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REDUCTION OF FUEL CONSUMPTION BY EARLY ANTICIPATION AND ASSISTANCE OF DECELERATION PHASES

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ABSTRACT

This work deals with the investigation of advanced driver assistance system (ADAS) which helps the driver to perform phases of deceleration in an efficient and safe manner. The concept of the assistance system is supported by early recognition of deceleration situations with the help of new sources of traffic information such as GPS based systems, car-to-car, and car-to-infrastructure communication. The system presents visual information to the drivers in order to enhance their anticipation. Together with the representation of emerging situation, the assistance suggests coasting a vehicle from the currently driven speed to the upcoming lower goal speed in order to reduce fuel consumption. If coasting does not suffice, the system will suggest moderate braking. It is left to the driver's consideration to accept the system's advice.

The analysis of the estimated fuel consumption and the acceptance of the assistance system are done using situational, driving, visual, and subjective data which were collected during the experiment drives in the fixed-base simulator. Twenty six test subjects took part in the experiment; their average age was thirty four years. After a simulator training, they had to complete three experiment drives in the permuted order each lasting between seventeen and twenty minutes: one drive without any assistance (baseline condition), one with the innovative visual assistance using a bird's eye-view perspective on the emerging deceleration situation, and one with an iconic representation of it. Visual concepts are displayed in the digital instrument cluster. Each drive consists of thirteen deceleration situations which occur on rural, highway, and city roads.

This work presents the results regarding the influence of the system on the driving behavior. The analysis data of two assisted drives are compared to the baseline condition. The results show the significant reduction of the estimated fuel consumption in particular situations (up to 50%) and in the entire drive (approximately on 4%). Maximum decelerations are significantly reduced in the investigated safety critical situation. The drivers are able to avoid collisions, which happened during baseline drives.

TECHNICAL PAPER

OBJECTIVE

The objective of the study is to investigate the effects of an assistance which expands the natural anticipation horizon of the driver on the maneuvering level. The assistance informs the driver early enough about the upcoming deceleration situation and suggests an appropriate action in order for the driver to benefit in efficiency, comfort, and safety.

EXPERIMENTAL DESIGN

In the following, the information about the test subjects, hardware and software tools used for the implementation of the experiment course and analysis of the collected data, as well as descriptions of investigated situations and assistance concepts are provided.

Subjects

Twenty six participants (seventeen male and nine female) took part in the experiment. All of them hold valid category B German driving licenses. The average age of the test subjects was thirty four years (standard deviation, sd = 13,6 years) at the time the experiment took place. The driving experience varies: seven participants drive less than 10.000 km per year, eleven – between 10.000 and 20.000, and eight – more than 20.000 km per year.

Hardware and Software Tools

The experiment was performed at the fixed-base simulator located at Lehrstuhl für Ergonomie, Technische Universität München. The field of the driver's front view of 180° is used in the described experiment drives. The landscape and driving environment are simulated using SILAB software (1), which allows flexible and precise creation of the driving situations including the control over simulated traffic. The driving data of the test vehicle as well as relevant situational data, e.g. distance and speed of other traffic participants, are recorded at 60Hz within the SILAB framework. The visual data are collected at 25Hz using DIKABLIS software (2). The descriptive analysis of driving data is done with MATLAB and Excel, the statistical analysis is performed using SPSS.

Experiment Course

Each of the test subjects drives experiment course three times in the permuted order: without the assistance (baseline condition), with a "birds-eye view perspective" visual assistance (3), and with iconic visual assistance (see "Investigated assistance concepts"). The goal and functionality of the visual assistance is explained to the test subject before the experiment starts. One drive lasts between fifteen and seventeen minutes, during which the test subject covers 21,5km and is confronted with thirteen different deceleration situations. The order of deceleration situations and surrounding landscape is changed in every of the three drives to avoid recognition effects. In the following the description of investigated deceleration situations is provided.

