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Ideas for Next Lighting Generations in Digitalization and Autonomous Driving

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Abstract

Digitalization in Industry and Society is progressing quickly. Up to now, just 5 static and standard lighting applications have been dominating in the U.S. (Low/High Beam, Daytime Running Lamp Turn Indicator & Position Lamp).

The global interest in standardization of light driven messages from autonomous vehicles to other traffic participants has opened new research needs and research findings. In Europe, GTB has established a working group dedicated to this topic.

The article will discuss the possible contribution of signalling and lighting functions to Digitalization and Autonomous driving by explaining the first elements of functional definition and research results.

Introduction

The new worldwide era of LED and digital light sources allows several new approaches, e.g. Matrix Beam as the evolution of static high beams is in European vehicles since 2013. So adaptive driving beams offer the chance to have a quasi-permanent high beam usage without glare to oncoming or preceding traffic participants [1]. The digitalization arriving in high resolution beam patterns allows to indicate the predictive display of driving paths in construction zones.

Additional new applications are visible at the horizon for signaling applications. While vehicles are approaching piloted or fully autonomous driving abilibty, the question rises, how the contribution of lighting functions can support this new type of traffic. Even when this is a future topic, it seems worth to address the coming issues possibliy related to lighting. There are many ideas on how lighting and lamps may look like and how they can support, most of them can be separated into either communication or information functions.

So besides the ideas for digital light in low/high beam new ideas for communication for the driver and other street participants with signal functions are rising.

Main/Low Beam Functions

Since the Introduction of Adaptive Driving Beam Functions in Europe back in 2013 [1], the use of LED as small and switchable light source has fostered new ideas for lighting functions. Starting with rather small amounts of LED from 10-25 per headlamp, future technologies will enable high resolution light distributions with some thousand light sources like micro LED arrays or Digital Mirrors and Liquid crystal based elements. This light distribution will enable the driver to drive better and safer through difficult traffic situations [8].

ADB/Matrix Light

The first application of a new digital light is the Matrix beam light distribution. By switching off segments of the high beam section, other traffic participants can be blinded out in order to prevent glare effects.

Two scenarios have been investigated: one scenario with an oncoming car, another scenario with a preceding car. In order to make the different headlights comparable, similar dark zones have been virtually generated and represent best case scenarios.

The analysis of the light distribution shows that a good gradient from 2-4° can be achieved by each of the technologies.

The width of the light distribution remains as in a standard high beam, the only difference being the blocked segments. Depending on the given driving situation, illumination levels of more than 200 lx can be achieved for each LED. Visibility improvements of up to 18 m object detection distance in real experiments with visual tasks have been confirmed. Static experiments show improvements beyond 45 m in object detection distance. Glare investigations show no massive negative impact towards the benefits. Between 57% and 74% of accident avoidance potential was calculated for modern matrix systems [8].

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FIGURE 1 Example of a Matrix Light distribution that prevents other traffic participants from glare despite constantly driving with high beam.

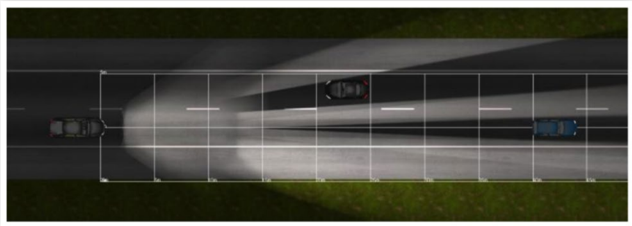
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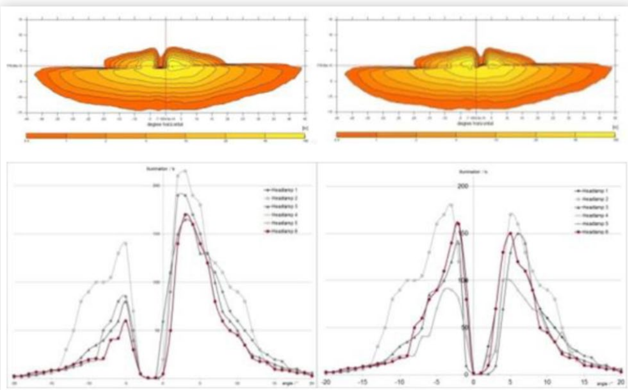
FIGURE 2 & 3 Oncoming car situation: Example for a light distribution and horizontal cut @0° for 6 selected headlights

