Proceedings

ATZ live

Peter Pfeffer *Editor*

13th International Munich Chassis Symposium 2022

Volume 2: chassis.tech plus

Springer Vieweg

Proceedings

Ein stetig steigender Fundus an Informationen ist heute notwendig, um die immer komplexer werdende Technik heutiger Kraftfahrzeuge zu verstehen. Funktionen, Arbeitsweise, Komponenten und Systeme entwickeln sich rasant. In immer schnelleren Zyklen verbreitet sich aktuelles Wissen gerade aus Konferenzen, Tagungen und Symposien in die Fachwelt. Den raschen Zugriff auf diese Informationen bietet diese Reihe Proceedings, die sich zur Aufgabe gestellt hat, das zum Verständnis topaktueller Technik rund um das Automobil erforderliche spezielle Wissen in der Systematik aus Konferenzen und Tagungen zusammen zu stellen und als Buch in Springer.com wie auch elektronisch in Springer Link und Springer Professional bereit zu stellen. Die Reihe wendet sich an Fahrzeug- und Motoreningenieure sowie Studierende, die aktuelles Fachwissen im Zusammenhang mit Fragestellungen ihres Arbeitsfeldes suchen. Professoren und Dozenten an Universitäten und Hochschulen mit Schwerpunkt Kraftfahrzeug- und Motorentechnik finden hier die Zusammenstellung von Veranstaltungen, die sie selber nicht besuchen konnten. Gutachtern, Forschern und Entwicklungsingenieuren in der Automobil- und Zulieferindustrie sowie Dienstleistern können die Proceedings wertvolle Antworten auf topaktuelle Fragen geben.

Today, a steadily growing store of information is called for in order to understand the increasingly complex technologies used in modern automobiles. Functions, modes of operation, components and systems are rapidly evolving, while at the same time the latest expertise is disseminated directly from conferences, congresses and symposia to the professional world in ever-faster cycles. This series of proceedings offers rapid access to this information, gathering the specific knowledge needed to keep up with cutting-edge advances in automotive technologies, employing the same systematic approach used at conferences and congresses and presenting it in print (available at Springer.com) and electronic (at Springer Link and Springer Professional) formats. The series addresses the needs of automotive engineers, motor design engineers and students looking for the latest expertise in connection with key questions in their field, while professors and instructors working in the areas of automotive and motor design engineering will also find summaries of industry events they weren’t able to attend. The proceedings also offer valuable answers to the topical questions that concern assessors, researchers and developmental engineers in the automotive and supplier industry, as well as service providers.

Peter Pfeffer
Editor

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ISSN 2198-7432 ISSN 2198-7440 (electronic)
Proceedings
ISBN 978-3-662-68162-6 ISBN 978-3-662-68163-3 (eBook)
https://doi.org/10.1007/978-3-662-68163-3

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Vorwort

Herzlich willkommen

Im Dreiklang aus Fahrer, Fahrzeug und Fahrwerk ist letzteres die entscheidende Note, um Bestwerte bei Fahrsicherheit, Sportlichkeit und Komfort zu komponieren. Trends wie das automatisierte Fahren und die Antriebselektrifizierung lösen weitere Rückwirkungen auf die Chassisarchitekturen aus. Nur interdisziplinäre Ingenieurteams, die am Gesamtkunstwerk Chassis arbeiten, können diese Herkulesaufgabe meistern. Agile Entwicklungsmethoden und Computer-simulationen sowie Fahrsimulatoren und realer Fahrversuch helfen dabei – für heutige und zukünftige Systeme.

Das 13. Internationale Münchner Fahrwerk-Symposium chassis.tech plus möchte erneut bis zu 500 Fachleute zum Erfahrungsaustausch zusammenbringen. Hier können Expertinnen und Experten für Radaufhängung, Lenkung, Bremse und Reifen/Räder sowie ADAS gemeinsam neueste Informationen erhalten und aktuelle Entwicklungen ausführlich diskutieren.

Seien Sie gespannt auf Keynotes von Dr. Hans-Jörg Feigel (Continental), Helge Westerfeld (Bosch), Patricio Barbale (S&P Global Mobility) und Andreas Rigling (ADAC) am ersten Tag des Symposiums, aber auch auf die Kurzinterviews mit wichtigen Experten. Am zweiten Tag werden Prof. Dr. Frank Gauterin (Karlsruher Institut für Technologie) und Leonardo Bagnoli (Ducati) ihre wertvollen Einschätzungen präsentieren.

Wir freuen uns, Sie im Bayerischen Hof im Herzen von München oder virtuell im Live-Stream begrüßen zu dürfen, und wünschen Ihnen eine anregende Veranstaltung.

Prof. Dr. Peter Pfeffer
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Wissenschaftliche Leitung des
Symposiums, Munich, Germany

Preface

Welcome

In the triad of driver, vehicle and chassis, the latter is the decisive factor in composing the best values in terms of driving safety, sportiness and comfort. Trends such as automated driving and drive electrification have further repercussions on chassis architectures. Only interdisciplinary teams of engineers working on the overall work of art that is the chassis can master this Herculean task. Agile development methods and computer simulations, as well as driving simulators and real driving tests, will help – for current and future systems.

The 13th International Munich Chassis Symposium chassis.tech plus once again aims to bring together up to 500 experts to exchange experiences. Here, experts for wheel suspension, steering, brakes and tires/wheels as well as ADAS can jointly obtain the latest information and discuss current developments in detail.

You can look forward to keynote speeches by Dr. Hans-Jörg Feigel (Continental), Helge Westerfeld (Bosch), Patricio Barbale (S&P Global Mobility) and Andreas Rigling (ADAC) on the first day of the symposium, as well as short interviews with key experts. On the second day, Prof. Dr. Frank Gauterin (Karlsruhe Institute of Technology) and Leonardo Bagnoli (Ducati) will present their valuable assessments.

We look forward to welcoming you to the Bayerischer Hof in the heart of Munich or virtually via live stream and wish you a stimulating event.