"Construction site behind a right curve". This situation occurs on the two-lane rural road, where the permissible speed is 100km/h if not explicitly changed by other speed limit signs. The test subject has to decelerate in front of the construction site located on the driven lane in order to let the oncoming cars pass. The site is located 200m after the right curve with 700m radius. The situation becomes visible at the distance of 400m-450m, while optimal coasting phase assuring efficiency benefit lasts 500m.

“Construction site behind a left curve”. This is another rural road situation. The difference to the previously described situation is 500m curve’s radius, and the construction site is located directly in the curve. The driver is able to see the situation at 280m.

“Speed limit on the rural road”. The driver has to decrease the driven speed down to 70km/h due to an incoming sharp curve in this situation. The sign becomes visible approximately 200m before it is reached, while the coasting from 100km/h down to 70km/h lasts 400m.

“Town entrance”. The driver has to decrease the speed to 50km/h when entering an urban area according to German traffic regulation rules. Even though this investigated situation is well-visible at larger distances, it is still unclear if the driver without assistance starts coasting early enough to perform the efficient deceleration maneuver. Coasting from 100km/h to 50km/h lasts 600m.

“First and second slower front vehicles in the vicinity of prohibited overtaking”. On the rural road, drivers are confronted twice with slower vehicles driving 80km/h in the vicinity of prohibited overtaking. Even though both situations are well-visible, it is questionable if the drivers are able to perform deceleration maneuvers in an efficient manner without an additional information.

“Slower front vehicle and oncoming traffic”. Drivers approach a vehicle driving 60km/h on the rural road. They are allowed to overtake it after the opposite lane is free from the oncoming traffic.

“Parking car and oncoming traffic”. The permissible speed limit is 50km/h in the town. In this situation, the driver has to decelerate because of the parking car occupying the driven lane. After the oncoming traffic on the opposite lane has passed, the driver can overtake the obstacle. The situation becomes visible at the distance of 200m, which is also the distance needed for an optimal coasting phase.

“First and second red traffic lights”. The traffic lights are in the red phase before the driver stops in front of them. Afterwards they change their color to green.

“Speed limit on the highway”. It is allowed to drive at any speed on German highways, if not explicitly changed by additional speed regulation signs. In the situation, the allowed speed is set to 120km/h on this particular segment of the experiment course. Situation becomes visible after the beginning of optimal coasting phase should have taken place.

“Stagnant traffic on the highway”. The driver approaches a traffic congestion moving at 60km/h on the highway. This situation is well-visible and occurs shortly after “Speed limit on the highway”.

“Highway jam”. This is the only critical situation investigated in the experiment. Drivers are on the highway and drive with deliberately chosen speed. They approach a curve behind which the idle vehicles are located on all of the lanes. This jam tail becomes visible 250m-300m before the driver has to come to a stop.

Investigated Assistance Concepts

Two types of assistances are tested: visual assistance with a bird's-eye view perspective on the situation (in the following called Bird's-Eye), and iconic (Iconic) visual assistance. Both of these human-machine interfaces (HMI) are presented to the driver in the instrument cluster.

The Bird's-Eye HMI depicts the virtual road, driven vehicle, and the deceleration situation when it emerges. This HMI possesses continuous characteristics: the presentation of the driven vehicle on the occupied lane is always displayed in the instrument cluster. The deceleration situation is superimposed on the virtual road when necessary, e.g. in Fig.1a the construction site and oncoming traffic are depicted. The legitimate traffic sign is shown at the side of the virtual road to enhance the comprehensibility of the emerging situation. This information appears at the point of time when the efficiency optimized action should start, so-called beginning of the optimal coasting phase: the green color of the vehicle suggests coasting in order to decrease speed. If pure coasting is not sufficient to reach the required lower speed, the color of driven vehicle changes to orange suggesting active braking. It is left to the driver to decide with which strength to brake. The authors tried to achieve the driver's understanding of the driving situation, the most beneficial action at the particular point of time, and provide the feeling of the speed at which the situation emerges.