FIGURE 4 & 5 Preceding car situation: Example for a light distribution and horizontal cut @0° for 6 selected headlights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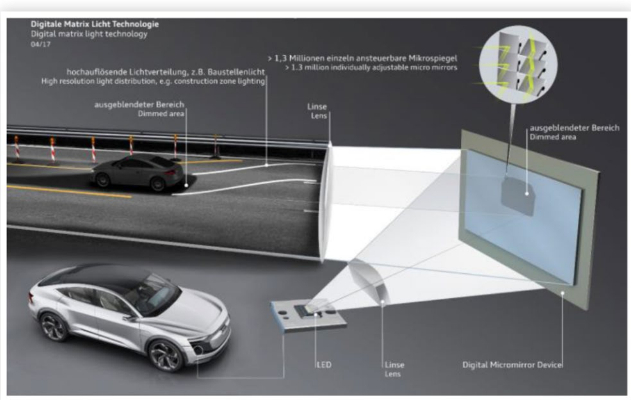
Digital Matrix Light (DML)

The next step to increase the lighting possibilities is to increase the resolution by creating a Digital Matrix Light (DML) (Fig. 6). High-resolution headlight systems can be based on the concept of digital micro mirror device (DMD) or Liquid Crystal Technology (LC). In a digital mirror system, a strong light source illuminates an array of many micro mirrors. Each mirror is controlled individually, allowing high resolution light distribution to be generated. Every mirror has two stable states to switch between. Rapid tilting of the micro mirror allows all dimming levels to be controlled with pixel accuracy. In DMD systems, a WVGA resolution of more than one million segments is possible. Depending on the quality of the sensor data, for example, the exact vehicle contour of an oncoming vehicle could be masked, while the rest of the scene remains illuminated. In addition to these anti-glare systems, further marking lighting assistance systems are possible.

High-resolution DML headlights make mold-breaking innovations for environment interaction feasible. Communication with pedestrians through recommending light functions for marking light and new functions for supporting the driver in unclear situations have been developed.

FIGURE 6 Digital Matrix Light will allow a high resolution and additional lighting possibilities on the road.



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Construction Zone Light

The design of a new lighting function has to follow various contributions. A summary of the parameters comprises [2] *Adaptation, Reference, Length, Width, Speed.* A prototype headlamp was built, allowing various parameters for designing a construction light. One example is shown in Fig. 7. The width was selected to 20cm with a contrast ration of 1:3,5 versus the standard low beam in the prototype headlamp. The bending of the light stripes was derived by calculating the speed dependent driving path and the steering wheel position.

The effect of the construction zone light and the customer's acceptance are strongly dependent on these parameters. Therefore, the preferences of drivers have to be evaluated using market analysis and studies.

Situation Definition The construction zone light as understood in this paper projects two light stripes on the road anticipating the width of the vehicle on the coming scenery in the area of roadwork. Basic intention is to increase safety and comfort for the driver.

Overtaking in Critical Situation. Critical situations during nighttime driving can be an overtaking attempt on multi-lane road, where the outer lane is used for overtaking and on both sides are massive objects, like in Fig. 8 there are limits by a truck on the right and delineators at the left side. The overtaking situation has to be evaluated whether the width of the lane during the dynamic driving situation is sufficiently safe for the driver to overtake.

FIGURE 7 Example of a light distribution indicating the width of the drivers car intended to be used in overtaking or construction zone areas.