Prof. Dr. Peter Pfeffer
Hochschule München University
of Applied Sciences, Scientifc Director
of the Symposium, Munich, Germany

Conference Report

13th Munich Chassis Symposium – chassis.tech plus 2022

There was a mood of excitement when, after a two-year break because of the pandemic, the 13th chassis.tech plus was at last held again as an in-person event. More than 300 participants traveled to Munich and were obviously pleased to be able to meet face-to-face once more. Together with the 100 people who took part via live stream, they held in-depth discussions on the latest trends in chassis development, which ranged from the influence of software to the importance of sustainability.

The chassis symposium was organized by ATZlive in cooperation with TÜV Süd. Over 400 attendees took part on July 05 and 06, 2022, (in person and via live stream). The symposium focused on two key trends: software and sustainability. The Scientific Director, Professor Peter E. Pfeffer from Munich University of Applied Sciences, aptly summed up the first of these themes at the end of the event when he said: “It’s all about software, software and software.” He highlighted in particular the ongoing development of the processes and the increasingly professional methods, together with the influence of the software-defined vehicle, which is also having an impact on chassis design. As far as development tools are concerned, driving simulators of different kinds will become increasingly important for the creation of good products and will fill the gap between computer simulation and real road trials. All of this is not merely an end in itself, but is done with the aim of cutting costs and shortening development times.

Reducing the Carbon Footprint of Entire Supply Chains

The second theme – “the sustainability of the chassis” – attracted considerable attention. Hans-Jörg Feigel from Continental came up with the motto “The sustainability quota is the new horsepower” in his keynote speech on the first day. More and more vehicle manufacturers are requiring their suppliers to take substantial measures to reduce the carbon footprint of their products and their companies along the entire supply chain. In future chassis systems, modularization offers significant potential for improving sustainability. The smaller number of control units will reduce the use of resources and the amount of cabling needed. In addition, modules can be reused. The option of updates ensures that the car will have a longer service life. Brake-by-wire systems are more environmentally friendly because of their lower losses and lack of operating fluids.

In purely mechanical and electrical systems, Feigel expects changes of a more evolutionary nature to take place. By contrast, the revolutionary transformation will occur in the area of self-driving vehicles and cars used as second homes. The solution for both of these developments lies in a new software architecture that is modular and scalable and can be adapted to each application, as well as allowing for over-the-air updates. The keyword in this respect is “software as a product” which will result in “major changes to our current business models.” Just as the integral body with the safe passenger compartment became a standard feature of cars and was mastered by the engineers of the time, so steer-by-wire and brake-by-wire systems now open up new possibilities for packages, modularization and different applications.

New Dimensions in Vehicle Dynamics Control and Braking Systems

In his keynote speech, Helge Westerfeld from Bosch emphasized the fact that the work on vehicle dynamics control was by no means at an end. Its origins lie in the development of the Electronic Stability Program (ESP) system by the automotive supplier Bosch and the car manufacturer Daimler way back in 1995. However, the cooperation between carmakers and suppliers will have to change significantly with the introduction of new assistance systems for automated driving. The coexistence of systems from level 0 to level 4 remains an issue. A distinction needs to be made between vehicle motion control and the vehicle motion management system developed by Bosch which represents a more integrated approach to vehicle dynamics control. This opens up new dimensions in model-based control systems and multi-actuator integrations that will increase road safety, ride comfort and driving pleasure.

Patricio Barbale from IHS Markit, which is now a subsidiary of S&P, focused in his plenary presentation on the market penetration of assistance systems for automated driving. The figures he quoted reflected a certain disillusionment with the trend for automation, because the other key trend of electrification is taking off at a much faster rate. In 2019, the prediction was that electric cars would make up only 14 % of global sales by 2031. However, the current estimate (in 2022) is the impressive figure of 41 % for 2031. By contrast, the proportion of vehicles with level 3 functions is expected to rise from 2 to only 4 % in Europe, from 3 to 4 % in China and from 4 to 7 % in North America between 2026 and 2033. Barbale believes that the market penetration of Electro-hydraulic Brake (EHB) systems in particular will be good and expects the market share to reach 60 % by 2033. The next step will be toward electro-mechanical brake systems, which are likely to have a market share of between 5 and 10 % by 2033.

Next Event Held in June 2023

The date for the next chassis.tech plus was announced during this year's symposium in the Hotel Bayerischer Hof. The chassis community will come together once again on June 20 and 21, 2023, to hear many interesting presentations about the latest innovations in chassis systems. Hopefully there will be the same mood of excitement next year.

Michael Reichenbach

Tagungsbericht

13. Münchner Fahrwerk-Symposium – chassis.tech plus 2022

Leuchtende Augen: Nach zwei Jahren Coronapause konnte die 13. chassis.tech plus endlich wieder vor Ort stattfinden. Über 300 Teilnehmende genossen es sichtlich in München, dass Gespräche wieder in persona möglich waren. Zusammen mit den 100 virtuell Zuhörenden wurde intensiv über die Trends der Fahrwerksentwicklung diskutiert, vom Softwareeinfluss bis zur Nachhaltigkeit.

Das Fahrwerk-Symposium wurde von ATZlive in Kooperation mit dem TÜV Süd veranstaltet. Insgesamt waren über 400 Teilnehmerinnen und Teilnehmer am 5. und 6. Juli 2022 dabei (vor Ort und virtuell). Zwei Trends ließen sich auf dem Symposium ausmachen, und zwar Software und Nachhaltigkeit. Zum Ersten: „Es geht um Software, Software und Software“, wie es der Wissenschaftliche Leiter am Ende der Veranstaltung treffend zusammenfasste. Prof. Peter E. Pfeffer von der Hochschule München hob vor allem die Weiterentwicklung der Prozesse und die Professionalisierung der Methoden sowie den Einfluss des softwaredefinierten Fahrzeugs hervor, der auch vor dem Chassis nicht haltmache. In der Kette von Entwicklungswerkzeugen werde zudem der Fahrsimulator unterschiedlicher Ausprägung immer wichtiger für eine gute Produktentwicklung, um die Lücke zwischen der computergestützten Simulation und dem realen Fahrversuch zu schließen. Dies alles geschehe nicht aus Selbstzweck, sondern um Kosten zu sparen und Entwicklungszeiten zu verkürzen.

