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Enhancing digital rear-view mirrors in Trucks using overlayed graphics

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Abstract

As the automotive industry becomes increasingly digitalized, Camera Monitoring Systems (CMS) are replacing traditional mirrors, offering improved aerodynamics and wider fields of view. However, depth perception remains a challenge, and unclear overlays can reduce driver trust. This study investigates how different CMS augmentations affect distance estimation during overtaking. Thirty participants viewed video clips across three road scenes using one baseline and three augmented interface concepts. They estimated vehicle distances, rated certainty, and reported preferences. The Lines concept, using distance lines and vehicle outlines, produced the most favorable results with the lowest absolute errors and highest clarity and reliability ratings, although it introduced systematic overestimation. The Corner concept led to consistent underestimation but offered some perceived benefits, while the Dashed concept performed similarly to the baseline. The final design builds on the strengths of the Lines concept, with refinements inspired by Corner to enhance visibility and stability. Recommendations include using intuitive depth cues, accessible colors, and well-timed visual elements. Future research should explore sound cues, symbolic warnings, and long-term user acceptance.

Keywords: Digital Rear View Mirrors, Camera Monitoring Systems (CMS). Augmented Reality (AR), Depth Perception, Distance Judgement

Introduction

The use of digital rear-view mirrors or Camera Monitor Systems (CMS) as an alternative to traditional side-view mirrors is becoming more common in the automotive industry (see Figure 1), offering several practical benefits. Since 2016, UN regulations have allowed manufacturers to replace mandatory mirrors with camera-based systems[1].

Replacing traditional mirrors with CMS brings both benefits and challenges for the automotive industry. By using external cameras and digital displays, CMS improves rear visibility by reducing blind spots, expanding the field of view, and better performance in poor weather conditions. The improved aerodynamics can also contribute to lower fuel and energy consumption [2].

At the same time, CMS introduces new challenges, particularly in relation to depth perception and distance judgement, both of which are critical for safe driving at higher speeds [3]. To address these limitations, some systems incorporate Augmented Reality (AR) overlay, graphical elements added to the camera feed, to provide clearer and more intuitive visual support, helping drivers better interpret their surroundings.

These questions are central to the SCREENS II research initiative[4], which focuses on improving safety and usability in increasingly automated vehicles. This project reflects a broader industry trend toward developing digital driving environments that are not only technically advanced but also safe, user-friendly, and ergonomically designed.

Figure 1: A digital side-view mirror on the left side of the truck.

Current implementations of Camera Monitor Systems (CMS) still have certain limitations. One of the main concerns is reduced depth perception compared to natural human vision, as well as the risk of cognitive overload when too much information is presented on the screen. These issues may lead to frustration and, in worst case scenarios, unsafe decisions that could result in serious injury or even fatal accidents.

This study aims to investigate how to support drivers in making better decisions and improving depth perception, while keeping cognitive load to a minimum. The work is based on user testing carried out by using a design thinking approach[5]. Focusing on visual overlays, the article seeks to contribute to the development of future CMS solutions, with the goal of improving user experience and promoting safer traffic environments.

To gain a deeper understanding of the context, developing a solution and testing it, the following research questions have been explored through design thinking:

- RQ1: What are the current challenges and limitations of Camera Monitoring Systems (CMS) in providing depth perception and distance judgement to drivers in various traffic situations?

- RQ2: How does the usage of different augmentations on a CMS influence depth perception and distance judgement?
    - H2: Overlays that provide clearer geometric cues will reduce directional bias relative to the baseline.
- RQ3: How can augmentations on a CMS be designed to help drivers judge distance, enhance depth perception, and ensure usability as well as driver safety?
    - H3: The preferred concept will be the one that combines accuracy and perceived clarity.

This article is based on a M.Sc. thesis, and it will concentrate on RQ2 and RQ3. Please, see the thesis for more information[5].

Background

As CMS increasingly replaces traditional mirrors in heavy vehicles, new possibilities emerge, not only through the technology itself, but also through the design flexibility of digital displays. Unlike conventional mirrors, CMS can enhance road safety by providing clearer and more consistent visual information, especially in rain or low-light conditions [2, 6, 7]. Cameras tend to stay cleaner due to their placement and protected lenses, and in-cabin screens are unaffected by rain or dirt.

One promising area for further improvement is the use of graphical overlays. These can support drivers in tasks such as distance estimation, overtaking, and maneuvering [8, 9], potentially making CMS even more effective and user-friendly.

