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Boosting Advanced Driving Information: a Real-world Experiment About the Effect of HUD on HMI, Driving Effort, and Safety

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Abstract

The head-up-display (HUD), which reflects driving information into the windshield has the goal to lower driving effort from the information uptake and thereby, increase our safety by reducing risks associated to e.g., fatigue and stress. However, the user acceptance of the Advanced Driving Assistance Systems (ADAS) is remarkably low. This motivated us to test the HUD by conducting a real-world experiment with 48 subjects who drove in real traffic conditions two premium vehicles in a highway in Germany. After each ride, participants rated their driving experience in terms of Human-Machine Interface (HMI), their feelings of safety and driving effort. Results from CMP regressions (Roodman, Stata J. **11**, 159–206 (2011)) show that the HUD has a significant positive effect on the driving effort and safety feelings, and on the overall driving experience. Moreover, we find that this effect is stronger among risk-averse drivers, elderly, students, and females. In particular, women felt significantly safer while the HUD was activated. To reverse low ADAS acceptance, specific differentiation settings regarding the driver's profile are discussed.

Keywords Advanced Driving Assistance Systems (ADAS) · Head-up Display (HUD) · Driving effort · Human-Machine-Interface (HMI) · User experience · Safety · Risk-aversion

1 Introduction

The information displayed to the drivers has gained increasing attention in direct proportion to the booming of advanced driving assistance systems (ADAS). However, it is not a secret that most of the drivers remain skeptical about these new technologies. Drivers consider them as a very appealing "*addendum*", even desirable, but in practice, this is another story i.e., the ADAS user acceptance in terms of usability remains remarkably low. One might think that "flashy" information and more than "enough" of it is always good, but while driving, this can be even deadly. Then we should ask, what do I really care about the traffic information while I drive? How much, how and when, or what type, are just a few questions about the information displayed while driving. The traditional dashboard display (head-down-display, HDD) has not been removed from the latest models; instead, it has been complemented with a head-up- display (HUD) which reflects driving information into the windshield. The HUD shows us driving-related content with the goal to lower driving effort from the information uptake, and thereby, increase our safety by reducing the risks associated to e.g., fatigue, stress, and distractions [15, 31, 46]. A natural consequence is that customer expectations and preferences, about what and how this new information should be displayed, have become more relevant for safety, policymaking and customer satisfaction.

Nowadays we are used to adjust our devices e.g., smartphone, laptop, notepad, etc., but twenty years ago Gish and Staplin [18] already proposed to study the customers preferences and attitudes towards the in-car displays. This literature, however, is still scarce, and to some extent, limited to the classical HDDs (e.g., [16, 53]). Most importantly, the relationship between the drivers' expectations about improvements on safety and mental workload, and

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customer satisfaction are still largely unknown or not fully understood (e.g., [7, 42, 54]). Recent studies on Lane Keeping Assistance Systems (LKAS) confirm the aforementioned findings (e.g., [1, 2, 30]). Furthermore, given the high costs of real-world experiments involving autos with ADAS and the complexity that involves carrying out them in real traffic conditions, a large proportion of the available empirical evidence has been collected using hypothetical experiments, simulations, questionnaires and surveys ([27] provide a comprehensive overview). In general, the scope of these studies relates to the ADAS technical improvements (e.g., [32, 33, 39]), their inclusion into traffic situations (e.g., [14, 17]) and transportation (e.g., [9, 50]), as well as the associated risks and safety issues (e.g., [6, 13, 35, 40, 43, 48]).

This has motivated us to conduct a real-world driving experiment with the aim to provide new insights about the driving experience using ADAS. More specifically, we attempt to uncover relevant factors surrounding the HMI that might contribute to increase the user acceptance on these new technologies. Therefore, our main hypothesis is straightforward: the HUD improves the HMI, reduces the perceived driving effort and increases the feelings of safety. Regardless it is a general assumption, several questions remain: e.g., how does the HUD influence the driving experience?, is it context and demographics dependent?, how should it be designed to reverse low acceptance? A detailed hypotheses formulation will help us to answer these and further questions.

H1: HUD is associated with psychological factors (e.g., risk-aversion).

H1a: Drivers' risk-aversion mediates the effects of HUD on the perceived driving effort and safety feeling.

H2: The HUD effect is context dependent (e.g., vehicle model).

H3: The effect of HUD differs among demographics (e.g., gender, age, occupation).

H4: Operability, displays, design, monitoring and warnings (HUD components) determine the HMI assessment.

We address these assumptions using a novel approach: we present a field experimental design where we test the use of HUD in real roads, but still under control conditions. Additionally, we collected data from 48 subjects who were asked to drive and evaluate the ADAS from two premium vehicles equipped with HUD and LKAS: a prototype Porsche Panamera Turbo, 2016 and a BMW 520d, 2017. The experimental route consisted of a well-known federal highway in the Allgäu region in Germany. The road has a length of approx. 61 km in which subjects were asked to drive at a speed between 100 and 130 km/h. Moreover our data analysis strategy consists of the well-stablished multi-equations Mixed Process Model (by Roodman [47]) which allows us to observe the effects of HUD accounting for identification, dependency and endogeneity concerns.

Our findings thus add to an emerging real-world experimental research on ADAS. In particular, our results bring new insights into two streams of the existing driving experience literature: on the user acceptance on the one hand (see for example [15, 20]), and on the other, on the role of behavioral constructs such as risk-aversion, and the overall feelings of driving effort and safety (e.g., [11, 41, 58, 61]; and evidence thereafter). Indeed, we find that these behavioral factors are important for the user-driving experience on ADAS. Our findings show that these variables reinforce or diminish the HUD positive effects on driving. For instance, the drivers' risk-aversion can determine whether the effect of the HUD on the driving experience is positive and significant. Moreover, we answer the question about which HMI components could be improved in order to increase the user acceptance. Average responses from our experimental drivers suggest that a simple and intuitive monitoring system, as well as comprehensible and opportune warning displays are decisive to fulfill the driver's expectations. In the conclusion section of this paper, we recommend concrete actions on the HUD design to increase user acceptance.

The rest of the paper is organized as follows. In the next section, we present the methodology, in Section 3, we summarize our main results, and later, we conclude.