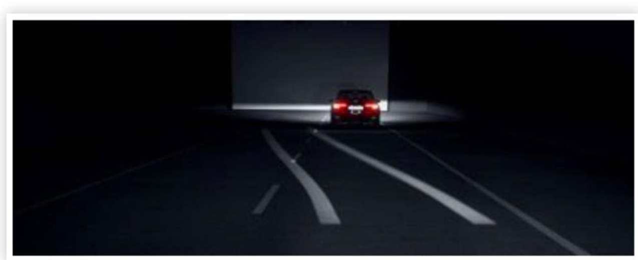
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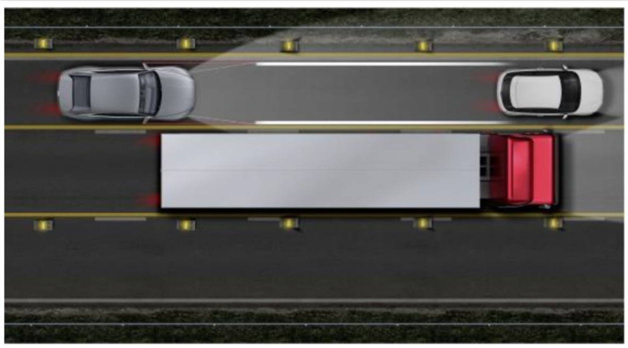
FIGURE 8 Example of a situation where the width of the driver's vehicle plays an important role in evaluating the driving situation while taking over [2].



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Construction Zone with Varying Lane Direction. Passing or overtaking other vehicles in construction zones may be additionally complicated when the lanes show curvatures. In many cases the curve radii of the lanes are rather small and require quick and precise steering reactions by the driver. In Fig. 9 the lane change covers two lanes on a total of approx. 75m.

The ultimate difficulties in construction zones occur, when the lanes are curved and additionally the width of the driver's lane changes. German motorway lanes are constructed with a standard width of 3,75m, giving for two lanes a total width of 7,5 m [6]. Fig. 9 already shows a decrease of the lane width from 3,75 m to about 3 m.

In Fig. 10 the graph shows the resulting changes in the gap to left and right lanes when a decrease of width in a construction zone to approx. 2,8 m occurs, allowing a maximum car width of 2 m for the left lane.

The only variable in the lanes in a construction zone is the gap from the car to the lane end.

Reduced lane width results in increased preciseness of steering wheel actions. Although reduced speed of 45mph / 70km/h is mostly demanded in construction zones, the car

FIGURE 9 Example of a situation where the lanes in a construction zone show some curvature and show reduction in width. [3]

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FIGURE 10 Comparison of normal lane width to construction zone lane width. A normal lane delivers a distance of 0,875m between borderline and car, In Construction Zones with reduced lane width the gap is reduced to 0,4 m.

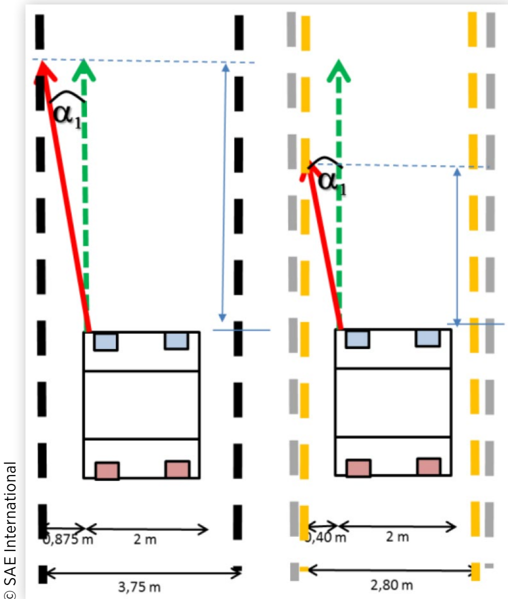

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FIGURE 11 Added difficulties in construction zones when the width of the lane changes extremely, allowing only 2 m width of cars.[5]

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speed is equivalent to about 20 m/s. An angular change of the car driving direction of only 3° would move a centric driving car within 0,38 seconds to the limits of the lane. (Table 1) That is equivalent to a loss of 55% of reaction and correction time

TABLE 1 Elapsed time in construction zones to reach the lane limits (see Fig. 10) under different speed situations.

	Normal Lane	Construction Zone
Lane Gap Delta / m	**0,875**	**0,4**
steering delta α / °	**3**	**3**
travelling distance / m	**16,70**	**7,63**
elapsed time / s @ 30 mph	**1,25**	**0,57**
elapsed time / s @ 45 mph	**0,83**	**0,38**
elapsed time / s @ 60 mph	**0,63**	**0,29**

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Test Setup for Construction Zone Light (CZL)

In the first scenario the test persons are driving in an artificial construction zone where the lane width changes significantly, as described in Fig. 12 and Fig. 10. The test persons were driving a car with a prototype headlamp, allowing a construction zone light as described in Fig. 7.