While CMS offers many benefits, there are also some drawbacks. These include higher costs, increased maintenance needs, and concerns about reliability and potential system failures [7, 10]. One technical challenge is handling rapid changes in lighting, such as when entering tunnels or shaded areas, which can affect visibility and delay image adjustment [6].

From the driver's perspective, CMS changes how visual information is accessed. Unlike mirrors, the field of view cannot be adjusted by moving the head, and the displays are positioned inside the cabin rather than outside. Another key limitation is that standard displays are two-dimensional, which makes it harder to judge distances accurately, especially in fast-moving traffic where depth perception is essential [7].

Because CMS displays are flat, binocular and oculomotor cues play a limited role. Drivers must therefore rely on pictorial and geometric cues such as relative size, familiar size, linear perspective, and height in the field, as well as motion cues created by the optic flow. These are well-established depth cues in human perception and form the basis for how 2D displays can support distance judgment[11].

The overlays in this study were designed to strengthen these available cues in a clear and consistent way. Research on CMS combined with Augmented Reality (AR) shows that the design of visual overlays plays a key role in how drivers process information and make decisions [8, 12, 13] highlight the need for driver support in complex situations such as lane changes, overtaking, and navigating roundabouts, which are often perceived as the most challenging.

In takeover scenarios, Lorenz*, et al.* (2014) [14] compared two AR designs, one showing a red restricted lane, and another a green safe lane. While both were effective, the green lane led to more consistent steering behavior. More recent findings by Lee and Ju (2024) [15] show that AR signals in CMS can reduce collisions and improve reaction times during lane changes, underlining the potential of AR to enhance safety and driver awareness.

Method

Three different AR overlays were developed through a design thinking process [5], see Figure 2. The design had to meet the regulation that not more than 2.5% of the field of view in the CMS are allowed to be covered with the overlay graphics[1]. These were used in an experiment for evaluating if such augmentations are advantageous and finding out which ones are preferred.

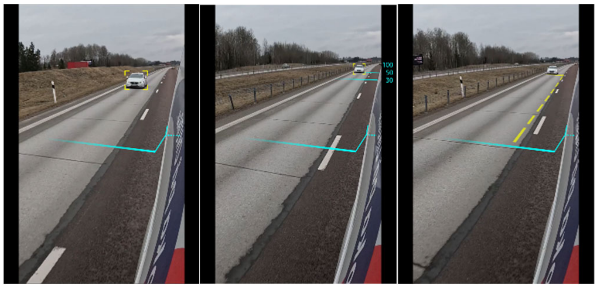

Figure 2: AR overlay concepts used in the experiment. The concepts are named from left to right: Corner, Lines and Dashed.

The experiment builds upon and takes inspiration from the "Last Safe Gap (LSG)" session conducted by Thulinsson and Söderlund in their M.Sc. thesis work [16, 17]. In that session, videos were showing a vehicle travelling at a constant speed in the right lane of a two-lane highway, while another car approached from behind in the left lane.

Stimuli

The video prototypes were created from material produced by Thulinsson and Söderlund[16, 17]. The clips were edited to ensure the correct FOV for Class II and wide Class IV cameras. Three base videos, labelled A, B, and C, showed the same overtaking car in different road environments, preventing participants from using environmental familiarity as a depth cue. Four concepts, Corner, Lines, Dashed, and a baseline without augmentation, were added in Adobe After Effects, designed to follow the movements of both the overtaking and own vehicle. One beep was inserted in each video, marking one of the three target distances: 6, 25 or 80 meters. With three scenes and four concepts, and one beeped distance per video, this resulted in 3 × 4 × 3 = 36 videos.

Videos were made to ensure that all participants got the same information. Videos for created for:

- Introduction of the project
- Introduction to the test procedure
- Introduction to practice-session
- Practice-session
- Recap
- Introduction to the concept
- Sure/Safe question

The videos were made with a simple presentation slide complementary auditory, with an Al voice [18].

Apparatus

The laboratory setup for the test is shown in Figure 3. The environment was designed to approximate a realistic user context, in line with recommendations to conduct trials with representative users under realistic conditions [19].

Illumination was measured after one hour with both light and TV on: 1250 lux horizontally and 450 lux vertically, taken at the participant's ocular reference point (635 mm above the chair seat). Measurements were directed towards the ceiling (horizontal) and the TV (vertical), which displayed a frozen start scene. Artificial lighting with a color temperature of 6500 K simulated daylight conditions.