2 Experimental Design and Procedure

The study was conducted under a within-subject design in which each subject was asked to drive two different vehicles: a prototype Porsche Panamera Turbo, 2016 (A) and a BMW 520d, 2017 (B), both equipped with HUD and LKAS (see Table and Fig. 1). In order to distinguish the effects of driving with HUD compared with driving without it, each subject drove a route with the HUD activated, and the same route without HUD, first driving vehicle A and immediately after the vehicle B. Therefore, each subject drove the route four times, twice with vehicle A –with and without HUD activated- and twice with vehicle B –with and without HUD activated- The order of the vehicle to drive first, and whether the HUD is activated or not was randomized to account for potential order effects.

Fig. 1 HUD and HDD from vehicles A (left) and B (right). Source: Porsche and BMW websites

Table 1 Vehicles' technical information and ADAS settings

Concept	Vehicle A	Vehicle B
Model	Panamera Turbo 2016	520d Limousine 2017
Power	404 kW (550 PS)	140 kW (190 PS)
ADAS Icons	small LKAS[a] icon + big ACC[b] icon	combined LKAS + ACC icon
HUD[c]		
Manufacturer	Panasonic	Continental AG
Gral. Settings	wide /high / inclined	wide / high / rotation
View	standard/ compact / customized	standard/ compact / customized
Speed Presentation	numeric	numeric + colorful transitions
Speed Limit Warning	actual	actual + coming up limit
Operation	touchscreen menu in settings' section	iDrive menu + manual rotary switch
LKAS		
Manufacturer	Porsche	Continental AG
Intervention Moment	soon / late	soon / late
LKAS Hands-off Warning	static: steering wheel with red hands	dynamic (gradual): steering wheel with yellow hands
Warning Volume	low / medium /high	low / medium /high

Abbreviations: [a] Lane Keeping Assistant [b]Adaptive Cruise Control [c]Head-up Display

2.1 The Two Vehicles

They were selected from three main assumptions: first, due to their first-class nature, they are easily recognized by drivers. This highlights the devices, features and systems under evaluation. Second, they include state-of-the-art ADAS which in addition, are designed with highest standards to satisfy even demanding users. Third, the use of two vehicles allows us to test whether the hypothesis of our study is sensitive to certain models. Significant differences between the cars e.g., autos from different segments may lead to a confound effect on our results. For example, differences in results may be driven by marked differences between vehicles' level of technology, comfort and safety, and not due to the activation of ADAS. We are aware that further research is required to complement this assumption, e.g., more models from different segments should be compared.

For a detailed description of the two vehicles, including technical information and a comparison of their systems, see Table 1.

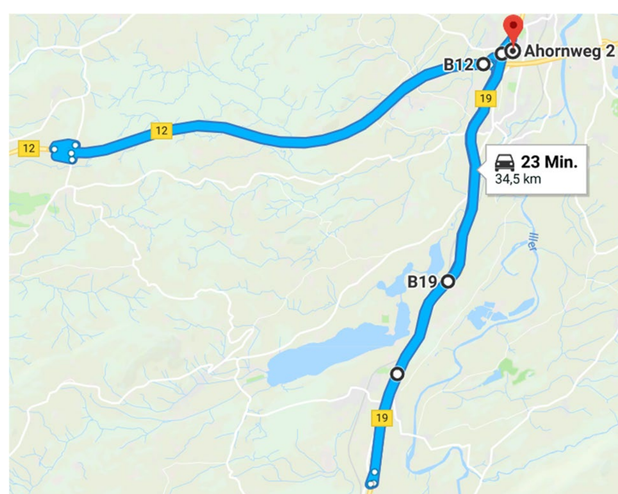

Fig. 2 Route: B12 and B19 in Allgäu, Germany. Map extracted from Google Maps

Fig. 3 LKAS from vehicles A (left) and B (right). Source: Porsche and BMW websites

2.2 The Driving Course

The route consisted of a well-known federal highway in the Allgäu region in Germany (see map in Fig. 2). This has a length of approx. 61 km which was traveled at a speed of 100–130 km/h and taking an average driving time of 45 min in each vehicle. More precisely, subjects drove both the Bundesstraße 12 (B12) and Bundesstraße 19 (B19). These routes were chosen due to their differences in terms of curves pronunciation, scenarios and landscape. In this way, participants experienced a wide variety of maneuvers appropriate for driving evaluation purposes. To avoid the formation of expectations or strategic responses, subjects were not informed about the aim of the study. They were simply informed that the main goal was to test the vehicles and make a general assessment i.e., after each of the four rides, each subject responded a set of questions to evaluate their overall driving experience.

With the aim of creating a complete experience using ADAS, we let the LKAS function activated so that drivers acquire a deeper feeling of driving with assistant systems. Another reason to use LKAS in our setting is that for some drivers, the HUD might be seen as a simple substitute for the HDD, therefore, the evaluation might differ depending on whether the information displayed is related to ADAS or not. Notice that LKAS is one of the most recognized features within assistant systems. Basically, it ensures that the vehicle automatically remains in its lane as it is shown in Fig. 3. Moreover, to avoid a bias in evaluations due to differences between ADAS configuration in vehicle A and B, we asked subjects to drive each car using the default settings, both for LKAS and HUD.

2.3 The Driving Experience Assessment

Although most of HMI evaluation criteria focuses on usability [15], other driving related constructs such as safety issues and driving effort might have an important impact on user acceptance. We thus experimentally investigate the relationship between these concepts: HMI, Driving Effort, and Safety. Previous work has started to address the relevance of these factors. For instance, in a recent cross-cultural study conducted in UK and China, Large et al. [31] evaluate the HMI using a simulator. They find that Chinese drivers were more concerned about the aesthetics of in-vehicle technology designs than about the associated potential distractions. UK subjects, on the other hand, were more concerned about the safety. Similar results are also found in Young et al. [64]. Therefore, the way in which driving safety is associated to user acceptance is considered critical due to its several implications, not only on the automotive industry, but also on the society [15, 20]. Furthermore, behavioral and individual characteristics are also investigated. Risk attitudes towards driving safety have been well documented since several decades ago (e.g., [41, 61]; and evidence thereafter). More recent studies have shown that personality traits such as risk-aversion are strongly associated with speeding behavior among young drivers (e.g., [36, 56]), and with driving decision making under uncertainty (e.g., [35]). As regards to driving effort, back in 1989 [11] Davis et al. proposed a framework to qualify automotive HMI cognitive ergonomic quality. In this model, the driver acceptance is dependent on a perceived ease of use, defined as the degree to which a person believes that the HMI in question will reduce the driving effort. Later in 2003, Venkatesch et al. developed a theory on usage behavior where the intention to use is influenced, among other factors, on the effort expectancy.