Co_2-Fussabdruck entlang der Lieferketten reduzieren

Zum Zweiten erhält das Thema „Nachhaltigkeit des Fahrwerks“ immer mehr Aufmerksamkeit. Dazu rief Hans-Jörg Feigel, Continental, am ersten Tag in seiner Keynote das neue Motto „Die Nachhaltigkeitsquote ist die neue Pferdestärke“ aus. Immer mehr OEMs forderten von den Zulieferern substanzielle Aktivitäten, um den CO2-Fußabdruck in ihren Produkten und Unternehmen entlang der Lieferketten zu reduzieren. Für zukünftige Chassissysteme biete die Modularisierung ein großes Potenzial für die Nachhaltigkeit: Die reduzierte Anzahl an Steuergeräten spare Ressourcen ein und verringere den Verkabelungsaufwand. Module könnten wiederverwendet werden. Die Möglichkeit zu Updates garantiere eine längere Lebensdauer des Produkts Automobil. Brake-by-Wire-Systeme seien umweltfreundlicher dank weniger Verluste und da sie ohne Betriebsstoffe auskämen.

Bei der reinen Mechanik und Elektrik erwarte er eher evolutionäre Änderungen, während sich die Revolution durch selbstfahrende Mobile und den Pkw als zweites Zuhause abzeichne. Die Lösung für beides liege in einer neuen Softwarearchitektur, die modular und skalierbar an die jeweilige Anwendung angepasst werden kann, ohne auf Updates per Funk zu verzichten. Hier sei „Software as a Product“ das Schlagwort schlechthin, was „unsere heutigen Geschäftsmodelle stark verändern wird“. So wie damals die Revolution der selbsttragenden Karosserie mit der sicheren Fahrgastzelle beim Pkw Einzug hielt und von den Ingenieuren beherrscht wurde, so offeriere nun das Steer-by-Wire und Brake-by-Wire viele neue Freiheiten bei Packaging, Modularisierung und Anwendungsfall.

Neue Dimensionen bei Fahrdynamikregelung und Bremssystemen

Helge Westerfeld, Bosch, zeigte in seiner Keynote auf, dass die Arbeiten zum Thema Fahrdynamikregelung nicht ruhen werden. Ihre Anfänge liegen mit der Entwicklung des Systems ESP durch den Zulieferer Bosch und den Automobilhersteller Daimler im Jahr 1995 zwar weit zurück. Aber aktuell wird sich in der Zusammenarbeit zwischen OEMs und Zulieferern mit der Einführung neuer Assistenzsysteme für das automatisierte Fahren viel ändern müssen. Denn das Thema Koexistenz der Systeme von Level 0 bis 4 bleibt bestehen. Es sei zu unterscheiden zwischen Vehicle Motion Control und dem vom eigenen Haus propagierten Vehicle Motion Management, dass die Fahrdynamikregelung ganzheitlicher abbilde. Bosch öffne somit neue Dimensionen modellbasierter Regelungen und Multi-Aktuator-Integrationen, um ein Mehr an Straßensicherheit, Fahrkomfort und Fahrspaß zu generieren.

Die Marktdurchdringung von Assistenzsystemen für das automatisierte Fahren stellte Patricio Barbale von IHS Markit, mittlerweile eine Tochterfirma von S&P, in den Mittelpunkt seines Plenarvortrags. Dabei spiegelten seine Zahlen etwas Ernüchterung beim Automatisierungstrend wider, weil das andere Trendthema Elektromobilität sehr viel besser hochlaufe: Ging man 2019 noch von einem globalen Absatzanteil an Elektrofahrzeugen von nur 14 % für das Jahr 2031 aus, rechnet man aktuell (2022) mit beachtlichen 41 % Anteil für 2031. Demgegenüber steige der Anteil von Fahrzeugen mit Level-3-Funktion von 2026 auf 2033 bloß von 2 auf 4 % (Europa), von 3 auf 4 % (China) und von 4 auf 7 % (Nordamerika). Speziell für elektrohydraulische Bremssysteme (EHB) sieht Barbale eine bereits gute Marktdurchdringung, 2033 erwartet er einen EHB-Anteil von 60 %. Der nächste Schritt gehe in Richtung elektromechanischer Bremssysteme, für die mit 5 bis 10 % Marktanteil 2033 gerechnet werden könne.

Erneutes Treffen im Juni 2023

Der Termin für die nächste chassis.tech plus wurde im Bayerischen Hof schon bekanntgegeben. Die Fahrwerk-Community wird sich am 20. und 21. Juni 2023 wieder für zahlreiche interessante Vorträge über die Innovationen des Fahrwerksystems treffen – dann hoffentlich auch wieder mit strahlenden Gesichtern.

Michael Reichenbach

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The Back Ring Light Element (BRLE) – Where User Experience Meets Safety

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Abstract. Ambient light is becoming more and more a common feature in the cars of not only the premium, but also the middle-class market. From the first beginnings of illuminating door handles and door compartments, ambient illumination is proceeding to become a design feature ubiquitous within a car's interior. The Back Ring Light Element (BRLE) incorporates this trend for the steering wheel. Apart from mitigating the distraction potential of these design features, the upper steering wheel rim is usually recommended through various studies as a perfect warning location for forward-collision warnings or takeover requests; but if this is a valid use case for an ambient lighting technology remains unclear. Therefore, a study in a static driving simulator was conducted. The results of this study seem to be promising in terms of using multiple use cases within the same feature, the BRLE with ambient lighting technology in the steering wheel.

