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RESEARCH ARTICLE

Assisted Partial Take-Over in Conditionally Automated Driving: A User Study

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ABSTRACT This paper discusses the concept of take-over (TO) in conditionally automated vehicles. Most of the current studies consider TO as a discrete event that is completed when the driver takes full control of the vehicle. Two problems with this approach are that the driver 1) needs time to gain sufficient situational awareness and 2) sometimes takes over only the lateral or only the longitudinal coordination of the vehicle, neglecting the other. To overcome these two problems and increase the quality (effectiveness, efficiency, and satisfaction) of TO, we propose two new approaches to the take-over process: partial take-overs (PTO) and assisted take-overs (ATO). The proposed PTO approach allows the driver to take over only the lateral or longitudinal coordination of the vehicle separately, instead of assuming a full TO. With ATO, the driver is monitored even after taking control of the vehicle and is assisted with automatic soft braking as well as additional warning and emergency braking if the time to collision falls below the appropriate critical levels. The approaches were evaluated in a user study with 44 participants in a driving simulator. We were able to confirm that the proposed ATO approach significantly improves the TO quality in terms of both effectiveness and efficiency without compromising driver satisfaction. Contrary to our expectations, the PTO approach did not have a significant effect on the effectiveness of TO, but only provided significantly lower reaction time to first braking and longer time to lane crossing. When combined, ATO and PTO were at least as useful as either approach individually and should be considered in future TOR user interfaces.

INDEX TERMS Automated vehicles, conditional driving automation, take-over, driving simulator, user study.

I. INTRODUCTION

Conditionally automated vehicles, as defined by the Society of Automotive Engineers – SAE (Level 3) [1], represent an important step toward fully automated driving. They are equipped with advanced driver assistance systems (ADAS) that perform specific driving tasks such as steering, braking, and acceleration. Although the human driver does not need to constantly monitor the vehicle, he or she must still be prepared to take back full or a partial control of the vehicle when needed. The process of regaining control of the vehicle is called *take-over* (TO) and is initiated with a take-over request (TOR) when the vehicle's automation system is no longer capable of safely handling a particular situation. This can happen for a variety of reasons, such as when the vehicle encounters unexpected obstacles or road conditions, when sensor systems fail, or when the vehicle approaches the limits of its automation capabilities [2], [3]. In the unfortunate event of an accident, it would likely still be the human driver who would be held responsible for the accident [4].

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When the take-over request is issued, the vehicle typically provides the driver with a multimodal visual and/or auditory and/or tactile warning, such as a flashing light or a beep, to alert the driver of the need to take over. The driver must then take immediate action to regain control of the vehicle by using either the steering wheel, pedals, or other controls, depending on the vehicle [5]. Due to its critical importance to driver safety and well-being, the TO user interface (UI) represents one of the most important research tasks to be solved before the introduction of conditionally automated vehicles.

The design of the most useful (effective, efficient, satisfying [6]) UI for take-over requests is still under research [5], [7]. Most of the current studies consider TO as a discrete event that is completed when the driver takes full control of the vehicle. However, the driver needs time to gain sufficient situational awareness and may sometimes take over only the lateral or longitudinal coordination of the vehicle, neglecting the other. To overcome these two problems and improve the quality of TO, we propose two new approaches to the take-over process.

In the first approach, the driver is monitored even after taking control of the vehicle and assisted if his or her actions are deemed unsuitable to successfully take control of the vehicle. We call this an assisted take-over (ATO) approach. Second, we allow the driver to take over only the lateral or longitudinal coordination of the vehicle while the other part remains under automatic control. We call this a partial take-over (PTO) approach.

The rest of the paper is organised as follows: The next section presents related work, initial research gaps and our hypotheses. Section III presents the methodology of the user study conducted. Section IV presents the results of the proposed TO approaches for each measured TO quality aspect. Discussion and limitations are presented in Section V. Section VI briefly highlights the important conclusions and further work.

II. RELATED WORK

A. TAKE-OVER REQUESTS

Over the past 10 years, research on take-over requests has developed rapidly. Initially, scientists investigated how early in advance a TOR should be issued (i.e., the TOR lead time) and what modalities are appropriate for issuing a TOR [7]. Eriksson and Stanton found in their literature review that drivers' reaction times were not significantly affected by different TOR lead times [8]. In contrast to their results, Gold et al. observed faster responses with shorter lead times, but of poorer quality [9]. Similarly, Sanghavi et al. observed faster but poorer responses at a lead time of 3 seconds and concluded that a lead time of 7 seconds provided the best results in terms of workload and manoeuvre quality [10]. In a more recent study, Shi et al. concluded that take-over (TO) performance was optimal at a lead time of 6 seconds without a specified secondary task [11]. Overall, the most commonly used lead times in the reviewed literature are 3, 4, 5, 6, 7, and 9 seconds, with a mean lead time of 6.37 ± 5.36 seconds [8]. Therefore, we used a lead time of 6 seconds in our study.

B. MODALITIES AND STIMULI TYPES

Among the earlier studies on TOR modality, Petermeijer et al. observed shorter reaction times for auditory or tactile modality compared to visual modality [12]. Researchers agree that the driver's tactile input channel is the least overloaded during driving, and thus many studies focus precisely on tactile UIs [13], [14], [15]. Vibrations or different tactile patterns alone generally did not improve reaction time itself, but reduced driver effort and increased situational awareness [16], [17]. A similar effect was observed by Borojeni et al. when using ambient light UI (LED strips with changing light patterns) [18]. Ultimately, most came to the same conclusion that the use of a multimodal UI proves best for issuing a TOR [19], [20], [21].

Later research focused on identifying the best types of stimuli for issuing a TOR, such as sound beeps [22], conversational agents [23], text-based information on the dashboard [24], head-up display icons [25], a steering wheel that changes shape [26], a rotating seat [27], etc. For visual UIs, Hong and Yang introduced a pillar of LEDs to convey additional information to TOR [28]. However, they found that although drivers responded faster, this resulted in unstable steering manoeuvres. Politis et al. recommend the use of abstract visual warnings in non-critical situations and a combination with auditory information in critical situations [22]. Wang et al. observed lower speed and standard deviation of lane position for conversational voice agents [23]. For tactile interfaces, Huang and Pitts concluded that meaningful stimuli generally lead to poorer take-over quality [17]. However, Shi et al. showed that directional tactile interfaces resulted in shorter reaction times when the TOR lead time was higher [29]. Furthermore, Figalova et al. suggested that ambient light describing current automation status and reliability increased take-over performance without increasing mental workload [30]. The results of Wu et al. suggest that steering cues should be given to the driver to reduce steering reaction time and improve take-over safety [31]. Considering that the results of the studies that investigated the most appropriate type of TOR stimuli often contradict each other, we can conclude that a general agreement on the universally best TOR stimuli has not yet been reached.

Naujoks et al. proposed a detailed list of guidelines and verification methods for interaction in automated vehicles (e.g., what elements to use in UI, what information to convey, what modalities are appropriate for certain urgencies, etc.) that could be applied to TOR UIs [32]. A recent study by Gruden et al. [33] compared two modalities (auditory-ambient vs. tactile-ambient) of a TOR UI with and without directional information. Based on their results, they created some guidelines for TOR UI designers:

- auditory modality should be used to achieve faster attention,

- when combined, tactile stimuli should provide a non-directional warning, while auditory stimuli could provide directional information,
- non-directional stimuli (less information) result in faster take-over time,
- UI–specific training procedures should be completed before use.

C. NON-DRIVING RELATED TASKS AND SITUATIONAL AWARENESS

Research by Wandtner et al. [34] and Müller et al. [35] has shown that the modality of a non-driving related task (NDRT) performed by the driver before a TOR also has a significant impact on the TO quality. For example, Shi and Bengler have shown in a field experiment that watching a movie or reading leads to longer reaction times than playing games [36]. To address this problem, Yang et al. divided non-driving activities during automated driving into active and passive types, where each type could be given a customized version of TOR [37]. Pakdamanian et al. developed context-aware advisory warnings depending on the type of non-driving task [38]. Li et al. also proposed an algorithm to adapt the TOR lead time to the driver's fatigue state [39].