Despite in different research fields the use of subjective measures is arguable, these have been recognized as meaningful tools for studies on user acceptance (see for example [15, 55]). The ISO 9241 – 210 (2006) states that a human-centered design follows an iterative process: (a) the analysis represents a starting point where researchers are able to understand the context, thus able to identify the user necessities and requirements, followed by (b) the design itself, where a new concept is conceived, and (c) the assessment of the concept is conducted. Inspired in the previous arguments, we propose an HMI assessment which contains the following constructs: HMI, Safety, Driving Effort, Operability, Information Displays, Design, Monitoring, and Warnings.

2.4 The Questionnaire

The procedure to apply our questionnaire is as follows. After each ride, we provided to the participants a fixed evaluation sheet based on a seven-points Likert-Scale. Below we present the wording of the questions:

> From a scale where 1 = not satisfied and 7 = very satisfied, rate the following evaluation criteria for the LKAs

HMI Interaction "To what extent have you met your expectations regarding the communication, functionality, and aim of ADAS during the steering maneuvers, which possibly leads to driving corrections?"

Safety Feeling "To what extent have you met your expectations regarding a reliable, trustworthy and predictable ADAS that can drive you safely?"

Driving Effort "To what extent ADAS helped to meet your expectations regarding the driving effort?"

Operability "To what extent have you met your expectations regarding a self-explanatory and easy to operate ADAS?"

Information Display "To what extent have you met your expectations regarding a self-explanatory, comprehensive and easy ADAS display?"

Design "To what extent have you met your expectations regarding a comprehensible ADAS design?"

Monitoring "To what extent have you met your expectations regarding simple and intuitive monitoring actions from the system?"

Warnings "To what extent have you met your expectations regarding comprehen-sible, coherent, and opportune warning displays from ADAS?"

2.5 Procedure

A total of 48 subjects participated in the study and invited through e-mail using the mailing list from the University of Applied Sciences Kempten. Both, written and verbal consent for participation were stated to all participants. The objectives, times and steps of the study were informed and discussed allowing a period of time for underlined questions. Those who accepted the invitation participated voluntarily without any type of payment or incentive. Participants were received at the Adrive Living Lab facilities which is part of the Mechanical Engineering Faculty. Before the rides, subjects were instructed in detail about the route, the vehicles to be tested, and common procedures. In addition, they answered a questionnaire about general demographics such as gender, age, occupation, etc. They had the time to get familiar with each vehicle i.e., adjust the seat, mirrors, steering wheel, etc., and to briefly drive them before the actual test. An experimenter accompanied each participant during the tests to provide further instructions, and most importantly, to always ensure safety. All sessions were conducted in German language.

The composition of our experimental sample is as follows: from 48 participants, 11 are female (23 %). Most subjects were students (67 %) while the rest of the sample was composed by academic-administrative staff (and a small proportion by people under retirement). The average age was 38 years old ($Md = 29$).

3 Results

In this section we summarize our main results. Given that the use of two premium vehicles and their associated expenditures make our experiment highly costly, we executed it using a within-subject design. The responses from the drivers are therefore not independent. We coupe this identification issue by proposing a model where we jointly estimate our variables of interest: Driving *Effort*, *Safety Feeling*, and the overall *HMI* assessment. Below, we first start by introducing basic descriptive statistics.

3.1 Descriptive Statistics

To study the distributional characteristics of our variables of interest, we present the following box plots (1–3) in Fig. 4. The scores are based on the 1–7 scale and each variable shows two boxes: when the HUD was not activated (our benchmark) versus when it was (labeled as "HUD"). The graph on the left (1) shows the scores from the evaluations over the perceived *Driving Effort*. Here we see that the median of our benchmark scores is, $Md = 4$ vs. $Md = 5$ when HUD was on. Similar distribution is observed for *Safety Feeling* (2) with $Md = 4$ vs. $Md = 5$. With respect to the HMI Interaction (3), we see that the median score of our benchmark $Md = 5$ with a relatively large box, uneven in size, and skewed towards the lower quartile. The large box indicates that in general, drivers hold quite different opinions. Its uneven size skewed towards less positive scores shows that half of the drivers' rates falls below 5, with a wide variation on their scores. In comparison, when the HUD was on, both the upper quartile and the $Md = 6$ indicating more consensus towards more positive scores. Overall, the box plots show that the use of the HUD outperformed the HDD. Estimations of Maximum Likelihood z-tests indicate that differences between these conditions are statistically significant: Driving