Figure 1a: Bird's-Eye HMI

Figure 1b: Iconic HMI

The Iconic HMI is intermittent. The symbols of the traffic sign with brake/accelerator pedals appear only when the driver preferably should start the efficiency optimized action (Fig. 1b). The accelerator pedal is orange and starts to move when coasting is reasonable. The brake pedal moves if braking is necessary. No information about the remaining distance or time to the situation is provided.

Analysis Approach

The focus of the presented analysis is put on the reduction of the estimated fuel consumption in most of the investigated situations as well as in the entire drive, and on the minimization of experienced decelerations especially in the safe critical situation.

The situation-oriented analysis is done for the course segments. An analyzed situation segment starts where the optimal coasting should begin when driving the permissible speed plus 100m to take into account faster driving test subjects, and ends when the situation is bypassed. In the safety critical situation, the analyzed segment begins 1000m before it, which is the point at which the comfortable braking not exceeding $-3m/s^2$ (4) should take place in order to avoid collisions. This is the only situation in which the explicit focus of analysis is safety rather than efficiency.

Following dependent measures reflecting the focus of analysis are considered:

- Time-to-Collision, also known as Time-to-Contact (TTC), in [s] – calculated according to Formula 1 for the first point in time, when the driver completely releases the accelerator and starts coasting the vehicle. For the safety critical situation also TTC at the point when the driver first starts braking is taken into account.

$$TTC[s] = \frac{d_{obstacle}[m]}{v_{driven}[m/s] - v_{obstacle}[m/s]}$$

Formula 1: Calculation of TTC

In Formula 1: $d_{obstacle}$ – distance between the driven vehicle and the obstacle in the deceleration situation; v_{driven} – speed of the driven vehicle; $v_{obstacle}$ – speed of the obstacle, in case of a static object i.e. construction site or speed limit sign is equalled to 0m/s.

- Estimated fuel consumption, in [%] – calculated for the vehicle dynamics model in the fixed-base simulator at the Lehrstuhl für Ergonomie, which resembles one of the BMW 3i motors with automatic transition. The value of the estimated fuel consumption is given in percents to emphasize the tendency of its change while driving with assistance compared to the baseline condition; 100% corresponds to an estimated fuel consumption in the baseline drives.

- Maximal deceleration, in [m/s^2].

RESULTS

In this work, the results of driving behavior are presented. The results regarding the subjective evaluation of comprehensibility and helpfulness of the concepts are described in (5). Generally it can be stated that Bird's-Eye concept is perceived subjectively much better than Iconic. However, in the reported results on driving behavior no significant differences are established between the concepts.

In the following, the results are given for the entire drive and for separately investigated situations. In the provided figures, mean values and standard deviations are presented. The statistical analysis is done via the repeated-measures ANOVA (analysis of variance) with post hoc comparisons using Bonferroni corrections. 0,05 is the chosen significance level.

The assistance has a significant influence on the estimated fuel consumption determined for the entire course (Fig.2): $F(2;24)=9{,}203$, $p<0{,}001$. Driving with Iconic or Bird's-Eye assistance, the test subjects save approximately 4% of the fuel (post hoc comparison Iconic vs. baseline: $p=0{,}001$; Bird's-Eye vs. baseline: $p=0{,}022$). The duration of the assisted drives increase on 2% (Fig.2), however, not significantly: $F(2;24)=3{,}21$, $p=0{,}058$.

The situation-oriented analysis shows, that the assistance significantly helps to reduce the estimated fuel consumption in four investigated deceleration situations.