The chair was positioned so that each participant's ocular reference point was about 120 cm from the TV (Figure 3). A 65-inch LG OLED 4K TV was used to simulate the driver's view through a windshield, offering a wide field of vision. The screen was set to 660 cd/m2 brightness, 4K resolution, and 60 fps to ensure clarity and realism under ambient lighting conditions. The experiments utilized a Thrustmaster T248 steering wheel and pedal set featuring force feedback and magnetic paddle shifters. This setup was chosen to enhance the realism and ecological validity of the experiment and to increase participant engagement. One computer had the playlists, and the other was used to collect the verbal data from participants. For the test execution, VLC media player version 3.0.21[20] was used to make playlists and randomize the order of the videos within the concepts. This was to make the process smoother and avoid buffering and being able to use the material in 4K. An iPad was used to collect background information and self-reported data from the participants. A Snellen chart designed for a 3-metre viewing distance was used to assess participants' visual acuity prior to testing. The Ishihara's tests for Color Deficiency booklet was presented to screen participants for color vision deficiencies.

Figure 3: The test set-up.

Procedure

An exploratory within-subject study was designed to investigate the research questions empirically. To address the research questions, visual perspective was broken down into a combination of two parameters: camera height and field of view (FOV). It was found that a CMS-style video would be relevant and give acceptable ecological validity to the study.

The test followed the structure below (during step 4 (a-g), the participants were seated in the test environment, whereas during the other steps they were not).

1. Welcome
2. Information and consent-form
3. Vision tests
4. Sessions part
    a. Introduction videos
    b. Training session
    c. Introduction to the first test
    d. Recap of task
    e. Questions (if any)
    f. Concepts video loop i.e. watching and rating
5. Post Questionnaire
6. Thank you and gift card

Participants were welcomed to the lab and provided with an information sheet, which had also been sent to them in advance. They signed an informed consent form and completed a background questionnaire before undergoing vision tests for visual acuity (Snellen) and color deficiency (Ishihara). Afterwards, they viewed introduction videos explaining the CMS, the task, and the training procedure, with an emphasis that the evaluation focused on the system and not on the individual. A short training exercise ensured that they could respond aloud, after which they were introduced to the first concept and were reminded of the procedure. During the concept loop, nine videos per concept were shown, and at each beep participants estimated the overtaking car's distance aloud before answering two Likert-scale (1–7) questions: *"Hur säker är du på ditt svar?"* ("How sure are you of your answer?") and *"Hur trygg skulle du känna dig att byta fil vid pipet?"* ("How confident would you feel changing lanes at the beep?"). On screen, the instruction *"Svara genom att säga högt"* ("Say your answer out loud") was displayed together with the questions. The System Usability Scale (SUS), translated into Swedish, was completed between concepts, and at the end a post-questionnaire compared the concepts, asking for descriptive words and preferences. Finally, participants were thanked and received a gift card.

Each participant was assigned one of ten randomized playlists, each containing 36 videos (three scenes for each of the four concepts, each shown once with one of the three beep distances). The playlists presented nine videos for each of the four concepts, with both the order of concepts and the order of videos within each concept randomized.

Participants

Participants were recruited via the Accindi platform[21], which connects researchers with volunteers for user studies, as well as through personal contacts and visitors to the RISE lab office building in Stockholm, Sweden. They were informed beforehand that participation would be compensated with a 200 SEK gift card. Eligibility required a category B driving license and proficiency in Swedish. In total, 30 participants took part, with a gender distribution of 18 males (60%) and 12 females (40%). The average age was 34 years, and the median age was 29. The average length of time participants with a B driving license had held it was 13 years, the lowest being 8 months and the longest 41 years. For those with C license, the average was 7 years spanning from 1 year to 15 years.

Statistical analysis

All participant data were compiled in long format, with both directional error (guessed minus actual) and relative error ((guessed minus actual) / actual x 100) calculated. Positive values indicated overestimation, while negative values indicated underestimation. Relative error was used to enable comparison across short and long distances, since the same absolute error has greater impact at close range than at longer distances.

Table 1: Summary statistics of relative distance estimation error by concept. Note. n = observations per concept. Positive directional error = overestimation; negative = underestimation. 95% Confidence Intervals (CI) computed via t-distribution. All values in percent (%), except for n.