Each type of TOR UI attempts to maximize the driver's situational awareness so that the driver can easily refocus on the driving task. Kim et al. reported that the complexity of the road plays an additional role in the recovery of situational awareness and should be taken into account [40]. Capallera et al. constructed a multimodal system to increase situational awareness by conveying information about the driving environment [41]. Their system was able to increase drivers' situational awareness but did not show positive effects on TO quality. Scharfe-Scherf et al. even attempted to assess drivers' situational awareness to classify their readiness to take over the vehicle [42]. However, Pipkorn et al. concluded that drivers cannot be assumed to be ready to respond to events shortly after TOR [43].

D. GUIDING DRIVERS THROUGH A TAKE-OVER

A common feature of all the research studies on TOR UIs presented in the previous subsections is that they consider the driver only up to the moment of a take-over request, then issue the TOR and wait for the driver to intervene without further assistance. None of the UIs presented above actively adapted to the driver's actions after the TOR was issued. While the driver is taking over the driving task, he or she may look at the road to regain situational awareness, but would still benefit from assistance systems (ADAS) due to lack of time, fatigue, poor weather conditions, etc. [44].

Morales-Alvarez et al. confirmed that it pays off to guide the driver throughout the whole take-over process [45]. They used haptic guidance by continuously applying torque to the steering wheel in the suggested direction, relative to the current position. Mukhopadhyay et al. assisted drivers with lane detection in extended reality (XR) in the first few seconds after a TOR [44]. However, their display did not monitor or adapt to drivers' responses. Shull et al. [46] and Ma et al. [43] suggested that a multi-stage warning system could improve take-over performance, while Butmee et al. concluded that an automated stopping manoeuvre seems to be a better alternative to manual take-over of the vehicle [47]. Similarly, Pipkorn et al. [43] and Butmee et al. [47] suggested that in some overwhelming situations, manual take-overs should be avoided altogether and the vehicle should simply be stopped automatically. Gruden et al. [33], [48] noted in their study that some drivers do not reduce their cruising speed after TOR and could benefit from automatic soft braking simultaneously with TOR.

E. PARTIAL TAKE-OVERS

Gruden et al. [33] also observed that some drivers had adopted only lateral (i.e., by steering) or longitudinal (i.e., by braking) coordination of the vehicle, rather than both, resulting in poorer take-over performance. The authors suggested that in these cases it might be better to simply reduce the level of automation and leave either automatic cruise control (ACC) or lane-keeping assist (LKA) activated, rather than adopting a full TO. Such a partial TO could allow the driver to take control only in the lateral or longitudinal direction, depending on what he or she feels capable of doing, while the other direction remains under automatic control of the vehicle.

F. AIM OF THE STUDY

The aim of this study is to show that assisting drivers after TOR with a multilevel progressive approach and the possibility of partial take-over improve the quality of TOs. To achieve our objectives, we propose two novel holistic take-over approaches in which the driver can continue to be *assisted* even after taking *partial* or *full* control of the vehicle.

The *partial take-over (PTO) approach* is based on the findings of Gruden et al. [33] presented in the previous subsection. In PTO, the automation level is only lowered when the driver starts to perform TO actions instead of switching completely to manual driving. It provides a new valuable option to the driver – when a TO is performed by steering only, longitudinal coordination remains under automatic control. To our knowledge, this is the first study of partial take-overs.

The *assisted take-over (ATO) approach*is designed as a three-step progressive process that includes:

1. *automatic soft braking*simultaneously with the TOR,
2. *an additional warning* if the driver would not respond appropriately to TOR,
3. *emergency braking to full stop*as a last resort.

The three-step process was developed using observations and recommendations from previous research:

1. Automatic soft braking was included based on the recommendations of Gruden et al. [48], who reported that some drivers did not reduce their cruise speed after TOR.

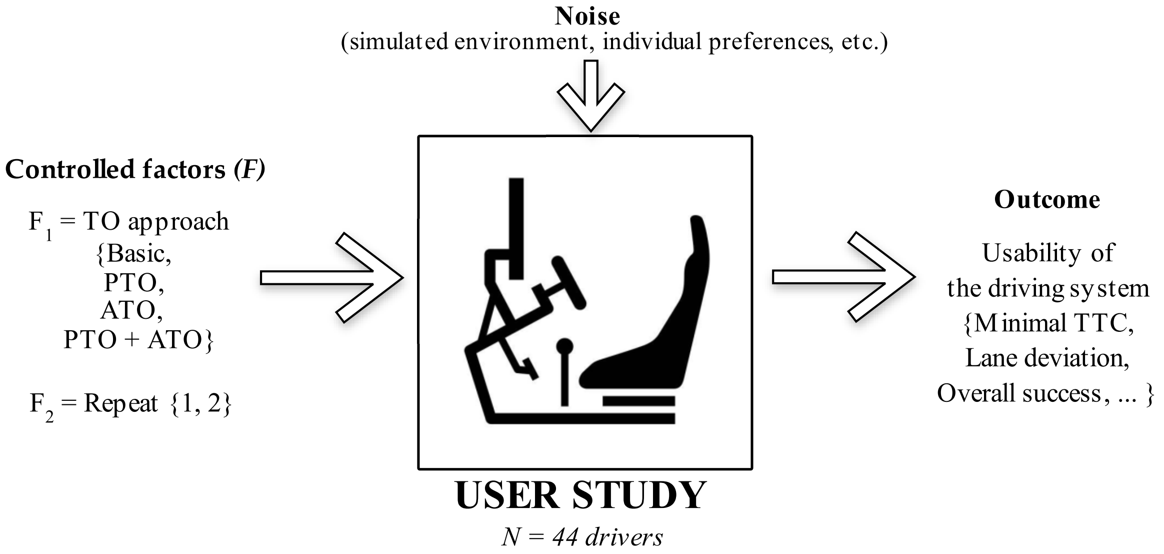

FIGURE 1. **Graphical representation of the user study.**

2. Since Shull et al. [46] and Ma et al. [49] recommended a multi-stage TOR system, we use additional warnings to alert drivers of impending danger if they do not respond appropriately while there is still some time left. The warning appears when the time to collision (TTC) falls below a critical value (e.g., 3 seconds [50]),
3. Emergency braking was introduced as a last resort according to the recommendations of Pipkorn et al. [43] and Butmee et al. [47]

Our research hypotheses are the following:

1. The PTO approach provides better TO quality than classic multimodal TOR UIs.
2. The ATO approach provides better TO quality than classic multimodal TOR UIs.
3. The combination of PTO and ATO approaches provides better TO quality than either approach on its own.

III. METHODOLOGY

To evaluate the proposed partial take-over (PTO) and assisted take-over (ATO) approaches, we conducted a user study with within-subject design (repeated measures) in a driving simulator. Each participant experienced eight situations requiring a take-over, two situations with each of the four experimental conditions, which included all possible combinations of the proposed TO approaches. The four experimental conditions include:

1. **Basic** (full) take-over – without PTO or ATO,
2. **Partial**take-over (PTO),
3. **Assisted**take-over (ATO),
4. **Combination**of partial and assisted take-over (PTO + ATO).

To mitigate the potential learning effect due to the within-subject design, the order of experimental conditions was randomized using the Williams' design (generalized Latin square, which is also counterbalanced for first-order carry-over effects) [51]. The outcome of the user study was the usability of the driving system, measured as a combination of several TO quality aspects (e.g., minimal time-to-collision (TTC), lane deviation, overall success). They are presented in detail in subsection III-D. Fig. 1. graphically represents the conducted user study.

A. TECHNICAL SETUP

The TO approaches were evaluated in a Nervtech^{TM} high fidelity driving simulator [52] at the University of Ljubljana, Faculty of Electrical Engineering. It consists of three curved Full HD screens covering a viewing angle of about 160 degrees, a 4-DOF (degrees of freedom) motion platform, a driver's seat, a cockpit, a steering wheel with handles, a gear stick, and a set of pedals (Fig. 2). The SCANeR Studio software tool from AVSimulation [53] was used to develop and execute the driving scenarios.