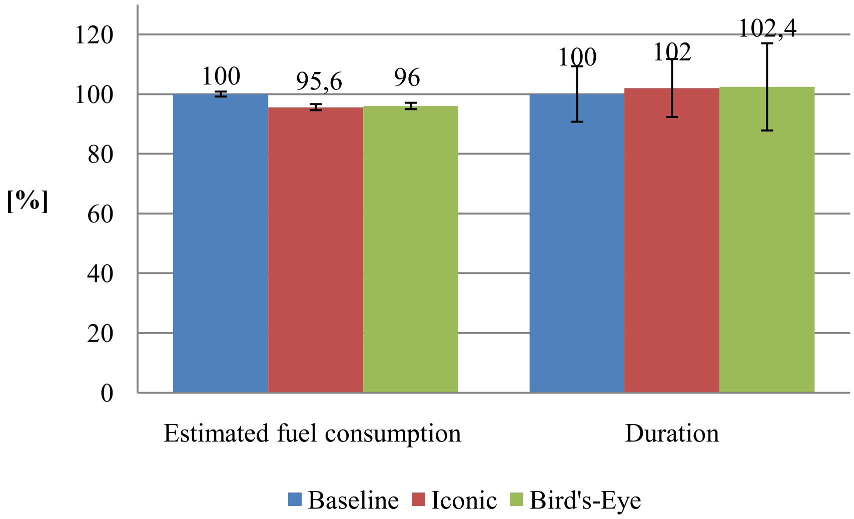

Figure 2: Entire course – effect of the assistance

In “Construction site behind a right curve”, the drivers are not able to see the situation when the assistance proposes the coasting phase to be started, approximately 500m before the site. Nevertheless, the drivers accept the advice of the system and start coasting a vehicle. The corresponding TTCs are depicted in the Fig.3a. This significantly earlier start of the coasting phase, $F(2;24)=64,390$, $p<0,001$ ($p=0,012$ for Iconic and $p=0,001$ for Bird’s-Eye in post hoc comparisons to the baseline), results in the reduction of the estimated fuel consumption (Fig.2b): $F(2;24)=35, 247$, $p<0,001$ ($p=0,046$ in post hoc comparison between Iconic and the baseline, $p<0,001$ between Bird’s-Eye and the baseline). The difference between the mean values in the Bird’s-Eye and Iconic assisted drives is not influenced by the assistance concept. In Bird’s-Eye drives, additional factors contribute to comparatively lower fuel consumption (for the detailed explanation see (6)).

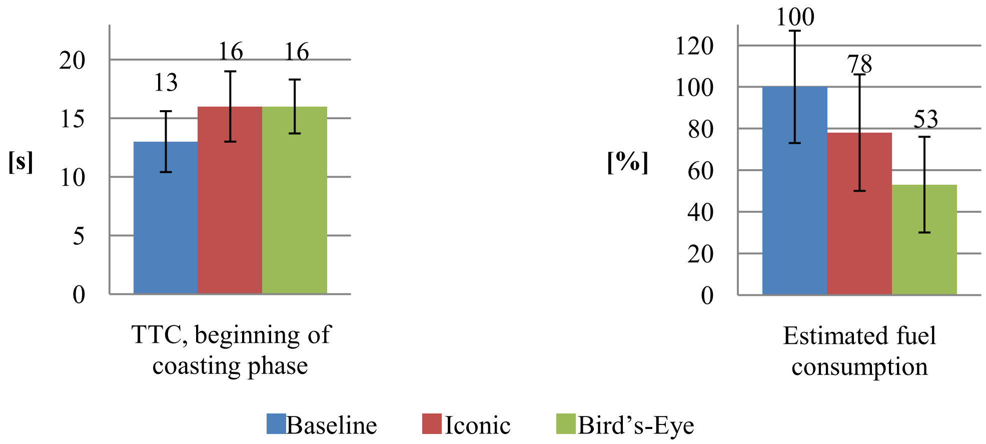

Figure 3a: “Construction site behind a right curve” – effect of the assistance on the beginning of the coasting phase

Figure 3b: “Construction site behind a right curve” – effect of the assistance on estimated fuel consumption

In “Construction site behind a left curve” the drivers also accept the advice of the system and start coasting phase significantly earlier compared to the baseline condition: $F(2;24)=14,563$, $p<0,001$. However, earlier start of the coasting phase does not result in the reduction of the estimated fuel consumption. The drivers are informed via the assistance about the construction site early enough to reduce their speed, let the oncoming traffic pass, and accelerate before coming too close to a construction site. During the unassisted drives, the test subjects come to a full stop just before the construction site. Due to the longer lasting accelerations in the assisted drives no fuel reduction is detected.