		Directional relative error (%)				**Absolute relative error (%)**			
Concept	**n**	**Mean**	**SD**	**95% CI low**	**95% CI high**	**Mean**	**SD**	**95% CI low**	**95% CI high**
Base	270	−10.8	54.9	−17.4	−4.2	45.4	32.5	41.5	49.3
Corner	270	−31.0	45.3	−36.5	−25.6	46.3	29.4	42.8	49.8
Dashed	270	−13.8	55.9	−20.5	−7.1	45.6	35.2	41.4	49.8
Lines	270	+18.0	58.4	+11.0	+25.0	38.6	47.3	33.0	44.3

Data was analyzed using one-way repeated measures analysis of variance (RM-ANOVA) with Concept (Base, Corner, Dashed, Lines) as the within-subject factor, computed on per-participant means across trials. Sphericity was assessed using Mauchly's test, with Greenhouse-Geisser correction applied if violated. Effect size was reported as partial eta-squared, with .01, .06, and .14 used as benchmarks for small, medium, and large effects respectively. Post-hoc pairwise comparisons were conducted using Holm-corrected t-tests via estimated marginal means (emmeans), with degrees of freedom approximated using the Kenward-Roger method[22], which adjusts for the covariance structure of the repeated measures design. Effect sizes for pairwise comparisons were expressed as Cohen's d[23, 24], calculated as the mean difference divided by the pooled within-group standard deviation, with .20, .50, and .80 used as benchmarks for small, medium, and large effects respectively. Normality of model residuals was verified using Shapiro-Wilk tests[25]. As a non-parametric robustness check, Friedman tests[26] were conducted alongside the RM-ANOVA, with effect size reported as Kendall's W, where values below .10, between .10 and .30, and above .30 are considered small, medium, and large respectively. Significant Friedman tests were followed up with Wilcoxon signed rank pairwise comparisons with Holm correction, and effect size reported as r = Z / sqrt(n). All analyses were conducted in R (version 4.3.3) using the packages rstatix, lme4, lmerTest, and emmeans.

Ethical considerations

Participants were fully informed about the study through a written information sheet and gave active consent before testing, with the option to withdraw at any time. All data were anonymized, handled by RISE for research purposes only, and the study was ethically pre-assessed as negligible in risk in line with *Good Research Practice* [27]. Participation was voluntary, and each participant received a gift card as compensation.

Results

The means of the relative errors of the concepts, aggregated across all participants, video variants, and distances, are shown in Figure 4 along with their corresponding 95 % confidence intervals (CI). For more detailed descriptive statistics see Table 1.

The repeated-measures ANOVA revealed a significant effect of Concept on relative error, F(3, 87) = 14.30, $p < .001$, partial $\eta^2 = .33$, indicating a large effect of the visual concept on the directional bias in distance estimation. Sphericity was not violated (Mauchly's W = 0.93, p = .85), so no correction was applied. Neither Background nor Distance showed significant effects in the original model, and no other interaction effects emerged.

Holm-corrected post-hoc comparisons (Kenward–Roger df[22]) showed that the concepts differed substantially in how they biased estimates:

- Lines vs Base: 28.8 percentage points, t(87) = 3.79, p = .001, Cohen's d = 0.74 (large effect)
- Corner vs Base: 20.2 percentage points, t(87) = 2.66, p = .028, Cohen's d = 0.52 (medium effect)
- Corner vs Lines: 49.1 percentage points, t(87) = 6.45, p < .001, Cohen's d = 1.26 (very large effect)
- Dashed vs Lines: 31.8 percentage points, t(87) = 4.18, p < .001, Cohen's d = 0.82 (large effect)

Two contrasts did not reach significance:

- Corner vs Dashed: p = .051, Cohen's d = 0.44.
  Although marginal after Holm correction, the medium effect size suggests a trend that may warrant further investigation with larger samples.
- Base vs Dashed: p = .700, Cohen's d = 0.08, indicating that Dashed neither improved nor impaired distance estimation relative to the baseline.

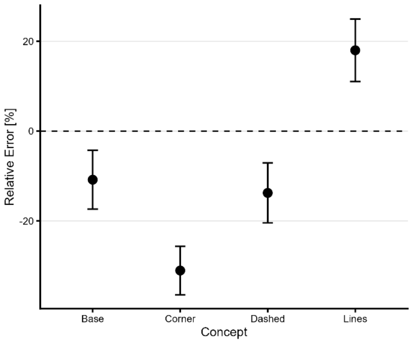

Figure 4:The mean relative error by concept. Error bars represent 95% confidence intervals.