The scenarios involved a 30-km long, narrow, three-lane highway with low traffic density and eight randomly positioned roadblocks due to construction or stalled vehicles. The environmental conditions were extreme – heavy snowfall at dusk – resulting in poor visibility. The vehicle was conditionally automated (SAE level 3 [1]). By default, it drove in fully automated mode at 110 km/h in the middle lane and requested TO six seconds before a critical situation, i.e., 183 m before the roadblock, assuming constant vehicle speed.

Each TO approach was assessed twice by each driver. Once, the critical situation was presented with a partial roadblock occupying the middle and right lanes and the driver had to avoid the roadblock by steering to the left (Fig. 3a), while the other time the roadblock occupied the middle and left lanes and the driver had to avoid it by steering to the right (Fig. 3b). The driver took control of the lateral coordination of the vehicle by turning the steering wheel more than 2 degrees.

FIGURE 2. The Nervtech^{TM} driving simulator at the University of Ljubljana.

(a)

(b)

FIGURE 3. Examples of critical situations where the driver had to take over the vehicle. In (a) , the driver had to avoid the roadblock by steering to the left; in (b), the driver had to avoid the roadblock by steering to the right.

The longitudinal coordination of the vehicle was taken over when the driver applied the brake by more than 10% [54]. After the critical situation was resolved and driving conditions returned to normal, a synthetic female voice prompted the driver to re-engage fully automated driving by pressing the button on the steering wheel.

As suggested by the National Highway Traffic Safety Administration (NHTSA) [55] and Kyriakidis et al. [56], the vehicle should always inform the driver about the status of its automation systems. The guidelines of Naujoks et al. [32] define the following five possible states of the system: 1) available, 2) activated, 3) unavailable/disabled, 4) failing, 5) requesting take-over (TOR). Considering the reviewed literature [12], [32], [57], [58] and the symbols commonly used by vehicle manufacturers, we created icons for each of the five system states (Fig. 4). The icon representing the current state of the automation system was constantly visible on the dashboard display.

In all four experimental conditions (basic, PTO, ATO, and PTO + ATO), a take-over request (TOR) was issued via a multimodal TOR UI designed to follow the recommendations in [59] and [60]:

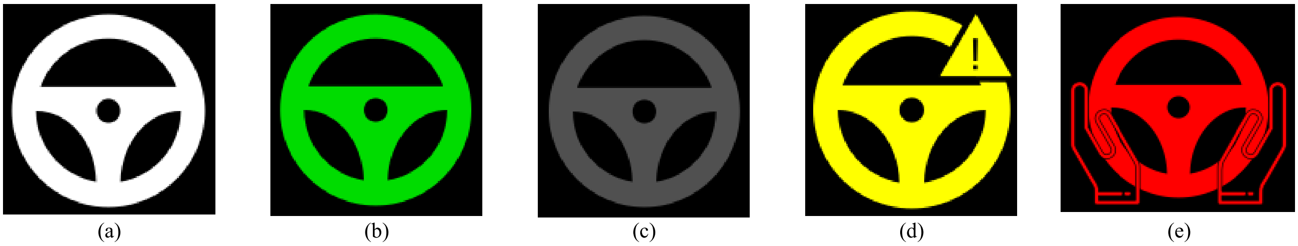

FIGURE 4. Dashboard icons, representing the state of the automation system: (a) available, (b) activated, (c) unavailable, (d) failing, (e) requesting take-over.

FIGURE 5. Symbols used for visual TOR UI. The symbol in figure (a) represents an obstacle on the right side of the road, and the symbol in figure (b) represents an obstacle on the left side of the road.

1. *Auditory stimuli*: directional [21], Boeing 747 cabin altitude warning tone from the left or right speaker, depending on the position of the obstacle;
2. *Tactile stimuli*: non-directional alert [16], DC vibration motors in the driver's seat (6 evenly distributed motors, 12 V / 70 mA, 12000 rpm);
3. *Visual stimuli*: categorical information [61], the familiar symbol of a traffic sign on the dashboard representing the cause of TOR. The symbols used in the study are shown in Fig. 5.

The **PTO** approach consisted of a multimodal TOR and an additional option of partial take-over, which only lowers the level of automation. When a TO was performed by the steering, the longitudinal control of the vehicle remained automatic, i.e., SAE L3 conditionally automated driving was disabled, and automatic cruise control (ACC) was activated. If the driver did not perform TO, the vehicle would eventually come to a stop before hitting the obstacle, as longitudinal control would remain automatic. This differs from the basic approach (full take-over), in which the automation algorithms would not interact with the vehicle after TOR was issued.

The **ATO** approach consisted of a multimodal TOR and additional assisting manoeuvres. They adapted to the driver's responses (or lack of responses) from the moment TOR was issued until the driver re-engaged the L3 automatic driving mode. The adaptation was performed in three phases:

1. Automatic soft braking simultaneously with TOR.
2. When the time-to-collision (TTC) fell below a critical value, a non-directional auditory and tactile warning tone was played, along with sudden short brake applications that resulted in a strong jerk. The critical value of 3 seconds was suggested by Minderhoud and Bowy [50]).
3. Additionally, if the TTC fell below 1.5 seconds, emergency braking was initiated. The timing was originally proposed by Hang et al. [62] and experimentally fine-tuned to stop the vehicle under the given experimental conditions – heavy rain.

The **PTO + ATO** approach consisted of a multimodal TOR, the possibility of partial take-overs and additional assisting manoeuvres.

B. PARTICIPANTS AND THEIR TASKS

We recruited $N = 44$ younger and middle-aged volunteers with a valid driver's license to participate in the study. Thirteen of them (30%) were female, and the mean age of the participants was 28.7 ± 10.3 years.

The study was conducted at the University of Ljubljana, Faculty of Electrical Engineering, in accordance with the Code of Ethics of the University of Ljubljana, which is consistent with the Declaration of Helsinki. Invitations were sent to the faculty's mailing list. Participants did not receive any reward for their participation. Each participant signed an informed consent form before participation.

The main task of the participants was to ensure safe driving continuity. The vehicle was conditionally automated (SAE level 3), meaning that drivers could perform a secondary task during fully automated driving. In our study, we instructed them to play the game Tetris [63] on a smartphone. In this way, we aimed to divert their attention from driving (equally for all participants) and create a realistic situation. Drivers were instructed to take control of the vehicle as soon as a take-over request was issued, to ensure continuity of safe driving, and to switch back to fully automated driving mode as soon as it was available.

The Georgia Tech Simulator Sickness Screening Protocol (GTSSSP) [64] was used as a screening tool to identify drivers susceptible to simulation sickness. In this protocol, potential drivers were asked to complete the same questionnaire before and after the short test drive in a simulator, in which they were asked to rate the 17 perceived symptoms of discomfort (from 0 to 10). The pre- and post-questionnaire scores were then compared (subtracted). If any of the 17 calculated differences were greater than 5 or if three individual differences were simultaneously greater than 3 the participant was not allowed to continue as a precaution.

C. PROCEDURE

1) PREPARING THE DRIVER

First, the study conductor explained the purpose and objectives of the study to the driver. The driver then:

- Signed an informed consent form,
- Completed a brief demographic questionnaire, and
- Completed the GTSSSP pre-drive questionnaire.

Then the conductor gave some technical instructions (handling the driving simulator, pedals, and handles, adjusting the driver's seat, taking over the vehicle, etc.) and firmly attached the wearable sensor devices. The preparation process took about 10 minutes.

2) TEST DRIVE

After the preparation, the driver was asked to drive in the simulator and test its functionalities, especially:

- Fully automated driving mode,
- Take-over with or without take-over request,
- Manual driving mode,
- Multimodal take-over request, and
- Secondary task.

Drivers were not given any specific information about the ATO and PTO functionalities or when they would be activated. After approximately 8 minutes of test driving, drivers completed the post-drive GTSSSP questionnaire, and the conductor determined whether it was safe for the driver to continue the experiment or to terminate the procedure as a precaution. In the present study, no driver exceeded the GTSSSP threshold, so all were asked to continue with the experiment.