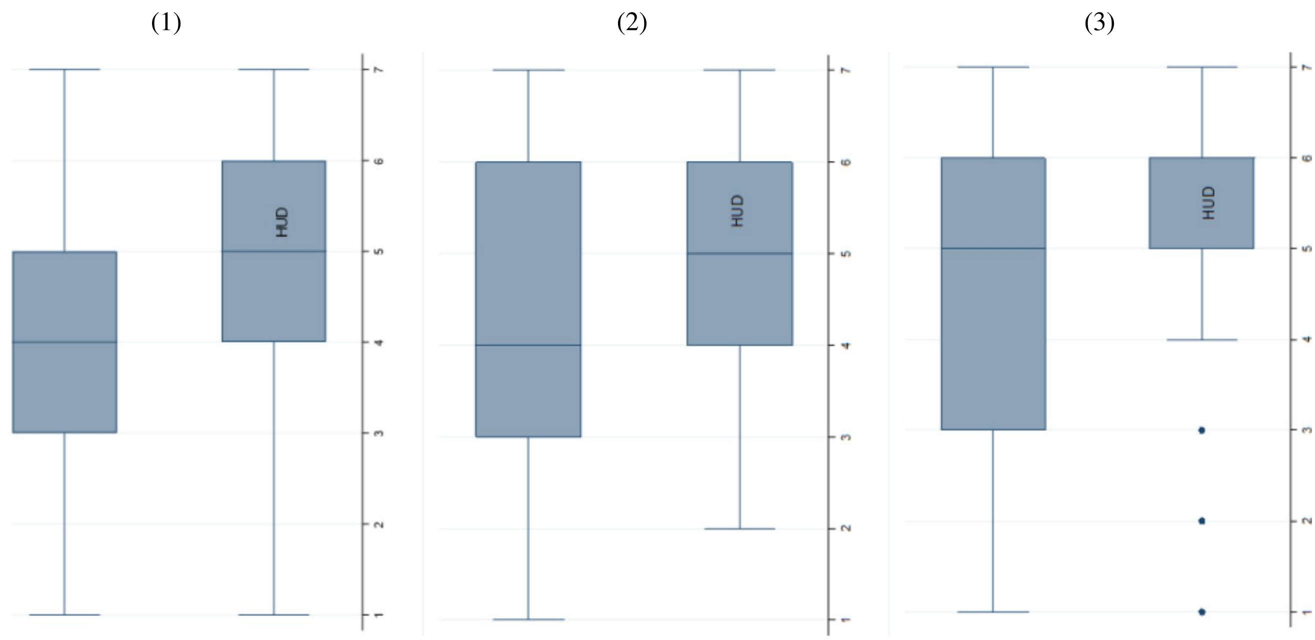

Fig. 4 Distribution of Driving Effort (1) Safety Feeling (2), and HMI Interaction (3)

Effort with $z = 6.08$, $p < 0.01$; Safety Feeling with $z = 5.79$, $p < 0.01$ and HMI Interaction with $z = 5.38$, $p < 0.01$, respectively. As a robust examination, we run the semi-parametric Signed-rank test for dependent observations, and we find similar results. In addition, larger boxes from the HDD suggest that opinions from drivers differ in a greater extend when only the HDD is used, than when it is complemented with the HUD. In the last case, from the shorter boxes, we see that the opinions are more unified.

In the next section, we formally test the effect of the HUD as well as its relationship with relevant driving variables. In addition, we apply statistical models to shed light on how our three parameters of interest are determined.

3.2 Three-equations Mixed Process Model

To tackle the challenges from identification issues, we specify and jointly estimate a system of three-equations. These include the estimation of robust standard errors clustered at the subject level, thus accounting for the dependency and endogenous nature of our variables of interest. The estimations are based on a system of equations using the well-known mixed-process model by Roodman [47]. As robust test, we also run standard OLS and truncated Tobit regression models. We find similar results as those presented in this paper.

Table 2 shows each specification (in rows) and the corresponding coefficients (βs) for each explanatory variable that jointly correlate with each of the three dependent parameters (in columns). From the first row, we see that the positive β for HUD shows that its activation outperformed significantly the use of the HDD alone in: the perceived *Driving Effort* and *Safety Feeling*, and on the overall *HMI Interaction* assessment. This HUD effect holds after controlling for exogenous variables such as gender, age, weather conditions, and the type of vehicle. In fact, we do not find evidence that the cars used in our experiment made a significant difference on the results (with β= -0.191; $p = 0.504$). In addition, we find that the HUD effect is strongest at the *HMI Interaction* with $\beta = 0.802$ i.e., for drivers, the HUD has a stronger effect on their *HMI Interaction* valuation than on their *Driving Effort* and *Safety Feeling*.

3.2.1 HMI Components

Because the HUD, compared with the HDD, has a statistically significant and positive effect, we now ask which of the ADAS components actually make a difference for the drivers. While we do not find a significant effect from the *Operability, Information Displays, and Design*; the β for *Monitoring* indicates that simple and intuitive monitoring actions from the system have a significant impact on the three variables of interest: *Driving Effort, Safety Feeling* and on the *HMI Interaction* assessment. The β is the largest at the second column (*Safety Feeling*) indicating that the concept of monitoring is particularly important to create a feeling of safety among drivers. In line with this, previous research shows that drivers using the HUD spend more time monitoring the road environment (e.g., [3, 28, 38]). To a lesser extent, we find that the *Warning Displays* are important,

Table 2 Conditional mixed-process regressions[a]

Variable	Driving Effort (1)	Safety Feeling (2)	HMI Interaction (3)	Controls	P > X^2
HUD (1)	0.736*** (0.121)	0.758*** (0.131)	0.802*** (0.149)	yes	< .001
monitoring (2)	0.222* (0.114)	0.342*** (0.117)	0.293*** (0.102)	id.	id.
warnings (3)	0.202** (0.083)	0.137 (0.109)	0.157** (0.074)	id.	id.
safety feeling (4)	0.801*** (0.080)	na.	0.627*** (0.080)	id.	id.
gender (5)	-0.936 (0.388)	-0.249 (0.366)	-0.017 (0.481)	id.	id.
age (6)	0.005 (0.017)	-0.001 (0.014)	-0.021** (0.011)	id.	id.
occupation (7)	-0.430 (0.572)	0.376 (0.465)	0.819** (0.354)	id.	id.
HUD*safety feeling (8)	0.106** (0.041)	na.	-0.136** (0.052)	id.	id.
HUD*gender (9)	0.865*** (0.321)	0.571** (0273)	0.116 (0.274)	id.	id.
HUD*age (10)	0.017** (0.007)	0.009 (0.008)	-0.005 (0.005)	id.	id.
HUD*occupation (11)	0.451** (0.205)	0.136 (0.271)	-0.543 (0.332)	id.	id.

[a]CMP models [47] with robust std errors clustered at subject level in ()

HUD =1 when HUD was activated, Gender= 1 for female driver, Occupation= 1 when student, and 0= otherwise

***p < .01, **p < .05, *p < .10; *n* = 182

specifically for the *Driving Effort* and for the overall *HMI Interaction* evaluation (3). Previous studies support these findings. For instance, Kim et al. [23] tested screen-fixed warnings in a HUD and found that they improved the driver's performance. Häuslschmid et al. (2015) compared 2D hazard warnings with HUD screen-fixed warnings and find that the augmented version does not outperform the conventional one, however, they find that, in general, the use of warnings increases the eyes-on-the-road time; while Pomarjaschi et al. [45] found that markup warnings can reduce the eye movements, reaction times, and collisions. We thus ask whether and how the feelings of safety can contribute to explain the perceived driving effort and the HMI Interaction assessment. To this purpose, we now consider *Safety Feeling* as an explanatory variable. From its positive and significant *βs* in columns (1) and (3), we infer that the feelings of safety contribute to reduce the perceived driving effort and to help drivers to meet their expectations in terms of HMI Interaction. Later on, in this section, we deepen the analysis of the HUD effect by estimating models with interaction terms.