To verify the RM-ANOVA findings, three additional analyses were conducted. Firstly, normality of residuals was confirmed via Shapiro-Wilk tests (relative error: W = 0.978, p = .138; absolute error: W = 0.981, p = .198), supporting the parametric assumptions. Secondly, non-parametric Friedman tests corroborated the ANOVA results: Concept had a significant effect on relative error, chi-squared(3) = 31.20, p < .001, but no meaningful effect on absolute error, chi-squared(3) = 8.36, p = .039. The latter was statistically marginal but with negligible effect size (Kendall's W = 0.012) and no significant pairwise differences following Holm correction.

Across all analyses, the same pattern emerged: Lines consistently differed from all other concepts, Base and Dashed performed similarly, and Corner produced systematic underestimation. The consistency of results across parametric, non-parametric, and effect-size-based analyses demonstrates the robustness of the findings.

The interaction between Concept and Distance is shown in Figure 6. The concept Lines and Base produced relative errors of similar magnitude at medium and long distances, though in opposite directions. At the short distance, Base appears to perform better, while at the long distance Dashed performs better, as both show relative errors closer to zero.

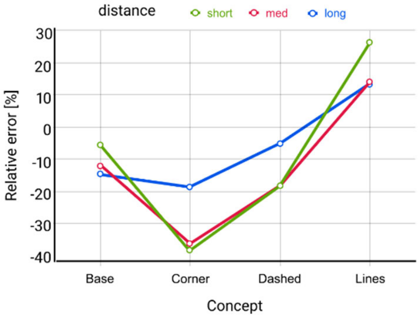

Figure 5:The relative error at different distances for the four concepts.

The absolute value of the relative error was also analyzed, to better understand which of the concepts had smallest error regardless of the direction. Figure 6 presents the mean absolute relative error for each concept, aggregated across all participants, video variants, and distances, along with the corresponding 95% confidence intervals (CI), see also Table 1. The RM-ANOVA found no significant effect of Concept on absolute relative error, F(3, 87) = 1.05, p = .373, partial eta-squared = .04, a negligible effect. All six post-hoc contrasts were non-significant after Holm correction (all p > .74), with effect sizes ranging from d = 0.01 to d = 0.37, none approaching practical significance. Although Lines included numeric distance markers, it did not remove bias. Participants still overestimated distances, and there was no significant effect of Concept on absolute error. This means the advantage of Lines cannot be explained only by numeric labels but instead also comes from how its geometric and motion cues support depth perception on a 2D display.

Table 1 summarizes the relative and absolute error statistics. Lines produced the strongest directional bias (overestimation), while Base and Dashed showed the smallest biases and were statistically indistinguishable from each other. Corner consistently led to underestimation. Based on Cohen's d_n (paired), all significant contrasts correspond to medium-to-very-large effect sizes.

The results on participants' certainty showed that at medium and long distances, the Lines concept produced significantly higher confidence in answers compared to the other concepts (all p < 0.002). At the short distance, the only significant difference was found between Corner and Base (p = 0.005).

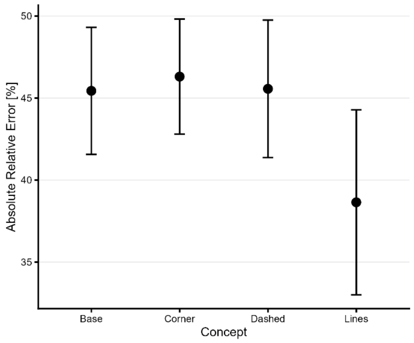

Figure 6: The means of absolute relative error for the concepts. Error bars represent 95% confidence intervals.

Discussion

The distance judgement test relied on frame-based alignment of the overtaking car with the van's rear and the "end of truck" marking, combined with known vehicle speeds and frame rate, to derive distances from 1 to 100 meters. This approach introduced potential errors from subjective frame selection, camera distortion, and rounding in calculations. More robust methods, such as multiple observers, calibrated camera setups, or marking each meter frame, could reduce these issues. Despite these limitations, the results remain meaningful since the analysis focused on differences within each participant's responses across concepts rather than on absolute accuracy.

Due to time constraints, not all measures were taken to verify the accuracy of the distance estimations. Distances were derived by identifying the frame where the overtaking car aligned with the "end-of-truck" marker and calculating from known speeds and time. While this method was applied consistently and results are reliable in a comparative sense, accuracy could have been improved with verified reference distances, for example by using lane markings, roadside posts, or vehicle-based sensors such as radar or lidar.

CMS displays are two-dimensional, so drivers must rely mainly on pictorial or geometric cues such as relative size, linear perspective, and height in the field, as well as motion cues from optic flow. These cues help explain why the overall structure of the Lines overlay, not only its numbers, influenced performance.