Test persons had to start in the prototype car where the additional construction zone light could be activated by the test supervisor. In Fig. 12 the setup is shown in detail. The basic distance to the overtake-car was 50m. Both cars had to accelerate to normal driving speed. The test persons were instructed to overtake the second car but should only do so when they felt able to drive safe. The basic lane width of 3,75m was limited to a lane width for the test car of 3,1 m. Compared to the actual allowed construction lane widths in German motorways [Ref. 6] the test setup was not in the range of worst case but in a normal construction zone width.

21 Test persons performed the test during comparable night conditions, i.e. no rain, dry and normal wind conditions.

Physical Test Results The test showed that many impact parameters have to be considered in order to achieve substantial results. Since not every driver was able to repeat his driving behavior when driving multiple times an identical test scenery, some of the results were not delivering consistent results. Recorded parameters like deceleration or acceleration profiles did not deliver reliable results in this test.

Steering Wheel Movement. When the analysis was limited to the steering wheel movement during the test scenery, especially when looking to small angle variations when the drivers where entering a construction zone with limited lane width, some interesting results could be derived.

The analysis of the recording of steering wheel corrections showed different behaviour of drivers with or without CZL. About 80% of the drivers used less than 3 small steering corrections. On the other hand, the standard overtaking situation without CZL showed only about 60% of driving situations with less than 3(="few") , and about 35% between 3 and 6 (="some"). Only some drivers without CZL needed more than 6 steering wheel corrections (="many"). The analysis summarized in Fig. 13 indicates that a driver with an activated CZL needs less corrections. Fewer corrections indicate the drivers were much better enabled to guide their car safely through the difficult situation in the setup (Fig. 12).

FIGURE 12 Test setup for an overtaking maneuver in a construction zone.

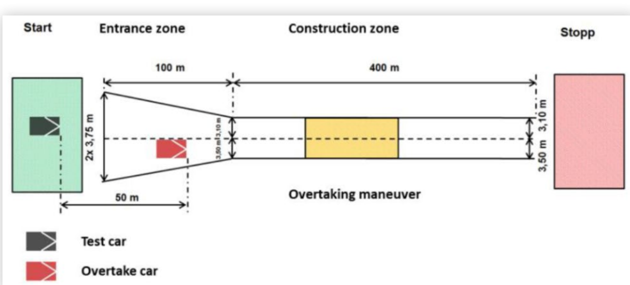

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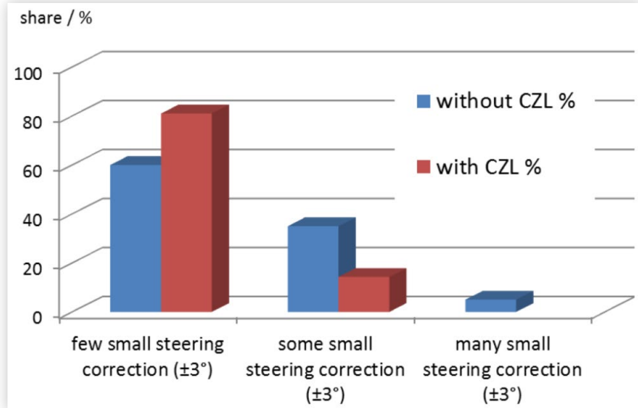
FIGURE 13 Analysis of small steering wheel corrections when test drivers were passing and overtaking a car in the test setup described in Fig. 12.



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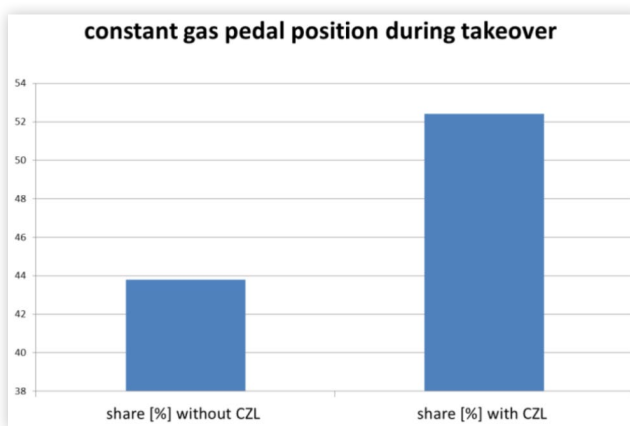
Gas Pedal Position During Takeover. Any speed change in a critical situation (without escape chance like in a construction zone) can lead to car to car accidents and enormous traffic jams creating additional danger. So it can be assumed that a system that can enable the driver to drive through such critical situation without dramatic speed change will improve traffic safety.