Keywords: Back Ring Light Element · Lightbar · Visual Warning · Steering Wheel · Driving Simulator Study

1 Introduction

The development of forward collision warning (FCW) systems aims to prevent or reduce the impact of frontal collisions by alerting the driver and facilitating response times in advance of an impending collision. Several studies in this research area investigated usability of different uni- or multimodal warnings [1–7]. Visual warnings are well suited for transporting semantic information, through symbols, color, intensity, or spatial proximity to the hazard [10]. Positioning a visual warning in the steering wheel aims to guide the driver's view directly to the threat on the road, as it has a high spatial compatibility between warning location and threat direction. The steering wheel is in the driver's direct or peripheral view during the driving task, so that the gaze would not be diverted too far, such as with a visual warning down in the cluster panel. As a warning design for critical situations, a combination of tactile or auditory warning with visual warning is recommended to combine the advantages of faster reactions to tactile or auditory stimuli and semantic information transfer by visual cues [1, 2, 8–10]. One visual warning

P. Pfeffer (Ed.): IMCS 2022, Proceedings, pp. 1–14, 2024.
https://doi.org/10.1007/978-3-662-68163-3_1

concept has been developed at Joyson Safety Systems under the name of BRLE (Back Ring Light Element). This is an illumination system which can be attached to the back of the steering wheel and, depending on the respective purpose and need can be used both for the already mentioned passenger warning and/or also as ambient light (Fig. 1).

Fig. 1. BRLE as one steering wheel illumination concept from joyson safety systems

To investigate the BRLE in the present study, we initially focused on the visual warning only to examine the effect of positioning the visual steering wheel illumination per se and not to incorporate effects from other modalities, before investigating multisensory warnings.

In this paper BRLE illuminations are evaluated in forward collision warnings on rural roads in a human-machine interaction (HMI) study. The goal of the study is to compare four different BRLE steering wheel illuminations in upper and/or lower steering wheel rim regarding usability, that is defined by [11] as “degree to which a product can be used by specified consumers to achieve quantified objectives with effectiveness, efficiency, and satisfaction in a quantified context of use”. In our study, effectiveness is operationalized as driving data, efficiency is operationalized as reaction times, mental workload, eye gaze, glare data, and satisfaction is operationalized as users’ acceptance, qualitative data, and preference. Hypotheses are:

H_0: The experiment conditions (BRLE illuminations) have no effect in the population. Deviations of the group means from overall mean are only random. Population means in all conditions are identical ($\mu_{\text{Baseline}} = \mu_{\text{Full Rim}} = \mu_{\text{Lower Rim}} = \mu_{\text{Upper Rim}}$).

H_1: There are differences between at least two of the experiment conditions (BRLE illuminations) means in the population ($\mu_j - \mu \neq$ for at least one condition j).

2 System Structure and Illumination Concepts

The on the backside on the steering wheel positioned and predominantly freestanding illumination element essentially consists of a carrier housing for mechanical attachment, two printed circuits boards (PCB) fitted with several RGB-LEDs for the illumination of the upper and lower halves of the steering wheel as well as a light chamber for each PCB (Fig. 2).

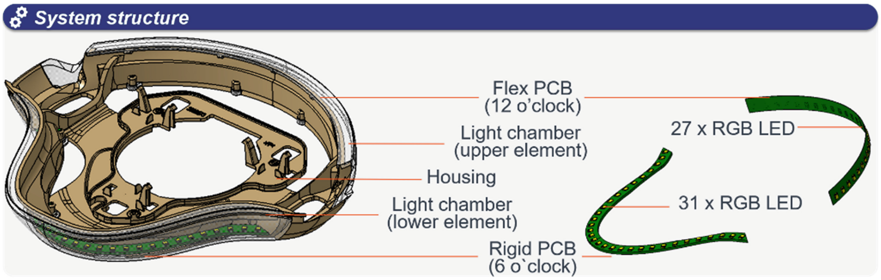

Fig. 2. System structure of the illumination element "BRLE" mainly consisting of a housing, two PCBs with LEDs, two separate light chambers and light exit surfaces

Housing and attachment. For easy assembly and disassembly, the illumination element in the prototype was fixed to the rear hub of the steering wheel by clip connections. Both the mounting concept and the outer contour of the BRLE can be adapted to the respective steering wheel design.

PCBs and light sources. A rigid PCB with a total of 31 RGB LEDs, each with a luminous flux of 3.6 lumens (red: 1.10 lm, green: 2.34 lm, blue: 0.16 lm), was selected for the lower steering wheel illumination. In the upper half of the BRLE there is a flexible circuit board with 27 RGB LEDs (same type as in lower half). By additive color mixing of the RGB values a multitude of colors (approx. 16.7 million) can be displayed. The control via bus system allows a visualization of animations.

Light chamber. The LEDs emit light into a light chamber with a white coating and high reflectivity. The light is scattered to achieve a uniform light distribution and homogeneous emission.

Light emission surfaces and lightning modes. In order to provide a light emission out of the light chamber, a light exit surface with a high transmittance is necessary. Depending on the position of these light exit surfaces, there are different use cases and lightning modes for the BRLE.

With a frontal light emission (reference system: driver's perspective), the BRLE can be used as a warning illumination and achieves a high luminance.

A lateral light emission essentially results in indirect illumination for ambient lightning.

Because the upper and lower halves of the BRLE are designed with two separate circuit boards and light cambers, a combination of both lightning modes in one illumination element is also possible.

