fitch et al., 2011), but that driver glance behavior can also be heavily influenced by properties of the CMS, like a wider-angle lens and CMS display placement (Fitch et al., 2008). Research in a driving simulator has found that participants initiated lane changes earlier with a CMS and that depending on the location of the CMS displays, off-road eye glance durations were shorter with a CMS compared to outside rearview mirrors (Beck et al., 2017; Large et al., 2016).

1.1.3 Image Quality

The ANPRM also states that a CMS should provide the minimum parameters concerning resolution, contrast, color, and tone as to provide equivalent image quality to rearview mirrors. NHTSA research (Mazzae et al., 2018) found image clarity to be comparable to outside rearview mirrors and found that the displays provided good visibility, particularly during dusk and dawn. This research also found sunlight glare on the display to be a potential cause for concern. Glare from headlights may also present as an issue during driving in the darkness (Fitch et al., 2011). While CMS displays being located within the vehicle avoids some issues affecting mirrors, such as a rain-covered window impeding view of the mirror image, CMSs can be affected by image quality issues of their own including but not limited to distortion and blooming of other vehicles' headlamps.

1.2 Study Objectives

While CMSs may be designed to either replace or supplement OE mirrors, this report specifically describes research that examines the case of CMS technology replacing OE outside rearview mirrors for a light vehicle. This study sought to obtain initial information regarding how driving performance may be affected when driving with a CMS. The objective of this research was to perform a human subjects experiment to examine drivers' use of a CMS in a light vehicle as compared to the European-specification OE outside rearview mirrors, to gather information regarding differences in driver behavior and performance. This experiment examined lane-change performance, eye-gaze behavior, detection of an unexpected obstacle, and subjective ratings of ease of use, image quality, comfort, and perceived safety associated with a CMS compared to European-specification OE outside rearview mirrors to answer the following research questions.

1. Does lane-change performance differ when driving with the tested CMS compared to European-specification OE outside rearview mirrors?
2. Does driving with the tested CMS result in differences in distance judgments when passing a slower lead vehicle compared to European-specification OE outside rearview mirrors?
3. Does driver eye-gaze behavior during lane change and passing maneuvers differ with the tested CMS compared to European-specification OE outside rearview mirrors?
4. Does driver head movement during lane change and passing maneuvers differ with the tested CMS compared to European-specification OE outside rearview mirrors?
5. Does illumination from the tested CMS visual displays hinder drivers' ability to detect forward obstacles in darkness?
6. Do drivers' subjective impressions of general use, comfort, and visibility differ for the tested CMS compared to European-specification OE outside rearview mirrors?

The information collected can provide insight into CMS design, performance, and conceivable issues associated with the replacement of OE outside rearview mirrors with CMSs.

2.0 Description of the Tested Rear Visibility Technologies

2.1 Test Vehicle

The test vehicle was a compact European-market model that has a similar U.S. version. The vehicle had both European-specification OE mirrors and a production-ready prototype CMS installed by the vehicle manufacturer. The test vehicle's mirrors had the following characteristics.

- Inside rearview mirror: Planar
- Outside rearview mirror – driver side: Convex (radius of curvature 1,300 mm) and a 40-mm aspheric area at the far edge of the mirror surface
- Outside rearview mirror – passenger side: Convex (radius of curvature 1,300 mm)

Each rear visibility technology was tested separately. In the European-specification OE outside rearview mirrors condition, the CMS displays were powered off. The vehicle's OE inside rearview mirror was available for use in both the European-specification OE outside rearview mirrors and CMS conditions. A schematic layout of the vehicle is shown in Figure 1.

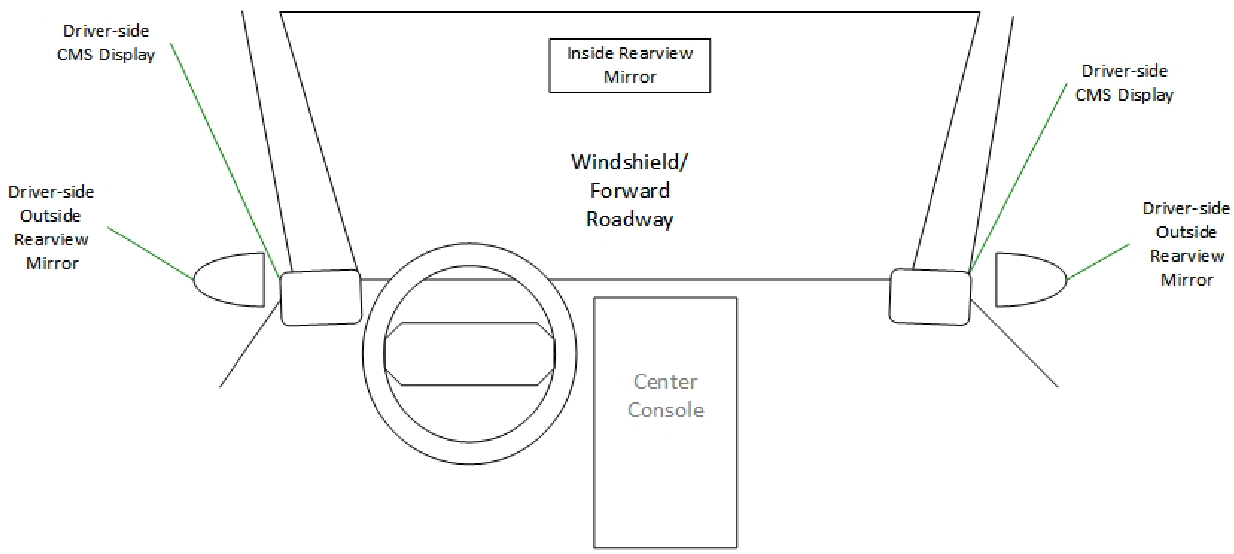

Figure 1. Visual schematic of areas of interest located throughout the vehicle

CMS components included two exterior-mounted cameras and two electronic visual displays mounted inside the vehicle just aft of the respective A-pillars at a height like that of outside mirrors. Each camera's horizontal field of view angle was approximately 46°.

The fields of view for both rear visibility technologies were determined for a visual target consisting of a 3-inch (7.62 cm) diameter red, circular reflector mounted atop a traffic cone. The visual target's overall height was 26.4 inches (67.1 cm). The target was considered visible when the entire reflector could be seen in either of a system's electronic visual displays. The test vehicle's European OE driver-side outside rearview mirror was not planar and, thus, not FMVSS No. 111 compliant. The driver-side mirror was primarily convex (1,300 mm radius of curvature) with a small outer aspheric section. The passenger-side mirror was convex (1,300 mm radius of curvature). The outside mirrors' horizontal field of view angles as estimated for a 50th percentile male driver were approximately 19° and 13° for the driver side and passenger sides, respectively.

Test participants were permitted to adjust the mirrors, so the available fields of view may have differed for each driver. Even though the OE driver-side outside rearview mirror was convex (i.e., not FMVSS No. 111 compliant), this vehicle was used for this preliminary research as it provided a way to test a CMS and mirrors within the same vehicle.

3.0 Method

This experiment compared drivers' use of European-specification OE outside rearview mirrors with that of a CMS during test-track driving.

3.1 Participants

Eleven participants (3 female/8 male; median age of all participants: 36.27 years) were included in this study. Participants were contractor employees at NHTSA's Vehicle Research and Test Center who had no familiarity with the study and were recruited through interoffice communications. Requirements for participation included being between the ages of 25 to 65, having an active valid U.S. driver's license with no uncorrected vision or hearing problems, having driven at least 11,000 miles annually, having no more than 2 points on their driver's license, and having no recent criminal convictions. Participants were also required to be able to read and speak English and be willing to spend up to three hours participating in the study. Participants were required to be in good health, not requiring assistive devices to safely operate a vehicle, and be able to drive continuously for 3 hours.

Additionally, recruitment included only current or previous owners of the U.S. version of the vehicle model tested (two participants), or owners of a similar compact light vehicle (nine participants).

3.2 Approach

This experiment used a two (rear visibility technology) × two (lighting condition) within-subjects experimental design. Rear visibility technology was a within-subjects variable with two technologies: European-specification OE outside rearview mirrors and CMS. Lighting condition was a within-subjects variable with two levels: daylight and darkness. Daylight was defined as between the times of sunrise and sunset. Darkness was defined as commencing 30 minutes after the end of the evening astronomical twilight period. Only one darkness test session would be conducted in an evening and data collection would begin soon after the darkness period began. Participants completed two experimental sessions in which experimental conditions were quasi-randomized. During one session, participants completed both rear visibility technology conditions within one lighting condition. The order of rear visibility technology was randomized and counterbalanced within lighting condition. Six of the participants completed the daylight conditions first and five completed the darkness conditions first. Daylight and darkness experimental sessions were not completed on the same day. The experimental design is summarized in Table 1.

Table 1. Summary of experimental design

<table>
<tr><th>Experimental Session</th><th>Rear Visibility Technology</th><th>Lighting Condition</th><th>Participants</th></tr>
<tr><td rowspan="2">1</td><td>European-Specification OE Outside Rearview Mirrors</td><td rowspan="2">Daylight</td><td rowspan="4">11</td></tr>
<tr><td>CMS</td></tr>
<tr><td rowspan="2">2</td><td>European-Specification OE Outside Rearview Mirrors</td><td rowspan="2">Darkness</td></tr>
<tr><td>CMS</td></tr>
</table>

3.3 Apparatus

3.3.1 Instrumentation and Equipment

3.3.1.1 Vehicle Position Data Acquisition

An in-house developed data acquisition system, VCDAS (Video and CAN Data Acquisition System) was used to record data extracted from the vehicle's CAN bus and an Oxford Technical Solutions[1] RT3000 v2 and RT-Range. Vehicle control data included steering rate, accelerator use, brake use, and turn signal use. The RT3000 v2 and RT-Range were used to record vehicle position, acceleration, velocity, and longitudinal and lateral distances between the test vehicle and the scenario vehicles. An RT-Range Hunter unit was installed in the test vehicle through which all RT-Range data were collated and calculated. RT-XLAN antennas were mounted on the two scenario vehicles for collecting and transmitting information back to the Hunter unit for processing. CAN bus and RT-Range data were recorded continuously throughout the data collection at a rate of 200 Hz.

For video data collection, a camera was positioned near the passenger A-Pillar to capture video of the driver. An Audio-Technica Pro70 microphone[2] was located above the inside rearview mirror to capture audio during the experimental session.

3.3.1.2 Eye-Tracking System

A Smart Eye Pro eye-tracking system[3] and iMotions software[4] were used to gather driver eye-gaze information during the experiment. The Smart Eye system was an off-the-head eye tracking system that consisted of 4 cameras size 31 mm x 31 mm and 3 infrared flashes to illuminate the driver's face with infrared light mounted in various locations in the vehicle. The cameras were synchronized and recorded at a frequency of 60 Hz. Eye tracking data were time-synchronized with vehicle position data through VCDAS.

3.3.2 Scenario Vehicles

Two scenario vehicles were used to create the need for the participant to change lanes and pass a slower lead scenario vehicle. The scenario vehicles were visually identical model year 2015 and 2016 Chrysler 200 sedans. The scenario vehicles had electronic visual displays that showed the scenario drivers the distance between the scenario vehicle and the participant vehicle. The scenario vehicle drivers used the displayed distance information to maintain 60 m to the participant vehicle throughout most of the lane change scenarios.

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[1] Oxford Technical Solutions Ltd., Oxfordshire, United Kingdom. www.oxts.com
[2] Audio-Technica U.S., Inc., Stow, OH. www.audio-technica.com
[3] Smart Eye, Gothenburg, Sweden. www.smarteye.se
[4] iMotions, Copenhagen K, Denmark. www.imotions.com

3.3.3 Test Scenarios

During the two experimental sessions, participants performed two driving tasks: (1) making required lane changes on the test track, and (2) responding to an unexpected obstacle detection event.

3.3.3.1 Lane-Change Scenarios

For lane-change scenarios, participants drove on the 7.5-mile (12.1 km) oval test track at the Transportation Research Center proving ground in East Liberty, Ohio. The test track consists of two straightaways, each about 2 miles long, separated by the curved segments that are approximately 1.75 miles long. While one straight section had four lanes and the other had five, participants' driving was restricted to two specific lanes.

Participants were instructed to maintain a speed of 60 mph and to pass any slower moving vehicles if needed to maintain that speed. The participant's task was to maintain a constant speed, while the scenario vehicles varied their position and speed to elicit the desired lane-change scenarios. Unbeknownst to the participant, the scenario vehicles used the real-time display to maintain set distances and speed around the participant vehicle and would vary speed to create the need for the participant to make a lane change and pass a slower moving vehicle. Lane changes were made only on straight sections of the track and not on curved sections. During the first lap, participants entered the test track and completed a practice lap without making any lane changes to become familiar with driving on the test track. During the remaining laps, participants completed lane changes along each straightaway and then exited the track when complete.

The lane change scenarios for a left passing maneuver are shown in the figure below.

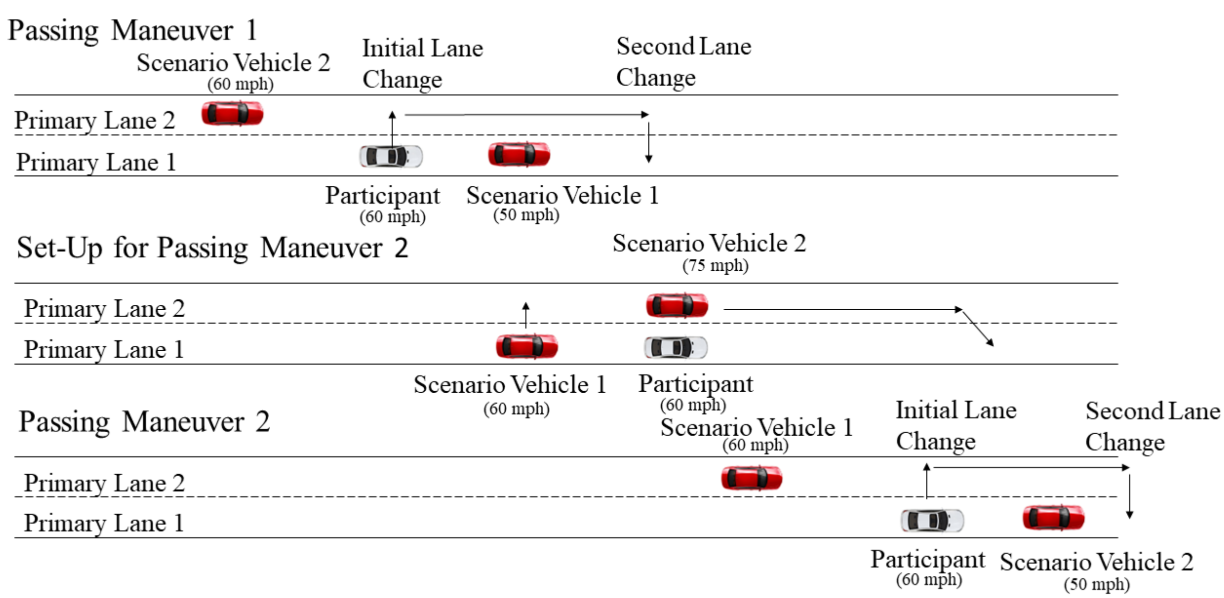

Figure 2. Visual representation of the lane change scenarios in a left passing maneuver

A straightaway with passing maneuvers proceeded in the following stepwise order:

- Around the curves, scenario vehicle 1 and scenario vehicle 2 maintained 60 m from the participant vehicle.
- At the start of the straight, scenario vehicle 1 slowed to 50 mph forcing the participant (maintaining 60 mph) to need to make a lane change and pass scenario vehicle 1.
- At the start of the straight, scenario vehicle 2 moved to the adjacent lane and maintained a rear distance of 60 m to the participant and a speed of approximately 60 mph.
- Once the participant made the second lane change in front of scenario vehicle 1, scenario vehicle 2 would increase speed to 75 mph and then change lanes in front of the participant at 60 m and then without braking slow to 50 mph forcing the participant to complete a second passing maneuver.
- As soon as scenario vehicle 2 changed lanes in front of the participant vehicle, scenario vehicle 1 would move to the adjacent lane and increase speed back to 60 mph and maintain a rear distance of 60 m to the participant.
- Following the second passing maneuver, scenario vehicle 1 would increase speed to 75 mph and change lanes back in front of the participant at 60 m causing all vehicles to be in the original formation around the curve.

Drives required an equal amount of left and right lane changes, the order of which was randomized and counterbalanced. During each session, participants completed two drives, one with the tested CMS and one with European-specification OE outside rearview mirrors.

Participants completed approximately 5 laps around the test track for a total of 37.5 miles and made lane changes along the straightaways. Occasionally, participants completed an additional lap due to other traffic on the track preventing the execution of the lane change scenario on a given straightaway. However, this was infrequent as only 6 out of 44 sessions required 6 laps and one session required 7 laps. No sessions required more than 7 laps.

3.3.3.2 Unexpected Obstacle Detection Scenario

The unexpected obstacle detection event involved participants detecting an object in their path in front of the garage door where the participant was to return the vehicle. Following the second darkness test-track drive, participants were instructed to drive the vehicle back to the garage where the object was in the path of the participants' access to the garage. To return to the garage, participants had to drive around a corner and around an additional vehicle that was parked to the side of the object, blocking participants from seeing it before pulling straight into the garage. The object was a realistic plush raccoon toy with the following dimensions: 17.7 x 5.9 x 11.8 inches. After participants either stopped or hit the object, the experimenter told the participants to stop and put the vehicle in park at the present location. For participants who stopped before hitting the object, the distance was measured between where the participant stopped and the object.

Participants were presented with the unexpected obstacle detection event following the second darkness test-track drive. This means that five participants experienced the unexpected obstacle detection event at the end of the first experimental session and the remaining six participants experienced the unexpected obstacle detection event at the end of the second experimental session.

3.4 Vehicle Preparation Procedure

CMS components (i.e., camera lenses and electronic visual displays) were cleaned to ensure they were free of dirt and other substances that could have impacted performance.

3.5 Procedure

At the start of each experimental session, the participant was asked to read an informed consent form providing study information and detailing the experimental task. After the participant read the form, an experimenter presented a brief oral summary of the protocol and participation requirements, after which the participant was given another opportunity to ask questions. After all questions were answered, the participant was asked to sign an electronic informed consent form on a tablet computer. Following informed consent, the participant received instructions and guidelines about driving on the test track. The participant was instructed to drive normally and maintain a constant speed of 60 mph. Additionally, the participant was instructed to change lanes to pass any slower moving vehicles, if needed, and return to the original lane afterward. The participant was instructed that while they should pass a slower moving vehicle if needed, ultimately safe driving should be the highest priority.

The experimenter then showed the participant the test vehicle and demonstrated use of the assigned rear visibility technology. Next, the participant's eye gaze was calibrated using the eye tracker. Following calibration, the experimenter moved to the rear passenger seat of one of the scenario vehicles to prevent observation biases as well as to provide and monitor communication with the participant through a closed hands-free phone line whereby any communication other than from the experimenter was blocked. The experimenter wore a hands-free Bluetooth earpiece with a microphone and participants could communicate with the experimenter through a hands-free Bluetooth speaker in the test vehicle. While the experimenter limited communication to the participant and other experimental personnel to allow the participant to drive normally without additional distractions, the earpiece allowed communication about the primary driving lane and deviations from the procedure due to other traffic, track issues, or weather conditions. The two scenario vehicle drivers communicated to each other through a second, separate closed hands-free phone line using Bluetooth speakers.

The participant was instructed to follow one of the scenario vehicles to the test track and then completed five full laps. During the test-track drives, participants only drove in lanes one and two. Lane changes were performed in lanes one and two on straight road sections and participants always drove around the curves in lane one. To ensure an equal number of left and right lane changes, participants were informed that each straightaway would have a primary driving lane. Immediately before reaching each straightaway, the experimenter would communicate which primary lane the participant should start in (one or two). Scenario vehicles driving in the primary lane would decrease speed, creating the need to make a lane change. For primary driving lane one, participants stayed in lane one and when encountering a slower moving vehicle in front of them, participants performed a left passing maneuver. For primary driving lane two, participants were prompted by the experimenter to move into lane two at the end of the previous curve, and then stay in lane two and pass any slower moving vehicles by performing a right passing maneuver. At the end of a primary-lane two straightaway, the experimenter prompted the participant to get back into lane one before entering the curve.

After completing all lane changes, the participant followed one of the scenario vehicles off the test track to a pull-off area to park the vehicle. The participant then completed a post-drive subjective questionnaire on a tablet computer to gather ratings regarding ease of use, image quality, comfort, and perceived safety of the rear visibility technology.

Following the post-drive questionnaire, the experimenter provided instructions for the second drive and demonstrated use of the second assigned rear visibility technology. For example, if the participant completed the first drive with the European-specification OE outside rearview mirrors, they would complete the second drive with the tested CMS, or vice-versa. The participant was given the opportunity to adjust the rear visibility technology and ask questions. A second gaze calibration was performed. Once the participant was ready to continue, they were instructed to follow the scenario vehicle back to the test track to complete the second drive. The participant completed the second drive on the test track and was then instructed to exit the test track to park and complete the second post-drive questionnaire.