During the test setup the overtaking situation also the gas pedal position was recorded.

In Fig. 14 the share of test drives are displayed where the test drivers did not change the gas pedal position during the test setup takeover activity. Change of gas pedal means changing speed and a potential accident root cause. In about 15% more driving actions the test drivers with CZL did keep the gas pedal position constant. That indicates, the drivers were able from the very beginning of the overtaking situation to correctly evaluate the situation and felt no need to brake or accelerate their activity. This was proven by the following sequence where the drivers had to answer about their opinion on CZL.

FIGURE 14 Analysis of gas pedal position when test drivers were passing and overtaking a car in the test setup described in Fig. 14.



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Questionnaire Results After the test drives, the test persons have been asked to answer various questions about their experience with the new Construction Zone Light (CZL).

In Fig. 15-Fig. 17 some results of the questionnaire are shown. The test persons were asked to evaluate how they were able to estimate the width of the lane by the assistance of the Construction Zone Light (Fig. 15) . 18 out of 21 drivers gave a rank 1, 2 or 3 as answer to this question. That means about more 80% positive feedback.

Fig. 16 evaluates the question about the probability that abrupt braking might occur during the maneuver in Fig. 11. The question covered the impression whether the CZL would lead to fewer braking needs. None of the interviews showed an answer indicating no change with CZL. About 80% gave a much better ranking they felt to drive without the urge for abrupt braking.

The overall rating on the Construction Zone Light achieved 95% positive feedback (Fig. 17).

Conclusion. The use of additional lighting elements in critical situations shows positive effects. During the critical situation in construction zones the reaction times are limited, the safety gap to the lane limits can be less than 50%. That means that all elements that help the driver to keep his car inside the lane limits are helpful.

The study showed that gas pedal position changes (Delta 15%) and decreased steering angle frequency (Delta about 20%) showed better results with the construction zone light CZL. This is only an indirect link to traffic safety, but a good indication of improvement. Overall feedback of the drivers gave positive results. The drivers felt less forced to make abrupt braking maneuvers and had much better estimation of the own lane width.

FIGURE 15 Subjective evaluation "Lane width estimation" asked after the night drive in the test setup described in Fig. 12.

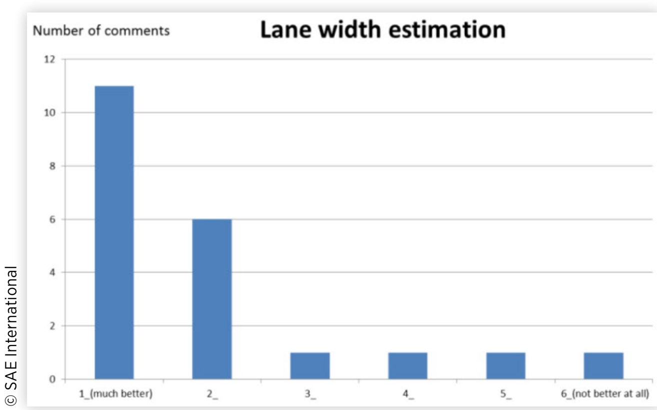


FIGURE 16 Subjective evaluation "Abrupt braking probability" asked after the night drive in the test setup described in Fig. 14.