In summary, a distinction must therefore be made between the following lightning modes:

- Full warning illumination: Frontal light emission at upper and lower element
- Full ambient illumination: Lateral light emission at upper and lower element
- Combined warning and ambient: Frontal light emission at upper or lower element / lateral light emission on upper or lower element (Fig. 3)

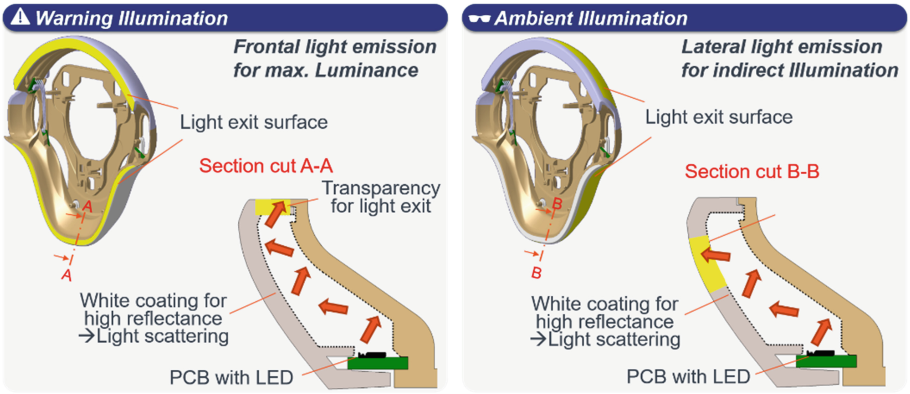

Fig. 3. General light concept for full warning and full ambient illumination

System validation. Optical simulations were implemented for system validation of the illumination concept. In addition to simulations real measurement on the sample part were done the evaluate especially the luminance output as well as the homogeneity of the light emission and the optical efficiency.

3 Driving Simulator Study

3.1 Methods

Participants. 32 employees of Joyson Safety Systems Aschaffenburg GmbH were tested in a fixed-based driving simulator in Berlin from July 14th until August 5th 2021 between 8:00 a.m. and 6:00 p.m. Balancing of gender and age was attempted [12], but due to the local restrictions in the pandemic situation not completely possible. Of the 32 participants, 26 were male and 6 were female. Average age was 40 years; two subjects belonged to the 18–24 age group, 17 to the 25–39 age group, twelve to the 40–54 age group, and one to the 55+ age group. All participants held a driver's license, eleven participants had a driving experience of more than 10,000–20,000 driven kilometers per year, 13 drove 5000–10,000 km and eight less than 5000 km. 30 subjects were familiar with driving simulators. Participants were healthy and had no impairments in auditory or tactile perception. Each subject underwent both experimental conditions. Subjects were not familiar with any details of the study and were able to receive credit for participation as work time.

Study design. In a within-subjects design, four illumination experiment conditions were compared: BRLE full warning emission surface with correlating full rim illumination, BRLE upper warning emission surface with correlating upper rim illumination, BRLE lower warning emission surface with lower rim illumination and no illumination as baseline (Fig. 4). BRLE upper warning emission surface illumination is part of the two experiment conditions with full rim and upper rim only illumination. In the 12 o'clock position, the upper BRLE, has a luminance of 276 cd/m^2, in the 6 o'clock position a luminance of 464 cd/m^2 with half of power.

Fig. 4. Experiment conditions with full rim, upper rim only or lower rim only illumination on the steering wheel, integrated in the driving simulator cockpit. In the baseline condition, there was no (visual) warning at all.

Measures. Driving performance, reaction times, mental workload, eye gaze, glare, acceptance, qualitative data and preference were measured.

Driving performance. Driving performance was recorded with SILAB simulation software (Version 7.0) by Würzburg Institute for Traffic Science [13]. Sequences from onset of the warning to 200 m thereafter were considered. Longitudinal driving parameters/measured variables were mean and standard deviation (SD) of speed [km/h], minimal acceleration [m/s^2], minimal time to collision [s] and collisions. For an effective collision warning, no collision and a higher time to collision (furthest distance to the obstacle) are to be desired. To avoid a collision, braking (minimal acceleration) was necessary, which results in higher SD of the speed due to speed reduction. Lateral driving data were lane keeping quality, including the area between the factual driven path and individual perceived center of the lane [m^2], SD of lane departure [m], mean and SD of steering wheel angle velocity [°/s] and acceleration [°/s^2] as well as the number of spontaneous steering behaviors resulting in lateral vehicle deviation of more than 20 cm. Lane keeping quality and SD lane departure values should be as small as possible. Lower steering wheel velocity, acceleration and spontaneous steering behavior are desirable, as this poses less risk of steering wheel tearing and the associated breakaway of the vehicle.

Reaction times. The time [ms] between onset of the warning to the first reaction (accelerator pedal release, braking or steering) and the time from accelerator pedal release till braking were evaluated, which should be as low as possible.

Mental workload. Subjects rated their workload during the forward collision warnings on NASA TLX scale [14] at the end of each test route. NASA TLX measures mental demand, physical demand, temporal demand, performance, effort, and frustration level. The scales range from low (score = 0) to high (score = 100). Overall workload score was calculated by adding the scores of the six scales and dividing it by the number of scales.

Eye gaze. Video recordings and subsequent time coding with annotation software ELAN (Version 5.7) by Max Planck Institute for Psycholinguistics [16] were used to determine the number of subjects who looked down at the steering wheel away from the road when the steering wheel was illuminated in the warning situation. For these subjects, the time between the steering wheel lighting up until they looked down at the steering wheel and the duration of their gaze on the steering wheel [ms] were evaluated.

Glare. Glare was measured on a five-point glare scale with the verbal anchors no glare-glare noticeable – glare between noticeable and disturbing – glare disturbing – glare unacceptable. An adapted version of the seven-point Discomfort Glare of Interior Lighting scale [17] with only five levels was used in this study as the degree of detail with five levels was sufficient and thus consistent with the other questionnaires.

Acceptance. Subjects' attitudes toward the BRLE illuminations were rated on five-point bipolar Van der Laan-acceptance scale [15] on the two dimensions "satisfaction by the product" and "usefulness of the product". The factor usefulness was captured by the items useful-useless, good-bad, effective-superfluous, helpful-worthless, and activating-sleep inducing. The factor "satisfaction" was measured with the items pleasant-unpleasant, nice-annoying, pleasant-annoying, and desirable-not desirable. The construct validity could be proven factor-analytically by the authors. With reliability coefficients of Cronbach's $\alpha = 0.85$ for the subscale satisfaction and Cronbach's $\alpha = 0.81$ for the subscale usefulness, the items correlate to a good to very good degree and thus indicate a high measurement accuracy of the questionnaire. After each test course, subjects were asked to rate the BRLE illuminations with Numerically, the gradations of the scale were coded from 1 to 5, where 1 and 2 represented negative adjectives, 4 and 5 represented positive adjectives, and 3 represented the neutral middle category. The negative and positive adjectives were presented varying on the left and right sides of the scale. For both factors, the raw scores of the corresponding items were summed and divided by the number of items so that a maximum of 5 points could be obtained.