3) THE DRIVE

The main driving phase was divided into four randomly arranged parts, one for each evaluated TO approach (basic, PTO, GTO, PTO + GTO). The drive began in fully automated mode and the driver was asked to play the game on a smartphone. During each part of the driving phase, the vehicle issued two take-over requests. After the second TO was successfully completed and driving conditions returned to normal, the conductor paused the simulation and asked the driver to complete the User Experience Questionnaire (UEQ) [65] on a tablet PC while still seated in the simulator. After completing the questionnaire, the conductor resumed the simulation and repeated the same procedure for other TO approaches.

At the end, the driver was asked about his or her experience and the conductor noted the comments and suggested improvements to the simulation environment, the proposed TO approaches, and the study procedure.

D. MEASURES OF SYSTEM USABILITY (DEPENDENT VARIABLES)

To obtain an overall assessment of the system's usability, as defined by Frøkjær et al. [6], we need to determine its effectiveness, efficiency and satisfaction. *Effectiveness* primarily refers to the successful achievement of the desired result. As for effectiveness, we measured and examined five dependent variables, which are listed in Table 1.

Efficiency generally refers to the relationship between effectiveness (achieving the desired outcome) and the resources spent to achieve the outcome. Typical examples of TO efficiency are the time required to perform a TO (reaction time) and the amount of information given [6]. In terms of efficiency, we measured and examined seven dependent variables, which are listed in Table 2.

Satisfaction is a mostly subjective measure that adds details about the user experience to the usability rating. To measure satisfaction, we used the User Experience Questionnaire (UEQ) [65], which measures six user experience scales:

- Attractiveness,
- Perspicuity,
- Efficiency,
- Dependability,
- Stimulation,
- Novelty.

In addition to the UEQ, we measured drivers' satisfaction and well-being with the physiological signals listed in Table 3. The following wearable devices were used:

- Eye-tracking glasses: Tobii Pro Glasses 2 [66], to measure gaze and pupil diameter with a sampling frequency $\mathrm{f}_{\mathrm{s,eye}} = 50$ Hz;
- A medical-grade wristband, Empatica E4 [67], with a photoplethysmography (PPG) sensor with a sampling frequency of $\mathrm{f}_{\mathrm{s,PPG}} = 64$ Hz and an electrodermal activity (EDA) sensor with a sampling frequency of $\mathrm{f}_{\mathrm{s,EDA}} = 4$ Hz to measure heart rate and skin conductance;
- A medical-grade chest strap, Bittium Faros 360 [68], to measure a single-channel electrocardiogram (ECG) with a sampling frequency of $f_{s,ECG} = 100$ Hz.

E. STATISTICAL ANALYSIS

Statistical analysis was performed in SPSS version 23 [78]. When comparing continuous dependent variables

TABLE 1. **Dependent variables regarding the take-over effectiveness.**

Dependent variable	Description	References	Expected trend
Minimal time-to-collision (TTC)	Measured in s: at every moment t of a TO, TTC(t) represents the time to reach the collision point, assuming constant vehicle speed and acceleration; we studied minimal value of TTC(t) during the time interval of a TO.	[50], [54], [69]–[71]	Increase
Maximal lateral acceleration	Measured in m/s^2, representing strong lateral deviations due to sudden oversteering: maximal value between a TOR and the moment the vehicle passed the roadblock or came to a complete stop.	[9], [69], [72]	Decrease
Maximal deceleration	Measured in m/s^2: maximal value between a TOR and the time when the vehicle passed the roadblock or stopped completely.		Decrease
Collision	Binary: true if the driver was involved in a collision during a TO (i.e., an unsuccessful TO).	[9], [54], [69], [70]	Decrease
Brake application	Binary: true if the driver applied a brake pedal during a TO.	[69], [70]	Increase

TABLE 2. **Dependent variables regarding efficiency of a take-over.**

Dependent variable	Description	References	Expected trend
Reaction time (take-over time)	Measured in ms; the duration from the moment of a TOR to the moment of the actual TO.	[12], [14], [19]	Decrease
Reaction time to first braking	Measured in ms; the duration from the moment of a TOR to the moment of the first application of the brake pedal.	[33]	Decrease
Time to lane crossing (TTLC)	Measured in ms; the duration from the moment of a TOR to the moment the centre of the vehicle changed lanes.	[73]	Stabilize
Maximal steering wheel angle	Measured in rad; maximal value between a TOR and the moment when the vehicle passed the roadblock or stopped completely.	[74]	Decrease
Maximal lateral trajectory deviation (LTD)	Measured in m; distance from the center of the target lane when abiding the roadblock (positive values mean a greater distance than required, negative values mean a smaller distance than required): maximal value between a TOR and the time the vehicle has passed the roadblock or stopped completely.	[74]	Approach zero
Duration of short TTC	Measured in s; sum of durations while the TTC was less than 1.5 s.	[75]	Decrease
Take-over performance index (TOPI)	A general TO performance measure combined as a geometric mean of sigmoid functions of 1) risk of collision (minimal TTC), 2) intensity of response (maximal deceleration, maximal steering wheel angle), and 3) quality of trajectory (maximal LTD).	[74]	Increase

TABLE 3. **Dependent variables related to satisfaction with a take-over (physiological measurements).**

Dependent variable	Description	References	Expected trend
Mean heart rate	Measured in beats per minute (bpm); represents driver arousal: mean of an interval beginning with a TOR and ending when the vehicle has passed the roadblock or stopped completely.	[76]	Decrease
Heart rate variability (HRV) RMSSD	Measured in ms; root mean square of the successive differences (RMSSD) of the inter-beat intervals. It reflects the activity of the parasympathetic nerve system and is not affected by the respiratory process.	[76]	Decrease
Mean pupil diameter	Measured in mm; represents driver cognitive load: mean value of an interval starting with a TOR and ending when the vehicle has passed the roadblock or stopped completely.	[77]	Decrease

(e.g., maximal deceleration or reaction time), mixed linear model analysis was performed. When comparing categorical dependent variables (e.g., number of collisions or brake applications), a mixed-effects generalized linear model with Poisson distribution and log link function was used. In both cases, the approach and successive TOR events were considered as repeated measures. The approach was considered as a fixed effect with a possible random intercept. Study results were grouped based on subject identification (clustering variable). Bonferroni confidence interval adjustment was used for pairwise comparisons among approaches.

IV. RESULTS

Each participant experienced eight situations requiring a take-over, two situations with each of the four experimental conditions. Together with the 44 drivers, this resulted in

TABLE 4. Type III tests of fixed effects of the take-over effectiveness variables.

Fixed effect	df	F / χ^2	Sig.
		Minimal TTC	
Intercept	(1, 43.0)	F = 930	< .001 ***
Approach	(3, 42.8)	F = 9.14	< .001 ***
		Maximal lateral acceleration	
Intercept	(1, 43.1)	F = 393	< .001 ***
Approach	(3, 43.2)	F = 16.5	< .001 ***
		Maximal deceleration	
Intercept	(1, 43.0)	F = 256	< .001 ***
Approach	(3, 43.1)	F = 9.09	< .001 ***
		Collisions	
Intercept	1	$\chi^2 = 63.1$	< .001 ***
Approach	2	$\chi^2 = 5.66$	.059
		Brake application	
Intercept	1	$\chi^2 = 4.98$	.026 *
Approach	3	$\chi^2 = 2.27$	.518

*p < .05, **p <.01, ***p < .001.

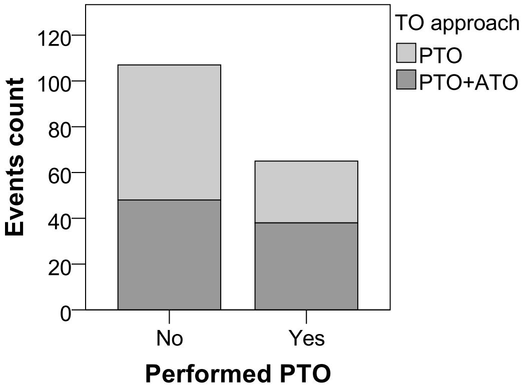

FIGURE 6. Count of events with partial take-overs.