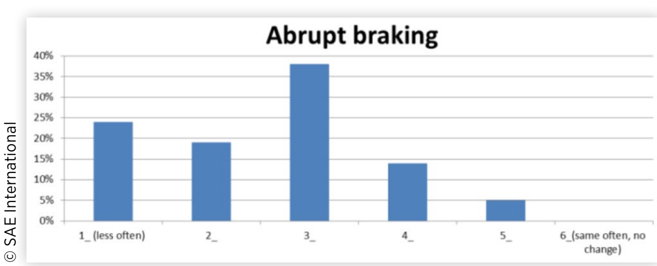
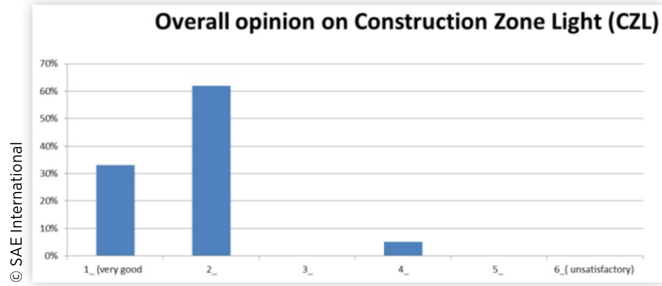


FIGURE 17 Subjective evaluation "Overall opinion on Construction Zone Light CZL" asked after the night drive in the test setup described in Fig. 14.



Car2Pedestrian Communication in 1D and 2D Display

Low and High beam functions predominantly create benefits for the driver. There are actual tests running to investigate the improvements a digital signal function can give to other traffic participants.

Especially on communication in the situation of autonomous driving vehicles the signaling functions can play a major part in exchanging information about the car's situation and next actions. The assumption for a future scenario is that an autonomous vehicle should communicate or inform other traffic participants about his actual status and next driving intention.

In a laboratory and indoor investigation, a car was placed on a road in order to assess the various possibilities for communication with other traffic participants. Predominantly the short distance communication like with pedestrians in front of a crosswalk or other situations when there should be a communication between car and pedestrian was under investigation.

Test Setup and Test Description

35 test persons were investigated during the research. The age range was from 22-55 years.

All test persons filled a questionnaire. 28 test persons confirmed they are frequent drivers, 5 described their driving amount as "normal" and 2 commented their driving habit seldom or very rare. 18 test persons used eyeglasses and 2 male test persons had deuteranope/tritanope colour deficiency.

The test started with achromatic display (i.e. white on black background) with a maximum size possibility of approx. 300 × 250 mm. The symbols and graphics were displayed

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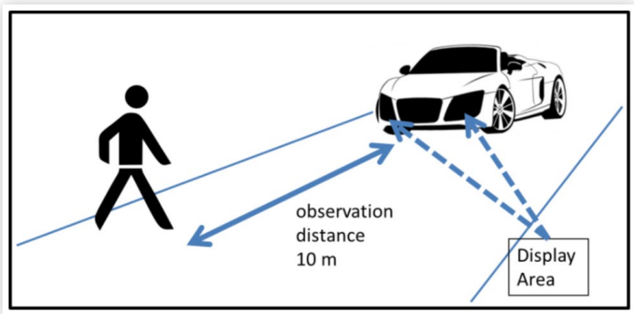
FIGURE 18 Test setup for the evaluation of car2pedestrian communication



symmetrically on the left and right side of the vehicle front. (Fig. 18).

In total 30 different situations were displayed to the test persons, 13 situations covered static symbols and 17 situations covered animated symbols or graphics. "Animation" was either an idling/roaming movement or a dynamic shift throughout the display area in horizontal or vertical direction.

The research setup was split into several sections. Basic and core research for the investigation were

- Intuitiveness of the symbols
- Static vs. dynamic signals
- 1-dimensional vs. 2-dimensional display
- Correctness of signal interpretation

In Fig. 19 the real setup in the laboratory is shown. A car is positioned on a laboratory road and static room illumination is activated. Due to the reflections in the windscreen there is additional glare contribution to the observer.

FIGURE 19 Test setup for the evaluation of 1-D and 2-D Signalling functions for autonomous driving.

Intuitiveness of Symbols

First section was intuitiveness of the symbols. Basic investigation target was to see how long a test person in the setup needed to come to a conclusion, what the display should communicate.

All test persons have not been trained or had seen the test symbols or setup before. This should guarantee a direct response without any additional influence from the test persons. First question was: "Please push the button if you understand what the car wants to communicate and indicate the situation."

All answers to the question were allowed, the core indicator was the reaction time from the beginning of display to the answer. It showed that some symbols were creating very quick response, even when the test persons had never seen that situation before. Some needed much longer time.

So it could be derived that there are symbols which deliver "intuitive" answers and a "Intuitiveness gap" could be calculated.