In practical driving situations, both the accuracy and the direction of estimation bias have safety implications. Overestimation is more dangerous, because the driver believes the distance is larger than it really is and may initiate lane changes with inadequate margins. Underestimation can be conservative, since it tends to preserve headway, but it may also reduce efficiency if drivers hesitate unnecessarily. In our data, Lines combined clear structure and strong preferences with a tendency to overestimate. This means that a design must mitigate the overestimation risk through calibration, clearer scale anchoring, and consistent disappearance rules, while preserving the clarity that users valued.

Final Design

The results show that the Lines concept was the most effective overall because its combination of geometric structure, motion behavior and labeled distances supported depth perception better than the other concepts. Lines produced the lowest absolute error, even though participants tended to overestimate distances when using it. In addition, participants rated Lines as clear, reliable, and helpful in the post-questionnaire and selected it as the most desirable of all concepts. This combination of high accuracy and strong subjective preference indicates that Lines provides the best foundation for further development of an overlay-based driver-assistance system for truck overtaking. Because Lines showed a tendency toward overestimation, the final design includes adjustments that tighten the mapping between the overlay and real distances and reduce permissive interpretations of gap size. This aims to maintain clarity while lowering the risk that drivers will assume larger-than-actual gaps.

The Corner concept produced systematic underestimation but offered certain advantages. Some participants appreciated its stable geometric cues, and it performed better than Base and Dashed in several of the pairwise comparisons. The updated analysis also showed a medium effect size for the Corner versus Dashed comparison, and although it did not remain significant after correction (p = .051), it suggests a trend that may be meaningful in larger samples.

Based on the combined insights from the results and user feedback, the final design builds primarily on the strengths of the Lines concept while incorporating selected refinements inspired by Corner. Three adjustments were made:

1. The corner elements were thickened to improve visibility at longer distances.
2. The fading behavior of the Lines overlay was adjusted to create a more consistent and predictable disappearance.
3. The motion of the overlays was smoothed so that they move more naturally in relation to the overtaking vehicle.

These refinements maintain the clarity and guidance of the Lines concept while adding improved visibility and structural stability. The resulting hybrid design reflects both objective performance data and user preferences and is well suited for future development of driver-assistance overlays in trucks., see Figure 7.

The final design, based on the Lines concept, incorporates visual features to support depth perception while minimizing distraction. A cyan end-of-truck line highlights the trailer edges and indicates when a vehicle is overtaking, yellow vehicle outlines mark approaching cars to improve spatial awareness, and distance indicators at 30, 50, and 100 meters provide clear depth cues, disappearing as vehicles pass each marker. Distance numbers are placed on the screen frame for constant visibility, and all graphics are slightly faded to soften contrast and avoid blocking more of the CMS view than necessary, while remaining most salient when proximity is critical.

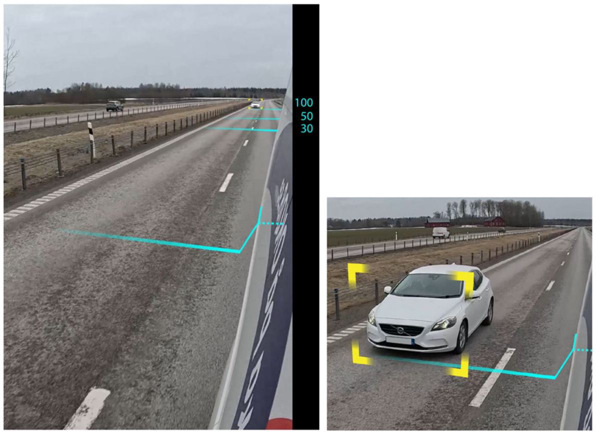

Figure 7: Final concept with an approaching car at a distance to the left and one close to the right.

Conclusions

This project was set to improve the safety and usability of Camera Monitoring Systems (CMS) by exploring how drivers perceive and interact with overlays that support distance judgement and depth perception. The results confirmed that transitioning from mirrors to screens brings challenges such as reduced depth cues, difficulty in adapting to fixed viewpoints, and limited clarity in existing overlays, contributing to user resistance and trust issues (RQ1).