During a darkness session, while the participant was completing the post-drive questionnaire, the scenario vehicle without the experimenter drove back to the laboratory building to set up the unexpected obstacle event. Following completion of the post-drive subjective questionnaire, the participant was instructed to return to the laboratory. While returning to the laboratory, the participant was instructed to return the vehicle to a specific garage door near the laboratory. In the darkness session, as the participant was pulling up to the garage door, they experienced the obstacle detection event and the response was recorded. Following completion of the obstacle detection task, the participant was debriefed on the purpose of the experiment and paid for participation.

A time breakdown for each component of a daylight experimental session follows.

- Instructions, pre-brief, training, and eye tracker calibration (40 min)
- Test-track drive 1 (40 min)
- Post-drive questionnaire (10 min)
- Eye tracker re-calibration (5 min)
- Test-track drive 2 (40 min)
- Post-drive questionnaire (10 min)
- Post-trial debriefing (5 min)

A time breakdown for each component of a darkness experimental session follows.

- Instructions, pre-brief, training, and eye tracker calibration (40 min)
- Test-track drive 1 (40 min)
- Post-drive questionnaire (10 min)
- Eye tracker re-calibration (5 min)
- Test-track drive 2 (40 min)
- Post-drive questionnaire (10 min)
- Unexpected obstacle detection event (10 min)
- Post-trial debriefing (5 min)

Each participant's experimental session was approximately 3 hours.

3.6 Data Processing

Data streams were synchronized to a sampling rate of 60 Hz. Lane changes were defined by the heading angle and lateral offset to the lane line. The start of a lane change was designated by a heading angle of more than 1.2° and a lateral offset to the lane center of more than 1 meter. RT signal dropouts were rare but occasionally happened during a lane change or passing maneuver. RT dropouts were present in less than 4 percent of all passing maneuvers and linear interpolation was performed in these instances.

Each passing maneuver included the following.

1. As the participant approached the slower moving scenario vehicle, an initial lane change into the adjacent lane was made.
2. As the participant passed the slower scenario vehicle in the adjacent lane, a second lane change was performed that returned the test vehicle to the primary lane in front of the slower scenario vehicle.

Therefore, each passing maneuver had two lane changes, an initial lane change and a second lane change of opposite direction. For left passing maneuvers, the initial lane change was a left lane change and the second lane change was a right lane change. For right passing maneuvers, the initial lane change was a right lane change and the second lane change was a left lane change. For clarity, some analyses have separated data by lane change order in the passing maneuver. From the start of the initial lane change until the end of the second lane change is one complete passing maneuver.

4.0 Results

Data analysis focused on lane-change performance characteristics, eye-gaze behavior, unexpected obstacle detection, and post-drive subjective ratings.

Linear mixed effects analysis was performed in R (R Core Team, 2021) using the *lmer* package and figures were produced using the *ggplot2* package (Wickham, 2009). Satterthwaite (1946) approximations were used to determine denominator degrees of freedom for *p*- values. Tukey's method was used to correct for multiple comparisons. Significance was evaluated at $p < 0.05$, indicating a probability of 5 percent or less that a significant finding was due to chance. Since the overall study design was a repeated measures design and conditions within the same participant are not completely independent, analyses were conducted using linear mixed effects modeling.

4.1 Lane Change Performance

To assess whether driving with the tested CMS led to differences in lane change performance characteristics, the following metrics were used to quantify performance: time to complete a lane change, time to complete a passing maneuver, overtake distance to the passed slower moving vehicle, and the time to collision to the passed slower moving vehicle. Each participant completed 16 passing maneuvers per condition, resulting in a total of 64 passing maneuvers and 128 total lane changes across all conditions. Therefore, the total analysis included 704 passing maneuvers and 1,408 lane changes. Separate linear mixed effects models were run on the initial lane change duration in a passing maneuver, the second lane change duration during a passing maneuver, total passing maneuver completion time, overtake distance when making a lane change in front of a slower moving vehicle, and the time to collision when making a lane change in front of a slower moving vehicle. In these models, fixed effects of rear visibility technology, lighting condition, and lane change direction and their interactions were included as well as a random intercept term for participant.

4.1.1 Initial Lane Change Completion Time

To evaluate lane change performance, an analysis was performed on the time to complete the initial lane change in a passing maneuver. Results found a significant effect for lighting condition. The average initial lane change duration was longer for drives in darkness (M = 10.26 s, SE = 0.41 s) compared to daylight (M = 9.65 s, SE = 0.41 s, $p < 0.05$). All other tests failed to gain significance. Results are shown in Figure 3. Means and standard errors are shown in Table 2.

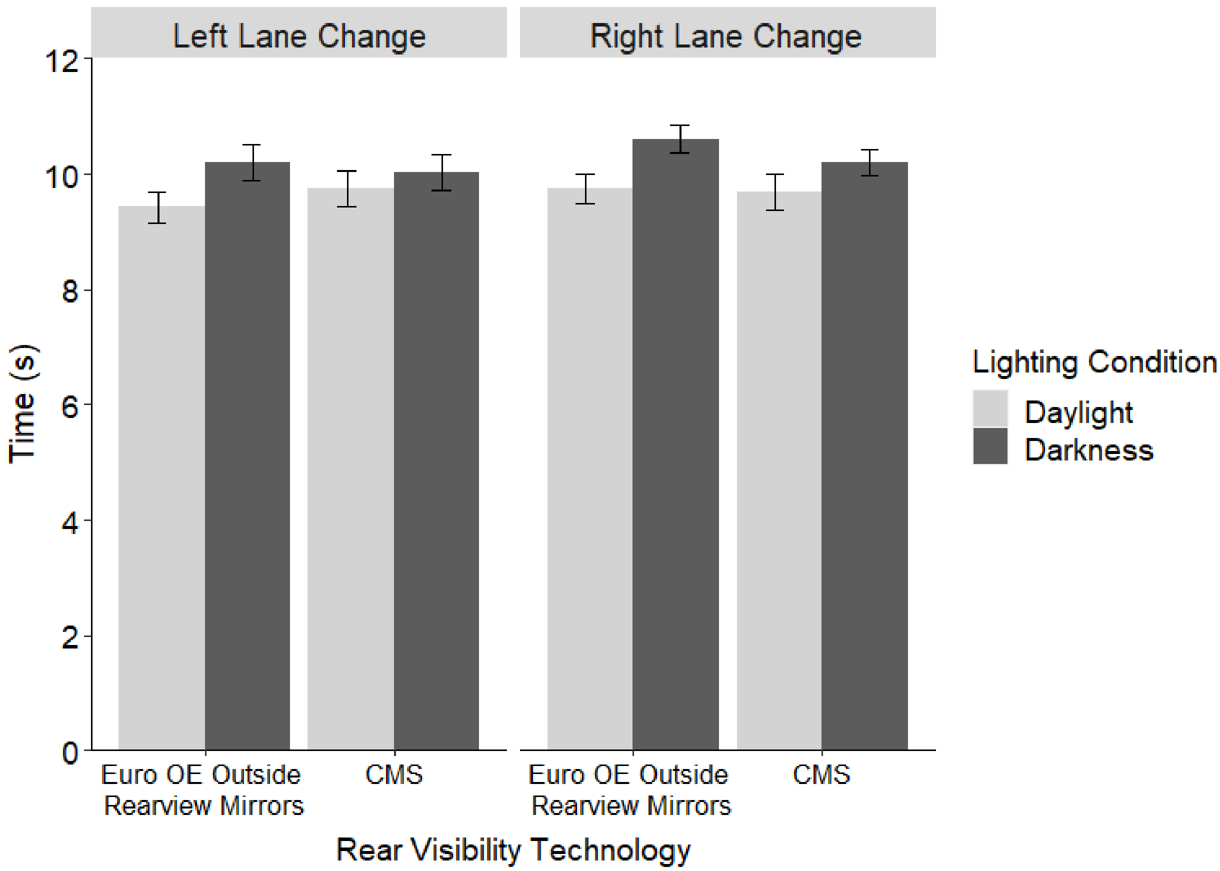

Figure 3. Average duration in seconds to complete the initial lane change in a passing maneuver. Error bars are standard error.

Table 2. Means and standard errors for initial lane change duration

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (s)	Standard Error (s)
Euro OE Outside Rearview Mirrors	Daylight	Left	9.42	0.27
		Right	9.75	0.26
CMS	Daylight	Left	9.75	0.30
		Right	9.68	0.31
Euro OE Outside Rearview Mirrors	Darkness	Left	10.21	0.31
		Right	10.61	0.24
CMS	Darkness	Left	10.03	0.32
		Right	10.20	0.22

4.1.2 Second Lane Change Completion Time

To evaluate lane change performance, an analysis was performed on the time to complete the second lane change in a passing maneuver. Results found significant effects for lighting condition and lane change direction. The average second lane change duration was longer for drives in darkness (M = 10.50 s, SE = 0.42 s) compared to daylight (M = 10.01 s, SE = 0.42 s, $p < 0.05$). The average second lane change duration was longer when making a right lane change (M = 10.53 s, SE = 0.42 s) compared to making a left lane change (M = 9.94 s, SE = 0.42 s, $p < 0.05$). All other tests failed to gain significance. Results are shown in Figure 4. Means and standard errors are shown in Table 3.

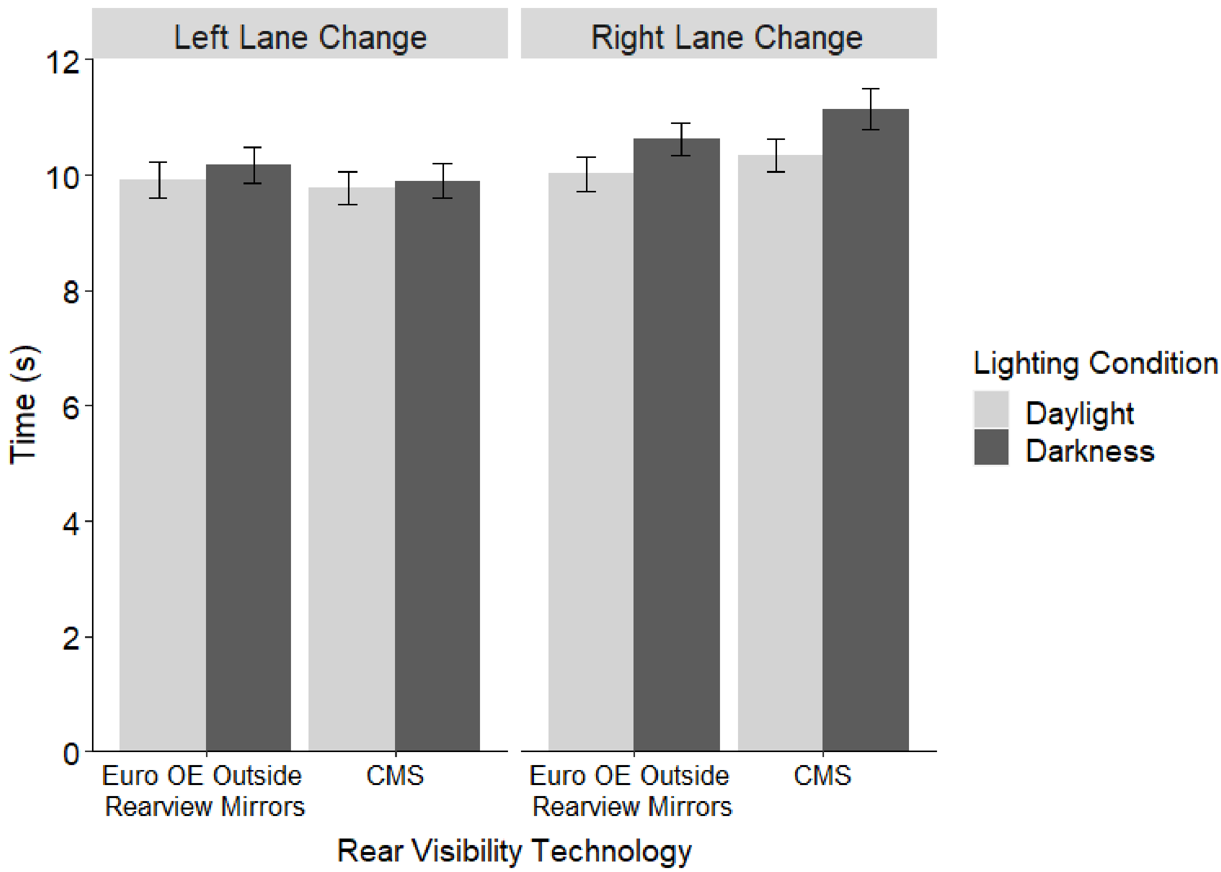

Figure 4. Average duration in seconds to complete the second lane change in a passing maneuver. Error bars are standard error.

Table 3. Means and standard errors for second lane change duration

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (s)	Standard Error (s)
Euro OE Outside Rearview Mirrors	Daylight	Left	9.91	0.31
		Right	10.02	0.29
CMS	Daylight	Left	9.78	0.27
		Right	10.34	0.28
Euro OE Outside Rearview Mirrors	Darkness	Left	10.17	0.31
		Right	10.63	0.28
CMS	Darkness	Left	9.90	0.29
		Right	11.15	0.35

4.1.3 Passing Maneuver Total Completion Time

Beyond individual lane change completion times, lane change performance was also evaluated by performing an analysis on the time to complete a full passing maneuver. Results found significant effects for rear visibility technology, lighting condition, and passing maneuver direction. The average time to complete a passing maneuver was longer for drives with the tested CMS (M = 30.36 s, SE = 1.94 s) compared to the European-specification OE outside rearview mirrors (M = 29.62 s, SE = 1.94 s). The average time to complete a passing maneuver was longer for drives in darkness (M = 30.52 s, SE = 1.94 s) compared to daylight (M = 29.50 s, SE = 1.94 s, $p < 0.05$). The average time to complete a passing maneuver was longer for right passing maneuvers (M = 30.31 s, SE = 1.94 s) compared to left passing maneuvers (M = 29.70 s, SE = 1.94 s). Results also found a significant lighting condition × passing maneuver direction interaction. Average time to complete a passing maneuver differed in daylight where completion time was longer for right passing maneuvers (M = 30.13 s, SE = 1.95 s) compared to left passing maneuvers (M = 28.81 s, SE = 1.95 s, $p < 0.05$). Passing maneuver completion time did not differ for left and right passing maneuvers in darkness ($p = 0.99$). All other tests failed to gain significance. Results are shown in Figure 5. Means and standard errors are shown in Table 4.

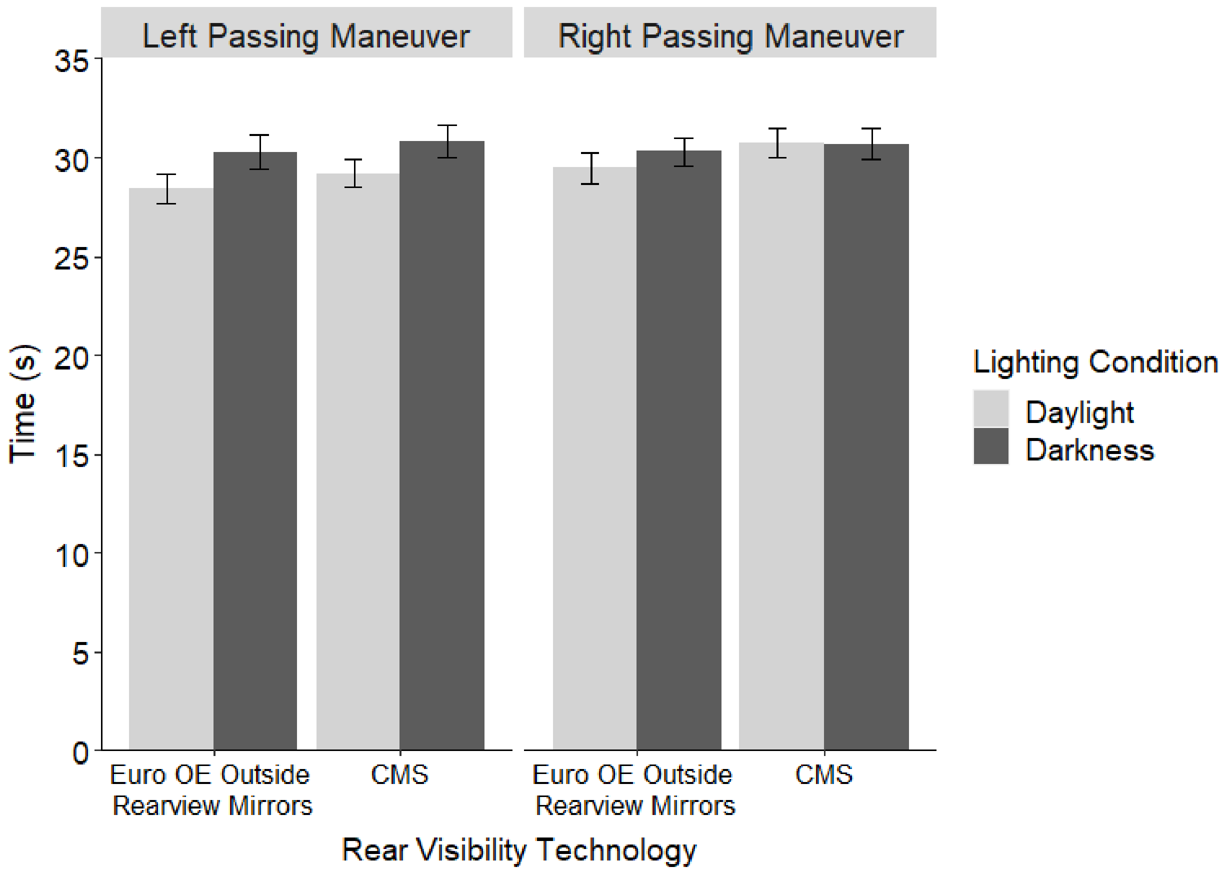

Figure 5. Average duration in seconds to complete a full passing maneuver which included both the initial and second lane changes. Error bars are standard error.

Table 4. Means and standard errors for passing maneuver completion time

Rear Visibility Technology	Lighting Condition	Maneuver Direction	Mean (s)	Standard Error (s)
Euro OE Outside Rearview Mirrors	Daylight	Left	28.41	0.75
		Right	29.47	0.76
CMS	Daylight	Left	29.20	0.70
		Right	30.78	0.74
Euro OE Outside Rearview Mirrors	Darkness	Left	30.29	0.84
		Right	30.31	0.70
CMS	Darkness	Left	30.80	0.82
		Right	30.67	0.79

4.1.4 Overtake Distance

To evaluate differences in distance judgments, an analysis was performed on the overtake distance when passing in front of the slower moving vehicle. The overtake distance was defined using the resultant distance which includes both the lateral and longitudinal distances to the passed slower moving vehicle. Results found significant effects for rear visibility technology, lighting condition, and lane change direction. The average overtake distance was greater for the tested CMS (M = 17.85 m, SE = 2.43 m) compared to the European-specification OE outside rearview mirrors (M = 15.81 m, SE = 2.43 m, $p < 0.05$). The average overtake distance was greater in darkness (M = 17.77 m, SE = 2.43 m) compared to daylight (M = 15.88 m, SE = 2.43 m, $p < 0.05$). The average overtake distance was greater for making a left lane change in front of the passed vehicle (M = 17.62 m, SE = 2.43 m) compared to making a right lane change in front of the passed vehicle (M = 16.04 m, SE = 2.43 m, $p < 0.05$). An important distinction to keep in mind is that this analysis is focused on the second lane change of the passing maneuver. This means that the result finding that the passed distance is greater for making a left lane change in front of the passed vehicle is a component of a right passing maneuver (whereby the participant passes the slower moving vehicle on the right).

Results also found significant rear visibility technology x lighting condition and rear visibility technology x lane change direction interactions. In daylight, the average overtake distance differed when comparing the tested CMS and European-specification OE outside rearview mirrors. The average overtake distance in front of the slower moving vehicle was greater for the tested CMS in daylight (M = 17.49 m, SE = 2.46 m) compared to the European-specification OE outside rearview mirrors in daylight (M = 14.27 m, SE = 2.46 m, $p < 0.05$). In darkness, the average overtake distance did not differ between the tested CMS and European-specification OE outside rearview mirrors ($p = 0.45$). Additionally, the average overtake distance differed between the tested CMS and the European-specification OE outside rearview mirrors when making a left lane change in front of the passed vehicle. The average overtake distance was greater for making a left change in front of the passed vehicle with the tested CMS (M = 19.20 m, SE = 2.46 m) compared to making a left change in front of the passed vehicle with European-specification OE outside rearview mirrors (M = 16.03 m, SE = 2.46 m, $p < 0.05$). The average overtake distance did not differ between the tested CMS and European-specification OE outside rearview mirrors when making a right lane change ($p = 0.42$). All other tests failed to gain significance. Results are shown in Figure 6. Means and standard errors are shown in Table 5.