The results are shown in Table 2 and graphic display in Fig. 20.3 of the quickest answers are compared to three of the slow answer groups.

The two-dimensional graphics and symbols created an average reaction time from 2,72-4,35 sec.

The one-dimensional graphics and symbols created an average reaction time from 7,57-9,27 sec.

Even though animation means elapsed time to perceive the movement and then find conclusions, it is visible that 2-dimensional animations like the arrow in Fig. 20 is about half the reaction time compared to one dimensional movement and one third of reaction time compared to idling graphics and symbols.

Symbol Correlation and Correctness

Second section was to investigate the correct understanding of the displayed symbols. The test persons had already seen the setup in the first check for intuitiveness. Now a set of answer possibilities was given. Each situation was displayed 3 times. The given answer portfolio of 7 situations was:

- Standing
- Acceleration
- Braking
- Turning

TABLE 2 Calculation of the intuitiveness gap as a relation from the specifically record reaction time to the minimum reaction time for the best displayed symbol (#27)

Symbol #	time/s	Intuitiveness gap
27	2,72	1,00
23	3,84	1,41
21	4,35	1,60
8	7,57	2,78
19	7,74	2,85
25	9,27	3,41

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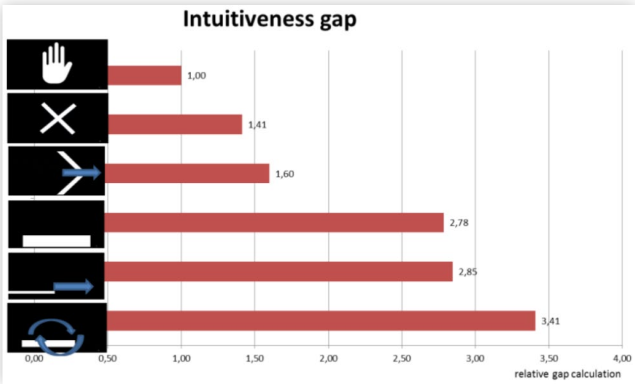
FIGURE 20 Results for the intuitiveness investigation for static and dynamic symbols and graphics. Blue arrows indicate animation and direction of the shift.



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- Car has seen me
- I can go
- I should stop/stand

The resulting second set of display started with the question: "Please push the button if you understand what the car wants to communicate and correlate the answer." The answer time was recorded again. Shortest answer time (#27) delivered a kind of benchmark how quick the test persons could correlate the answer to the displayed symbol. So the relation to this benchmark was calculated as "correlation gap".

The results are shown in Table 3 and graphic display in Fig. 21. Three of the quickest answers are compared to three of the slow answer groups. The two-dimensional graphics and symbols created an average reaction time from 1,49-1,98 sec. The slowest correlated symbols delivered average reaction times from 3,3-4.43 sec. Among the slowest correlation were one-dimensional symbols and one two dimensional symbol (#9). It was created with reference to the international start/stop symbol. A possible answer for the delay of correlation could be the complex graphics and thus a difficulty in understanding the message of such a symbol or the low knowledge about that symbol. Idling or soft moving symbols were not easy to correlate for the test persons and delivered the lowest reaction times. They needed about 3 times longer to find a correlated answer than to the quickest symbol.

TABLE 3 Calculation of the correlation gap as a relation from the specifically record reaction time to the minimum reaction time for the best displayed symbol (#27)

Symbol #	time/s	Correlation gap
27	1,49	1,00
21	1,85	1,24
20	1,98	1,33
8	3,30	2,22
9	3,79	2,55
25	4,43	2,98

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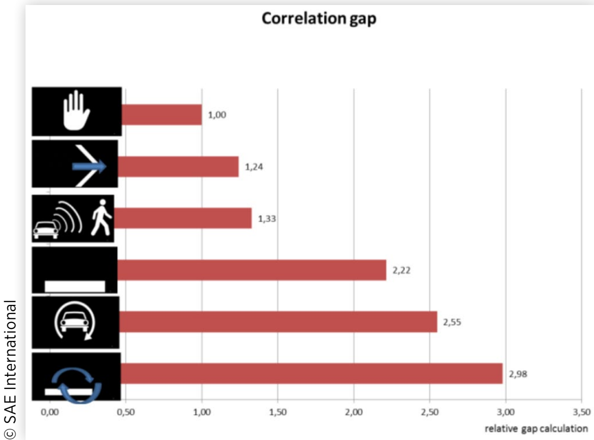
FIGURE 21 Results for the correlation gap investigation for static and dynamic symbols and graphics. Blue arrows indicate animation and direction of the shift.