The estimated consumption of fuel is reduced with the help of assistance in the situation “Slower vehicle and oncoming traffic” (Fig.4b): $F(2;24)=14{,}445$, $p<0{,}001$ ($p=0{,}002$ for Iconic and $p<0{,}001$ for Bird’s-Eye in post hoc comparisons to the baseline). The assistance advises the driver to coast the car down to 60km/h because of a slower moving lead vehicle with the explanation that the oncoming traffic prohibits immediate overtaking. Thus, the test subject coasts until the oncoming traffic passes and the overtaking maneuver becomes possible. During unassisted drives, the test subjects accelerate in the hope of overtaking the lead vehicle, and abruptly brake when the oncoming traffic becomes apparent. This is reflected by the significant reduction of the maximal decelerations in both Iconic and Bird’s-Eye assisted drives (Fig.4a): $F(2;24)=7{,}817$, $p=0{,}002$ (post hoc Iconic vs. baseline: $p=0{,}001$; Bird’s-Eye vs. baseline: $p=0{,}03$).

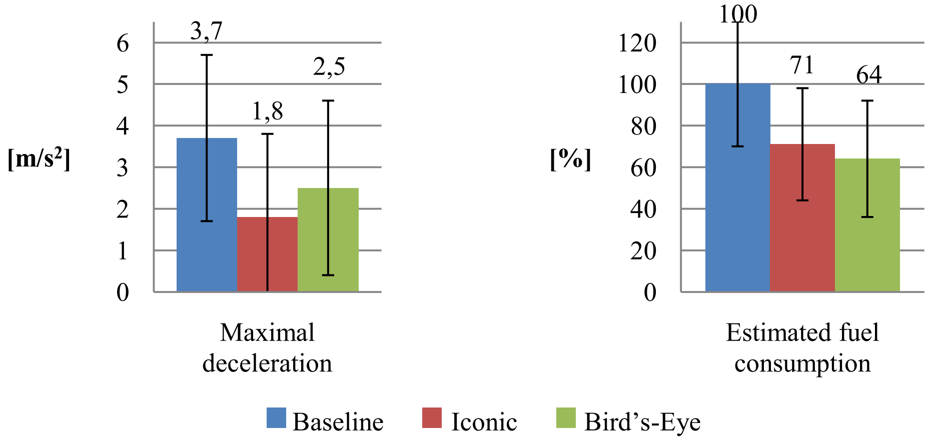

Figure 4a: “Slower vehicle and oncoming traffic” – effect of the assistance on maximal decelerations

Figure 4b: “Slower vehicle and oncoming traffic” – effect of the assistance on the estimated fuel consumption

During the situation “Speed limit on the rural road” the drivers are able to save 50% of the fuel (Fig.5b): $F(2;24)=6{,}848$, $p=0{,}005$ ($p=0{,}004$ for Iconic and $p=0{,}05$ for Bird’s-Eye in the post hoc comparison with the baseline).

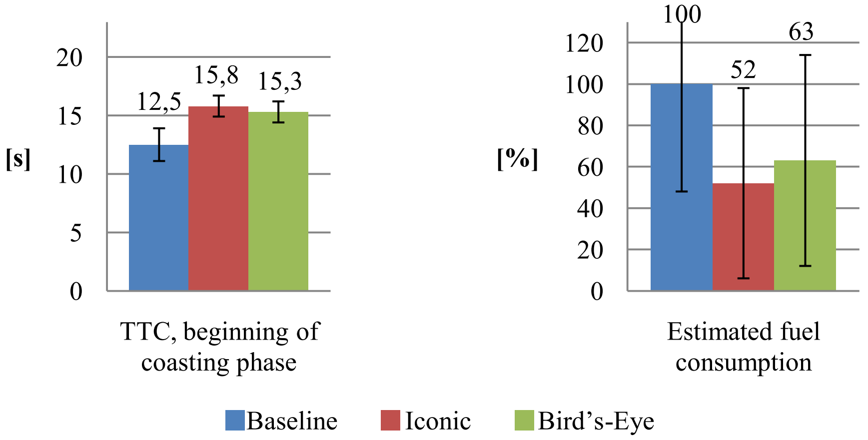

Figure 5a: “Speed limit on the rural road” – effect of the assistance on the beginning of the coasting phase