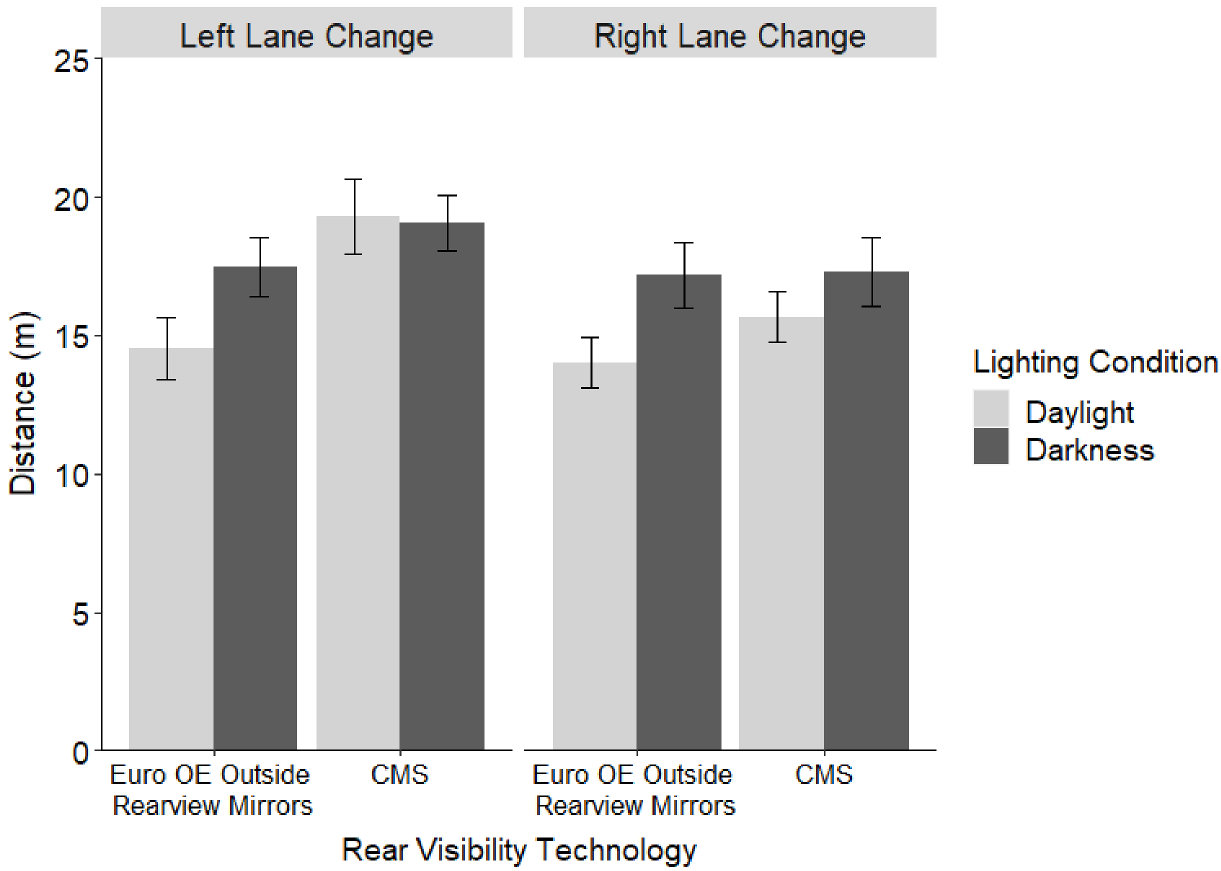

Figure 6. Average distance in meters when passing the slower moving scenario vehicle. Error bars are standard error.

Table 5. Means and standard errors for passing distance

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (m)	Standard Error (m)
Euro OE Outside Rearview Mirrors	Daylight	Left	14.55	1.12
		Right	14.00	0.91
CMS	Daylight	Left	19.32	1.37
		Right	15.66	0.92
Euro OE Outside Rearview Mirrors	Darkness	Left	17.50	1.06
		Right	17.18	1.17
CMS	Darkness	Left	19.09	1.01
		Right	17.31	1.23

4.1.5 Time to Collision

To further evaluate differences in distance judgments, an analysis was performed on the time to collision when passing in front of the slower moving vehicle. Results found significant effects for rear visibility technology, lighting condition, and lane change direction. The average time to collision was longer for the tested CMS (M = 5.07 s, SE = 0.78 s) compared to the European-specification OE outside rearview mirrors (M = 4.40 s, SE = 0.78 s, $p < 0.05$). The average time to collision was longer in darkness (M = 5.05 s, SE = 0.78 s) compared to daylight (M = 4.43 s, SE = 0.78 s). The average time to collision was longer for left lane changes (M = 5.14 s, SE = 0.78) compared to right lane changes (M = 4.34 s, SE = 0.78 s, $p < 0.05$). Like the overtake distance analysis, this analysis is focused on the second lane change of the passing maneuver. This means that the result finding that the time to collision is greater for making a left lane change is a component of a right passing maneuver (whereby the participant passes the slower moving vehicle on the right).

Results also found significant rear visibility technology × lighting condition and rear visibility technology × lane change direction interactions. In daylight, the average time to collision was longer with the tested CMS (M = 4.92 s, SE = 0.79 s) compared to the European-specification OE outside rearview mirrors (M = 3.93 s, SE = 0.79 s, $p < 0.05$). In darkness, time to collision did not differ between the tested CMS and European-specification OE outside rearview mirrors ($p = 0.18$). Additionally, the average time to collision was longer when making a left lane change in front of the passed vehicle with the tested CMS (M = 5.64 s, SE = 0.79 s) compared to making a left lane change in front of the passed vehicle with the European-specification OE outside rearview mirrors (M = 4.62 s, SE = 0.79 s, $p < 0.05$). When making a right lane change, time to collision did not differ between the tested CMS and European-specification OE outside rearview mirror conditions ($p = 0.22$). All other tests failed to gain significance. Results are shown in Figure 7. Means and standard errors are shown in Table 6.

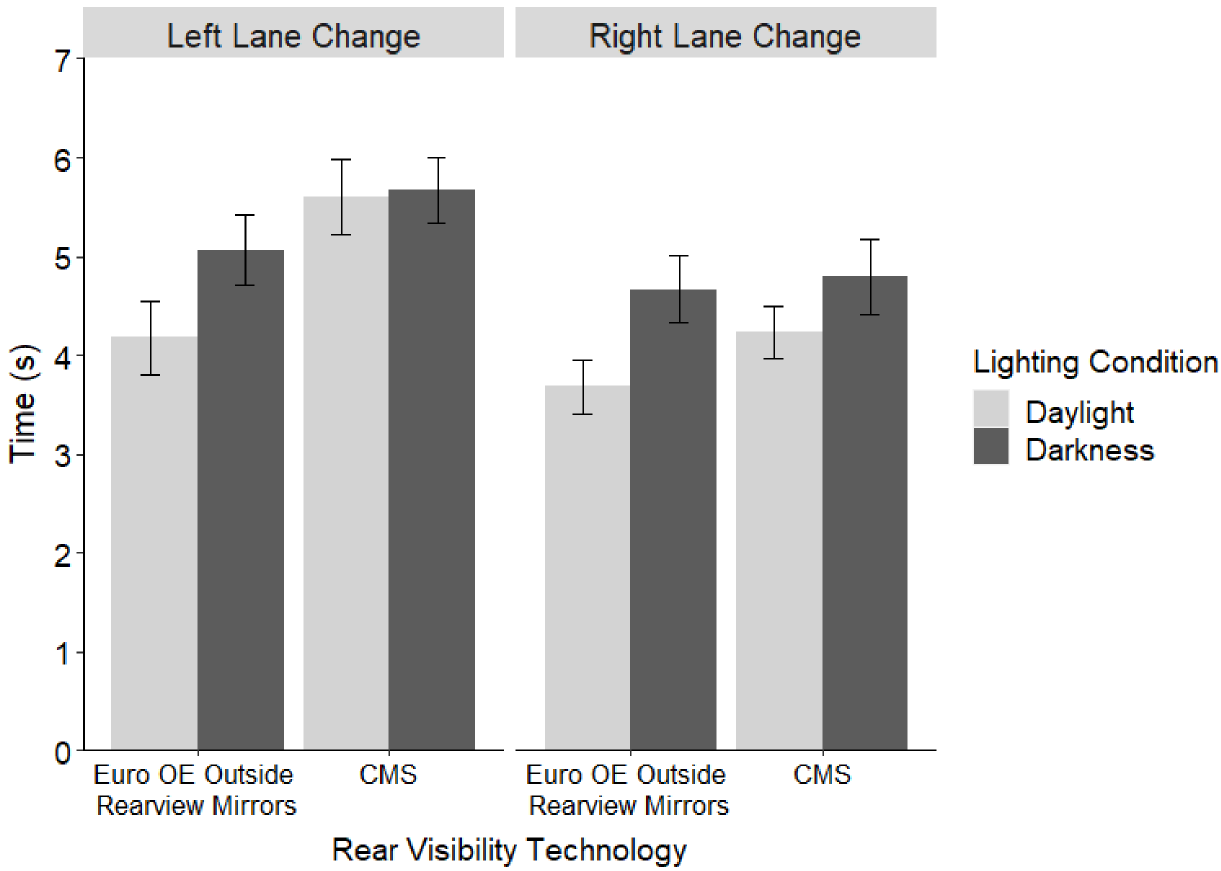

Figure 7. Average time to collision in seconds when passing in front of the slower moving scenario vehicle. Error bars are standard error.

Table 6. Means and standard errors for time to collision

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (s)	Standard Error (s)
Euro OE Outside Rearview Mirrors	Daylight	Left	4.18	0.37
		Right	3.68	0.27
CMS	Daylight	Left	5.60	0.38
		Right	4.23	0.27
Euro OE Outside Rearview Mirrors	Darkness	Left	5.07	0.36
		Right	4.67	0.34
CMS	Darkness	Left	5.67	0.34
		Right	4.79	0.39

4.2 Visual Behavior

Several metrics were used to assess whether driving with the tested CMS was associated with differences in eye-gaze behavior compared to European-specification OE outside rearview mirrors. Specifically, the number of visual fixations, average duration of fixations, total duration of fixations, and the number of long fixations were calculated using a velocity-threshold identification (I-VT) algorithm with a velocity threshold of 40 deg/s and a minimum fixation duration of 100 ms. A median filter with a window of three samples was used for noise reduction.

Since it is likely that drivers will look toward a mirror or display prior to initiating a lane change, this analysis looked at a lane change window of time that included the 3 seconds prior to lane change initiation until the lane change was completed. Graphs have been included that visually demonstrate fixation data to all areas of interest, but not all areas of interest were included in the analyses. Additionally, even though the CMS displays and outside mirrors were always present on the vehicle, since the CMS displays were not usable during the European-specification OE outside rearview mirror condition and vice versa, when comparing areas of interest, only useable areas of interest were included within a rear visibility technology condition.

Analyses were performed in a two-step process involving a first step linear mixed effects model, which included fixed effects of rear visibility technology, lighting condition, and lane change direction and their interactions as well as a random intercept term for participant. This model only included fixations to the CMS displays and European-specification OE outside rearview mirrors, not the inside rearview mirror.

A follow-up linear mixed effects model was performed which included fixed effects of rear visibility technology, lighting condition, and area of interest and their interactions as well as a random intercept term for participant. Six specific areas of interest were included in the second model: driver-side CMS display/European-specification OE outside rearview mirror, inside rearview mirror when driving with the CMS, inside rearview mirror when driving with the European-specification OE outside mirrors, and passenger-side rear CMS display/European-specification OE outside rearview mirror. The inside rearview mirror was separated out as such since specific planned comparisons were of interest. These planned comparisons included specifically comparing the driver-side CMS display to the driver-side outside rearview mirror, comparing the inside rearview mirror when driving with the CMS to the inside rearview mirror when driving with the outside rearview mirrors, and comparing the passenger-side CMS display to the passenger-side outside rearview mirror.

4.2.1 Number of Fixations

To evaluate differences in eye-gaze behavior, analyses were performed on the number of fixations made during a lane change. The number of fixations during a lane change is the sum of all the individual fixations made during a lane change. The number of fixations made when making lane changes with European-specification OE outside rearview mirrors to all areas of interest are shown in Figure 8.

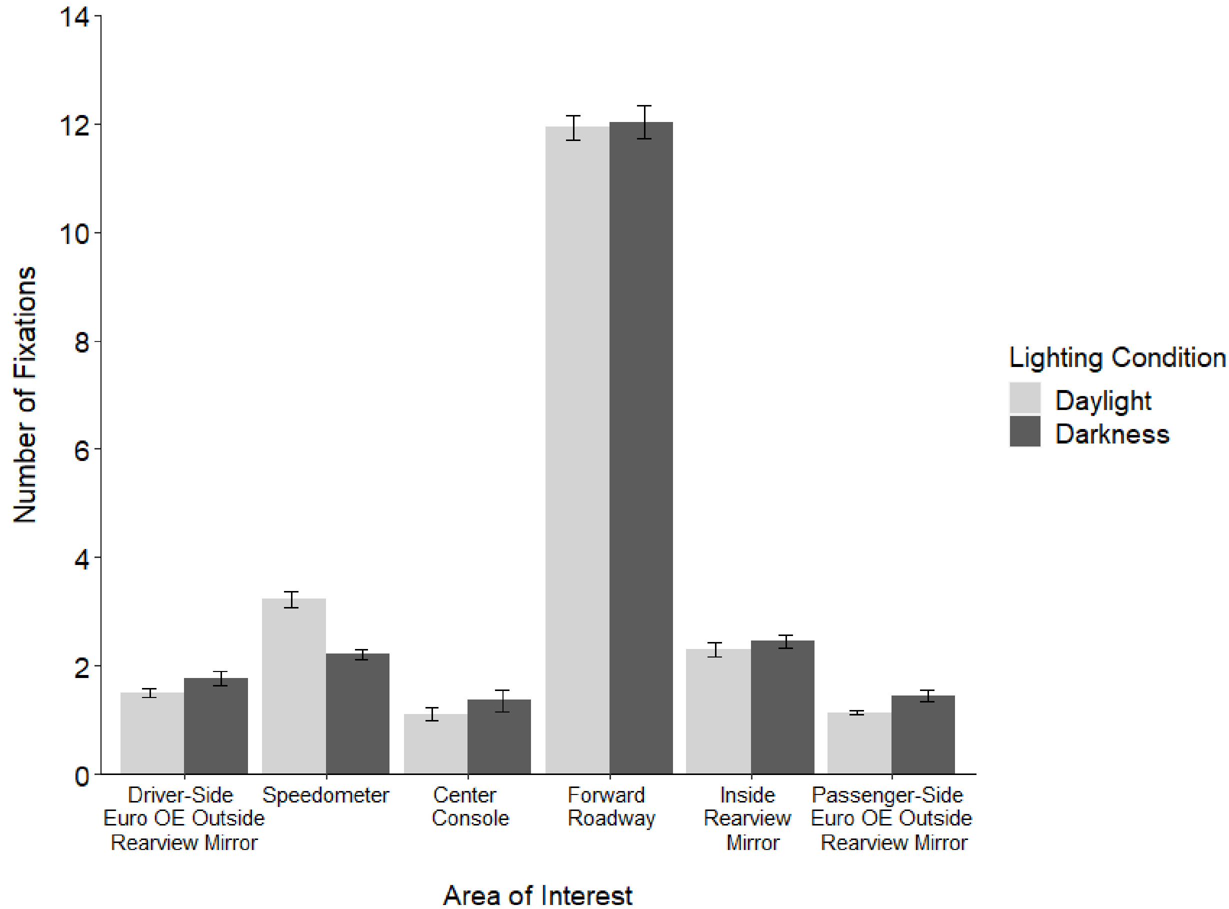

Figure 8. Average number of fixations across all areas of interest when making lane changes with European-specification OE outside rearview mirrors. Error bars are standard error.

The number of fixations made when making lane changes with the tested CMS to all areas of interest are shown in Figure 9.

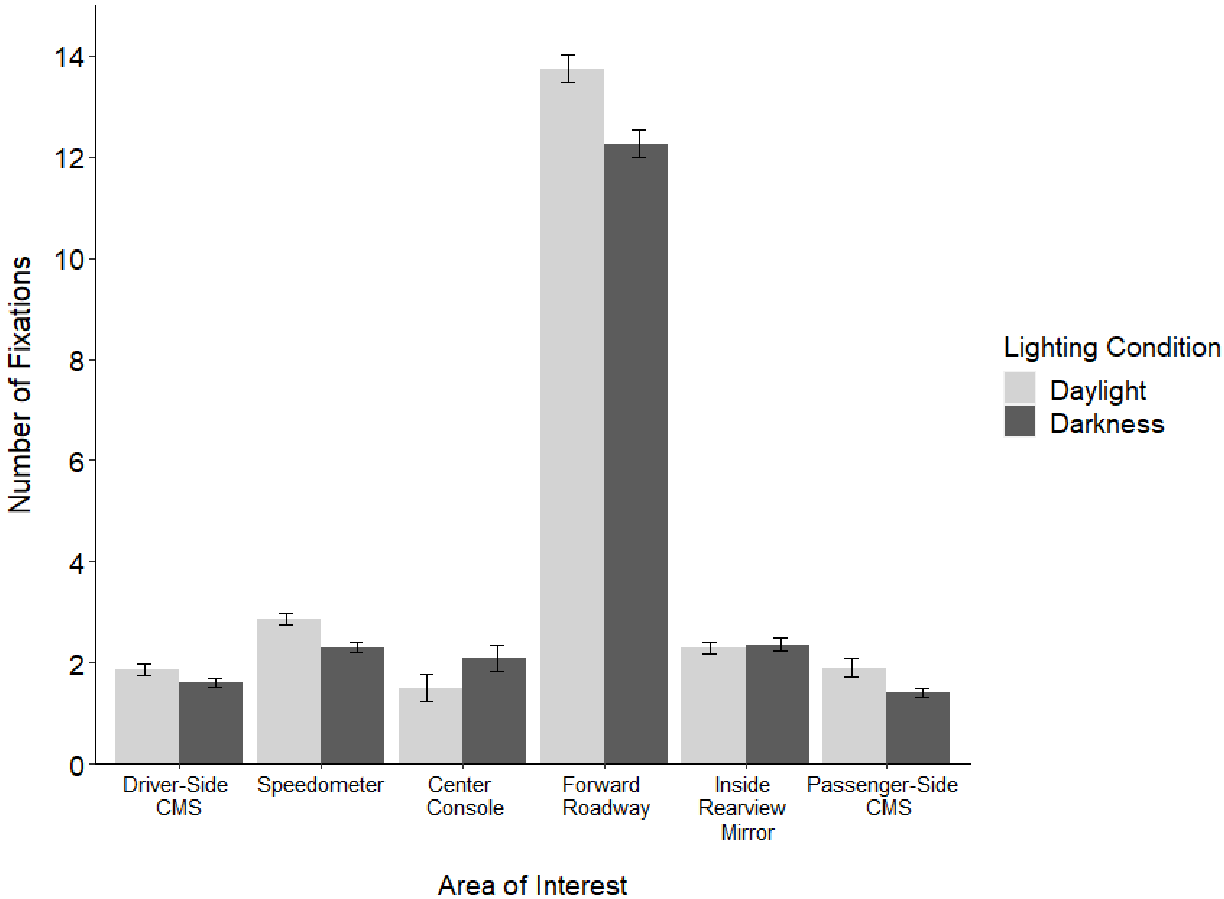

Figure 9. Average number of fixations to all areas of interest when making lane changes with the tested CMS. Error bars are standard error.

As shown in Figures 8 and 9, participants made more fixations to the forward roadway compared to any other location, which is logical considering this was a driving task. However, since the research questions involved comparing CMSs to European-specification OE outside rearview mirrors, analyses were conducted using relevant areas of interest to the research question as well as driving condition.

To evaluate differences in the number of fixations between the rear visibility technologies, a Poisson linear mixed effects model was run with the number of fixations during a lane change as the outcome variable, with fixed effects of rear visibility technology, lighting condition, and lane change direction and their interactions as well as a random intercept term for participant. Results found a significant rear visibility technology × lighting condition interaction. In daylight, participants made a greater number of fixations to the CMS displays ($M = 1.88$, $SE = 0.15$) compared to the European-specification OE outside rearview mirrors ($M = 1.34$, $SE = 0.07$, $p < 0.05$). In darkness, the number of fixations did not significantly differ between the tested CMS and European-specification OE outside rearview mirrors ($p = 0.32$). Results are shown in Figure 10. Means and standard errors are shown in Table 7.