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Correctness of Symbol Interpretation

The answers during the second set of display were not only recorded by reaction and answering time, but also whether the answers were correct.

In Table 4 and Fig. 22 the results for the correctness of the answers are given. The test persons had to evaluate the scenery according to the 7 scenery descriptions given in the questionnaire. Answer 8 was linked to "I do not know".

Best results were recorded for "I should stop/stand" (98%), "turning" (89%) and "the car has seen me"(83%).

TABLE 4 Correct answer for a selection of symbols displayed in the test setup (Fig. 18) The highest correlation was found for symbol (#27) (related answer: I should stop/stand)

Symbol #	Correct answer / %
19	57,14
21	82,86
16	55,57
27	98,10

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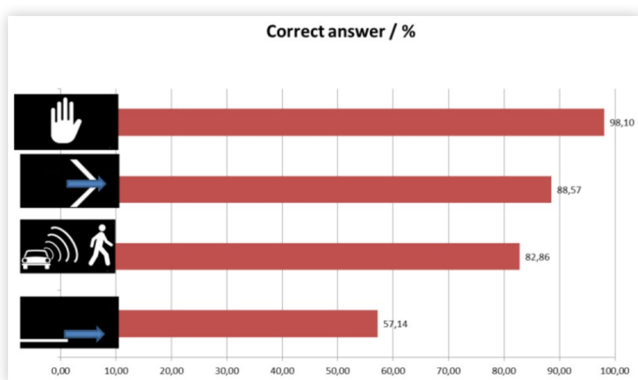
FIGURE 22 Results for the correct answer share for static and dynamic symbols and graphics. Blue arrows indicate animation and direction of the shift.



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Conclusion

There are very good results for symbols that are

a) two dimensional,
b) easy to understand, not complex and
c) dynamic or animated.

Even animation of one-dimensional symbols does not reach the correctness levels achieved with two-dimensional symbols.

A correctness rating of 98% and 88% gives high confidence that such symbols would be understood in the original intention for the car2pedestrian communication.

Minor correlation could be found for symbols that indicate the car is in standstill but active (like "ignition on, motor running"). None of the symbols intended to show that situation showed good correlation.

Summary

Digital Lights give benefits to drivers and other traffic participants. Matrix light and other digital applications like Construction Zone Light show very good benefits in terms of visibility, object detection and driver's ability to evaluate a scenery in terms of safety aspects.

In the presented experiments the benefits of a Construction Zone Light were demonstrated. The drivers passed the construction zone with less steering wheel movements and less variation of the gas pedal position. 95% positive feedback from the drivers shows the enormous traffic safety potential.

Signaling functions enable other traffic participants to see and understand the intention of an autonomous vehicle even when there is no driver or a totally distracted driver in that car. Car2pedestrian communication is a new field of investigation. The presented results give a good idea how future communication can be intuitive, clear and easy to understand.

The 1-D and 2-D investigations show that there is a clear preference for two-dimensional displays. Another preference are animated displays. The investigations show that reaction times are quicker (factor 2-3) and the correct correlation for the pedestrians with two-dimensional messages is superior to one-dimensional display, independent whether it is static or animated. 2-D animation seems to foster the understanding and reaction time.

A future field of investigations are the type and meaning for easy-to-understand symbols that give clear messages about the car intention and the communication with the pedestrian.

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Definitions/Abbreviations

ADB - Adaptive Driving Beam. Comprises all technical solutions that allow a continuous usage of driving beam despite oncoming or preceding traffic

CZL - Construction Zone Lighting allowing to estimate the width of the car

DMD - Digital Mirror Device

DML - Digital Matrix Light High Resolution Illumination of street scenery in low and high beam area

GTB - Groupe de Travail de Bruxelles, The International Automotive Lighting and Light Signalling Expert group in the ECE framework http://www.gtb-lighting.org/

LC - Liquid Crystal Technology

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