3.2.2 Demographics

Next, we introduce basic demographics in order to shed light on the heterogeneity in the drivers' responses. Here, the negative *βs* for *Gender* in the three equations indicate that, in general, women tend to be more demanding than men in terms of *Driving Effort, Safety Feelings*, and on the overall *HMI Interaction*. The *βs*, however, are not statistically significant. In contrast, *Age* is decisive for the *HMI Interaction* assessment with a $\beta = -0.021$ and $p < 0.05$. The negative β indicates that older individuals are more critical than younger drivers about the *HMI Interaction*. In line with this result, we also see that the *Occupation* is determinant for the *HMI Interaction*. The positive $\beta = 0.819$ and $p < 0.05$ show that students are less demanding compared to professionals when evaluating the *HMI Interaction*.

In the last four rows (8–11), we summarize the models including two-way interaction terms. The aim is to deeper the analysis on the HUD effect and on the rest of the explanatory variables.

3.2.3 Heterogeneity and Mediation Within the HUD Effect

By including interaction terms, we can distinguish how the HUD effect varies between basic demographics and how it interacts with the variables associated to the driving experience. First, from model (8) we see that the feelings of safety mediate the HUD positive effect on the *Driving Effort*, and on the *HMI Interaction* i.e., when the HUD is activated, the feeling of safety helps to reduce the perceived *Driving Effort*. In line with our result, Tönnis et al. [52] found that drivers feel safer when the HUD is activated, while Horrey et al. [22] and Yung-Liu and Wen [34] found that drivers feel less load and stress. Interestingly, from $\beta = -0.136$ and $p < 0.05$ we see that the positive effect of HUD on *HMI Interaction* diminishes as the satisfaction in terms of safety feeling increases. In other words, those drivers who felt satisfied in terms of safety feeling were more critical on the *HMI Interaction* valuation. This in turn suggests that our findings are driven by the drivers' risk-aversion i.e., whether the drivers felt safe during the rides. To validate our claim, we run a robust test by converting the *Safety Feeling* into a dichotomous covariate using its $Md = 5$ as cut-off. We then run a t-test for the difference of means between risk-averse and non-risk-averse drivers using a Tobit model with lower and upper bounds of 1 and 7 respectively and robust standard errors clustered at the subject level. This test shows that it was actually the risk-averse drivers who rated better the *HMI Interaction* while the HUD was activated (with $M = 5.67$), compared to those who stated less risk-aversion (with $M = 4.20$ with $t = -5.44$ and $p < 0.01$). In other words, the positive effect of HUD on *HMI Interaction* is stronger among risk-averse drivers. Research on the drivers' risk-aversion and the role of information is not new. de Palma et al. [12] found that the type of information about a route e.g., whether the information about the route is free, costly, or private information is evaluated differently depending on the driver's degree of risk-aversion, and in turn, this evaluation results in a driving decision with higher/lower expected utility. Furthermore, studies on the accuracy of travel information have shown that when the information is less accurate, drivers make a shift to the reliable route, even when it represents the useless alternative [4, 5].

We now turn to the way the HUD effect differs among demographics. Recent related work has shown that socio-economic characteristics including gender, age, and whether drivers are full-time employees should be taken into consideration (e.g., [29, 59]). From (9) we see that female drivers are more sensitive to the HUD than men are regarding *Driving Effort*. More specifically, the $\beta = 0.865$ indicates that when the HUD was on, women felt significantly less *Driving Effort*. The same is true in terms of the perceived feelings of safety. Here, women felt significantly safer than men did when the HUD was activated. However, we do not find evidence indicating that the HUD makes male and female drivers evaluate the HMI differently. These findings span to an extensive empirical literature on gender-differences in driving behavior (e.g., [26, 37, 60] and evidence thereafter). In a meta-analysis, Byrnes et al. [8] find that gender-differences in risky driving behavior seemed to increase with age. In model (10), the interaction HUD**age* shows that older drivers are more responsive to the HUD, and this is statistically significant when assessing their *Driving Effort*. The mediation HUD-*age* does not hold when drivers evaluate their safety feeling or their overall *HMI* experience. Related work indicates that the HUD can alleviate the effort for elderly drivers [24], however, it has been shown that its advantages are fewer among young drivers [62, 63]. We conclude the analysis studying the effect of HUD among different occupational activities. In particular, we look at how professionals, including those involved in full and part time positions differ from students when driving with HUD. The interaction term in (11) supports what we see in (10), more experienced drivers in terms of age and professional activities are more demanding when assessing the HUD, especially when evaluating their *Driving Effort*. Previous research has also distinguished the effect of driving information among experienced and less experienced drivers. For instance, Vaughn et al. [57] show that less experienced types (measured in travelling frequency) comply more with travel information than more experienced drivers. Moreover, it has been shown that as experience increases, drivers are more reluctant to use the available travel information [49]. Finally, the *βs* and *p-values* in the last two columns suggest that the occupation, as well as the age, are not determinants for the evaluation of the safety feeling and *HMI Interaction*.