Qualitative data. At the end of each test section, the test subjects were asked for feedback on the previously experienced steering wheel illumination, which they could write down in an open text field.

Preference. To determine the lighting concept with the highest preference, participants were presented with all pairwise combinations of the four conditions. In pairwise comparison, the test subjects judged which of the two illumination conditions presented they preferred. This procedure can be used to determine a binary ranking judgment, which can be checked for consistency and concordance. The consistency analysis checks the data to see whether the subjects have judged individually without contradiction. The concordance analysis can be used to examine the extent to which the judgments of the ten subjects agree. Social desirability responses are minimized by forcing subjects to choose the preferred concept in each comparison rather than rating all concepts as very good [18].

Driving Simulator. The experiment was conducted in the fixed based driving simulator of Joyson Safety Systems in Berlin with a mid-size sedan car interior with automatic transmission (Fig. 5). The mock-up consists of the anterior half of a car; its dashboard, two seats and center stack were built up from a BMW 3 series (E90, model year 2005–2008) cockpit. The simulator has an original BMW E90 accelerator pedal and a brake pedal with torque-controlled DC motor simulating the original brake pressure force. The street environment was projected on three silver screens (1.8 × 1m, 1920 × 1080 px) with a 117° horizontal and 47° vertical field of view. Two exterior mirrors and one interior mirror are simulated via smaller monitors.

Test courses. Four different test courses with 6–8 min duration and a forward collision warning with time to collision TTC = 3 s at the end of each test course were designed. Subjects drove manually on a two-lane rural road with oncoming traffic, a lane width of 3.5 m and a speed limit of 80 km/h. The test courses varied in terms of scenery, tree types and object density in order to create a realistic environment. Forward collision warning at the steering wheel lit up when a collision object – wildboars, a cyclist, a mountain biker or a tractor – suddenly entered the road from the right side. All collision objects were covered behind trees, bushes or houses and were only visible in the moment of the warning (Fig. 6).

Fig. 5. Static driving simulator in Berlin

Procedure. After the introduction, subjects signed a consent form and drove a 5-min familiarization course in the driving simulator. Participants drove the four tests courses containing one forward collision warning at the end of each course. The order of the experiment conditions in their combination with the test course were counterbalanced

Fig. 6. Visual warning with BRLE highlighted and four different collision objects: wildboars, cyclist, mountain biker and tractor

over the 32 subjects in order to avoid position, fatigue and practice effects. After each test course, workload, acceptance, glare scale and qualitative feedback were filled in. At the end of the study, subjects answered a short demographic questionnaire. Overall duration of the study was one hour.

3.2 Study Results

Mean differences in the metric scaled dependent variables between the four conditions were analyzed with repeated measurements ANOVA with statistic software R [19], in case the assumption of normality distribution and sphericity for ANOVA were met [20]. The probability of error was set to $\alpha = 0.05$. Normality distribution of the data was checked with Shapiro-Wilk test, skewness with D'Agostino test and kurtosis with Anscombe-Glynn test (s. Appendix). In case the normality distribution was significantly violated, a robust repeated measurements ANOVA based on 10% trimmed means was calculated [21]. Differences in reaction types were analyzed with $\chi 2$-test, number of collisions with Cochran's Q-test and preference with pairwise comparison judgements [18].

Driving performance.

Longitudinal driving data. No significant effects on mean or standard deviation of speed and minimal acceleration were found. Minimal TTC was lowest, thus worst with full rim illumination ($M = 2.52$ s, $SD = 2.59$ s), best with baseline ($M = 3.59$ s, $SD = 1.85$ s) and upper rim illumination ($M = 3.44$ s, $SD = 5.93$ s), but differences were not significant

(Fig. 7). No collision happened in the upper rim condition, one collision in the baseline condition and three each in lower and full rim condition. Cochran's Q-test revealed no significant differences in number of collisions between the conditions. Differences in number of collisions were not significant.

Lateral driving data. No significant effects on lane keeping quality or SD of lane position (Fig. 7) were found. On a descriptive level, SD lane position and lane keeping quality were worse with illumination conditions compared to baseline ($M_{SD\ lane\ position} = 0.13$ m, $SD_{SD\ lane\ position} = 0.12$ m; $M_{LKQ} = 9$ m^2, $SD_{LKQ} = 10.67$ m^2), worst with full rim illumination ($M_{SD\ lane\ position} = 0.18$ m, $SD_{SD\ lane\ position} = 0.16$ m; $M_{LKQ} = 16.4$ m^2, $SD_{LKQ} = 12.85$ m^2), where the variance was highest. Mean (Fig. 7) and SD of steering wheel angle velocity and acceleration as well as the number of spontaneous steering behaviors did also not differ significantly between the conditions. A higher variance in the steering wheel velocity and acceleration data in the full rim condition was remarkable.

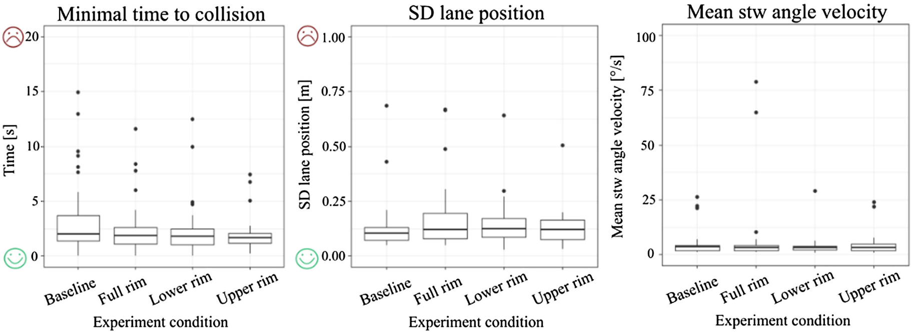

Fig. 7. Boxplots of minimal time to collision (TTC)[s], SD lane position [m] and mean steering wheel angle velocity [°/s]

Reaction data. Most participants (97%) reacted with braking. As most expected values were less than 5 and preconditions for $\chi 2$-test were not met, the more conservative Fisher's exact $\chi 2$-test was calculated revealing no significant differences in reaction types between the conditions. Only in the rim illumination conditions, a few subjects reacted with a steering movement first, but differences were not significant. First reaction time was longest with lower rim illumination ($M = 641.95$ ms, $SD = 421.35$ ms) and fastest with baseline ($M = 468.05$ ms, $SD = 326.32$ ms), but differences were not significant (Fig. 8). Furthermore, no differences could be found in time between accelerator pedal release till braking.