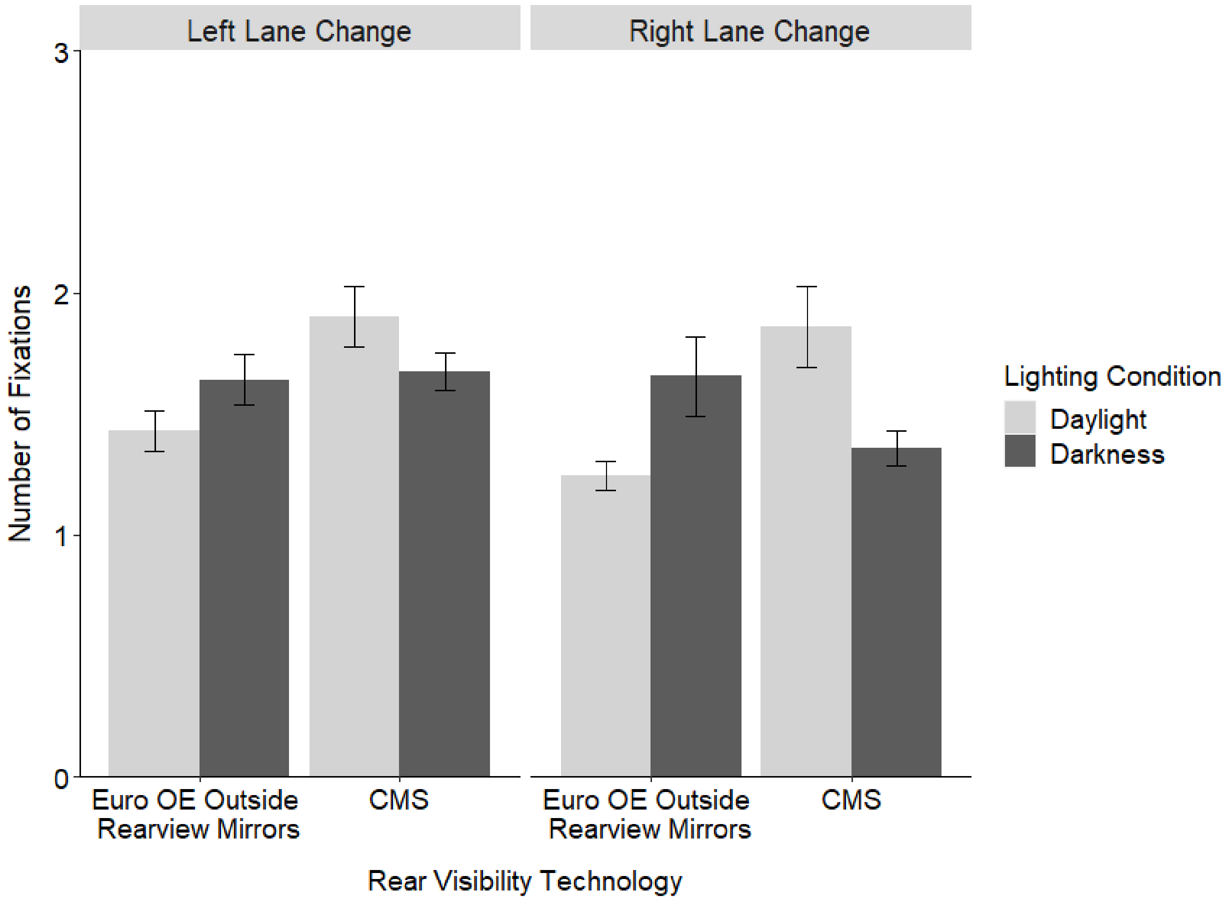

Figure 10. Number of fixations for left and right lane changes. Error bars are standard error.

Table 7. Means and standard errors for number of fixations during lane changes

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (n)	Standard Error (n)
Euro OE Outside Rearview Mirrors	Daylight	Left	1.43	0.08
		Right	1.24	0.06
CMS	Daylight	Left	1.90	0.13
		Right	1.86	0.17
Euro OE Outside Rearview Mirrors	Darkness	Left	1.64	0.10
		Right	1.66	0.17
CMS	Darkness	Left	1.68	0.08
		Right	1.36	0.07

To evaluate the differences in the number of fixations to specific areas of interest, a second Poisson linear mixed effects model was run with the number of fixations during a lane change as the outcome variable, with fixed effects of lighting condition, area of interest, and their interaction as well as a random intercept term for participant. Three specific planned comparisons were performed. The specific planned comparisons are shown in Table 8.

Table 8. Planned comparisons for area of interest main effect

Planned Comparisons		
1	Driver-side CMS display	Driver-side Euro OE outside rearview mirror
2	Inside rearview mirror when driving with the CMS	Inside rearview mirror when driving with Euro OE outside rearview mirrors
3	Passenger-side CMS display	Passenger-side Euro OE outside rearview mirror

Results did not find any significant comparisons. The number of fixations did not differ between the driver-side CMS display and driver-side European-specification OE outside rearview mirror (p = 0.96), nor between the inside rearview mirror when driving with the tested CMS compared to the inside mirror when driving with the European-specification OE outside rearview mirrors (p = 0.99), or between the passenger-side CMS display compared to the passenger-side European-specification OE outside rearview mirror (p = 0.23). Results are shown in Figure 11. Means and standard errors are shown in Table 9.

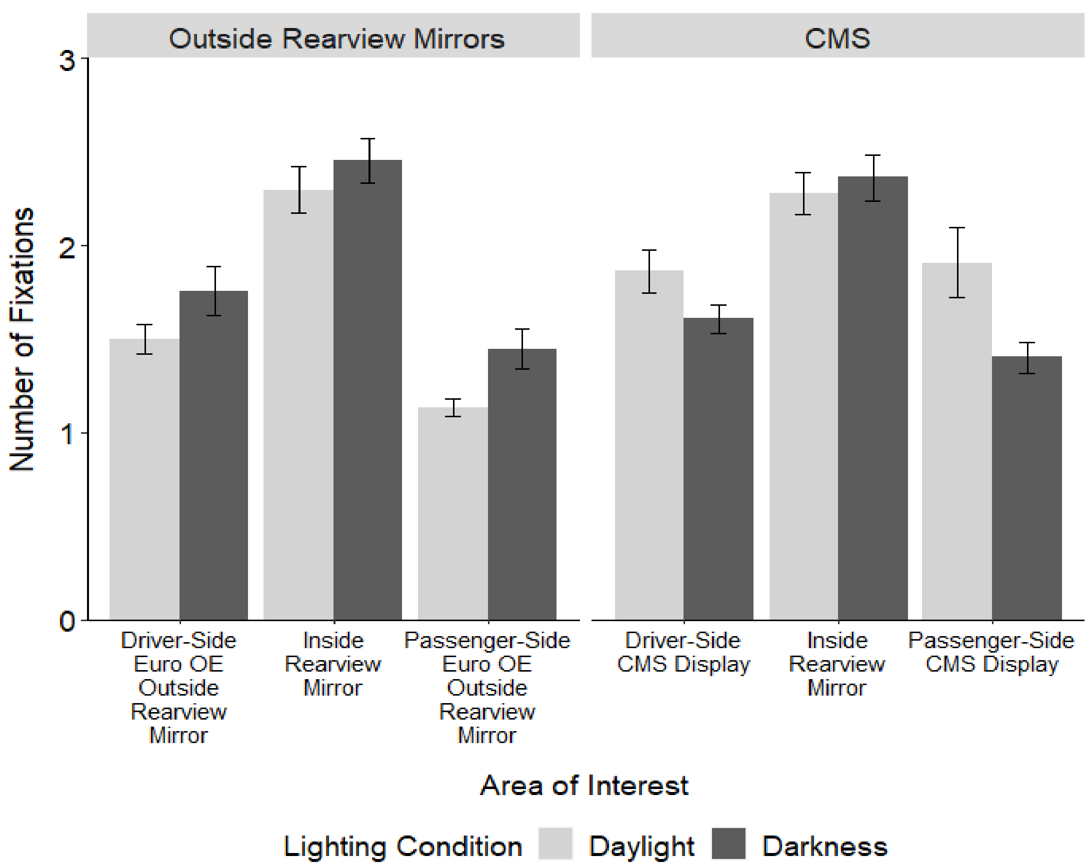

Figure 11. Number of fixations to relevant areas of interest during lane changes. Error bars are standard error.

Table 9. Means and standard errors for number of fixations during lane changes to areas of interest

Rear Visibility Technology	Lighting Condition	Area of Interest	Mean (n)	Standard Error (n)
Euro OE Outside Rearview Mirrors	Daylight	Driver-Side	1.50	0.08
		Inside Rearview Mirror	2.30	0.12
		Passenger-Side	1.14	0.05
CMS	Daylight	Driver-Side	1.86	0.12
		Inside Rearview Mirror	2.28	0.11
		Passenger-Side	1.91	0.19
Euro OE Outside Rearview Mirrors	Darkness	Driver-Side	1.76	0.13
		Inside Rearview Mirror	2.45	0.12
		Passenger-Side	1.45	0.11
CMS	Darkness	Driver-Side	1.61	0.07
		Inside Rearview Mirror	2.37	0.12
		Passenger-Side	1.40	0.08

4.2.2 Average Fixation Duration

To further evaluate differences in eye-gaze behavior, analyses were performed on the average fixation duration during a lane change. The average fixation duration is the average of the individual fixation durations during a lane change. Average fixation durations when making lane changes with European-specification OE outside rearview mirrors to all areas of interest are shown in Figure 12.

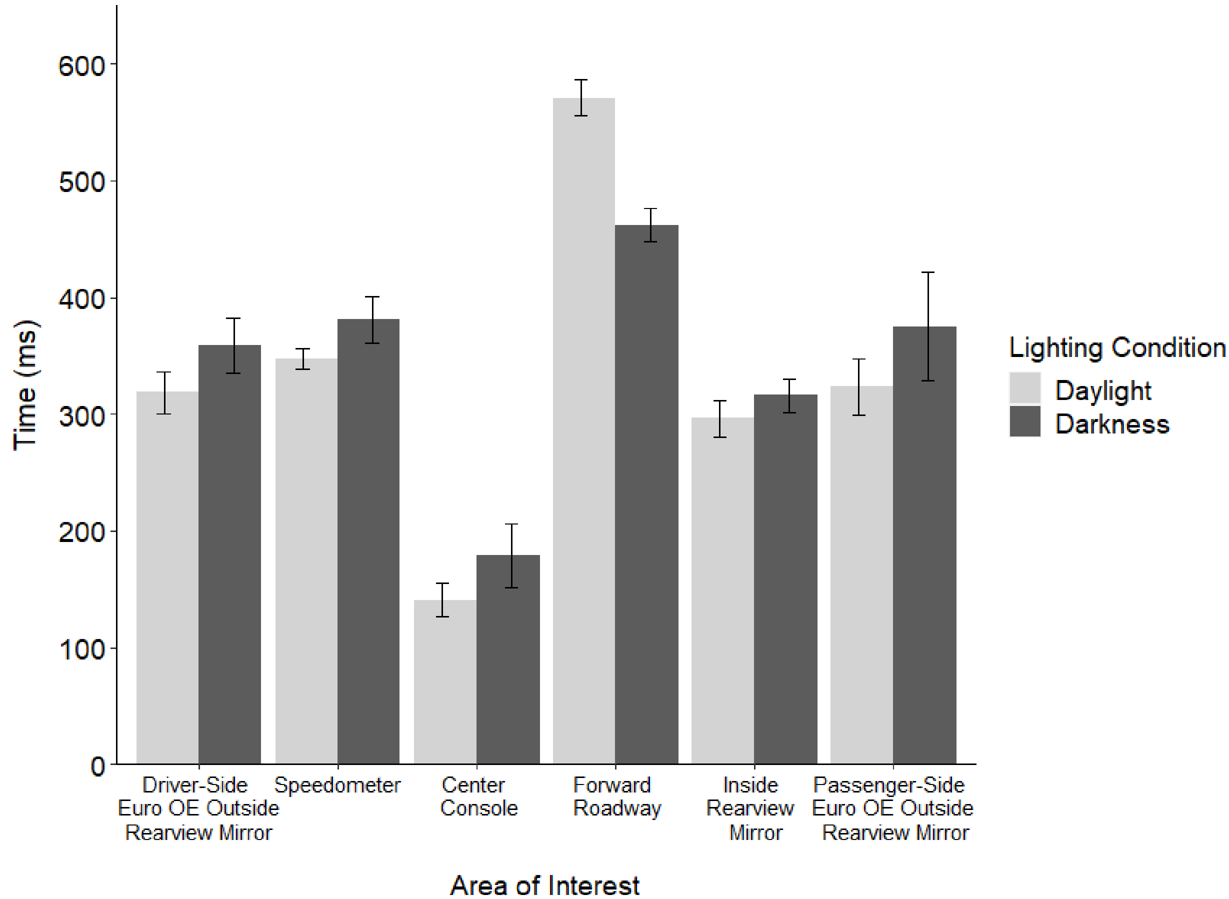

Figure 12. Average fixation duration to all areas of interest when making lane changes with European-specification OE outside rearview mirrors. Error bars are standard error.

Average fixation durations when making lane changes with the tested CMS to all areas of interest are shown in Figure 13.

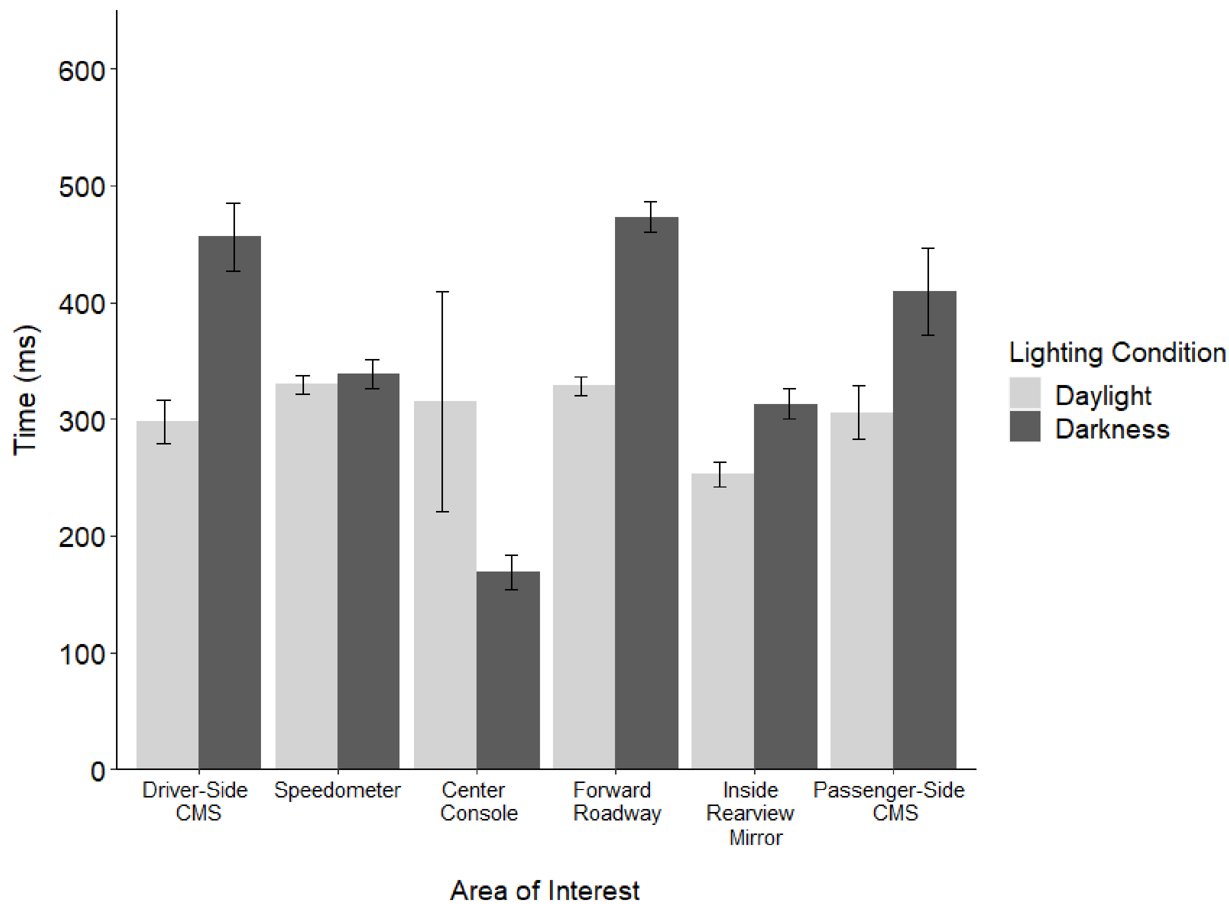

Figure 13. Average fixation duration to all areas of interest when making lane changes with the tested CMS. Error bars are standard error.

To evaluate differences in average fixation duration between rear visibility technologies, a linear mixed effects model was run with the average fixation duration during a lane change as the outcome variable, with fixed effects of rear visibility technology, lighting condition, lane change direction and their interactions as well as a random intercept term for participant. Results found significant effects for lighting condition and a significant rear visibility technology × lighting condition interaction. Participants fixated for a longer average duration in darkness (M = 355.75 ms, SE = 41.03 ms) compared to daylight (M = 309.91 ms, SE = 41.37 ms, $p < 0.05$). In darkness, participants fixated for a longer average duration to the CMS displays (M = 396.06 ms, SE = 42.05 ms) compared to the European-specification OE outside rearview mirrors (M = 315.45 ms, SE = 43.84 ms, $p < 0.05$). Average fixation durations did not significantly differ between the tested CMS and European-specification OE outside rearview mirrors in daylight (p = 0.78). Results are shown in Figure 14. Means and standard errors are shown in Table 10.

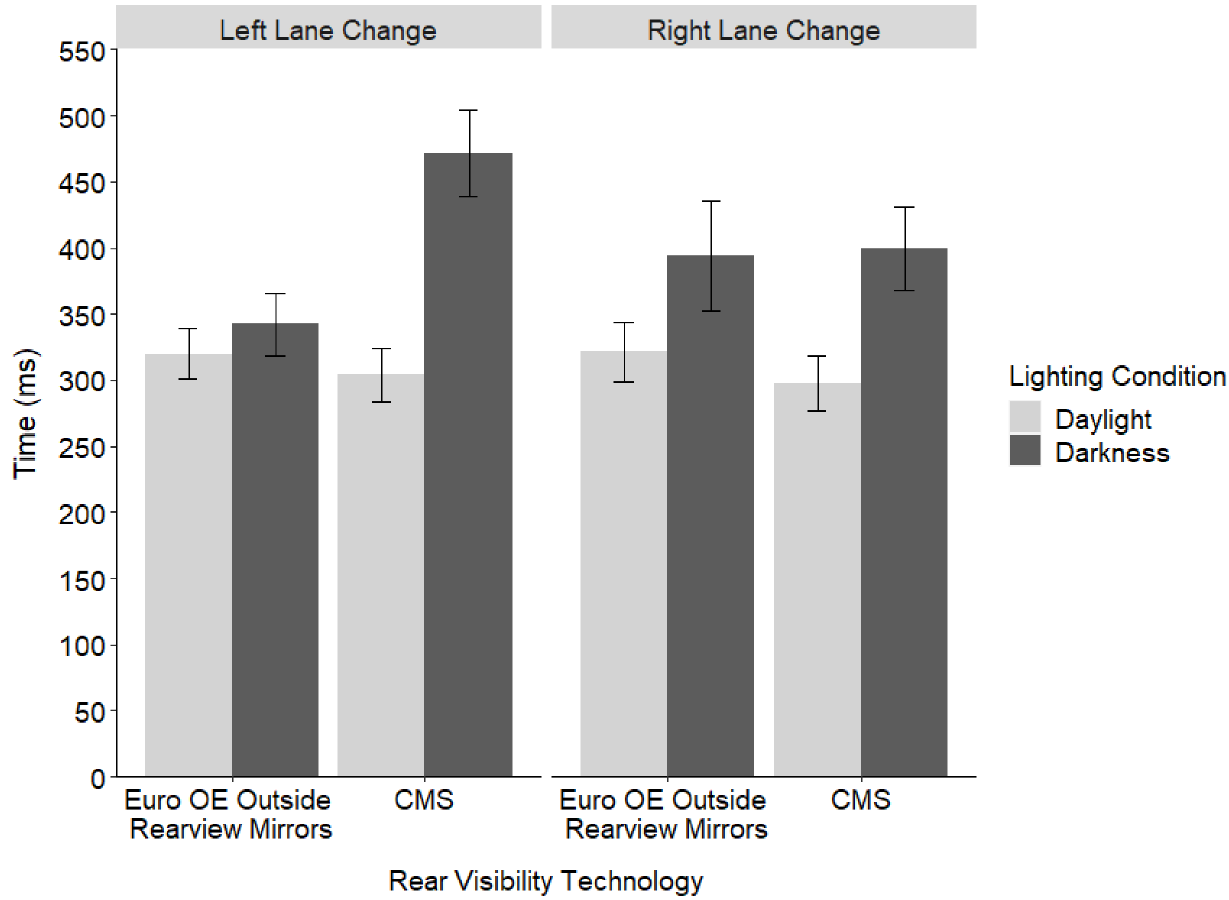

Figure 14. Average fixation durations for left and right lane changes. Error bars are standard error.