4 Discussion

The recent booming of ADAS has open an important debate among manufacturers and policymakers about how and what type of information is given to the driver. On the one hand, engineers have on concepts such as the HUD a particular "showcase" to present travel as well as non-travel related information. Yet, on the other hand, the advances on driving assistance systems have developed high expectations and preferences about the information displayed. Certainly, they should be considered because until now, the acceptance and ADAS activation rates are remarkably low. The general assumption, and thus the hypothesis of our study is that ADAS improve the driver experience by reducing the perceived driving effort and by increasing feelings of safety. Yet the question is whether this assumption is true, and if so, why their acceptance is low, and most importantly, how to increase it? We thus present an innovative experimental data collection from 48 drivers with the aim to provide a realistic assessment about the driving experience using ADAS, specifically, about the use of the HUD. To achieve this goal, we carried out a real-world driving experiment conducted under real-traffic conditions and using two premium vehicles. Our analysis and findings are based on a model where the driver acceptance about ADAS is conditional on two main factors: the perceived driving effort and the feelings of safety. Results from mixed-process regressions show that with sufficient variation on the feelings of safety from drivers, the valuation over the HMI Interaction can turn significantly negative. Not surprisingly, our findings relate to empirical evidence indicating that behavioral constructs such as risk-aversion play an important role in driving contexts (e.g., [4, 5, 12, 35]). From our data, we infer that risk-averse drivers are more responsive to the HUD than those who are not, those who, for instance, typically focus on other driving aspects such as time saving or comfort. The inspired feelings of safety thus work as a driving force able to amplify or diminish the positive effect of the HUD when evaluating the driving effort and HMI Interaction. Ultimately, this mechanism can affect positively or negatively the user acceptance. We might then ask which aspects from the HMI Interaction should be improved in order to increase the ADAS user satisfaction. Our results suggest that a simple and intuitive monitoring system, as well as a comprehensible and opportune warning display are decisive to fulfill the driver's expectations. Furthermore, three main forms to reinforce the HUD positive effect on driving can be considered: differentiate the driver preferences in terms of gender, age group, and occupation. More specifically, the HUD effect i.e., when the HUD is activated, becomes stronger among elderly drivers, students, and females who felt significantly less driving effort compared to when they drove with HDD only. In particular, women felt significantly safer while the HUD was activated. In sum, we propose the following concrete actions to improve the HUD design. First, an intelligent system should identify the driver's profile e.g., age group, gender, occupation, risk-aversion, etc., and activate the HUD accordingly. For instance, the system should differentiate two main profiles:

a) Highlight the HUD when the driver is female, belongs to an upper age group, or is risk-averse. For this profile, HUD should emphasize safety aspects e.g., proximity to pedestrian areas, speed limits, faster and louder warnings, and a simpler activation and visualization.
b) Offer a variety of customization options when the driver has a male, young or a risk-seeking profile. Settings might include more vivid colors, icon sizes, vehicle performance info and driving modes (e.g., sport, dynamic, comfort) rather than monitoring, warning or safety issues.

Advanced Methods such as AI, IoT and Blockchain-Tech, combined with Agile, Lean UX, A/B testing and Design-Thinking have proved effectiveness when capturing users' profiles and dynamically translate them into ad-hoc designs.

Finally, given the complexity to achieve internal and external validity when studying driving scenarios (i.e., real-world experimental costs, parameters' endogeneity, drivers' recruitment, legal-traffic issues, etc.), we believe that we have taken an important step towards the analysis of ADAS user acceptance. Yet, further research is needed to confirm, contrast, and question the existing evidence. A step forward is to study the role of objective data. Several researchers have already pointed out the lack of objective measures, as well as reliable and standardized methodologies to elicit them (e.g., [10, 15, 19, 25, 44, 51]). It is somehow clear that, for instance, parameters obtained from the vehicle's computer combined with physiological metrics in relation to driving effort and safety feeling would offer a more complete story of what drivers state in surveys and questionnaires. This certainly gives to researchers and practitioners a comprehensive understanding of driving behavior and users' preferences. Yet, after observing the heterogeneity in responses, we believe that not only correlations with objective data might shed light on unrevealed factors, but also, psychological constructs that up to now have not been considered. Methodologically speaking, several challenges are ahead. For instance, we acknowledge the limitations of testing two vehicles from the same segment. With this procedure, we gained on control of adjacent factors and at the same time, we provide evidence that our results and conclusions are not dependent on the car model, at least not on the vehicles used in our study. This may motivate further research e.g., how can IoT display the driver's preferences in real-time?, how ADAS activation and acceptance varies among different segments, manufacturers, and models? We believe that ADAS are no longer a matter of purely technical issues, but a concept that requires solutions from several other approaches. ADAS are no longer the future, but already the present in our roads.

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References

1. Aydogdu, S., Seidler, C., Schick, B.: Trust is good, control is better? – The influence of head-up display on customer experience of automated lateral vehicle Control. In: HCI in mobility, transport, and automotive systems. Springer Nature Switzerland AG, Berlin (2019)
2. Aydogdu, C., Schick, B., Wolf, M.: Claim and reality? Lane keeping assistant –The conflict between expectation and customer experience. In the 27th Aachen Colloquium Automobile and Engine Technology (2018)
3. Bark Karlin, C., Tran, K., Fujimura, Ng-Thow-Hing, V. (2014). Personal Navi: Benefits of an Augmented Reality Navigational Aid Using a See-Thru 3D Volumetric HUD. In: Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '14). ACM, New York, Article 1, 8 pages. https://doi.org/10.1145/2667317.2667329
4. Ben-Elia, R., Di Pace, G.N., Bifulco, Y., Shiftan: The impact of travel information's accuracy on route-choice. Transp. Res. Part C: Emerg. Technol. **26**, 146–159 (2013)
5. Bogers, E.: Traffic information and learning in day-to-day route choice. T2009/5, June 2009, trail thesis series, Delft University of Technology, Delft (2009)
6. Bock, F., German, R., Sippl, C.: Fully automated vehicles: Challenges, expectations and methods. In 17. Internationales Stuttgarter Symposium (pp. 1373-1387). Wiesbaden, Deutschland: Springer Vieweg (2017)
7. Boström, Alexander and Fredrik Ramström. (2014). Head-up display for enhanced user experience. Department of Applied Information Technology Chalmers University of Technology, Gothenburg. http://publications.lib.chalmers.se/records/fulltext/223949/223949.pdf