352 take-over events. Of the 176 take-overs when the PTO mechanism was used (PTO and PTO+ATO approaches), drivers performed partial take-overs in 65 events (37.8 %), see Fig. 6. Of the 176 take-overs when the ATO mechanism was used (ATO and PTO+ATO approaches), an additional warning was issued in 164 events (95.3 %), while the vehicle initiated emergency braking in 61 events (35.5 %), see Fig. 7.

In the following subsections, the results of the evaluation of the proposed approaches are presented separately for each element of the TO quality: effectiveness, efficiency, and satisfaction in terms of self-reported satisfaction and physiological measurements of the proposed approaches.

A. TAKE-OVER EFFECTIVENESS

Fig. 8 – 10 show the mean values of take-over effectiveness variables for all four approaches. Table 4 shows the type III tests of fixed effects of the takeover effectiveness variables. It shows that the approach has statistically significant effects on minimal TTC, maximal lateral acceleration and maximum deceleration. On the other hand, it has no significant effect on the number of collisions and brake applications. The pairwise comparisons of individual parameters are presented in more detail in the following subsections. The parameter estimates can be found in Appendix.

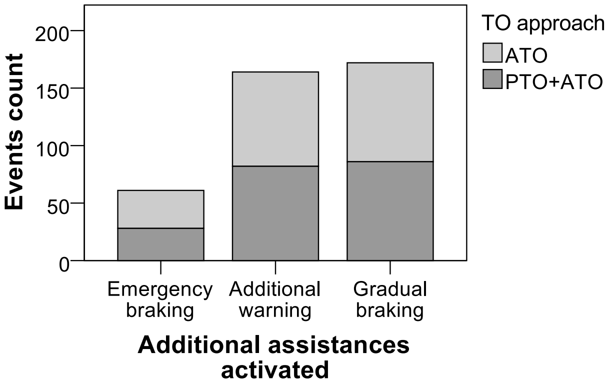

FIGURE 7. Counts of events with activated additional assistances.

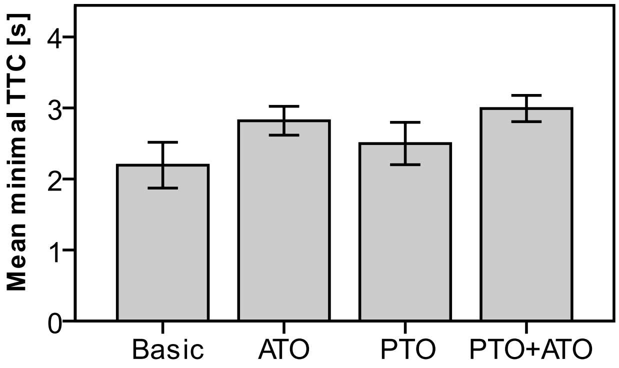

FIGURE 8. Mean value of minimal TTC per approach. The error bars represent two standard errors (SE).

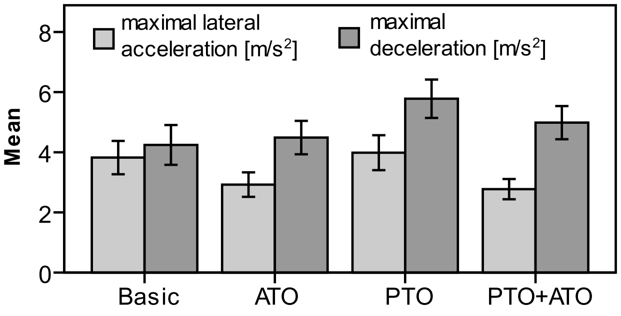

FIGURE 9. Mean values of maximal lateral acceleration and maximal deceleration per approach. The error bars represent two standard errors (SE).

1) MINIMAL TIME TO COLLISION

Pairwise comparisons (Table 5) show statistically significant differences in minimal time to collision between the Basic approach and the ATO and PTO+ATO approaches, and between PTO and PTO+ATO approaches. In the case of PTO+ATO, the minimal time to collision proved to be significantly longer compared to the Basic and PTO approaches.

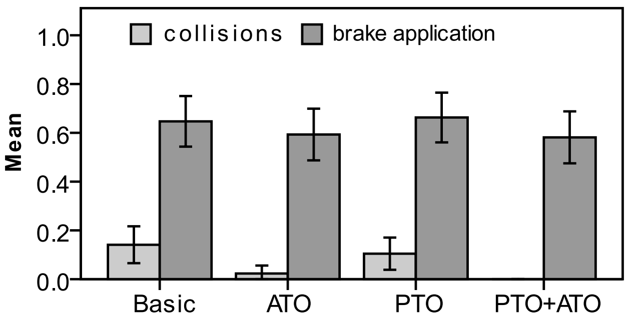

FIGURE 10. Mean values of collisions and brake applications per approach. The error bars represent two standard errors (SE).

TABLE 5. Pairwise comparisons for minimal TTC.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	-.812	.200	43.2	.001 **
	PTO	-.475	.220	43.3	.219
	PTO+ATO	-.958	.196	42.4	<.001 ***
ATO	PTO	.337	.199	43.0	.589
	PTO+ATO	-.146	.119	43.0	1.000
PTO	PTO+ATO	-.483	.161	43.0	.027 *

*p < .05, **p <.01, ***p < .001.

TABLE 6. Pairwise comparisons for maximal lateral acceleration.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	.990	.374	43.2	.068
	PTO	.017	.314	43.3	1.000
	PTO+ATO	1.48	.318	43.3	< .001 ***
ATO	PTO	-.973	.306	43.0	.017 *
	PTO+ATO	.484	.153	43.1	.017 *
PTO	PTO+ATO	1.46	.267	43.0	< .001 ***

*p < .05, **p <.01, ***p < .001.

TABLE 7. Pairwise comparisons for maximal deceleration.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	-.193	.306	43.2	1.000
	PTO	-1.65	.338	43.0	< .001 ***
	PTO+ATO	-.670	.319	43.2	.250
ATO	PTO	-1.46	.338	43.0	.001 **
	PTO+ATO	-.477	.302	43.0	.727
PTO	PTO+ATO	.983	.292	43.1	.010 *

*p < .05, **p <.01, ***p < .001.

TABLE 8. Pairwise comparisons for collisions.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	.23	.086	1	.041 *
	PTO	.09	.092	1	1.000
	PTO+ATO	.28	.076	1	.001 **
ATO	PTO	-.14	.070	1	.285
	PTO+ATO	.05	.032	1	.885
PTO	PTO+ATO	.19	.059	1	.010 *

*p < .05, **p <.01, ***p < .001.

TABLE 9. Pairwise comparisons for brake applications.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	.09	.127	1	1.000
	PTO	-.05	.109	1	1.000
	PTO+ATO	.12	.128	1	1.000
ATO	PTO	-.14	.107	1	1.000
	PTO+ATO	.02	.111	1	1.000
PTO	PTO+ATO	.16	.123	1	1.000

The same conclusion can be drawn when comparing ATO with the Basic approach.

2) MAXIMAL LATERAL ACCELERATION

Pairwise comparisons (Table 6) show statistically significant differences in maximal lateral acceleration between the PTO+ATO and all other three approaches as well as between the ATO and PTO. Maximal lateral acceleration was significantly lower for PTO+ATO compared to the other three approaches. The same conclusion can be drawn when comparing ATO with the PTO approach.

3) MAXIMAL DECELERATION

Pairwise comparisons (Table 7) revealed a significantly higher maximal deceleration when comparing PTO with the other three approaches.

4) COLLISIONS

Pairwise comparisons (Table 8) show statistically significant differences in the number of collisions when comparing Basic approach and ATO, Basic approach and PTO+ATO, and PTO and PTO+ATO approaches. No collisions were detected for the PTO+ATO approach (therefore, no statistical values are included in the table of fixed effects estimates for this parameter). Significantly more collisions were detected for the Basic approach compared to the ATO approach.

5) BRAKE APPLICATIONS

Pairwise comparisons (Table 9) show no statistically significant differences in the number of brake applications between the four approaches.