The user studies showed that augmentations primarily influence the directional bias of distance estimates rather than the absolute magnitude of errors (RQ2). Without overlays, participants tended to underestimate distances, a behavior that may be safer but less efficient. Among the concepts tested, Lines provided the clearest guidance, yielded the lowest absolute error, and produced the highest certainty and preference ratings, despite causing systematic overestimation. The Corner concept led to systematic underestimation but was perceived as stable and showed potential benefits, while the Dashed concept offered no measurable improvement over the baseline. Distance indicators were seen as especially helpful, while dashed lines caused confusion by resembling road markings.

The findings suggest that effective augmentations must be clear, intuitive, and consistent with drivers' mental models (RQ3). Based on both quantitative results and user feedback, the final design primarily incorporates the Lines concept, with refinements inspired by Corner to enhance visibility, smoothness, and predictability. Features should use simple and familiar depth cues such as linear perspective with labelled distances, employ accessible colors that adapt to different conditions, and ensure overlays appear and disappear at the correct time. Above all, the system must build trust by aligning accurately with the real environment, demonstrating reliability without causing distraction or cognitive overload.

References

[1] United Nations Economic Commission for Europe. (2013). *Regulation No. 46 (Rev.5): Uniform provisions concerning the approval of devices for indirect vision and of motor vehicles with regard to the installation of these devices*. United Nations Economic Commission for Europe.

[2] Szalo, G. and H. Degerman. (2024). *The difference between driving with a camera monitor system and mirrors*. Available from: https://www.volvotrucks.com/en-en/news-stories/insights/articles/2024/jan/driving-with-a-camera-monitor-system-or-mirrors.html, Access Date: 10 Sept. 2025.

[3] Flannagan, M.J. and M.L. Mefford. (2005). *Distance perception with a camera-based rear vision system in actual driving*. in *Driving Assessment Conference 3*. p. 59-65, DOI: https://doi.org/10.17077/drivingassessment.1143.

[4] Brunnström, K. (2023). *Safe chauffeurs in safe and healthy multimodal driver information environments" (SCREENS II)*. Available: https://www.ri.se/en/expertise-areas/projects/safe-chauffeurs-in-safe-and-healthy-multimodal-driver-information-env, Access Date: 12 Sept. 2025.

[5] Rosén, E.S. and F. Törner. *Perceiving the rear view : Design to enhance the human-machine interaction in Camera Monitoring Systems*. Student thesis. 2025, Available: http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-114116

[6] Schmidt, E.A., H. Hoffmann, R. Krautscheid, M. Bierbach, A. Frey, J. Gail, and C. Lotz-Keens (2016). *Camera-Monitor Systems as a Replacement for Exterior Mirrors in Cars and Trucks*, in *Handbook of Camera Monitor Systems: The Automotive Mirror-Replacement Technology based on ISO 16505*, A. Terzis, Editor. Springer International Publishing: Cham. p. 369-435, DOI: https://doi.org/10.1007/978-3-319-29611-1_12.

[7] Terzis, A. (2016). *Automotive Mirror-Replacement by Camera Monitor Systems*, in *Handbook of Camera Monitor Systems: The Automotive Mirror-Replacement Technology based on ISO 16505*, A. Terzis, Editor. Springer International Publishing: Cham. p. 3-50, DOI: 10.1007/978-3-319-29611-1_1.

[8] Johansson, P. and S. Jonason. *Designing Camera Monitoring Systems in Cars for Enhanced User Performance*. Chalmers University of Technology, Gothenburg, Sweden. 2021, Available from: https://hdl.handle.net/20.500.12380/302877

[9] Payandehmehr, B. and M. Placzkowska. *Digital mirrors : Supplementary information to increase driver's awareness of surroundings*. MMK 2015:80 IDE 156, Student thesis. 2015, Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-175366

[10] Moore, A., J. Yuan, S. Ou, J.R. Torres, V. Sujan, and A. Siekmann, (2023). *Key Considerations in Assessing the Safety and Performance of Camera-Based Mirror Systems.* Safety. **9**(4): p. 73.

[11] Bruce, V., P.R. Green, and M.A. Georgeson, (1986). *Visual Perception, Physiology, Psychology, and Ecology*. 3rd ed. Psychology Press, UK,

[12] Zhang, M., B. Gao, G. Kumlin Groth, D. Hermann, and K. Brunnström. (2024). *Digital rear view mirrors with Augmented Reality in comparison with traditional rear-view mirrors*. in *Electronic Imaging 2024*. p. 215-1 - 215-8, DOI: https://doi.org/10.2352/EI.2024.36.11.HVEI-215.