8. Byrnes, J., Miller, D.C., Schafer, W.D.: Gender differences in risk taking: a meta-analysis. Psychol. Bull. **125**, 367–383 (1999)
9. Crayton, T.J., Meier, B.M.: Autonomous vehicles: Developing a public health research agenda to frame the future of transportation policy. J. Transp. Health **6**, 245–252 (2017). https://doi.org/10.1016/j.jth.2017.04.004
10. Cavaye, A.L.M.: User participation in system development revisited. Inf. Manag. **28**(5), 311–323 (1995)
11. Davis, F.D., Bagozzi, R.P., Warshaw, P.R.: User acceptance of computer technology: a comparison of two theoretical models. Manage. Sci. **35**, 982–1003 (1989)
12. De Palma, A., Lindsey, R., Picard, N.: Risk aversion, the value of information, and traffic equilibrium. Transport. Sci. **46**(1), 1–26 (2012). https://doi.org/10.1287/trsc.1110.0357
13. Fagnant, D.J., Kockelman, K.: Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transp. Res. A Policy Pract. **77**, 167–181 (2015). https://doi.org/10.1016/j.tra.2015.04.003
14. Fernandes, P., Nunes, U.: Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow. IEEE Trans. Intell. Transp. Syst. **13**(1), 91–106 (2012). https://doi.org/10.1109/TITS.2011.2179936
15. François, M., Osiurak, F., Fort, A., Crave, P., Navarro, J.: Automotive HMI design and participatory user involvement: review and perspectives. Ergonomics **60**(4), 541–552 (2017)
16. Gabbard, J.L., Gregory, M., Fitch, Kim, H.: Behind the glass: driver challenges and opportunities for AR automotive applications. Proc. IEEE **102**(2), 124–136 (2014). https://doi.org/10.1109/JPROC.2013.2294642
17. Gold, C., Körber, M., Lechner, D., Bengler, K.: Taking Over Control From Highly Automated Vehicles in Complex Traffic Situations. Hum. Factors J. Hum. Factors Ergon. Soc. **58**(4), 642–652 (2016). https://doi.org/10.1177/0018720816634226
18. Gish, K.W., Staplin, L.: Human factors aspects of using head up dis- plays in automobiles: A review of the literature. National Highway Traffic Safety Administration (NHTSA) (report no: DOT HS 808 320), Washington, DC (1995)
19. Haines, P.H., Wilson, J.R., Vink, P., Koningsveld, E.: Validating a framework for Participatory Ergonomics (the PEF). Ergonomics **45**(4), 309–327 (2002)
20. Harvey, C., Stanton, N.A., Pickering, C.A., McDonald, M., Zheng, P.: Contextof use as: a factor in determining the usability of in-vehicle devices. Theor. Issues Ergon. Sci. **12**(4), 318–338 (2011)
21. Häuslschmid, R., Schnurr, L., Wagner, J., Butz, A.: Contact-analog Warnings on Windshield Displays promote Monitoring the Road Scene. In Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '15). ACM, New York, NY, USA, pp 64–71 (2015). https://doi.org/10.1145/2799250.2799274
22. Horrey William, J., Christopher D.Wickens, and Alexander, A.L.: The effects of head-up display clutter and in-vehicle display separation on concurrent driving performance. Proc Hum Factors Ergon Soc Annu Meet **47**(16), 1880–1884 (2003). https://doi.org/10.1177/154193120304701610
23. Kim Hyungil, A.M., Anon, T., Misu, N., Li, A., Tawari, Fujimura, K.: Look at me: Augmented reality pedestrian warning system using an in-vehicle volumetric head up display. In Proceedings of the 21st International Conference on Intelligent User Interfaces (IUI '16). ACM, New York, pp 294–298 (2016). https://doi.org/10.1145/2856767.285681546
24. Inuzuka Yasuhiro, Y., Osumi, and Hiroaki Shinkai. (1991). Visibility of Head up Dis- play (HUD) for Automobiles. Proceedings of the Human Factors Society Annual Meeting 35, 20 (1991), 1574–1578. https://doi.org/10.1177/154193129103502033
25. Ives, B., Olsson, M.: User involvement in information systems: A critical review of the empirical literature. New York University, New York (1981)
26. Jackson, T.T., Gray, M.: Field study of risk-taking behavior of automobile drivers. Percept Mot Ski **43**, 471–474 (1976)
27. Johnsen, A., Strand, N., Andersson, J., Patten, C., Kraetsch, C., Takman, J.: Literature review on the acceptance and road safety, ethical, legal, social and economic implications of automated vehicles. Deliverable 2.1 from the EU-H2020-project BRAVE – BRidging the gaps for the adoption of Automated VEhicles. Materialien aus dem Institut für empirische Soziologie an der Friedrich-Alexander-Universität Erlangen-Nürnberg, 2/2018, Nürnberg: IfeS (2018)
28. Kiefer, R.J.: Effect of a head-up versus head-down digital speedometer on visual sampling behavior and speed control performance during daytime automobile driving (Report No. 910111). Technical Report. SAE International, Warrendale (1991)
29. Knorr, F., Chmura, T., Schreckenberg, M.: Route choice in the presence of a toll road: the role of pre-trip information and learning. Transp. Res. Part F: Traffic Psychol. Behav. **27A**, 44–55 (2014)
30. Kuo, Y.-J., Seidler, C., Schick, B., Nissing, D.: Workload evaluation of effects of a lane keeping assistance system with physiological and performance measures. In Proceedings of the Human Factors and Ergonomics Society Europe Chap. 2019 Annual Conference (2019)
31. Large, D.R., Burnett, G., Crundall, E., Skrypchuk, L., Mouzakitis, A.: Evaluating secondary input devices to support an automotive touchscreen HMI: a cross-cultural simulator study conducted in the UK and China. Appl. Ergon. **78**, 184–196 (2019)
32. Lee, J., Abdel-Aty, M., Choi, K., Huang, H.: Multi-level hot zone identification for pedestrian safety. Accid. Anal. Prev. **76**, 64–73 (2015). https://doi.org/10.1016/j.aap.2015.01.006
33. Li, G., Li, S.E., Cheng, B., Green, P.: Estimation of driving style in naturalistic highway traffic using maneuver transition probabilities. Transp. Res. C Emerg. Technol. **74**, 113–125 (2017). https://doi.org/10.1016/j.trc.2016.11.011
34. Liu, Y.-C., Wen, M.-H.: Comparison of Head-up Display (HUD) vs Head-down Display (HDD): Driving performance of commercial vehicle operators in Taiwan. Int. J. Hum. Comput. Stud. **61**(5), 679–697. (2004). https://doi.org/10.1016/j.ijhcs.2004.06.002
35. Luzuriaga, M., Heras, A., Kunze, O.: Hurting others vs. hurting myself, a dilemma for our autonomous vehicle. Rev. Behav. Econ. **7**, 1–30 (2020). https://doi.org/10.1561/105.00000115
36. Machin, M.A., Sankey, K.S.: Relationships between young drivers' personality characteristics, risk perceptions, and driving behaviour. Accid. Anal. Prev. **40**(2), 541–547 (2008). https://doi.org/10.1016/j.aap.2007.08.010
37. McKelvie, S.J., Schamer, L.A.: Effects of night, passengers, and sex on driver be- havior at stop signs. J. Soc. Psychol. **128**, 585–590 (1988)
38. Medenica, Z., Kun, A.L., Paek, T., Palinko, O.: Augmented Reality vs. Street Views: A driving simulator study comparing two emerging navigation aids. In Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11). ACM, New York, pp 265–274 (2011). https://doi.org/10.1145/2037373.2037414
39. Naranjo, J.E., Gonzalez, C., Garcia, R., de Pedro, T.: Lane-Change Fuzzy Control in Autonomous Vehicles for the Overtaking Maneuver. IEEE Trans. Intell. Trans. Syst. **9**(3), 438–450 (2008). https://doi.org/10.1109/TITS.2008.922880
40. Observatorio Cetelem Auto (2016). El coche autónomo. Los conductores, dispuestos a ceder la conducción a la tecnología. Retrieved November 14, 2017 from http://www.elobservatoriocetelem.es/wp-content/uploads/2016/03/observatorio_cetelem_auto_2016.pdf