B. TAKE-OVER EFFICIENCY

Fig. 11 – 14 show the mean values of the take-over efficiency variables for all four approaches. Table 10 shows the type III tests of fixed effects on takeover efficiency variables. It shows that the approach has statistically significant effects on all seven efficiency measures. The pairwise comparisons of individual parameters are presented in more detail in the following subsections. The parameter estimates can be found in Appendix.

1) TAKE-OVER REACTION TIME (TOT)

Pairwise comparisons (Table 11) show that TOT was significantly higher in ATO compared with the Basic

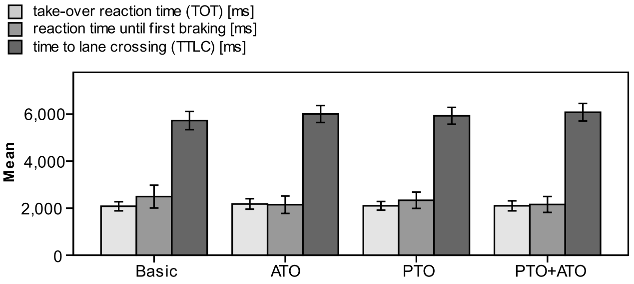

FIGURE 11. Mean values of take-over reaction time, reaction time to first braking, and time to lane crossing per approach. The error bars represent two standard errors (SE).

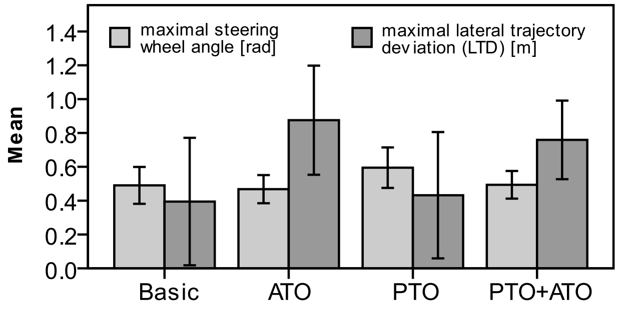

FIGURE 12. Mean values of maximal steering wheel angle and maximal lateral trajectory deviation per approach. The error bars represent two standard errors (SE).

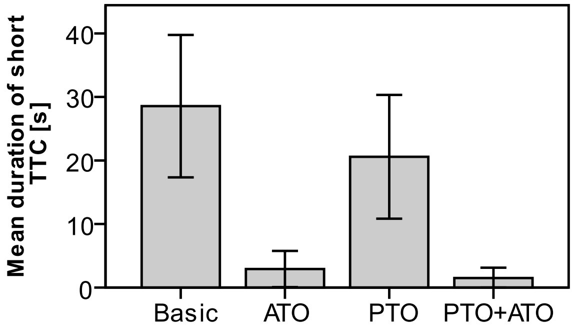

FIGURE 13. Mean duration of short TTC per approach. The error bars represent two standard errors (SE).

approach. No significant differences were found for the other approaches.

2) REACTION TIME UNTIL FIRST BRAKING

Pairwise comparisons (Table 12) show that reaction time to first braking was significantly higher for the Basic approach compared to the other three approaches. No significant differences were found for the other pairs of approaches.

3) TIME TO LANE CROSSING (TTLC)

Pairwise comparisons (Table 13) show that TTLC was significantly lower for the Basic approach compared to the other three approaches. No significant differences were found among for the other pairs of approaches.

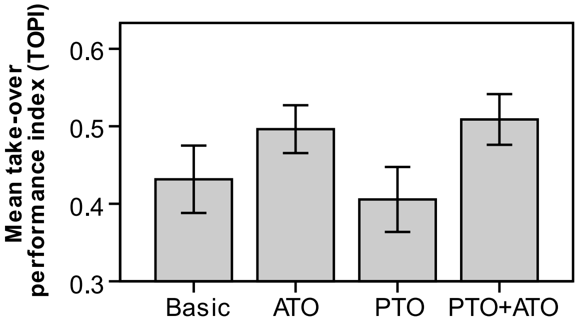

FIGURE 14. Mean take-over performance index (TOPI) per approach. The error bars represent two standard errors (SE).

TABLE 10. Type III tests of fixed effects of the take-over efficiency variables.

Fixed effect	df	F	Sig.
		Take-over reaction time (TOT)	
Intercept	(1, 43.0)	461	< .001 ***
Approach	(3, 42.7)	3.43	.025 *
		Reaction time until first braking	
Intercept	(1, 26.9)	224	< .001 ***
Approach	(3, 18.0)	10.4	< .001 ***
		Time to lane crossing (TTLC)	
Intercept	(1, 41.7)	1286	< .001 ***
Approach	(3, 38.3)	7.59	< .001 ***
		Maximal steering wheel angle	
Intercept	(1, 43.1)	220	< .001 ***
Approach	(3, 43.1)	2.95	.043 *
		Mean maximal LTD	
Intercept	(1, 55.0)	83.7	< .001 ***
Approach	(3, 47.3)	7.00	.001 **
		Mean duration of short TTC	
Intercept	(1, 55.0)	83.7	< .001 ***
Approach	(3, 47.3)	7.00	.001 **
		Mean TOPI	
Intercept	(1, 55.0)	83.7	< .001 ***
Approach	(3, 47.3)	7.00	.001 **

*p < .05, **p <.01, ***p < .001.

TABLE 11. Pairwise comparisons for take-over reaction time.

Approach I	Approach II	$\overline{\text{Diff.}}$ (I – II)	SE	df	Sig.
Basic	ATO	-332	105	40.7	.018 *
	PTO	-118	83.7	43.2	.993
	PTO+ATO	-68.9	90.2	41.7	1.000
ATO	PTO	213	89.2	42.5	.128
	PTO+ATO	263	111	42.0	.134
PTO	PTO+ATO	49.2	87.9	43.0	1.000

*p < .05, **p <.01, ***p < .001.

4) MAXIMAL STEERING WHEEL ANGLE

Pairwise comparisons (Table 14) show a significantly higher maximal steering angle for the PTO approach compared to PTO+ATO. No significant differences were found for the other approach pairs.

5) MEAN MAXIMAL LTD

Pairwise comparisons (Table 15) show a significantly lower mean maximal LTD for the Basic approach compared with

TABLE 12. Pairwise comparisons for reaction time until first braking.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	1102	204	18.5	< .001 ***
	PTO	1138	279	16.1	.005 **
	PTO+ATO	967	199	19.9	.001 **
ATO	PTO	36.2	236	23.0	1.000
	PTO+ATO	-135	120	20.4	1.000
PTO	PTO+ATO	-171	242	22.8	1.000

*p < .05, **p <.01, ***p < .001.

TABLE 13. Pairwise comparisons for time to lane crossing (TTLC).

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	-704	197	42.5	.005 **
	PTO	-473	128	27.8	.006 **
	PTO+ATO	-598	134	37.9	< .001 ***
ATO	PTO	231	143	25.2	.705
	PTO+ATO	106	176	36.3	1.000
PTO	PTO+ATO	-125	122	39.3	1.000

*p < .05, **p <.01, ***p < .001.

TABLE 14. Pairwise comparisons for maximal steering wheel angle.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	.073	.067	42.9	1.000
	PTO	-.094	.058	43.2	.672
	PTO+ATO	.059	.060	42.9	1.000
ATO	PTO	-.167	.074	43.0	.173
	PTO+ATO	-.014	.055	43.0	1.000
PTO	PTO+ATO	.154	.052	43.0	.033 *

*p < .05, **p <.01, ***p < .001.

TABLE 15. Pairwise comparisons for mean maximal LTD.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	-.761	.182	41.4	.001 **
	PTO	-.507	.205	75.0	.095
	PTO+ATO	-.649	.147	38.4	< .001 ***
ATO	PTO	.254	.113	144	.159
	PTO+ATO	.112	.091	131	1.000
PTO	PTO+ATO	-.142	.181	217	1.000

*p < .05, **p <.01, ***p < .001.