Table 10. Means and standard errors for average fixation durations during lane changes

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (ms)	Standard Error (ms)
Euro OE Outside Rearview Mirrors	Daylight	Left	320.21	19.15
		Right	321.52	22.42
CMS	Daylight	Left	304.31	20.24
		Right	298.09	20.84
Euro OE Outside Rearview Mirrors	Darkness	Left	342.12	23.94
		Right	394.35	41.72
CMS	Darkness	Left	471.48	32.94
		Right	399.73	31.98

To evaluate differences in average fixation duration to specific areas of interest, a second linear mixed effects model was run with the average fixation duration during a lane change as the outcome variable, with fixed effects of lighting condition, area of interest, and their interactions as well as a random intercept term for participant. Results found significant effects for lighting condition and area of interest, as well as a significant lighting condition x area of interest interaction. Participants fixated for a longer average duration in darkness (*M* = 343.19 ms, *SE* = 28.57 ms) compared to daylight (*M* = 287.15 ms, *SE* = 28.62 ms, $p < 0.05$). For area of interest, the same three specific planned comparisons in Table 8 were performed. Results did not find any significant comparisons. Average fixation durations did not differ between the driver-side CMS display and driver-side European-specification OE outside rearview mirror ($p = 0.09$), nor between the inside rearview mirror when driving with the tested CMS compared to the inside mirror when driving with the European-specification OE outside rearview mirrors ($p = 0.59$), or between the passenger-side CMS display compared to the passenger-side European-specification OE outside rearview mirror ($p = 0.99$).

For the lighting condition x area of interest interaction, six planned comparisons were performed as shown in Table 11.

Table 11. Planned comparisons for the lighting condition x area of interest interaction

Planned Comparisons		
1	Driver-side CMS display in daylight	Driver-side Euro OE outside rearview mirror in daylight
2	Driver-side CMS display in darkness	Driver-side Euro OE outside rearview mirror in darkness
3	Inside rearview mirror when driving with the CMS in daylight	Inside rearview mirror when driving with Euro OE outside rearview mirrors in daylight
4	Inside rearview mirror when driving with the CMS in darkness	Inside rearview mirror when driving with Euro OE outside rearview mirrors in darkness
5	Passenger-side CMS display in daylight	Passenger-side Euro OE outside rearview mirror in daylight
6	Passenger-side CMS display in darkness	Passenger-side Euro OE outside rearview mirror in darkness

Participants fixed for a longer average duration to the driverside CMS display in darkness (*M* = 436.75 ms, *SE* = 32.79 ms) compared to the driver-side European-specification OE outside mirror in darkness (*M* = 316.79 ms, *SE* = 34.86 ms, $p < 0.05$). All other comparisons failed to gain significance. Results are shown in Figure 15. Means and standard errors are shown in Table 12.

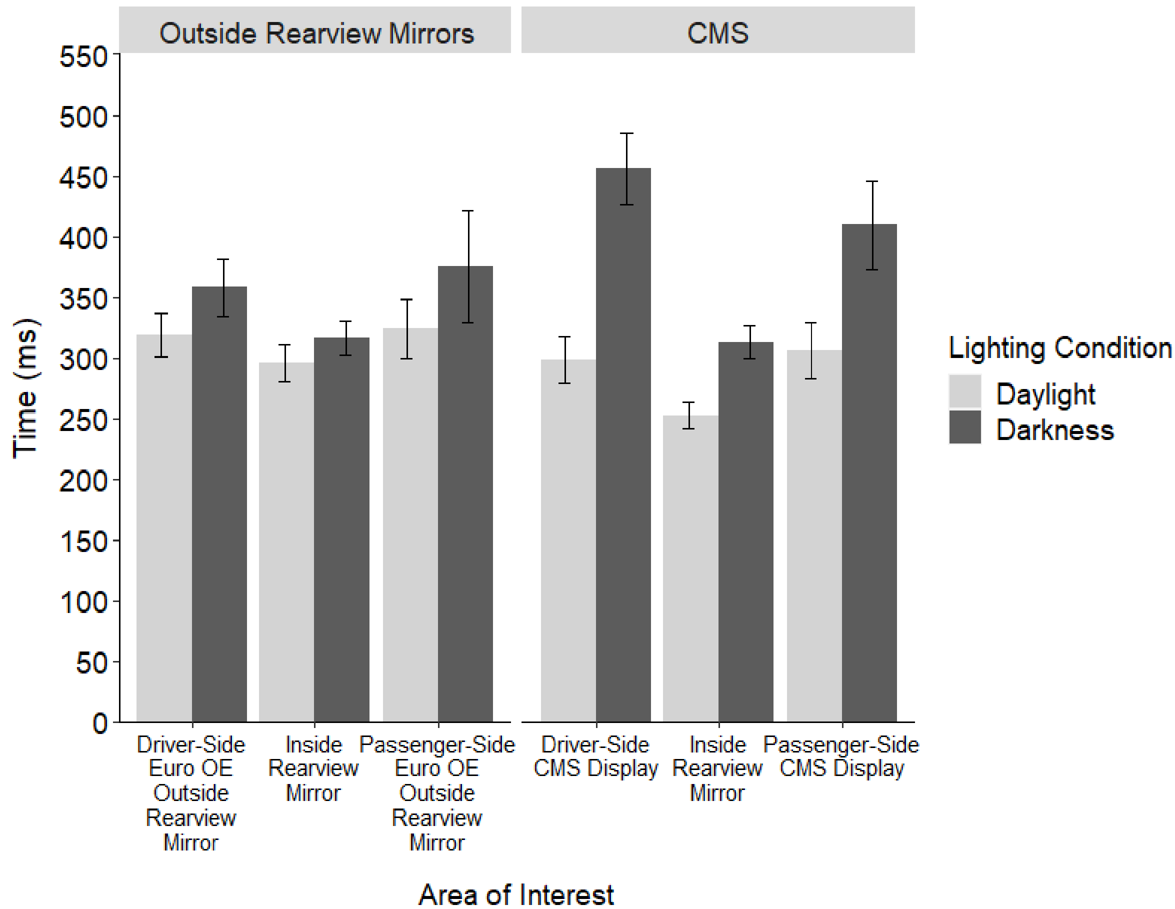

Figure 15. Average fixation duration to relevant areas of interest during lane changes. Error bars are standard error.

Table 12. Means and standard errors for average fixation durations during lane changes to areas of interest

Rear Visibility Technology	Lighting Condition	Area of Interest	Mean (ms)	Standard Error (ms)
Euro OE Outside Rearview Mirrors	Daylight	Driver-Side	318.70	17.97
		Inside Rearview Mirror	296.00	15.79
		Passenger-Side	323.55	24.38
CMS	Daylight	Driver-Side	298.29	18.67
		Inside Rearview Mirror	252.74	10.40
		Passenger-Side	305.48	23.01
Euro OE Outside Rearview Mirrors	Darkness	Driver-Side	358.37	23.67
		Inside Rearview Mirror	316.25	14.25
		Passenger-Side	375.09	46.49
CMS	Darkness	Driver-Side	455.92	29.58
		Inside Rearview Mirror	313.04	13.23
		Passenger-Side	409.38	36.88

4.2.3 Total Fixation Duration

Additionally, to evaluate differences in eye-gaze behavior, analyses were performed on the total fixation duration during a lane change. The total fixation duration is a sum of the individual fixation durations during a lane change. Total fixation durations when making lane changes with European-specification OE outside rearview mirrors to all areas of interest are shown in Figure 16.

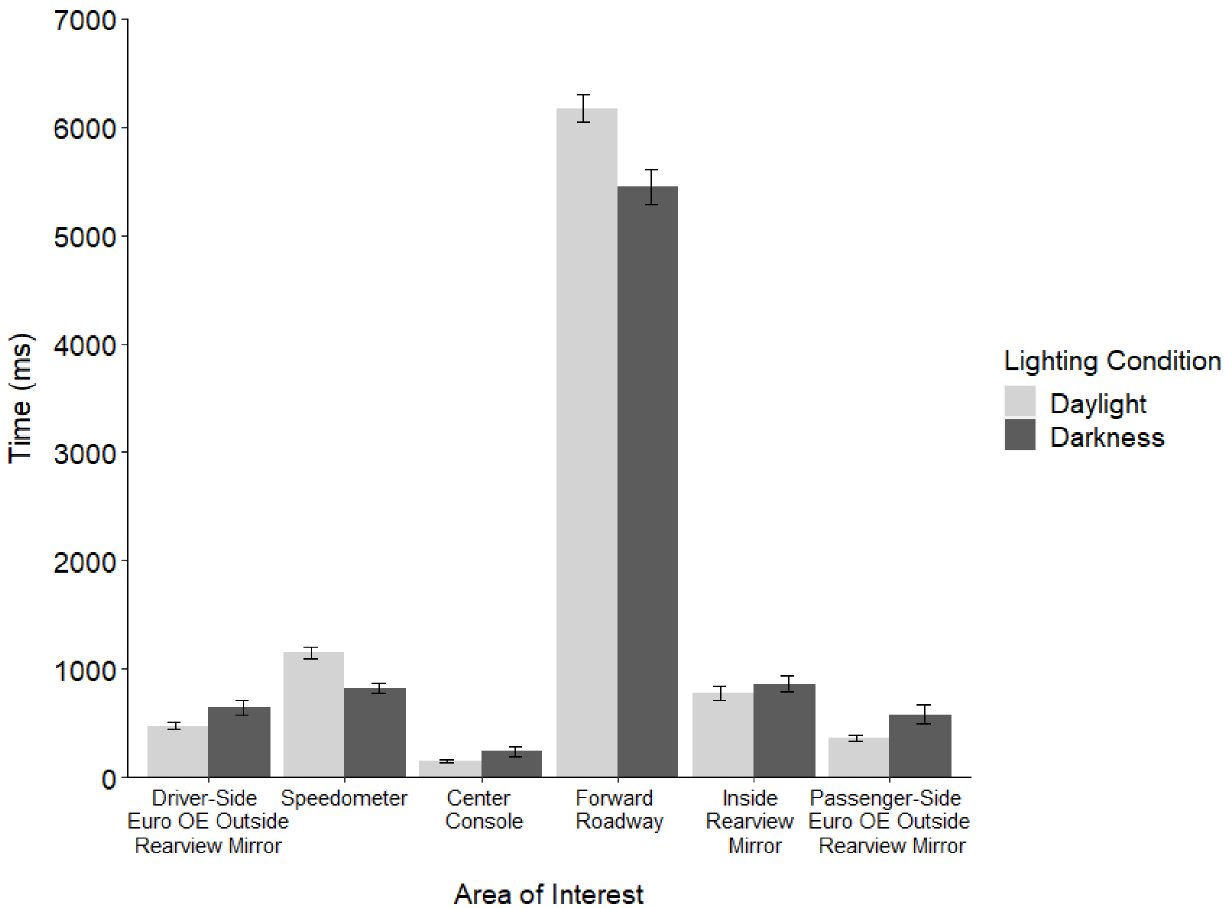

Figure 16. Total fixation duration to all areas of interest when making lane changes with outside rearview mirrors. Error bars are standard error.

Total fixation durations when making lane changes with the tested CMS to all areas of interest are shown in Figure 17.

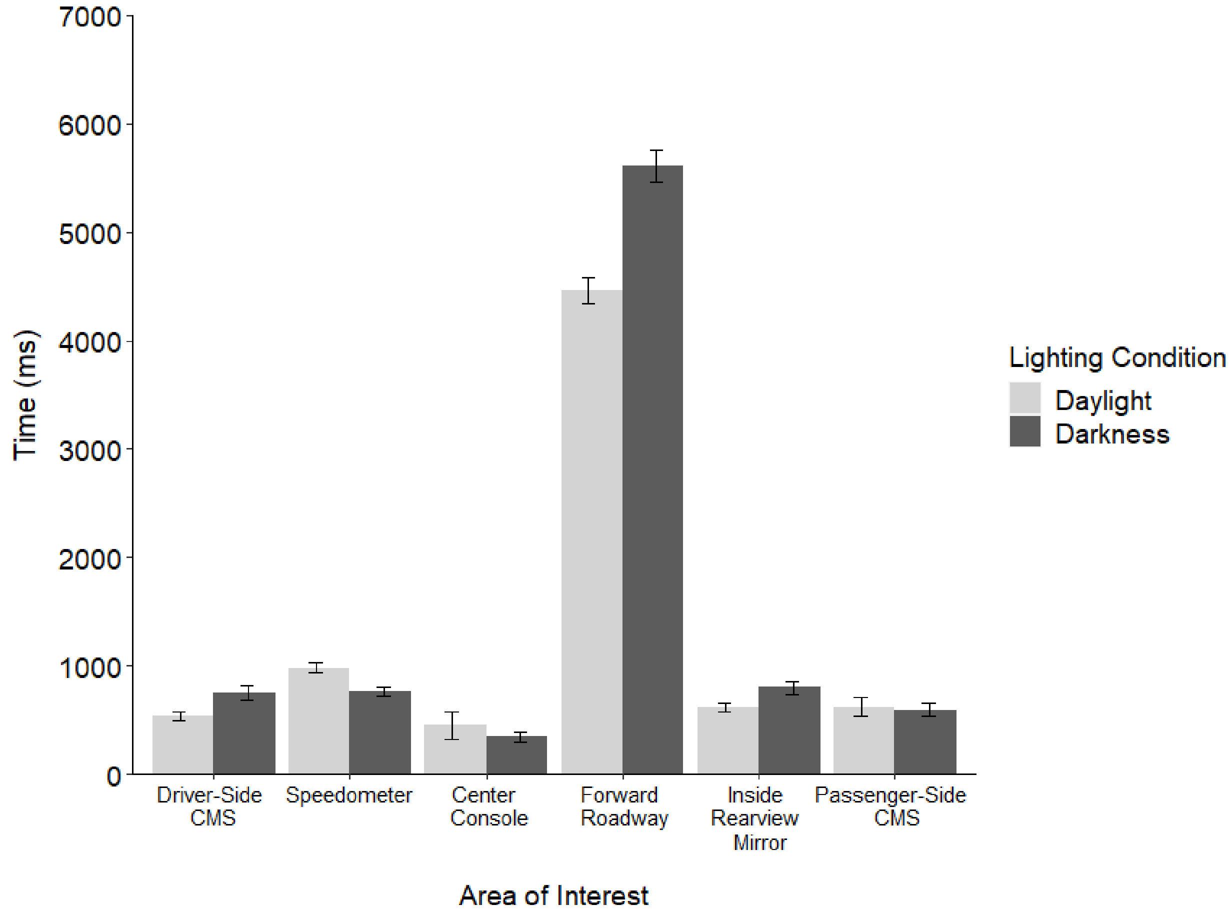

Figure 17. Total fixation duration to all areas of interest when making lane changes with the tested CMS. Error bars are standard error.

To evaluate differences in total fixation duration between rear visibility technologies, a linear mixed effects model was run with the total fixation duration during a lane change as the outcome variable, with fixed effects of rear visibility technology, lighting condition, lane change direction and their interactions as well as a random intercept term for participant. Results found a significant effect for condition and lane change direction, and a significant condition x lighting condition x lane change direction interaction. Participants fixated for a longer total duration to the CMS displays (M = 590.37 ms, SE = 88.70 ms) compared to the European-specification OE outside rearview mirrors (M = 473.07 ms, SE = 89.51 ms). Participants fixed for a longer total duration when making a left lane change (M = 570.26 ms, SE = 88.92 ms) compared to making a right lane change (M = 493.19 ms, SE = 89.18 ms). Participants fixated for a longer total duration to the CMS displays when making a left lane change in darkness (M = 734.64 ms, SE = 96.71 ms) compared to the European-specification OE outside rearview mirrors when making a left lane change in darkness (M = 534.29 ms, SE = 101.10 ms, $p < 0.05$). All other comparisons failed to gain significance. Results are shown in Figure 18. Means and standard errors are shown in Table 13.

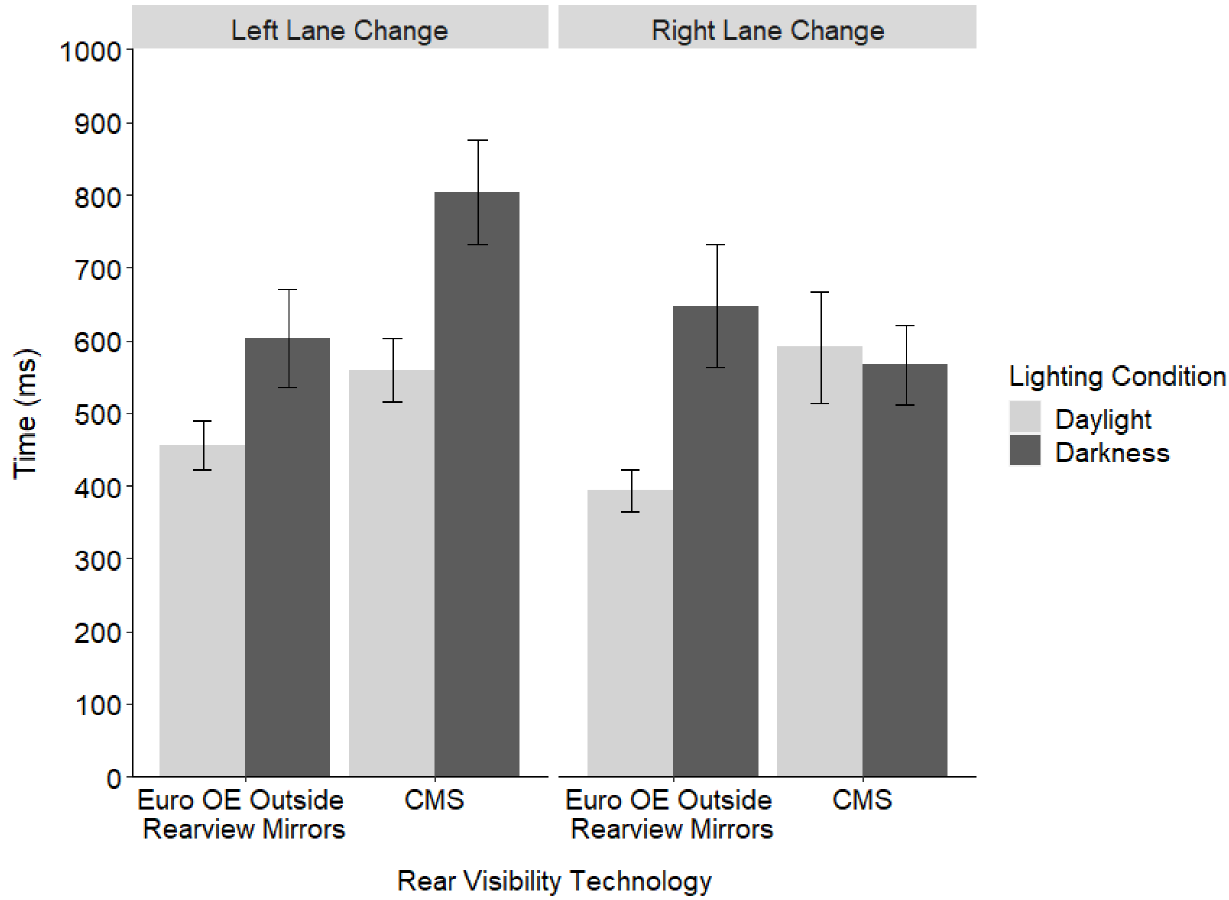

Figure 18. Total fixation durations for left and right lane changes. Error bars are standard error.

Table 13. Means and standard errors for total fixation durations during lane changes

Rear Visibility Technology	Lighting Condition	Lane Change Direction	Mean (ms)	Standard Error (ms)
Euro OE Outside Rearview Mirrors	Daylight	Left	455.99	34.67
		Right	393.29	29.24
CMS	Daylight	Left	559.51	44.54
		Right	590.24	76.69
Euro OE Outside Rearview Mirrors	Darkness	Left	603.47	67.64
		Right	647.62	84.20
CMS	Darkness	Left	804.17	71.81
		Right	566.38	55.19

To evaluate differences in total fixation duration to specific areas of interest, a second linear mixed effects model was run with the total fixation duration during a lane change as the outcome variable, with fixed effects of lighting condition, area of interest, and their interaction as well as a random intercept term for participant. Results found significant effects for lighting condition and area of interest. Participants fixated for a longer total duration in darkness (*M* = 644.93 ms, *SE* = 91.23 ms) compared to daylight (*M* = 500.07 ms, *SE* = 91.37 ms). For area of interest, the three specific planned comparisons were performed. Results did not find any significant comparisons. Total fixation durations did not differ between the driver-side CMS display and European-specification OE driver-side outside rearview mirror ($p = 0.58$), nor between the inside rearview mirror when driving with the tested CMS compared to the inside mirror when driving with the European-specification OE outside rearview mirrors ($p = 0.28$), or between the passenger-side CMS display compared to the passenger-side European-specification OE outside rearview mirror ($p = 0.71$). Results are shown in Figure 19. Means and standard errors are shown in Table 14.