[13] Zhang, M. and B. Gao. *The effect of CMS with AR on drivingperformance*. (diva2:1717225), RISE Research Institutes of Sweden, Chalmers University of Technology, M.Sc. thesis. 2022, Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-61469

[14] Lorenz, L., P. Kerschbaum, and J. Schumann. (2014). *Designing take over scenarios for automated driving:How does augmented reality support the driver to get back into the loop?* in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 58, p. 1681-1685, DOI: https://doi.org/10.1177/1541931214581351.

[15] Lee, H. and U. Ju. (2024). *A Study on the Effectiveness of Augmented Reality Signal-Integrated Camera Monitor Systems for Safe Lane Changing*. in *Proceedings of the 30th ACM Symposium on Virtual Reality Software and Technology*. Trier, Germany: Association for Computing Machinery, p. Article 51, DOI: https://doi.org/10.1145/3641825.3689523.

[16] Thulinsson, F., N. Söderlund, S. Rafiei, B. Schenkman, A. Djupsjöbacka, B. Andrén, and K. Brunnström. (2025). *Impact of Camera Height and Field-of-View on Distance Judgement and Gap Selection in Digital Rear-view Mirrors in Vehicles*. in *Electronic Imaging*. p. 199-1 - 199-8, DOI: https://doi.org/10.2352/EI.2025.37.11.HVEI-199.

[17] Thulinsson, F. and N. Söderlund. *Mirror, Mirror on the Car : An Explorative Study on how CMS Perspective Impact Driver Depth Perception and Decision Making*. (24039), UPTEC STS, Student thesis. 2024, Available: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-532768

[18] TTSMaker. (2025). *TTSMaker: Gratis Text till Tal.* Available from: https://ttsmaker.com/, Access Date: 19 Sept 2025.

[19] Rodgers, P. and A. Milton, (2013). *Research Methods for Product Design*.

[20] VideoLAN. *VLC media player*. Available from: https://www.videolan.org/, Access Date: 10 Sept 2025.

[21] Nabati, P., D. Muftic, and M. Olszewski. (2010). *Accindi*. Available from: https://www.accindi.se/, Access Date: 8 Oct 2024.

[22] Kenward, M.G. and J.H. Roger, (1997). *Small Sample Inference for Fixed Effects from Restricted Maximum Likelihood.* Biometrics. **53**(3): p. 983-997, DOI: 10.2307/2533558.

[23] Lakens, D., (2013). *Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs.* Frontiers in Psychology. **Volume 4 - 2013** DOI: 10.3389/fpsyg.2013.00863.

[24] Cohen, J., (1988). *Statistical Power Analysis for the Behavioral Sciences*. Routledge, DOI: https://doi.org/10.4324/9780203771587.

[25] Shapiro, S.S. and M.B. Wilk, (1965). *An Analysis of Variance Test for Normality (Complete Samples).* Biometrika. **52**(3/4): p. 591-611, DOI: 10.2307/2333709.

[26] Pereira, D.G., A. Afonso, and F.M. Medeiros, (2015). *Overview of Friedmans Test and Post-hoc Analysis.* Communications in Statistics: Simulation and Computation. **44**(10): p. 2636-2653, DOI: 10.1080/03610918.2014.931971.

[27] Swedish Research Council. (2024). *Good Research Practice 2024* (978-91-89845-30-5). Vetenskapsrådet, Stockholm, Sweden.

[28] Mann, S.P., A.A. Vazirani, M. Aboy, B.D. Earp, T. Minssen, I.G. Cohen, and J. Savulescu, (2024). *Guidelines for ethical use and acknowledgement of large language models in academic writing.* Nature Machine Intelligence. **6**(11): p. 1272-1274, DOI: 10.1038/s42256-024-00922-7.

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Shirin Rafiei received her B.Sc. and M.Sc. degrees in Electronics and Telecommunications in 2009 and 2014, respectively. Since 2020, she has been a researcher and Ph.D. fellow at RISE Research Institutes of Sweden and Mid Sweden University. Her research focuses on interdisciplinary mixed-method approaches, integrating UX and QoE in industrial remote-control systems. She also works in extended reality applications and explores user interaction paradigms using visual interfaces for remote control systems, with emphasis on visual perception.

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Börje Andrén has worked with optical research, image quality and color issues and visual ergonomics for both 2D and 3D for almost 43 years. He has participated in the development of the visual ergonomic part of the TCO label since 1995, developing requirements and test methods. For about ten years, Börje has helped Intertek Semko with the development of its visual ergonomics laboratory and measured and evaluated more than 4,000 screens.

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