TABLE 16. Pairwise comparisons for mean duration of short TTC.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	25.9	6.24	43.2	.001 **
	PTO	16.8	7.39	43.3	.168
	PTO+ATO	27.0	6.11	43.2	< .001 ***
ATO	PTO	-9.07	3.98	43.0	.167
	PTO+ATO	1.11	.645	43.0	.547
PTO	PTO+ATO	10.2	3.82	43.0	.064

*p < .05, **p <.01, ***p < .001.

TABLE 17. Pairwise comparisons for mean TOPI.

Approach I	Approach II	Diff. (I – II)	SE	df	Sig.
Basic	ATO	-.093	.024	42.3	.003 **
	PTO	.016	.025	42.4	1.000
	PTO+ATO	-.113	.024	40.7	< .000 ***
ATO	PTO	.109	.024	43.0	< .000 ***
	PTO+ATO	-.021	.020	43.0	1.000
PTO	PTO+ATO	-.093	.024	42.3	.003 **

*p < .05, **p <.01, ***p < .001.

the ATO and PTO+ATO approaches. No significant differences were observed for the other approach pairs.

6) MEAN DURATION OF SHORT TTC

Pairwise comparisons (Table 16) show a significantly higher mean duration of short TTC (< 1.5 s) in Basic approach compared with the ATO and PTO+ATO approaches. No significant differences were observed for the other approach pairs.

7) MEAN TOPI

Pairwise comparisons (Table 17) show that the mean value of TOPI was significantly lower for the Basic approach compared to the ATO and PTO+ATO approaches. The mean value of TOPI was also significantly lower for PTO compared with the ATO and PTO+ATO approaches.

C. SELF-REPORTED SATISFACTION AND PHYSIOLOGICAL MEASUREMENTS

1) SELF-REPORTED SATISFACTION

The results of the user experience questionnaire (UEQ) revealed no statistically significant differences among the TO approaches, neither in terms of attractiveness (F(3, 126) = 1.640, p = 0.184), nor in terms of perspicuity (F(3, 126) = 0.811, p = 0.490), efficiency (F(2.457, 103.180) = 0.512, p = 0.638), dependability (F(3, 126) = 1.809, p = 0.149), stimulation (F(3, 126) = 0.534, p = 0.660), or novelty (F(3, 126) = 0.174, p = 0.914). Additionally, after the experiment, most drivers reported that they could not detect or feel any differences among the trials with the different approaches. Some drivers even questioned whether there were any differences at all among trials.

2) PHYSIOLOGICAL MEASUREMENTS

Fig. 15 – 17 show the mean values of the physiological measurements for all four approaches. The results of the statistical analysis revealed no any statistically significant effect of the different TO approaches on mean heart rate (F(3, 105) = 0.433, p = 0.730) and mean pupil diameter (F(1.699, 69.650) = 0.613, p = 0.519). Although a marginally significant (considering the less strict alpha level of $\alpha = 0.1$) effect of the TO approaches was found on HRV RMSSD (F(3, 102) = 2.326, p = 0.079), with the lowest mean RMSSD (i.e., lowest driver demand) during the ATO approach, pairwise comparisons showed that the differences in RMSSD between

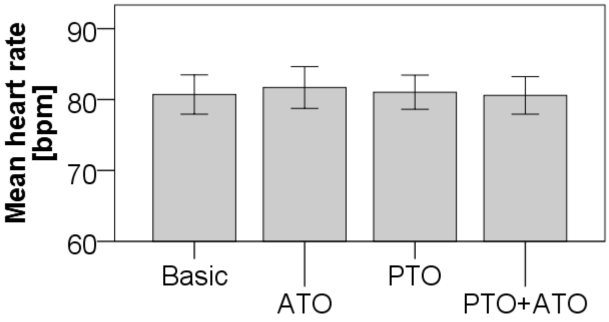

FIGURE 15. Mean value of heart rate per approach. The error bars represent two standard errors (SE).

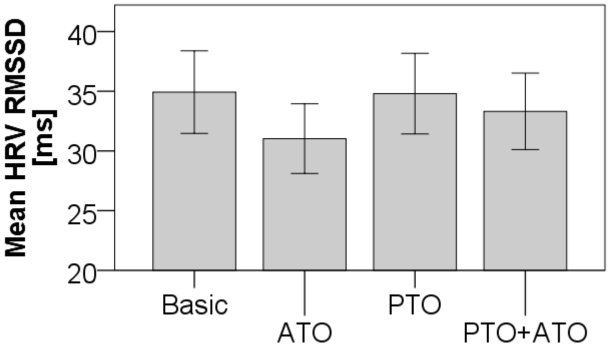

FIGURE 16. Mean value of root mean square of successive differences (RMSSD) of heart-rate variability per approach. The error bars represent two standard errors (SE).

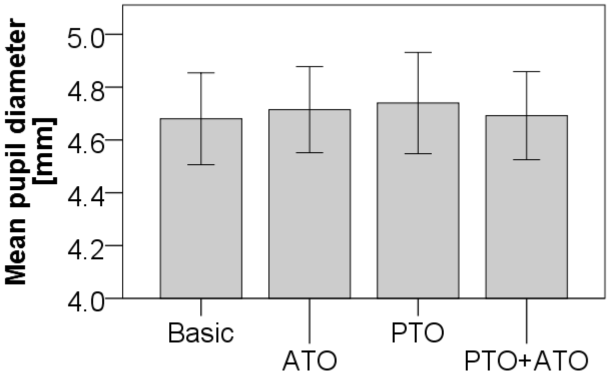

FIGURE 17. Mean value of pupil diameter per approach. The error bars represent two standard errors (SE).

pairs of TO approaches were not statistically significant ($p > 0.1$).

V. DISCUSSION

The results of our user study clearly show that the proposed partial and assisted TO approaches have a positive impact on the effectiveness and efficiency of a TO while at the same time they do not have a statistically significant impact on driver (dis)satisfaction. In our opinion, it is particularly important that the assistance systems implemented in the proposed approaches do not interfere or confuse the driver during the take-over, as some drivers in our study expressed their doubts about allowing the automation to intervene after the driver has taken control of the vehicle. However, in agreement with Mukhopadhyay et al. [44] and Butmee et al. [47], our results suggest that the additional automation helps the driver without the driver having to be aware of it.

A. PARTIAL TAKE-OVER (H1)

Based on the results of a previous study [33], we assumed that allowing partial take-overs would help drivers to perform a better and smoother take-over manoeuvre. Contrary to our expectations, the results showed that the PTO approach alone did not have a statistically significant positive impact on take-over effectiveness.

In terms of TO efficiency, the PTO approach resulted in significantly lower reaction times to first braking and longer times to lane crossing. The faster braking responses could be explained by the fact that the PTO-enabled vehicle did not completely turn off the automatic driving system after TOR (as in the basic approach), but left the ACC on, initiating automatic braking at a certain point, which likely encouraged the driver to also brake manually. Consequently, the driver had more time to regain situational awareness and react appropriately.

Furthermore, we found no statistically significant differences in self-reported satisfaction or physiological measurements between PTO and a classic multi-modal TOR UI. Therefore, we mainly reject our first hypothesis (H1): The PTO approach alone does not provide better TO effectiveness or satisfaction than classic multimodal TOR UIs, but only lower reaction times to first braking and longer times to lane crossing.

In conducting the user study, the conductor observed and noted several instances where drivers nevertheless benefited significantly from the PTO mechanism because they would most likely collide with the roadblock if longitudinal control (braking) did not remain automatic. Moreover, Fig. 10 shows that in about 40% of the take-overs the brake was not used at all, which sometimes led to collisions. Therefore, we believe that the use of PTO is reasonable, as it could prevent some (potentially fatal) accidents, even though the PTO approach was not shown to be more effective in our statistical analysis compared to other approaches. However, the latter may be attributed to the relatively small sample of drivers who experienced PTO.

B. ASSISTANCE AFTER A TAKE-OVER (H2)

Since almost every dependent measure showed statistically significant improvements in both TO effectiveness and TO efficiency when the ATO approach was used, we can reasonably conclude that providing assistance after a take-over improves TO quality, as suggested by Mukhopadhyay et al. [44]. Our findings are also in line with Shull et al. [46] and Ma et al. [49], who favoured a multi-stage warning over single TORs.