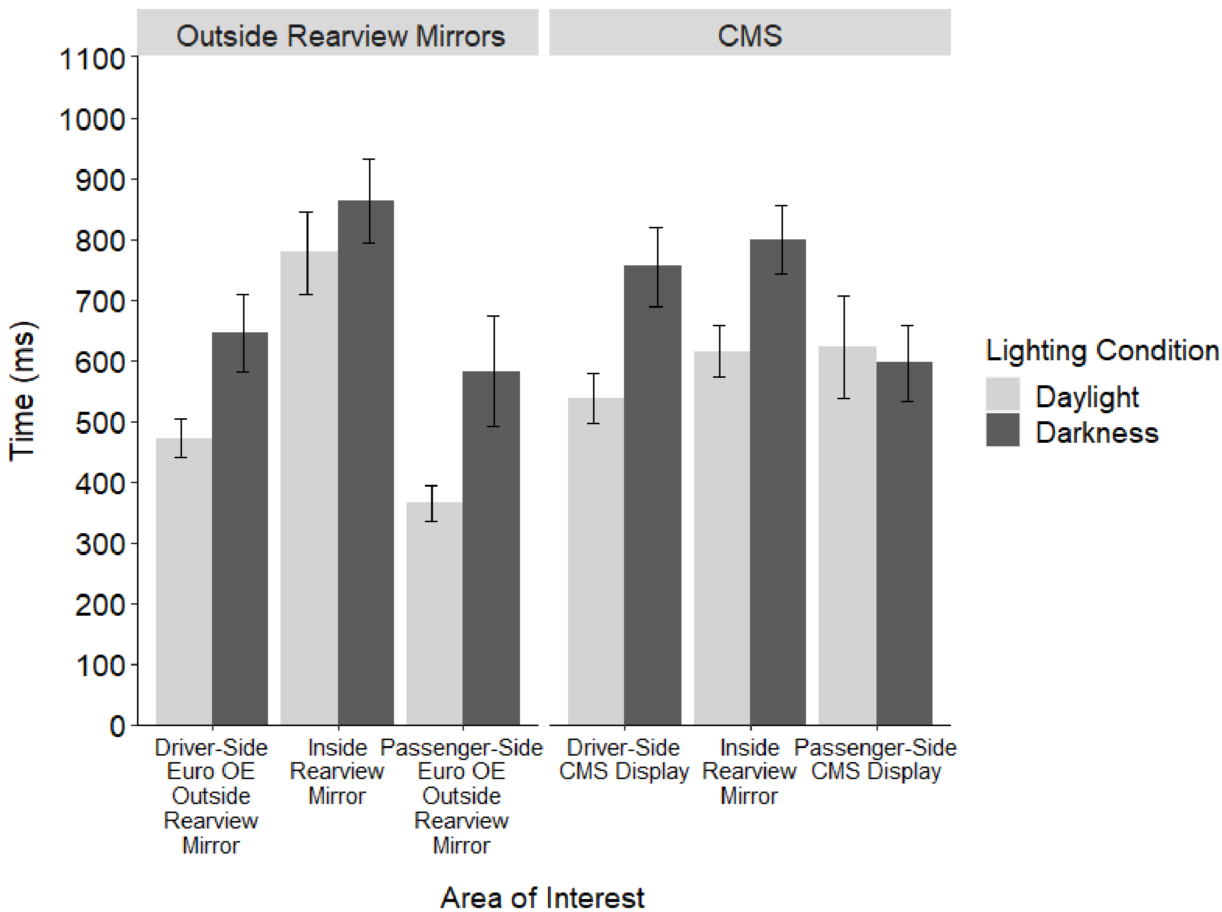

Figure 19. Total fixation durations to relevant areas of interest during lane changes. Error bars are standard error.

Table 14. Means and standard errors for total fixation durations during lane changes to areas of interest

Rear Visibility Technology	Lighting Condition	Area of Interest	Mean (ms)	Standard Error (ms)
Euro OE Outside Rearview Mirrors	Daylight	Driver-Side	471.96	32.73
		Inside Rearview Mirror	777.83	68.39
		Passenger-Side	365.85	29.50
CMS	Daylight	Driver-Side	538.79	41.16
		Inside Rearview Mirror	615.27	41.72
		Passenger-Side	622.07	85.27
Euro OE Outside Rearview Mirrors	Darkness	Driver-Side	645.10	64.86
		Inside Rearview Mirror	863.02	68.21
		Passenger-Side	581.82	90.78
CMS	Darkness	Driver-Side	754.53	64.49
		Inside Rearview Mirror	798.72	56.72
		Passenger-Side	595.52	63.65

4.2.4 Number of Long Duration Fixations

To evaluate whether participants were spending a significant amount of time looking away from the forward roadway, analyses were performed on the number of long duration fixations. A long duration fixation was classified as an individual fixation duration of greater than 1,000 milliseconds. The number of long duration fixations when making lane changes with European-specification OE outside rearview mirrors to all areas of interest are shown in Figure 20.

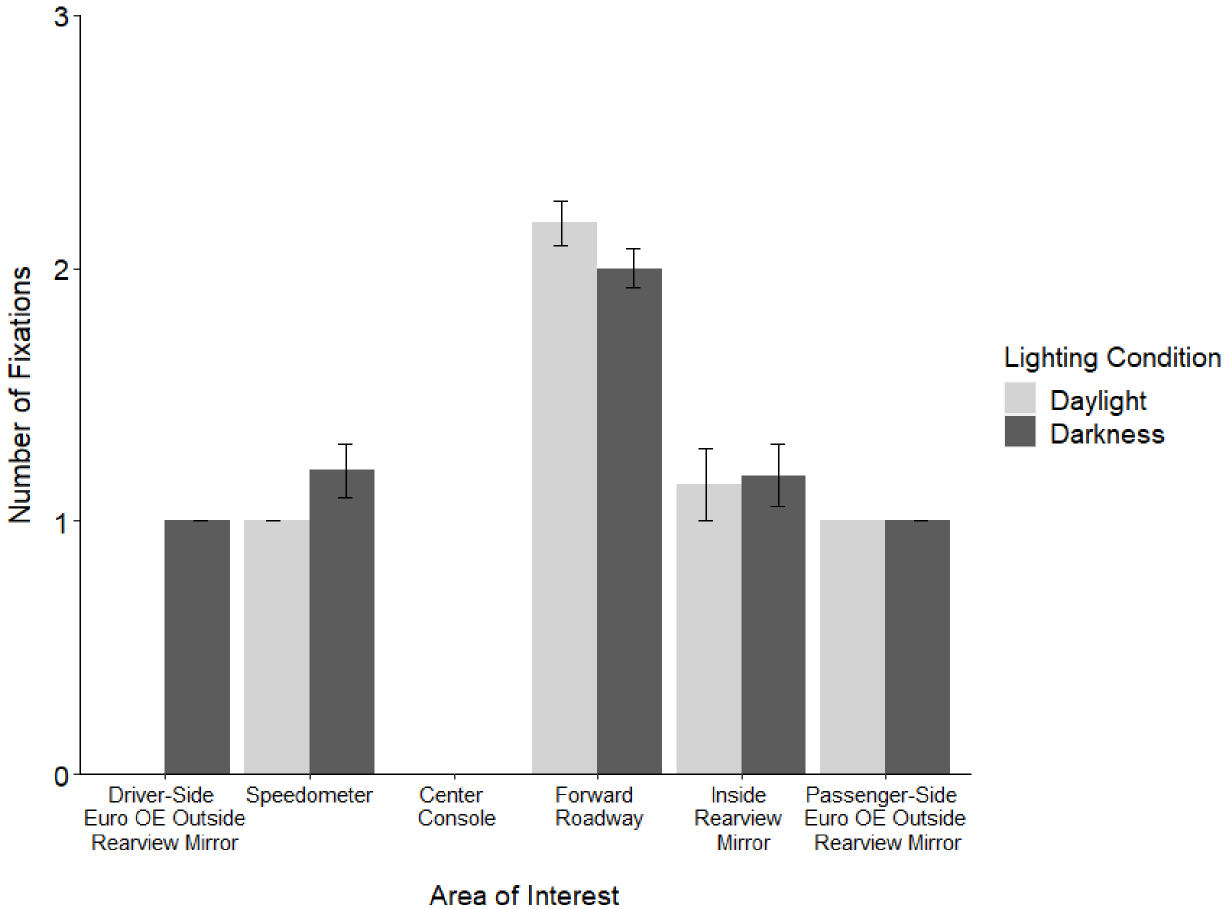

Figure 20. Average number of long duration fixations to all areas of interest when making lane changes with European-specification OE outside rearview mirrors. Error bars are standard error.

The number of long fixations made when making lane changes with the tested CMS to all areas of interest are shown in Figure 21.

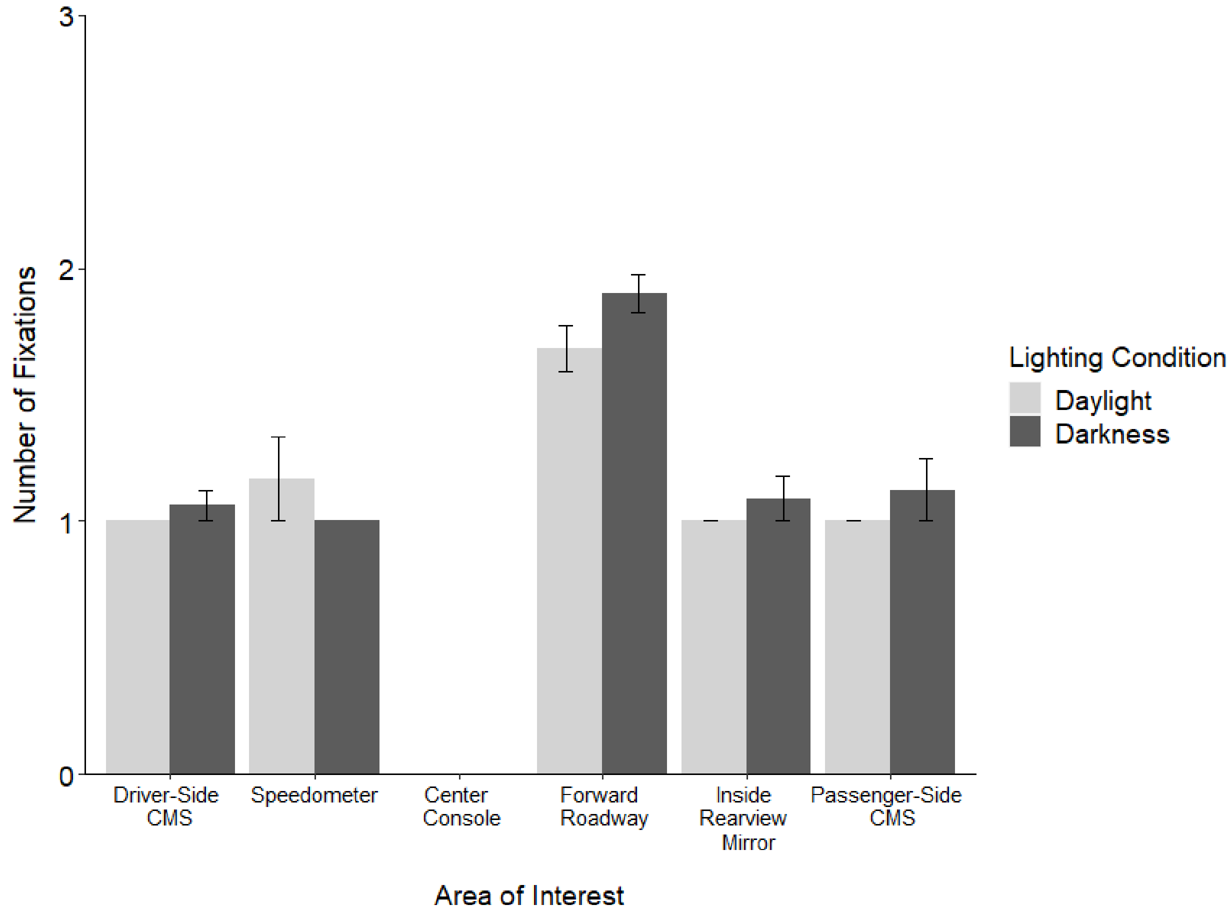

Figure 21. Average number of long duration fixations to all areas of interest when making lane changes with the tested CMS. Error bars are standard error.

There were not enough long duration fixations for a complete statistical model. The total number of long duration fixations across all participants are shown in Table 15 and Table 16.

Table 15. Total number of long duration fixations available for analysis across all participants

Rear Visibility Technology	**Lighting Condition**	**Lane Change Direction**	**Number (n)**
Euro OE Outside Rearview Mirrors	Daylight	Left	3
		Right	5
CMS	Daylight	Left	3
		Right	4
Euro OE Outside Rearview Mirrors	Darkness	Left	8
		Right	13
CMS	Darkness	Left	20
		Right	15

Table 16. Total number of long duration fixation available for analysis by area of interest across all participants

Rear Visibility Technology	Lighting Condition	Area of Interest	Number (n)
Euro OE Outside Rearview Mirrors	Daylight	Driver-Side	0
		Inside Rearview Mirror	7
		Passenger-Side	1
CMS	Daylight	Driver-Side	1
		Inside Rearview Mirror	4
		Passenger-Side	2
Euro OE Outside Rearview Mirrors	Darkness	Driver-Side	5
		Inside Rearview Mirror	11
		Passenger-Side	5
CMS	Darkness	Driver-Side	16
		Inside Rearview Mirror	11
		Passenger-Side	8

4.3 Head Movement

To assess whether participants were seeking a different viewing angle when making a lane change, analyses were performed on head movement. To quantify head movement using nomenclature from the eye-tracking system, head angle motion of the head in the "yes" (as in nodding one's head) direction (pitch), "no" direction (heading/yaw), and rotations towards the shoulder (roll) were analyzed. Directional movements are shown in Figure 22.

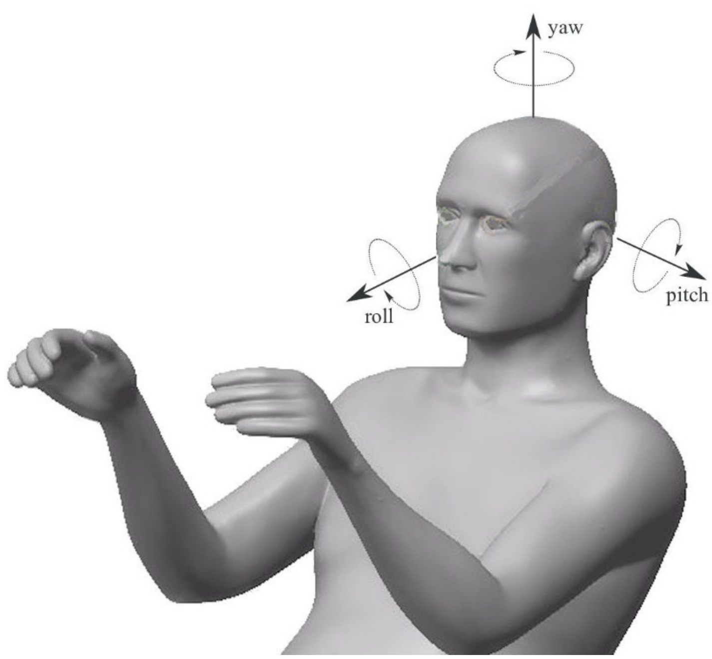

Figure 22. Visual representation of head movement directions

Head angles in these directions were available from the eye-tracker cameras. Within each lane change, head angle displacement was calculated for each frame of tracking. Angular displacement was calculated as the difference between each frame of head angle value and the overall mean of head angle within each lane change time period. The root mean square was then used to measure the magnitude of angular displacement of heading, pitch, and roll. Research has shown this as a valid way to measure head movement magnitude (Martin, et al., 2018). RMS was calculated as the square root of the mean of the squares of the head position angular displacements. To account for the varying lengths of lane change duration, the difference between each individual head position angle and the mean angle of that lane change was calculated. These differences were then squared to calculate RMS.

4.3.1 Heading Angle Displacement RMS

To assess differences in head movement in the "no" direction, a linear mixed effects analysis with fixed effects of rear visibility technology, lighting condition, lane change direction and their interactions and a random intercept for participant was performed on the angular displacement of the heading angle (i.e., yaw). Results found a significant effect for rear visibility technology, lane change direction, and a significant rear visibility technology x lane change direction interaction. Displacement RMS was greater with European-specification OE outside rearview mirrors ($M = 0.81$, $SE = 0.11$) compared to the tested CMS ($M = 0.68$, $SE = 0.11$, $p < 0.05$). Displacement RMS was greater for left lane changes ($M = 1.23$, $SE = 0.11$) compared to right lane changes ($M = 0.26$, $SE = 0.11$, $p < 0.05$). Specifically, displacement RMS was greater with European-specification OE outside rearview mirrors for left lane changes (M = 1.35, SE = 0.12) compared to the tested CMS for left lane changes (M = 1.11, SE = 0.12, $p < 0.05$). Displacement RMS did not differ between the European-specification OE outside rearview mirrors and the tested CMS when making right lane changes ($p = 0.78$). Results are shown in Figure 23. Means and standard errors are shown in Table 17.

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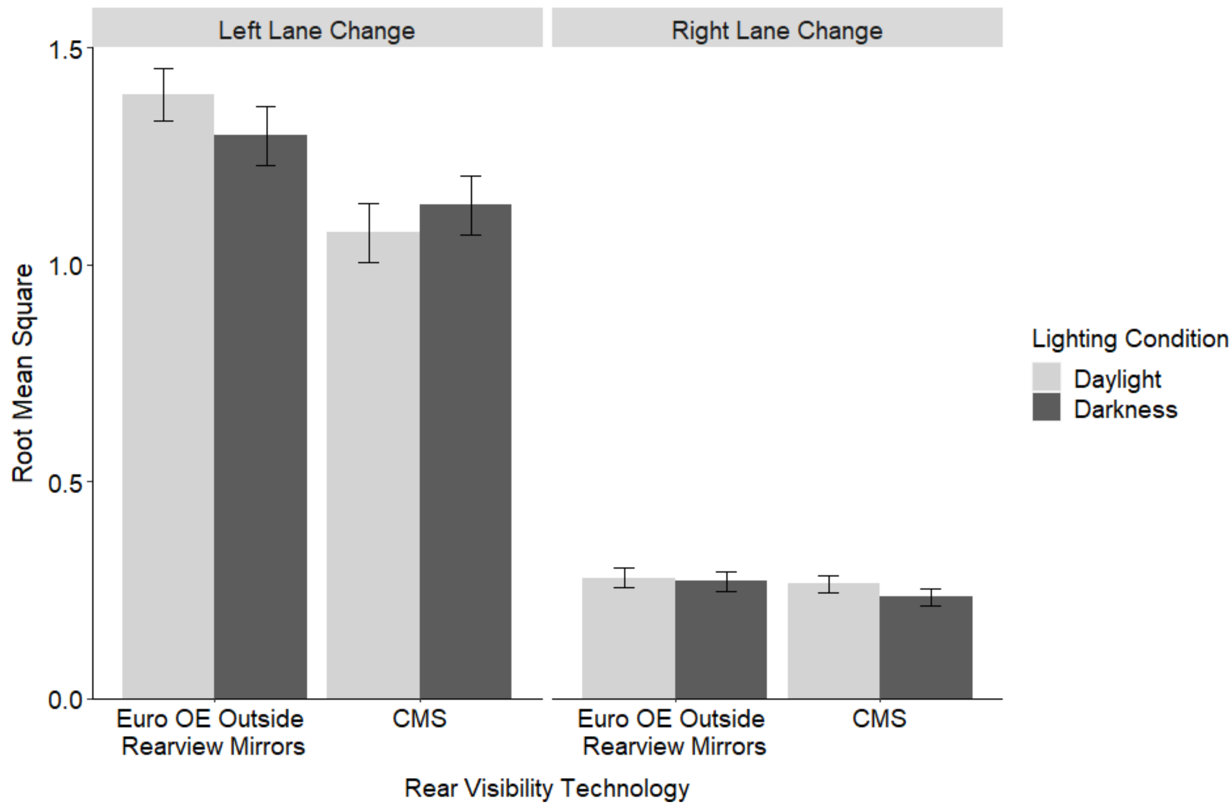

Figure 23. Root mean square of heading angular displacement. Error bars are standard error.