Workload. No differences in overall workload, the subscales mental workload, physical workload, temporal workload, effort, performance or frustration were found.

Eye gaze. 9 subjects in the full rim condition, 4 subjects in the upper rim condition and 7 subjects in the lower rim condition looked at the steering wheel when BRLE lit up. Differences in number of subjects looking down on the steering wheel did not differ significantly according to Cochran's Q. Due to a small amount of data and different distribution in the conditions, time between the steering wheel lighting up until subjects looked down at the steering wheel and the duration of gaze on the steering wheel was only analyzed on a descriptive level. Mean time between warning and gaze on the steering wheel was longest with upper rim ($M = 1.91$ s, $SD = 0.8$ s) compared to full rim ($M = 1.58$ s, $SD = 1.26$ s) and upper rim ($M = 1.42$ s, $SD = 1.44$ s). Duration of gaze on the steering wheel was longest with lower rim ($M = 0.63$ s, $SD = 0.4$ s) and full rim ($M = 0.6$ s, $SD = 0.72$ s) compared to upper rim ($M = 0.26$ s, $SD = 0.12$ s).

Glare. Robust Anova with a 5% trim revealed significant differences in glare rating ($F_{1.51,43.93} = 8.66$, $p = .002$). The lower trim level was chosen in order to keep the variance for each posthoc comparison, as with the default trim of 20% full rim and upper rim conditions could not be compared because their difference showed no variance. Robust posthoc test using Hochberg's approach showed, that upper rim ($M = 1.35$, $SD = 0.47$, $\psi = -0.28$ [-0.56, 0.00], $p < .018$) and full rim ($M = 1.47$, $SD = 0.57$, $\psi = -0.37$ [-0.61, -0.12], $p < .017$) received significantly higher glare ratings than lower rim ($M = 1.09$, $SD = 0.29$), as shown in Fig. 8.

Acceptance. No differences in acceptance or the acceptance subscale usefulness were found. Robust ANOVA revealed significant differences in satisfaction ($F_{2.92,\ 55.48} = 14.13$, $p < .001$) between the conditions (Fig. 8). Robust posthoc test using Hochberg's approach showed, that upper rim ($M = 2.14$, $SD = 0.47$, $\psi = 0.49$ [0.16, 0.83], $p < .001$) and full rim ($M = 2.12$, $SD = 0.51$, $\psi = 0.58$ [0.24, 0.91], $p < .001$) were rated significantly less satisfying than the baseline condition ($M = 2.7$, $SD = 0.36$).

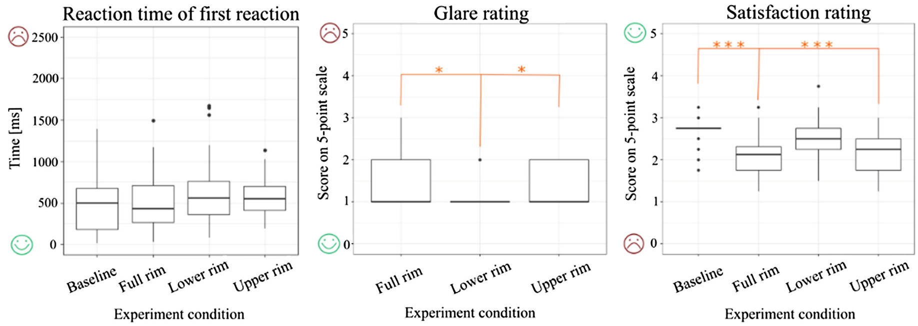

Fig. 8. Boxplots of first reaction time [ms], glare and satisfaction ratings on 5-point scales

Qualitative Feedback. Participants' comments were summarized, categorized and their valence as positive, negative or neutral was determined.

Full rim illumination. Overall, the full rim illumination was well accepted ("The light signal warned me very well. It was not disturbing or distracting" „Das Lichtsignal hat mich sehr gut gewarnt. Es war nicht störend oder ablenkend“). One participant found it supportive, but not decisive. Another person felt distracted by the light.

Upper rim illumination. The upper rim illumination was also well liked by the participants, but the difference to full rim illumination was not noticeable as subjects did not perceive the lower rim illumination so well: “In principle, the experience was the same as the one in which the full steering wheel rim was illuminated, as I only noticed the upper illumination there. So normally the lower half is not necessary”, “Prinzipiell war die Erfahrung gleich mit der, in der der komplette Lenkradkranz geleuchtet hat, da ich dort nur den oberen Leuchtstreifen wahrgenommen habe. Im Normalfall ist die untere Hälfte also nicht notwendig”. One participant found the upper rim illumination distracting.

Lower rim illumination. According to the vast majority, the lower rim light was hardly noticeable and by itself is too nondescript as a warning (“You do not notice the lower lighting so much”, “Die untere Beleuchtung nimmt man nicht so stark wahr”, “I am afraid that I would not have noticed the signal in daylight in the real vehicle”, “Ich fürchte, dass ich das Signal bei Tageslicht im echten Fahrzeug nicht wahrgenommen hätte”). One person found the lower illumination distracting, another person described an overlapping and thus worse visibility of the lower illumination through the eyeglass rim. A few participants liked the lower illumination and mentioned advantages when driver is distracted and looking down e.g. on a phone.