Figure 5b: “Speed limit on the rural road” – effect of the assistance on the estimated fuel consumption

Even though there are no significant differences found for the beginning of the coasting phases (Fig.5a), the test subjects while driving without assistance are accelerating on the straight parts of the course after first releasing the accelerator due to the incoming light curves before the speed limit sign becomes apparent. With assistance, they prefer to coast the vehicle until the speed limit sign is reached without accelerating "in between".

In "Speed limit on the highway" situation the drivers accept the advice of the assistance and start coasting earlier than without this information (Fig.6a): $F(2;24)=16{,}146$, $p<0{,}001$. Such behavior results in the reduction of the estimated fuel consumption (Fig.6b): $F(2;24)=18{,}039$, $p<0{,}001$ (post hoc comparison Iconic vs. baseline: $p<0{,}001$; Bird's-Eye vs. baseline: $p=0{,}001$). The mean values of fuel consumption between Iconic and Bird's-Eye assisted drives are not significantly different.

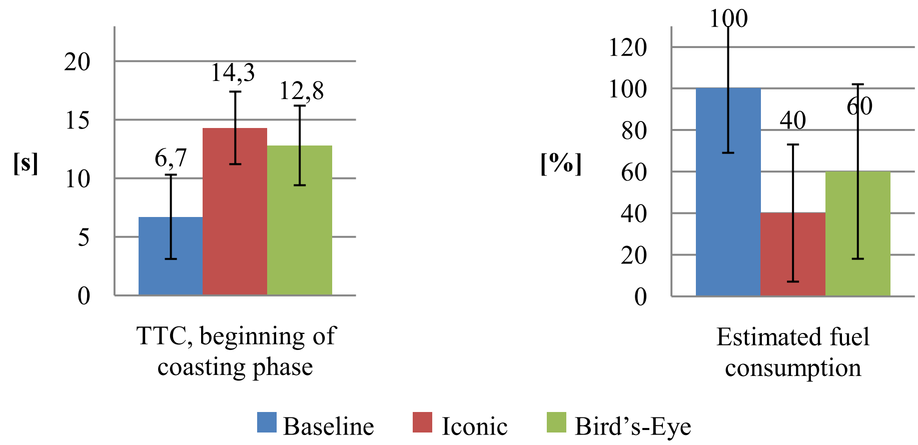

Figure 6a: "Speed limit on the highway" – effect of the assistance on the beginning of the coasting phase

Figure 6b: "Speed limit on the highway" – effect of the assistance on the estimated fuel consumption

Fig.7 depicts results of "Highway jam" situation. The drivers approach a jam behind a curve and have to come to a full stop. Here the efficiency gain is less important than the issue of safety. Without the assistance four collisions occurred, while with assistance – none.