41. Oppenlander, J.C.: Variables influencing spot speed characteristics. Highway Research Board, Special Report 89, National Academy of Sciences, Washington DC, United States (1966)
42. Park, Y.K., Park, D.E.: Evaluation for the usage of HUD contents depending on gender while driving. In SIGGRAPH Asia 2015 head-up displays and their applications. New York, NY, USA (2015). https://doi.org/10.1145/2818406.2835236
43. Piao, J., McDonald, M., Hounsell, N., Graindorge, M., Graindorge, T., Malhene, N.: Public Views towards Implementation of Automated Vehicles in Urban Areas. Transp. Res. Procedia **14**, 2168–2177 (2016). https://doi.org/10.1016/j.trpro.2016.05.232
44. Pilemalm, S., Timpka, T.: Third generation participatory design in HealthInformatics-making user participation applicable to large-scale information system projects. J. Biomed. Inf **41**(2), 327–339 (2008)
45. Pomarjanschi, L., Dorr, M., Barth, E.: Gaze Guidance reduces the number of collisions with pedestrians in a driving simulator. ACM Trans. Interact. Intell. Syst. **1**(2012). https://doi.org/10.1145/2070719.2070721
46. Porter, J.M., Summerskill, S.J., Burnett, G.E., Prynne, K.: BIONIC–"eyesfree" design of secondary driving controls. In: Proc. of the Accessible Design in the Digital World Conference, Dundee, UK (2005)
47. Roodman, D.M.: Fitting fully observed recursive mixed-process models with cmp. Stata J. **11**, 159–206 (2011)
48. Schoettle, B., Sivak, M.: A Survey of public opinion about autonomous and self-driving vehicles in the U.S., the U.K., and Australia (Report No. UMTRI-2014-21) (2014). Retrieved July 25, 2017 from https://deepblue.lib.umich.edu/bitstream/handle/2027.42/108384/103024.pdf?sequence=1&isAllowed=y
49. Shiftan, Y., Bekhor, S., Albert, G.: Route choice behaviour with pre-trip travel time in- formation IET Intel. Transport Syst. **5**(3), 183–189 (2010)
50. Smith, B.: Managing autonomous transportation demand. Santa Clara Law Rev. **52**, 1413 (2013)
51. Spinuzzi, C.: The methodology of participatory design. Tech. Commun. **52**(2), 163–174 (2005)
52. Tönnis, M., Lange, C., Klinker, G.: Visual longitudinal and lateral driving assistance in the head-up display of cars. In Proceedings of the 2007 6thIEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR '07). IEEE Computer Society, Washington, DC, USA, 1–4 (2007). https://doi.org/10.1109/ISMAR.2007.4538831
53. Tractinsky, N., Abdu, R., Forlizzi, J., Seder, T.: Towards personalisation of the driver environment: investigating responses to instrument cluster design. Int. J. Veh. Des. **55**(2–4), 208–236 (2011)
54. Tretten, P. (2011). Information design solutions for automotive displays : focus on HUD (PhD dissertation). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-26558
55. Van Der Laan, J.D., Heino, A., De Waard, D.: A simple procedure for the assessment of acceptance of advanced transport telematics. Transp. Res. Part C Emerg. Technol. **5**(1), 1–10 (1997)
56. Vassallo, S., Smart, D., Sanson, A., Harrison, W., Harris, A., Cockfield, S., McIntyre, A.: Risky driving among young Australian drivers: Trends, precursors and correlates. Accid. Anal. Preve. **39**, 444–458 (2007)
57. Vaughn, K., Abdel-Aty, M., Kitamura, R., Jovanis, P., Yang, H.: Experimental analysis and modeling of sequential route choice under atis in a simple traffic network. In: Proceedings of the 72nd Annual Meeting of the Transportation Research Board. Washington DC, USA (1993)
58. Venkatesh, V., Morris, M.G., Davis, G.B., Davis, F.D.: User acceptance of information technology: toward a unified view. MIS Q. **27**(3), 425–478 (2003)
59. Wang, J., A. Chang, L. Gao. (2017). Binary probit model on drivers route choice behaviors based on multiple factors analysis. In: V. Balas, L.C. Jain, X. Zhao (Eds.), Information technology and intelligent transportation systems, Advances in Intelligent Systems and Computing, vol. 454, pp. 213–220
60. Warren, R.A., Simpson, H.M.: Exposure and alcohol as risk factors in the fatal nighttime collisions of men and women drivers. J. Saf. Res. **12**, 151–156 (1980)
61. Wasielewski, P.: Speed as a measure of driver risk: Observed speeds versus driver and vehicle characteristics. Accid. Anal. Prev. **16**(2), 89–103 (1984). https://doi.org/10.1016/0001-4575(84)90034-4
62. Weintraub, D.J., Haines, R.F., Randle, R.J.: The utility of head-up displays: eye-focus vs decision times. Proc Hum Factors Ergon Soc Annu Meet 28(6), 529–533 (1984). https://doi.org/10.1177/154193128402800617
63. Weintraub, D.J., Haines, R.F., Randle, R.J.: Head-Up Display(HUD) Utility, II: Runway to HUD transitions monitoring eye focus and decision times. Proc Hum Factors Ergon Soc Annu Meet 29(6), 615–619 (1985). https://doi.org/10.1177/154193128502900621
64. Young, K.L., Rudin-Brown, C.M., Lenné, M.G., Williamson, A.R.: The implications of cross-regional differences for the design of In-vehicle Information Systems: a comparison of Australian and Chinese drivers. Appl. Ergon. **43**(3), 564–573 (2012)

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