Baseline. Subjects preferred to be warned by a light signal (“The early warning of the light signal would have made you react faster”, “Die frühzeitige Warnung des Lichtsignals hätte einen schneller reagieren lassen“). One person preferred not to be warned, another one said, that it does not make a difference to be warned by the BRLE or not.

Preference. Pairwise comparison judgments were used to determine the preferred visual warning location by comparing the four of them in pairs. First, individual consistency and concordance were tested [18, 22]. Pairwise comparisons of the four conditions resulted in (4 over 2) = six comparisons, with participants scoring each preference. The consistency coefficient applicable to each participant was defined from the respective number of circular triads resulting from inconsistent preferences. For each participant, the observed number of inconsistent triads was relativized to the maximum possible number of inconsistent triads and subtracted from 1. This would result in a value of 1 for the highest possible consistency and a value of 0 for the highest possible inconsistency. For each 16 participants, the consistency coefficient was $K = 1$, meaning that these participants individually made consistent pairwise judgments. For 11 participants the consistency coefficient was $K = 0.6$, meaning that these participants answered partly inconsistent. Two participants were excluded, because their consistency coefficient was $K = 0$, meaning that their answers were inconsistent. Another participant’s data were missing. The extent to which the 29 remaining participants agreed with each other in their judgments was determined with the help of concordance analysis. For this purpose, the corresponding pair judgments of the individual subjects were summed to determine the number of concordant pairs of judgments (J). The concordance measure A was calculated by relativizing the number of matching pairs of judges (J) on the 29 judges and the four concepts to be compared. This resulted in a concordance measure of $A = 40$ with the number of matched pairs of judges of $J = 1699$. Using J, the significance of the concordance was tested asymptotically via a χ^2 distribution. The coefficient of concordance of $A = 40$ was significant ($\chi^2(7) = 14.07$, $p < .001$), and subjects did not disproportionately agree in their pairwise comparison judgments. To determine the preferred experiment condition, the frequencies ($f_{\mathrm{Condition}}$) of preference scores for each condition were considered. In the pairwise comparisons, the conditions could be evaluated with a maximum of $f_{\text{Condition}} = 87$ preference bonuses because each was presented to the 29 participants for selection in three comparisons. Upper rim with $f_{\text{upper rim}} = 69$ won the most pairwise comparisons, followed by full rim with $f_{\text{full rim}} = 56$ and lower rim with $f_{\text{lower rim}} = 38$ preference bonuses. Baseline received the fewest preference bonuses and was preferred in only $f_{\text{Baseline}} = 11$ of 87 pairwise comparisons.

3.3 Discussion

A driving simulator study with 32 subjects was conducted for usability evaluation of the BRLE steering wheel for forward collision warning scenarios on rural roads. The study investigated whether full rim illumination, upper rim illumination, lower rim illumination or no warning was more suited as a forward collision warning. The influences on driving, reaction data, workload, acceptance, blinding, preference and qualitative data were analyzed.

The upper rim illumination resulted in highest TTC, meaning more distance to obstacle, and no collision happened with this experiment condition. On a descriptive level, fewer glances at the visual illumination and shorter glance durations were observed. The upper rim illumination was the most preferred, which also became clear in the positive feedback in the qualitative data. Disadvantages of the upper rim illumination were the reduced satisfaction compared to the baseline condition and it was more blinding than the lower rim illumination. The lower glare factor compared to the upper and full rim illumination, on the other hand, was an advantage of the lower rim illumination. However, this advantage came from the drawback that the lower rim illumination was hardly visible, which was reported by the test subjects. This probably also resulted in longer reaction times, in two cases no reaction at all and three collisions. On the other hand, a warning on the lower rim might be beneficial when a driver is distracted looking down on a smartphone. Qualitative feedback showed a very positive response to the upper rim illumination and it was the second most preferred. In contrast to these findings, the satisfaction on the acceptance scale compared to baseline was lower. Drawbacks in comparison to the other conditions were the lowest TTC on a descriptive level, meaning the lowest distance to the obstacle, the highest lane deviation, higher steering wheel angle velocity and acceleration and three collisions.

Concluding from the results, the upper steering wheel rim position would be recommended as the most suitable position for the visual warning. This was found to be the most effective in collision avoidance with highest TTC and no collisions compared to the other conditions. While it is conspicuous enough to be a helpful warning, it also appears to be the least distracting, but is more blinding than in the lower rim. While it was rated as significantly less satisfactory than baseline, it was the most preferred illumination location and there was very positive feedback in the qualitative data.

Some limitations of the study concern characteristics of the sample, generalizability of the data collected in the driving simulator, and the lighting conditions in the driving simulator. An attempt was made to distribute age and gender equally according to NHTSA guidelines [12], but this was not completely possible due to Covid-19 related internal recruitment. In particular, both older and female participants are underrepresented in the sample. Testing internally results in an overrepresentation of automotive employees and may have resulted in social desirability in the rating. The simulation in the driving simulator allowed for a realistic vehicle environment, but in the (static) driving simulator, subjects generally feel safer than in real traffic and may behave differently. Lighting conditions in the driving simulator are darker than lighting conditions in real traffic at night. The luminosity of the BRLE must therefore always be adapted to the lighting conditions in the real vehicle. There was also a training effect due to the repeated event exposure, through which subjects responded more proficiently in subsequent FCWs than in the first ones [23]. However, this training effect was counteracted by a counterbalanced sequence of experimental conditions.

In this study, the forward collision warning signal was investigated as a unimodal visual warning, to concentrate on the effects of positioning the visual signal. As a drawback, unimodal visual warnings bear the risk of going unnoticed when the driver is visually distracted by looking at a mirror or a non-driving related task [10]. Combining visual warnings with tactile or auditory stimuli can enhance reaction times [e.g. 1, 3, 5, 6, 8, 9] and multimodal warnings are recommended by [10] for the use of urgent warnings. After analyzing the position of the visual warning on the steering wheel, further development of BRLE illumination will combine the light signal with a tactile or auditory warning to combine the benefits of multiple modalities.

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