Contrary to our expectations, we found no statistically significant differences in self-reported satisfaction or physiological responses among the TO approaches studied. However, we partially confirm our second hypothesis (H2), as the ATO approach provides better TO effectiveness and efficiency than classic multimodal TOR UIs.

The only TO quality aspect (dependent variable) where the ATO approach performed significantly worse than the Basic approach was the take-over reaction time. However, we believe that longer reaction times with the ATO approach do not necessarily represent worse TOs because the ATO approach includes immediate automatic soft braking simultaneously with TOR, giving the driver some additional time to gain better situational awareness and perform a more appropriate manoeuvre.

C. ASSISTED PARTIAL TAKE-OVER (H3)

The results of our study showed that the combination of ATO and PTO was at least as beneficial as ATO or PTO approaches alone in every aspect measured. Moreover, maximal lateral accelerations were significantly lower only when ATO and PTO were combined compared to the Basic approach. Similarly, the combination of ATO and PTO significantly reduces the maximal steering wheel angle, resulting in better lateral stability of the vehicle. We therefore recommend the use of a combined assisted and partial TO approach, as this is the only approach that has a positive impact on most TO quality aspects. We confirm our third hypothesis (H3) by concluding that the combination of PTO and ATO approaches provides at least as good TO quality as either approach on its own.

D. LIMITATIONS OF THE STUDY

With regard to the PTO approach, a possible limitation of the evaluation procedure should be mentioned. Although the PTO functionality was enabled in 176 take-over events, it was fully experienced by drivers in only 37.8% of the events when they first took over the steering before possibly started to brake after some time. In other events, drivers initially applied the brakes themselves, thus taking over the longitudinal coordination of the vehicle, and the PTO functionality was not used. The purpose of PTO is to improve the TO quality only when drivers do not brake themselves. However, we could not force drivers to take-over the vehicle in a way to experience PTO and evaluate the approach without affecting the validity of the results. Therefore, our analysis included all cases in which PTO was available, regardless of whether drivers experienced the mechanism.

As with the PTO approach, we did not force drivers to experience the additional warnings and emergency braking features of the ATO approach and included all cases in which ATO was available in the analysis. Nevertheless, we found that almost every driver (95.3%) received an additional warning (when the TTC fell below 3 seconds) and that emergency braking was activated in as many as 35.5% of the cases. It seems that many more drivers benefited from the ATO approach compared to the PTO approach, supporting the hypothesis that continuous assistance after the moment of take-over is also useful.

TABLE 18. Minimal time to collision.

Parameter	Estimate [s]	Std. error	df	t	Sig.
Intercept	2.99	.0908	43.1	32.9	< .001 ***
Basic	-.958	.196	42.4	-4.90	< .001 ***
ATO	-.146	.119	43.0	-1.22	.228
PTO	-.483	.161	43.0	-3.00	.004 **
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 19. Maximal lateral acceleration.

Parameter	Estimate [m/s^2]	Std. error	df	t	Sig.
Intercept	2.54	.147	43.0	17.2	< .001 ***
Basic	1.47	.318	43.3	4.64	< .001 ***
ATO	.484	.153	43.1	3.16	.003 **
PTO	1.46	.267	43.0	5.46	< .001 ***
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 20. Maximal deceleration.

Parameter	Estimate [m/s^2]	Std. error	df	t	Sig.
Intercept	-4.93	.336	43.0	-14.7	< .001 ***
Basic	.670	.319	43.2	2.10	.042
ATO	.477	.302	43.0	1.58	.121
PTO	-.983	.292	43.1	-3.37	.002 **
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 21. Collisions.

Parameter	B	Std. error	df	χ^2	Sig.
Intercept	-30.0	.319	1	8843	< .001 ***
Basic	28.7	.400	1	5164	< .001 ***
ATO	26.9	.791	1	1160	< .001 ***
PTO	28.3				
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

Another point worth discussing is the thresholds chosen for issuing an additional warning (when the TTC drops to 3 seconds) and activating emergency braking (when the TTC drops to 1.5 seconds). Our results confirm that emergency braking is hardly sufficient to stop the vehicle when the TTC is 1.5 seconds or less, although this threshold has been recommended in related works [50], [62]. On the other hand, the study conductor noted that emergency braking was often triggered unnecessarily, for example, when the vehicle was already decelerating or turning away from the road barrier. Therefore, in the future, the thresholds for activating such assistance should be fine-tuned.

TABLE 22. Brake application.

Parameter	B	Std. error	df	χ^2	Sig.
Intercept	.151	.120	1	1.59	.208
Basic	.095	.106	1	.805	.370
ATO	.020	.095	1	.044	.835
PTO	.131	.100	1	1.72	.190
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 23. Take-over reaction time (TOT).

Parameter	Estimate [ms]	Std. error	df	t	Sig.
Intercept	1920	108	43.0	17.7	< .001 ***
Basic	-68.9	90.2	41.7	-.764	.449
ATO	263	111	42.0	2.37	.022 *
PTO	49.2	87.9	43.0	.560	.579
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 24. Reaction time until first braking.

Parameter	Estimate [ms]	Std. error	df	t	Sig.
Intercept	2310	209	22.5	11.1	< .001 ***
Basic	967	199	19.9	4.87	< .001 ***
ATO	-135	120	20.4	-1.12	.274
PTO	-171	242	22.8	-.706	.488
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 25. Time to lane crossing (TTLC).

Parameter	Estimate [ms]	Std. error	df	t	Sig.
Intercept	6021	211	43.1	28.6	< .001 ***
Basic	-598	134	37.9	-4.45	< .001 ***
ATO	106	176	36.3	.601	.551
PTO	-125	122	39.3	-1.02	.312
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 26. Maximal steering wheel angle.

Parameter	Estimate [rad]	Std. error	df	t	Sig.
Intercept	.449	.0346	43.0	13.0	< .001 ***
Basic	.0592	.0605	42.9	.980	.333
ATO	-.0136	.0547	43.0	-.249	.805
PTO	.154	.0525	43.0	2.93	.005 **
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 27. Mean maximal LTD.

Parameter	Estimate [m]	Std. error	df	t	Sig.
Intercept	.893	.0907	48.8	9.84	< .001 ***
Basic	-.649	.147	38.4	-4.41	< .001 ***
ATO	.112	.0907	130	1.23	.220
PTO	-.142	.181	217	-.786	.433
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 28. Mean duration of short TTC.

Parameter	Estimate [s]	Std. error	df	t	Sig.
Intercept	.675	.366	43.0	1.84	.072
Basic	27.0	6.11	43.2	4.41	< .001 ***
ATO	1.11	.645	43.0	1.73	.091
PTO	10.2	3.82	43.0	2.67	.011 *
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

TABLE 29. Mean TOPI.

Parameter	Estimate	Std. error	df	t	Sig.
Intercept	.515	.0174	43.0	29.6	< .000 ***
Basic	-.113	.0241	40.7	-4.71	< .000 ***
ATO	-.0207	.0203	43.0	-1.02	.314
PTO	-.130	.0209	43.0	-6.20	< .000 ***
PTO+ATO	0	0			

*p < .05, **p <.01, ***p < .001.

VI. CONCLUSION

To summarize the main contributions of our work, we have shown that the partial take-over approach does not significantly improve the effectiveness of TO alone, but provides shorter reaction times to first braking and longer times to lane crossing. On the other hand, we have found that assistance provided after a take-over significantly improved its quality. Therefore, we propose to include both PTO and ATO features in future TO user interfaces. Partial and assisted take-overs were found to have no impact on driver satisfaction.

Further research is needed to optimize the design and implementation of assisted partial take-overs in conditionally automated vehicles. In the future, it is expected that the physiological state of the drivers during the assisted partial take-over will be analysed in more detail. Since different drivers have different experiences and habits, future work could also include clustering or profiling based on, for example, driver demographics or previous driving experience. Furthermore, additional driver monitoring systems such as video and infrared cameras could be used in combination with advanced video processing techniques in the future to better adapt the assistance system in real time.

APPENDIX

ESTIMATES OF FIXED EFFECTS

See Tables 18–29.

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