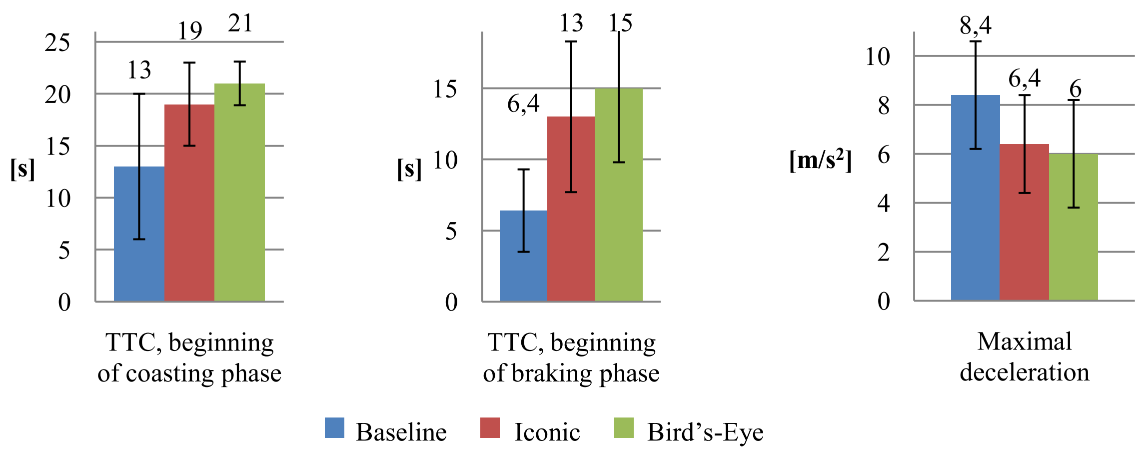

Figure 7a: "Highway jam" – effect of assistance on the beginning of a coasting phase

Figure 7b: "Highway jam" – effect of assistance on the beginning of braking phase

Figure 7c: "Highway jam" – effect of assistance on maximal deceleration

The coasting phase without the assistance starts in the curve with TTC of 13s, followed by hard braking with TTC=6,4s once the jam tail is seen by the drivers. With assistance the driver starts coasting significantly earlier ($F(2;24)=28,289$, $p<0,001$), just after the situational information is displayed. The braking phase for assisted drives begins with TTC 13s-15s in the curve, earlier than in baseline: $F(2;24)=28,817$, $p<0,001$. As a result, maximum decelerations are significantly reduced, $F(2;24)=11,929$, $p<0,001$ (for Iconic $p=0,005$ and for Bird's-Eye $p<0,001$ compared to the baseline), and collisions are avoided.

No significant improvement due to the assistance is established in the following situations: "Town entrance", "Parking car and oncoming traffic", "First and second traffic light", "First and second slower front vehicles in the vicinity of prohibited overtaking", and "Stagnant traffic on the highway". In the situations involving slower moving vehicles drivers start coasting phases in the baseline early and are able to perform deceleration maneuver in an efficient manner. The appropriate beginning of the coasting can be explained by the visibility of the situations at the distances, which are large enough for an optimal coasting phase to be performed, as well as driver's certainty in the necessity of deceleration. In the urban situations, no final conclusions about the potential of investigated assistance are reached. It is left to prove if the simulated conditions are close enough to those of the real life in order for the obtained results regarding driving behavior to be considered completely valid.

DISCUSSION

In the fixed-base simulator experiments, the quantity values for some of the driving measures may differ from those of real drives. However, the quality tendency can be derived. The presented results of the estimated fuel consumption and experienced maximum decelerations are to be viewed in comparison, in which the exact values are important to derive the tendency of change in assisted versus unassisted drives. To further suit this purpose, the comparison of estimated fuel consumption is presented in percents, where 100% is always the fuel consumption during the unassisted drive. Reaction times, e.g. the time distance to the situation when the driver starts to decelerate by releasing the accelerator, are comparable to those which can be obtained from the real drives. This is also validated by the unpublished experiments (7).

CONCLUSION

The results of the driving behavior analysis show the significant potential of the proposed assistance regarding the fuel reduction. 4% of the estimated fuel consumption is saved during the assisted drives compared to the baseline condition. Between the two investigated HMI assistance concepts, no significant differences regarding the driving behavior are established. However, Bird's-Eye HMI is perceived subjectively much better than Iconic HMI.

In four investigated situations the assistance helped to reduce the fuel consumption significantly. These are the situations, where the upcoming deceleration necessity is not visible at the point of time, when the optimal coasting leading to the reduction of the fuel consumption should start. In the situations, which are visible at the larger distances, no potential of fuel reduction is determined. Here the drivers react in efficient manner without additional information and are able to start coasting the vehicle at the optimal point of time without additional information.

The assistance is helpful in preventing collisions in safety critical situations, which become apparent to the driver for the comfortable deceleration action too late and therefore require emergency braking action.

In the simulated situations in the urban area no final conclusions regarding the assistance potential are reached.

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