Table 17. Means and standard errors for heading angle displacement RMS

Rear Visibility Technology	Lighting Condition	Lane Change Direction	RMS	Standard Error
Euro OE Outside Rearview Mirrors	Daylight	Left	1.39	0.06
		Right	0.28	0.02
CMS	Daylight	Left	1.07	0.07
		Right	0.26	0.02
Euro OE Outside Rearview Mirrors	Darkness	Left	1.30	0.07
		Right	0.27	0.02
CMS	Darkness	Left	1.14	0.07
		Right	0.23	0.02

4.3.2 Pitch Angle Displacement RMS

To assess differences in head movement in the “yes” direction, a linear mixed effects analysis with fixed effects of rear visibility technology, lighting condition, lane change direction and their interactions and a random intercept for participant was performed on the angular displacement of the pitch angle. Results found significant effects for rear visibility technology, lane change direction, and lighting condition. Displacement RMS was greater with the tested CMS (M = 0.046, SE = 0.004) compared to the European-specification OE outside rearview mirrors (M = 0.044, SE = 0.004, $p < 0.05$). Displacement RMS was greater in daylight (M = 0.047, SE = 0.04) compared to darkness (M = 0.043, SE = 0.004, $p < 0.05$). Displacement RMS was greater for left lane changes (M = 0.049, SE = 0.004) compared to right lane changes (M = 0.041, SE = 0.004, $p < 0.05$). All other tests failed to gain significance. Results are shown in Figure 24. Means and standard errors are shown in Table 18.

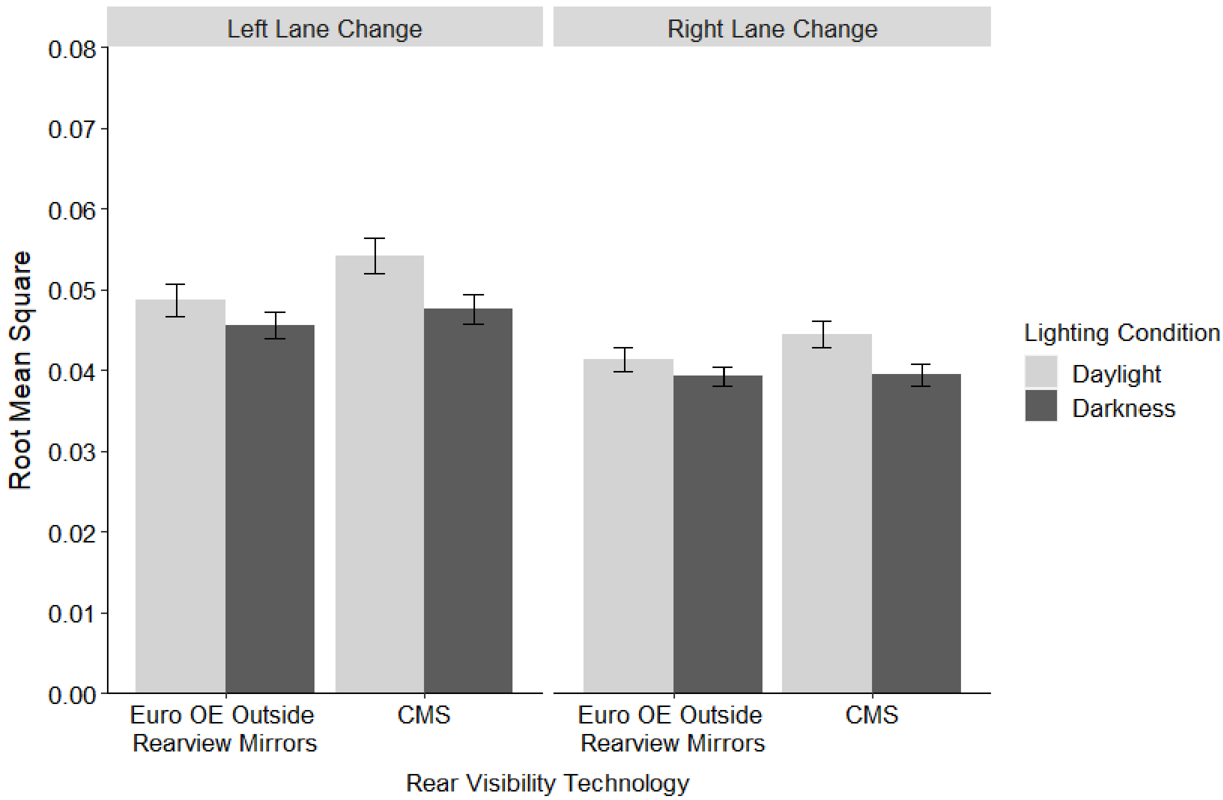

Figure 24. Root mean square of pitch angular displacement. Error bars are standard error.

Table 18. Means and standard errors for pitch angle displacement RMS

Rear Visibility Technology	Lighting Condition	Lane Change Direction	RMS	Standard Error
Euro OE Outside Rearview Mirrors	Daylight	Left	0.049	0.0020
		Right	0.041	0.0015
CMS	Daylight	Left	0.054	0.0022
		Right	0.044	0.0016
Euro OE Outside Rearview Mirrors	Darkness	Left	0.046	0.0017
		Right	0.039	0.0012
CMS	Darkness	Left	0.048	0.0018
		Right	0.039	0.0013

4.3.3 Roll Angle Displacement RMS

To assess differences in head movement in the shoulder-to-shoulder direction, a linear mixed effects analysis with fixed effects of condition, lighting condition, lane change direction and their interactions, and a random intercept for participant was performed on the angular displacement of the roll angle. Results found significant effects for lighting condition and lane change direction. Displacement RMS was greater in daylight ($M = 0.049$, $SE = 0.004$) compared to darkness ($M = 0.44$, $SE = 0.004$, $p < 0.05$). Displacement RMS was greater for left lane changes ($M = 0.47$, $SE = 0.004$) compared to right lane changes ($M = 0.45$, $SE = 0.004$, $p < 0.05$). All other tests failed to gain significance. Results are shown in Figure 25. Means and standard errors are shown in Table 19.

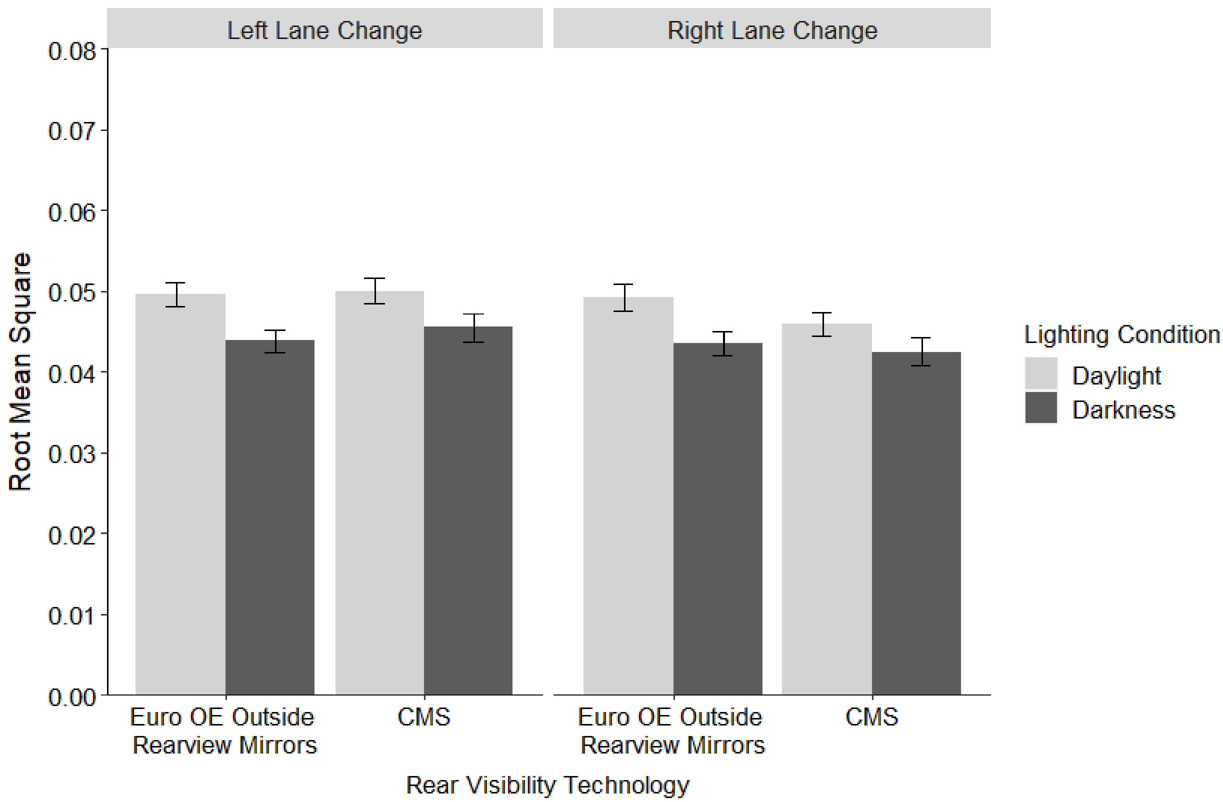

Figure 25. Root mean square of roll angular displacement. Error bars are standard error.

Table 19. Means and standard errors for roll angle displacement RMS

Rear Visibility Technology	Lighting Condition	Lane Change Direction	RMS	Standard Error
Euro OE Outside Rearview Mirrors	Daylight	Left	0.050	0.0015
		Right	0.049	0.0016
CMS	Daylight	Left	0.050	0.0015
		Right	0.046	0.0015
Euro OE Outside Rearview Mirrors	Darkness	Left	0.044	0.0014
		Right	0.044	0.0015
CMS	Darkness	Left	0.046	0.0017
		Right	0.043	0.0018

4.4 Unexpected Obstacle Detection Event

To assess whether illumination from the tested CMS visual displays hinder drivers' ability to detect forward obstacles in darkness, participants performed an unexpected obstacle detection task. Detection of the pathway obstructing object was quantified by whether the participant stopped before hitting the object. Additionally, the distance from where the participant stopped was measured for participants who stopped before hitting the object. One participant's data were removed for not following directions and reversing the vehicle to the object as opposed to pulling forward towards the vehicle, therefore ten participants' data were analyzed. Results found that all participants stopped before hitting the object. A Welch's two sample t-test found no significant difference in distance from the object ($t(7.96) = 0.57$, $p = 0.58$). On average, participants stopped 113.22 inches (SE = 12.06 in.) away from the object when driving with CMS and participants stopped 102.32 inches (SE = 14.54 in.) away from the object when driving with European-specification OE outside rearview mirrors. Results are shown in Figure 26.

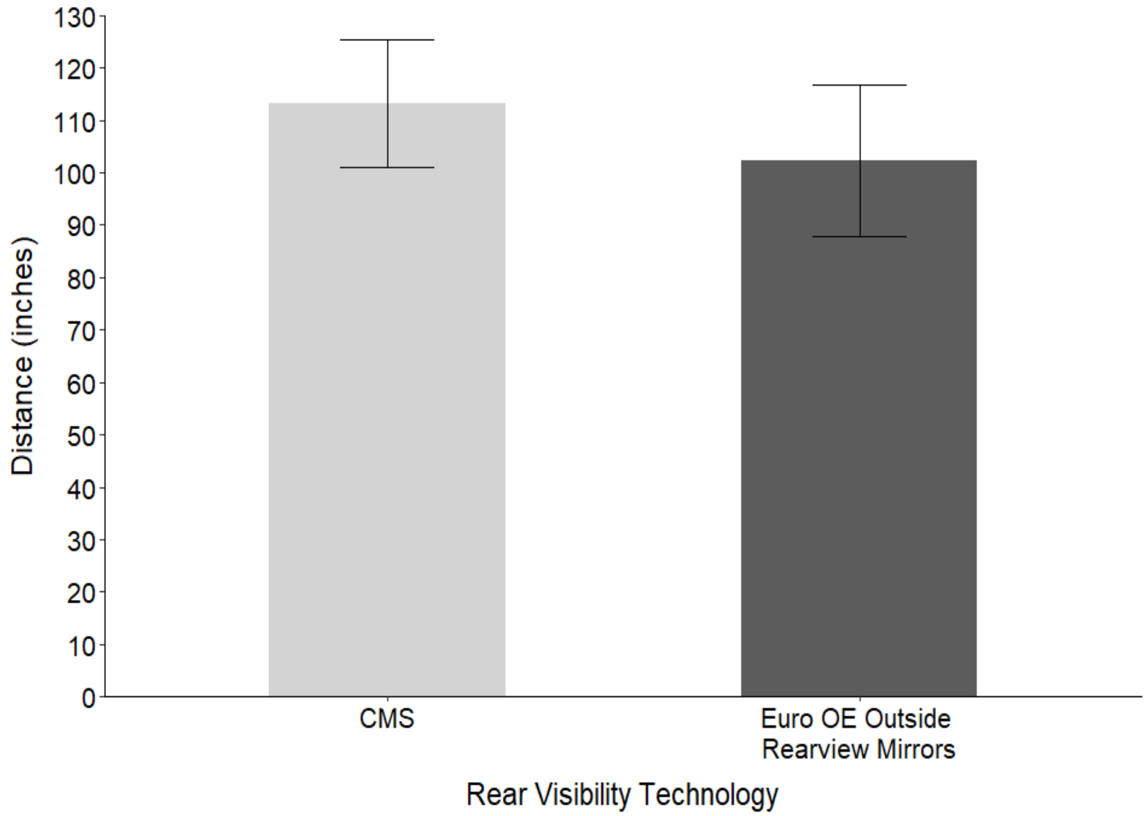

Figure 26. Average stopped distance to the object. Error bars are standard error.

4.5 Post-Drive Subjective Questionnaire

To assess drivers' subjective impressions of the rear visibility technologies, subjective ratings about each rear visibility technology were gathered via post-drive questionnaire. Questions were asked concerning the general ease of using each rear visibility technology, the image quality provided by each rear visibility technology, and how well each rear visibility technology aided in driving performance. Participants provided ratings on a Likert-type scale of 1 (*strongly disagree*) to 7 (*strongly agree*). Statistical comparisons were not performed on subjective ratings, but mean ratings are summarized below.

In general, participants rated the European-specification OE outside rearview mirrors ($M = 6.09$) as slightly easier to use than the tested CMS ($M = 5.59$). They also rated the European-specification OE outside rearview mirrors ($M = 6.09$) as slightly more comfortable to use than the tested CMS ($M = 5.64$). Participants rated the field of view size provided by European-specification OE outside rearview mirrors to be more acceptable ($M = 6.22$) compared to the tested CMS ($M = 5.64$).

Participants rated the image quality of the tested CMS as less than that of the European-specification OE outside rearview mirrors, particularly in darkness. The image quality of the tested CMS was rated a full scalar lower in darkness compared to daylight, while the rating difference between darkness and daylight with the European-specification OE outside rearview mirrors was negligible.

In daylight, participants found they were less able to judge distances to either the left or the right with the tested CMS. Participants rated being able to judge distances with the tested CMS better in the darkness, however, still rated this accuracy as lower than with the European-specification OE outside rearview mirrors.

When asked to choose which rear visibility technology they would prefer to use in everyday driving on their own vehicle, most participants chose the European-specification OE outside rearview mirrors over only the tested CMS or the possibility of having both the European-specification OE outside rearview mirrors and CMS on a vehicle. However, participants did not experience a drive with both rear visibility technologies in use at the same time.

Ratings to specific questions can be viewed in Appendix A.

5.0 Discussion

5.1 Findings regarding whether lane-change performance differs when driving with a CMS compared to European-specification OE outside rearview mirrors

Individual lane change completion times did not differ when driving with the tested CMS compared to the European-specification OE outside rearview mirrors. Participants were slower to complete lane changes in darkness compared to daylight, but there was no difference in lane change completion times between the tested CMS and the European-specification OE outside rearview mirrors. However, with the tested CMS, participants did take longer to complete an entire passing maneuver (i.e., two lane changes) as compared to the European-specification OE outside rearview mirrors.

5.2 Findings regarding whether driving with a CMS results in differences in distance judgments when passing a slower lead vehicle compared to European-specification OE outside rearview mirrors

Results found that participants maintained a greater overtake distance when passing a slower moving vehicle while driving with the tested CMS in daylight compared to driving with the European-specification OE outside rearview mirrors in daylight. Additionally, participants maintained a greater overtake distance with the tested CMS when making a left lane change back in front of the slower moving vehicle (i.e., passing on the right) compared to making a left lane change with the European-specification OE outside rearview mirrors.

5.3 Findings regarding whether eye-gaze behavior during lane change and passing maneuvers differs with the tested CMS compared to European-specification OE outside rearview mirrors

Analysis of participants' eye-gaze fixations showed that participants made a greater number of fixations in daylight to the tested CMS displays compared to the European-specification OE outside rearview mirrors. There was no difference in the number of fixations between rear visibility technologies in darkness. The number of fixations did not differ when comparing the driver-side CMS display to the driver-side European-specification OE outside rearview mirror, the inside rearview mirror between rear visibility technology conditions, or the passenger-side CMS display to the passenger-side European-specification OE outside rearview mirror.

Analysis of participants' average fixation durations showed that participants fixated for a longer average duration in darkness to the tested CMS displays compared to the European-specification OE outside rearview mirrors. There was no difference in the average fixation duration between rear visibility technologies in daylight. Additionally, in darkness, participants fixated for a longer average duration to the driver-side CMS display compared to the driver-side European-specification OE outside rearview mirror. Average fixation durations did not differ between the driver-side CMS display and driver-side European-specification OE outside rearview mirror in daylight or between the passenger-side CMS display and passenger-side European-specification OE outside rearview mirrors in either lighting condition. The average fixation duration to the inside rearview mirror did not differ between rear visibility technologies in daylight or darkness.

Analysis of participant total fixation durations showed that participants fixated for a longer total duration to the tested CMS displays compared to the European-specification OE outside rearview mirrors, specifically to the tested CMS displays when making a left lane change in darkness compared to the European-specification OE outside rearview mirrors when making a left lane change in darkness. Total fixation durations did not differ when comparing the driver-side CMS display to the driver-side European-specification OE outside rearview mirror, the inside rearview mirror between rear visibility technology conditions, or the passenger-side CMS display to the passenger-side European-specification OE outside rearview mirror.

Overall, participants did not make many long duration fixations to either the tested CMS displays or European-specification OE outside rearview mirrors.

5.4 Findings regarding whether head movements differed for CMSs compared to European-specification OE outside rearview mirrors

Results found that head movement in the heading direction (i.e., "no" motion), differed between the tested CMS and the European-specification OE outside rearview mirrors. Additionally, there was an interaction whereby for left lane changes, head movement in the heading direction was greater for European-specification OE outside rearview mirrors compared to the tested CMS. Additionally, head movement was greater in the pitch (i.e., "yes" motion) direction with European-specification OE outside rearview mirrors compared to the tested CMS. Head movement did not differ between the tested CMS and outside rearview mirrors in the roll direction (i.e., shoulder-to-shoulder motion).

5.5 Findings regarding whether illumination from the tested CMS visual displays hinders drivers' ability to detect forward obstacles

Results found no rear visibility technology-based difference in performance in the unexpected obstacle detection event. All participants saw the object and stopped before hitting it. Additionally, there was no difference between the European-specification OE outside rearview mirrors and the tested CMS for the distance from the vehicle's stopped location to the object.

5.6 Findings regarding whether drivers' subjective impressions of general use, comfort, and visibility differ for CMSs compared to European-specification OE outside rearview mirrors

Participants subjectively rated the European-specification OE outside rearview mirrors as easier to use, more comfortable to use, and providing better image quality than the tested CMS. The field of view size of the European-specification OE outside rearview mirrors was rated to be more acceptable compared to the tested CMS. Especially in daylight, participants found they were less able to accurately judge distances to either the left or the right with the tested CMS compared to the European-specification OE outside rearview mirrors. When asked to choose which rear visibility technology they would prefer to use in everyday driving, most participants chose the European-specification OE outside rearview mirrors over only the tested CMS or having both systems.

6.0 Summary and Conclusions

Analysis of study results identified differences in driver behavior and performance observed between the tested production-ready prototype CMS and the European-specification OE outside rearview mirrors in a model year 2018 European-market light vehicle. Participants took longer to complete a passing maneuver and in daylight maintained a greater overtake distance with the tested CMS compared to European-specification OE outside rearview mirrors. In darkness, lane change performance was similar between the tested CMS and the European-specification OE outside rearview mirrors. Separately, participants also maintained a greater overtake distance with the tested CMS when making a left lane change compared to making a left lane change with the European-specification OE outside rearview mirrors.

Participants' visual behavior also differed between the tested CMS compared to the European-specification OE outside rearview mirrors. In daylight, participants made a greater number of fixations to the tested CMS displays compared to the European-specification OE outside rearview mirrors. The number of fixations did not differ between rear visibility technologies in darkness. However, in darkness, average fixation durations were longer to the tested CMS displays compared to the European-specification OE outside rearview mirrors, specifically to the driver-side CMS display in darkness compared to the driver-side European-specification OE outside rearview mirror in darkness. Total fixation durations were also longer to the tested CMS displays, specifically the tested CMS displays when making a left lane change in darkness compared to the driver-side European-specification OE outside rearview mirror when making a left lane change in darkness.

Participants' head movements observed during lane change maneuvers differed between the tested CMS and the European-specification OE outside rearview mirrors in the heading and pitch directions. Overall, participants made more movements in the heading and pitch directions when driving with the European-specification OE outside rearview mirrors compared to the tested CMS. Additionally, there was an interaction whereby for left lane changes, head movement in the heading direction was greater for European-specification OE outside rearview mirrors than for the tested CMS.

Participants subjectively rated the OE mirrors as easier to use, more comfortable, and providing better visibility than the tested CMS. When asked to choose which rear visibility technology they would prefer to use in everyday driving, most participants chose the European-specification OE outside rearview mirrors over only the tested CMS or having both systems. However, it is worth noting that these differences were generally on the scale of half a level of a Likert scale rating, were not assessed statistically, and reflect a small sample's opinions about a specific CMS.

Overall, results of this small, preliminary study suggest that drivers' behavior in using the tested production-ready prototype CMS was different in terms of lane change performance, eye-gaze behavior, and subjective impressions. Results showed differences in overtake distance, passing maneuver completion time, number of fixations, average fixation durations, and total fixation durations when comparing the tested CMS to European-specification OE outside rearview mirrors. Participants made a higher number of fixations and fixated for a longer average and total duration to the tested CMS displays, albeit sometimes this was dependent on lighting condition or lane change direction. Further, participants were exposed to the CMS only for the duration of the study and were less familiar with the tested CMS overall compared to mirrors, although the OE driver-side convex (not FMVSS No. 111 compliant) mirror on the European-model test vehicle was also less familiar to the U.S. driver participants. This study is part of a larger research program that will gather additional data on drivers' use of CMSs to assess whether these trends are consistent with a larger sample size, other systems, and the implications for driving safety. It is anticipated that a larger sample size beyond the smaller sample size of this pilot study would yield results consistent with those already found here, but also provide more powerful results and conclusions.

7.0 References

49 CFR § 571.111, Standard No. 111; Rear visibility. (2023). www.ecfr.gov/current/title-49/subtitle-B/chapter-V/part-571/subpart-B/section-571.111

84 FR 54533. Docket No. NHTSA-2018-0021. (2019). Federal Motor Vehicle Safety Standard No. 111, Rear Visibility. Advance notice of proposed rulemaking. National Highway Traffic Safety Administration.

Ali, J. S. M., & Bazilah, F. F. (2014). Mirrorless car: A feasibility study. *Applied Mechanics and Materials, 663*, 649–654. https://doi.org/10.4028/www.scientific.net/amm.663.649

Beck, D., Lee, M., & Park, W. (2017). A comparative evaluation of in-vehicle side view displays layouts in critical lane changing situation. *Ergonomics, 60*(12), 1682–1691. https://doi.org/10.1080/00140139.2017.1343958

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.

Fitch, G. M., Blanco, M., Camden, M. C., Olson, R. L., McClafferty, J., Morgan, J. F., Wharton, A. E., Howard, H. E., Trimble, T., & Hanowski, R. J. (2011). *Field demonstration of heavy vehicle camera/video imaging systems* (Report No. DOT HS 811 475). National Highway Traffic Safety Administration. www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/812360_humanfactorsdesignguidance.pdf

Fitch, G. M., Wierwille, W. W., Schaudt, W. A., & Hanowski, R. J. (2008, September). Towards developing an indirect video visibility system for large trucks. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 52*(23), 1888–1892. https://doi.org/10.1177/154193120805202312

Flannagan, M. J., & Mefford, M. L. (2005). Distance perception with a camera-based rear vision system in actual driving. *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 59–65. https://ir.uiowa.edu/drivingassessment/2005/papers/9

Flannagan, M. J., Sivak, M., & Simpson, J. K. (2001a). *The role of binocular information for distance perception in rear-vision systems* (SAE Technical Paper No. 2001-01-0322). Society of Automotive Engineers. https://doi.org/10.4271/2001-01-0322

Flannagan, M. J., Sivak, M., & Simpson, J. K. (2001b, August 14-17). *The relative importance of pictorial and nonpictorial distance cues for driver vision.* Driving Assessment 2001[University of Iowa conference presentation], Aspen, CO. https://doi.org/10.17077/-drivingassessment.1041

Large, D. R., Crundall, E., Burnett, G., Harvey, C., & Konstantopoulos, P. (2016). Driving without wings: The effect of different digital mirror locations on the visual behaviour, performance and opinions of drivers. *Applied Ergonomics*, *55*, 138–148. https://doi.org/10.1016/j.apergo.2016.02.003

Martin, K. B., Hammal, Z., Ren, G., Cohn, J. F., Cassell, J., Ogihara, M., Britton, J. C., Gutierrez, A., & Messinger, D. S. (2018). Objective measurement of head movement differences in children with and without autism spectrum disorder. *Molecular autism*, *9*(1), 1–10. https://doi.org/10.1186/s13229-018-0198-4

Mazzae, E. N., Baldwin, G. H., & Andrella, A. T. (2018, October). *Examination of a prototype camera monitor system for light vehicle outside mirror replacement* (Report No. DOT HS 812 582). National Highway Traffic Safety Administration. https://rosap.ntl.bts.gov/view/dot/37682

SAE International. (2015). Operational definitions of driving performance measures and statistics*. Ground Vehicle Standard,* J2944_J2944. https://doi.org/10.4271/J2944_201506

R Core Team (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. www.R-project.org

Satterthwaite, F. E. (1946). An approximate distribution of estimates of variance components. *Biometrics Bulletin, 2*, 110-114. http://dx.doi.org/10.2307/3002019

Schmidt, E. A., Hoffmann, H., Krautscheid, R., Bierbach, M., Frey, A., Gail, J., & Lotz-Keens, C. (2016). Camera-monitor systems as a replacement for exterior mirrors in cars and trucks. In *A. Terzis (Ed.), Handbook of Camera Monitor Systems: Augmented Vision and Reality*, (Vol. 5, pp. 369–435). Springer. https://doi.org/10.1007/978-3-319-29611-1_12

Wickham, H. (2009) *ggplot2: Elegant graphics for data analysis*. Springer. https://doi.org/10.1007/978-0-387-98141-3

Wierwille, W. W., Schaudt, W. A., Blanco, M., Alden, A. A., & Hanowski, R. J. (2011). *Enhanced camera/video imaging systems (EC/VISs) for heavy vehicles: Final report* (Report No. DOT HS 811 483). National Highway Traffic Safety Administration. https://vtechworks.lib.vt.edu/bitstream/handle/10919/55079/811483.pdf?sequence=1

Appendix A: Frequency Tables to Post-Drive Questionnaire Questions

1. "It was easy to use camera-based system/mirrors while driving."

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	0	0.0	0	0.0	1	9.1	1	9.1
Moderately Disagree (2)	1	9.1	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	1	9.1	1	9.1	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Agree (5)	2	18.2	3	27.3	0	0.0	1	9.1
Moderately Agree (6)	4	36.4	4	36.4	3	27.3	3	27.3
Strongly Agree (7)	3	27.3	3	27.3	7	63.6	6	54.5
Mean	5.45		5.73		6.18		6.00	

2. "I was comfortable with the physical location of the camera-based displays/mirrors."

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	0	0.0	0	0.0	1	9.1	1	9.1
Moderately Disagree (2)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	1	9.1	2	18.2	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Agree (5)	5	45.5	1	9.1	0	0.0	0	0.0
Moderately Agree (6)	3	27.3	3	27.3	4	36.4	4	36.4
Strongly Agree (7)	2	18.2	5	45.5	6	54.5	6	54.5
Mean	5.45		5.82		6.09		6.09	

3. "The physical size of the camera-based displays was acceptable." (CMS only)

	Daylight		Darkness	
	N	%	*N*	%
Strongly Disagree (1)	0	0.0	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0
Somewhat Disagree (3)	0	0.0	0	0.0
Neither Disagree nor Agree (4)	3	27.3	2	18.2
Somewhat Agree (5)	0	0.0	0	0.0
Moderately Agree (6)	3	27.3	3	27.3
Strongly Agree (7)	5	45.5	6	54.5
Mean	5.91		6.18	

4. “If the size of the camera-based displays was not acceptable, what was wrong with it (e.g., was it too large or too small)?” (CMS only)

	Daylight		Darkness	
	N	%	*N*	%
Far too small (1)	0	0.0	0	0.0
Moderately too small (2)	0	0.0	1	9.1
Slightly too small (3)	2	18.2	2	18.2
Neither too large nor too small (4)	9	81.8	8	72.7
Slightly too large (5)	0	0.0	0	0.0
Moderately too large (6)	0	0.0	0	0.0
Far too large (7)	0	0.0	0	0.0
Mean	3.82		3.64	

5. “The size of the field of view displayed by the camera-based system/mirrors was acceptable.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	1	9.1	0	0.0	0	0.0	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0	1	9.1	0	0.0
Somewhat Disagree (3)	0	0.0	0	0.0	0	0.0	0	0.0
Neither Disagree nor Agree (4)	2	18.2	2	18.2	0	0.0	0	0.0
Somewhat Agree (5)	2	18.2	3	27.3	1	9.1	1	9.1
Moderately Agree (6)	1	9.1	1	9.1	2	18.2	6	54.5
Strongly Agree (7)	5	45.5	5	45.5	7	63.6	4	36.4
Mean	5.45		5.82		6.18		6.27	

6. “If the size of the field of view was not acceptable, what was wrong with it, (e.g., was it too large or too small)?”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Far too small (1)	1	9.1	0	0.0	0	0.0	0	0.0
Moderately too small (2)	0	0.0	0	0.0	0	0.0	0	0.0
Slightly too small (3)	1	9.1	1	9.1	1	9.1	2	18.2
Neither too large nor too small (4)	9	81.8	10	90.9	10	90.9	9	81.8
Slightly too large (5)	0	0.0	0	0.0	0	0.0	0	0.0
Moderately too large (6)	0	0.0	0	0.0	0	0.0	0	0.0
Far too large (7)	0	0.0	0	0.0	0	0.0	0	0.0
Mean	3.64		3.91		3.91		3.82	

7. "It was easy to incorporate the camera-based displays/mirrors into my normal driving eye glance patterns."

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	0	0.0	0	0.0	1	9.1	1	9.1
Moderately Disagree (2)	1	9.1	2	18.2	0	0.0	0	0.0
Somewhat Disagree (3)	2	18.2	0	0.0	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Agree (5)	1	9.1	2	18.2	1	9.1	2	18.2
Moderately Agree (6)	5	45.5	3	27.3	3	27.3	3	27.3
Strongly Agree (7)	2	18.2	4	36.4	6	54.5	5	45.5
Mean	5.18		5.45		6.00		5.82	

8. "The image displayed (image quality) by the camera-based system/mirror was clear."

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	0	0.0	1	9.1	1	9.1	0	0.0
Moderately Disagree (2)	0	0.0	1	9.1	0	0.0	1	9.1
Somewhat Disagree (3)	3	27.3	3	27.3	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Agree (5)	1	9.1	0	0.0	0	0.0	2	18.2
Moderately Agree (6)	3	27.3	4	36.4	4	36.4	3	27.3
Strongly Agree (7)	4	36.4	2	18.2	6	54.5	5	45.5
Mean	5.45		4.55		6.09		5.91	

9. "Objects displayed by the camera-based system/mirror appeared distorted."

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	4	36.4	1	9.1	5	45.5	3	27.3
Moderately Disagree (2)	3	27.3	3	27.3	5	45.5	5	45.5
Somewhat Disagree (3)	0	0.0	1	9.1	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	2	18.2	0	0.0	0	0.0
Somewhat Agree (5)	2	18.2	1	9.1	1	9.1	3	27.3
Moderately Agree (6)	0	0.0	2	18.2	0	0.0	0	0.0
Strongly Agree (7)	2	18.2	1	9.1	0	0.0	0	0.0
Mean	3.09		3.82		1.82		2.55	

10. “I could easily visually focus on objects displayed by the camera-based system/mirror.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	1	9.1	0	0.0	1	9.1	1	9.1
Moderately Disagree (2)	1	9.1	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	0	0.0	2	18.2	0	0.0	1	9.1
Neither Disagree nor Agree (4)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Agree (5)	3	27.3	1	9.1	1	9.1	1	9.1
Moderately Agree (6)	2	18.2	6	54.5	4	36.4	4	36.4
Strongly Agree (7)	4	36.4	2	18.2	5	45.5	4	36.4
Mean	5.27		5.55		5.91		5.55	

11. “I could easily discern other vehicles within the camera’s displayed images/using the mirror.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	0	0.0	0	0.0	1	9.1	1	9.1
Moderately Disagree (2)	1	9.1	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	1	9.1	1	9.1	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	1	9.1	0	0.0	1	9.1
Somewhat Agree (5)	1	9.1	2	18.2	0	0.0	1	9.1
Moderately Agree (6)	3	27.3	4	36.4	2	18.2	3	27.3
Strongly Agree (7)	5	45.5	3	27.3	8	72.7	5	45.5
Mean	5.73		5.64		6.27		5.73	

12. “I was comfortable with the brightness of the camera-based system’s visual displays/image displayed in the mirrors.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	0	0.0	0	0.0	1	9.1	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0	0	0.0	1	9.1
Somewhat Disagree (3)	1	9.1	1	9.1	0	0.0	1	9.1
Neither Disagree nor Agree (4)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Agree (5)	1	9.1	2	18.2	0	0.0	1	9.1
Moderately Agree (6)	2	18.2	4	36.4	3	27.3	5	45.5
Strongly Agree (7)	7	63.6	4	36.4	7	63.6	3	27.3
Mean	6.27		5.91		6.18		5.55	

13. “Outside light conditions negatively affected the quality of the image displayed by the camera-based system/mirror.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	3	27.3	2	18.2	5	45.5	1	9.1
Moderately Disagree (2)	4	36.4	1	9.1	4	36.4	2	18.2
Somewhat Disagree (3)	1	9.1	1	9.1	0	0.0	2	18.2
Neither Disagree nor Agree (4)	2	18.2	1	9.1	1	9.1	0	0.0
Somewhat Agree (5)	0	0.0	2	18.2	1	9.1	3	27.3
Moderately Agree (6)	1	9.1	1	9.1	0	0.0	2	18.2
Strongly Agree (7)	0	0.0	3	27.3	0	0.0	1	9.1
Mean	2.55		4.36		2.00		4.09	

14. “Environmental conditions (e.g., sun, clouds) made it difficult to use the camera-based system/mirrors.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	4	36.4	3	27.3	5	45.5	4	36.4
Moderately Disagree (2)	4	36.4	2	18.2	4	36.4	4	36.4
Somewhat Disagree (3)	1	9.1	2	18.2	0	0.0	0	0.0
Neither Disagree nor Agree (4)	2	18.2	3	27.3	1	9.1	3	27.3
Somewhat Agree (5)	0	0.0	1	9.1	1	9.1	0	0.0
Moderately Agree (6)	0	0.0	0	0.0	0	0.0	0	0.0
Strongly Agree (7)	0	0.0	0	0.0	0	0.0	0	0.0
Mean	2.09		2.73		2.00		2.18	

15. “I felt comfortable using the camera-based system/mirrors to make lane changes to the left.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	1	9.1	0	0.0	1	9.1	0	0.0
Moderately Disagree (2)	1	9.1	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	0	0.0	0	0.0	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	2	18.2	0	0.0	0	0.0
Somewhat Agree (5)	1	9.1	1	9.1	0	0.0	1	9.1
Moderately Agree (6)	4	36.4	6	54.5	4	36.4	5	45.5
Strongly Agree (7)	4	36.4	2	18.2	6	54.5	5	45.5
Mean	5.45		5.73		6.09		6.36	

16. “I felt comfortable using the camera-based system/mirrors to make lane changes to the right.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	2	18.2	0	0.0	0	0.0	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0	1	9.1	0	0.0
Somewhat Disagree (3)	0	0.0	0	0.0	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	2	18.2	0	0.0	0	0.0
Somewhat Agree (5)	2	0.0	2	18.2	1	9.1	2	18.2
Moderately Agree (6)	2	18.2	3	27.3	3	27.3	4	36.4
Strongly Agree (7)	5	45.5	4	36.4	6	54.5	5	45.5
Mean	5.36		5.82		6.09		6.27	

17. “I could accurately judge the distance to objects behind me on the left using the camera-based system/mirrors.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	2	18.2	0	0.0	0	0.0	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	2	18.2	0	0.0	0	0.0	1	9.1
Neither Disagree nor Agree (4)	1	9.1	3	27.3	0	0.0	1	9.1
Somewhat Agree (5)	3	27.3	3	27.3	0	0.0	3	27.3
Moderately Agree (6)	0	0.0	2	18.2	5	45.5	2	18.2
Strongly Agree (7)	3	27.3	3	27.3	6	54.5	4	36.4
Mean	4.36		5.45		6.55		5.64	

18. “I could accurately judge the distance to objects behind me on the right using the camera-based system/mirrors.”

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	2	18.2	0	0.0	0	0.0	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0	0	0.0	0	0.0
Somewhat Disagree (3)	2	18.2	0	0.0	0	0.0	0	0.0
Neither Disagree nor Agree (4)	1	9.1	3	27.3	0	0.0	2	18.2
Somewhat Agree (5)	3	27.3	2	18.2	1	9.1	3	27.3
Moderately Agree (6)	0	0.0	3	27.3	4	36.4	2	18.2
Strongly Agree (7)	3	27.3	3	27.3	6	54.5	4	36.4
Mean	4.36		5.55		6.45		5.73	

19. "I felt safe using the camera-based system/mirrors when changing lanes."

	CMS				European-specification OE outside rearview mirrors			
	Daylight		Darkness		Daylight		Darkness	
	N	%	*N*	%	*N*	%	*N*	%
Strongly Disagree (1)	1	9.1	0	0.0	0	0.0	0	0.0
Moderately Disagree (2)	0	0.0	0	0.0	1	9.1	1	9.1
Somewhat Disagree (3)	2	18.2	1	9.1	0	0.0	0	0.0
Neither Disagree nor Agree (4)	0	0.0	1	9.1	0	0.0	0	0.0
Somewhat Agree (5)	2	18.2	1	9.1	0	0.0	1	9.1
Moderately Agree (6)	2	18.2	5	45.5	4	36.4	3	27.3
Strongly Agree (7)	4	36.4	3	27.3	6	54.5	6	54.5
Mean	5.18		5.73		6.18		6.09	

20. "Which rear visibility technology would you prefer to use in everyday driving?"

	Daylight		Darkness	
	N	%	*N*	%
Camera-based system	2	18.2	2	18.2
Outside rearview mirrors	6	54.5	7	63.6
Both	3	27.3	2	18.2

20a. "If both, please explain:" (Qualitative)

	Daylight	Darkness
Prefer CMS location over mirrors	2	1
Prefer mirrors for objects in distance	2	0
Prefer mirrors for range perception	1	0
Prefer CMS for blind spot detection	1	0
More familiar with mirrors	1	0
Prefer image quality in mirrors	0	1
Both systems equally effective	0	1

21. "During today's driving, which rear visibility technology were you more comfortable with using to make lane changes while driving?"

	Daylight		Darkness	
	N	%	*N*	%
Outside rearview mirrors (1)	3	27.3	2	18.2
Moderately more comfortable with outside rearview mirrors (2)	1	9.1	1	9.1
Somewhat more comfortable with outside rearview mirrors (3)	4	36.4	3	27.3
About the same level of comfort (4)	2	18.2	3	27.3
Somewhat more comfortable with camera-based system (5)	0	0.0	1	9.1
Moderately more comfortable with camera-based system (6)	1	9.1	1	9.1
Camera-based system (7)	0	0.0	0	0.0
Mean	2.82		3.27	

22. “What did you like or dislike about the camera-based rear visibility system?” (Qualitative)

	Daylight	Darkness
Like: Eliminated blind spots	4	2
Like: Size/location of monitors/potential to change location of monitors	4	5
Like: Less glare	1	5
Like: Distance indicators on monitors	3	0
Like: Image quality	2	0
Like: FOV	3	0
Like: Miscellaneous (less drag, easier to clear lens)	0	1
Dislike: Image quality/distortion/ability to see distant objects	5	5
Dislike: Size/location of monitors	1	2
Dislike: Distance perception	4	0
Dislike: Distance indicators on monitors	2	0
Dislike: FOV	2	0

23. “Do you have any thoughts regarding this system as compared to the vehicle that you regularly drive?” (Qualitative)

	Daylight	Darkness
CMS eliminates blind spots better than mirrors	2	1
CMS has less glare	1	1
Generally positive about CMS	1	1
General discomfort with CMS/prefer own mirrors	3	3
Prefer features on own vehicle (blind spot mirrors, blind spot warnings)	1	1
Prefer image quality in mirrors	2	0
Prefer location of CMS	1	2
Prefer CMS image quality at night vs. day	0	2
Liked distance indicators on CMS	1	0
No preference	1	3
Prefer image quality of CMS	0	1
Prefer location/size of own mirrors	0	1

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