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Development and Evaluation of Advanced Cyclist Assistance Systems on a Bicycle Simulator

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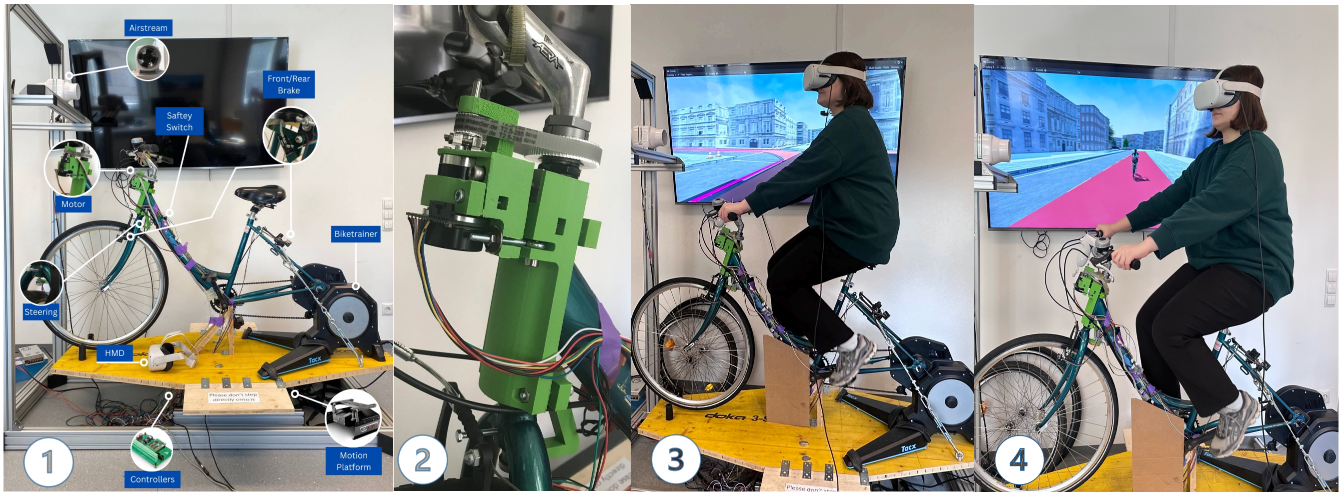

Figure 1: The structure of the advanced cyclist assistance system includes VR and motion components (1), the close-up photograph of the motor to conduct steering control in lain maintenance features (2), a participant experiencing Lane Maintenance Features (3), and Cruise Control (4) in the experiment.

ABSTRACT

Research on cycling safety has recently gained the attention of the HCI community. While there have been multiple proposals for automated driving features on bikes, we are unaware of a project that systematically aims to translate and evaluate driver assistance systems from the automotive to the bike domain to promote cycling safety in traffic. Thus, we implemented an adaptive cruise control and a lane-keeping/centering system with hard- and software on a motion-based bicycle simulator and investigated their potential in a virtual reality experiment. Based on performance measurements and subjective ratings, results showed significant improvements in technology acceptance, subjective workload, and driving performance regarding the cruise control. In contrast, the lane-centering and lane-keeping features were rated significantly worse than the baseline without such assistance. The paper concludes with a critical reflection on automated driving features for bicycles.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; **User studies**; *Usability testing*; *Virtual reality*.

KEYWORDS

Cycling Safety, Bicycle Simulator, Advanced Cyclist Assistance Systems, Virtual Reality, Hardware Design

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1 INTRODUCTION

With advanced flexibility and benefits for physical health, cycling is accepted by more people as a sustainable transportation method and a viable alternative to traditional automobiles [43]. However, the increasing complexity of urban traffic also brings more risks to cyclists' safety. The greater vulnerability of the riders who are relatively unprotected road users interacting with high-speed and mass traffic can result in severe consequences in collisions with other road users [16]. Countries worldwide are interested in enhancing cycling usage and safety and expanding their interest in smart cycling technologies [6]. In addition to already challenging and complex traffic situations, mobile devices are increasingly used for navigation, listening to music, answering calls, or texting – even while cycling [33, 39]. This situation can seriously affect the safety of cyclists in urban traffic and put them in danger of accidents [22].

To account for this situation, researchers proposed various approaches to improve cycling safety and experience, such as interactive technologies for mobile device usage during cycling [33, 69], interfaces to notify cyclists of the surrounding environments [13, 32, 47], tactile displays for communicating directional cues [41, 42], voice assistants [48], head-mounted notification systems [37, 59, 60], or helmets for communication on the go [29, 31, 58].

However, one possible approach has only received limited attention so far – namely, the field of active safety and advanced driver assistance systems (ADAS), which are common in many automobiles today. ADAS are developed to support drivers in different driving situations and increase safety [7]. ADAS provides drivers with timely warnings and actively intervenes to avoid hazardous situations or when the system detects a pressing crash [51]. According to the Society of Automotive Engineers (SAE), six levels of automation can be distinguished, ranging from no automation (Level 0) to full automation (Level 5) [8]. ADAS (SAE level 1) include (but are not limited to) systems such as Forward Collision Warning (FCW), Automatic Emergency Braking (AEB), Lane Departure Warning (LDW), Lane Keeping Assistance (LKA), Blind Spot Warning (BSW), and Adaptive Cruise Control (ACC) [23]. Existing research has shown that ADAS can positively influence traffic and road safety [14, 27, 46]. In the case of driver assistance systems, ACC affects the vehicle's longitudinal dynamics, whereas the LKA and the LCA impact the lateral dynamics [21].

In the past, ADAS has focused predominantly on automobiles. Given the recent technical improvements in machine learning, edge computing, and battery technology, we believe that future ADAS could also be developed to support cyclists. Using the proactive mechanism of ADAS to intervene in potential dangers could also improve the safety of cyclists riding in traffic. Drawing inspiration from existing systems, we propose that they could be adapted for bicycles, potentially enhancing (automated) bicycle design and promoting cycling safety within urban transportation networks. Although some researchers have already worked on highly automated bicycles [36, 66], we suggest taking a step back and climbing the ladder of the levels of automation more gradually in the bicycle domain, beginning with ADAS. In this work, we conducted and evaluated Lane Maintenance Features in the form of Lane Keeping (LKA) and Lane Centering Assistance (LCA), as well as Adaptive Cruise Control (ACC) on the bicycle. We implemented these systems in hard- and software on a dynamic motion-based bicycle simulator and conducted a Virtual Reality (VR) study to evaluate their effects on users' cycling performance and safety, technology acceptance, trust, and cognitive load.

2 RELATED WORK

In this section, we present related work from two main aspects: (1) cycling simulation for cycling safety and performance evaluation, and (2) advanced driver assistance systems to support road safety.

2.1 Cycling Simulation for Cycling Safety and Performance Evaluation

Studies have demonstrated that cycling offers considerable health advantages and is pivotal in fostering more livable and sustainable urban environments [50]. Numerous cities around the world have already established dedicated cycling infrastructure, with an increasing trend towards implementing car-free zones or the so-called cycle highways [38, 57]. However, cyclists' subjective perceived safety (defined as an "individual's experience of the risk of becoming a victim of crime and disturbance of public order" [35]) can differ from objective safety measures used for urban street design. Consequently, cycling safety is becoming a prominent research topic, and various studies have proposed the development of cycling systems equipped with emerging interactive technologies to improve cycling safety and comfort [2, 32, 34, 62, 63]. Current research on cycling systems augmented with interactive technologies mainly comprises two perspectives: the input from a user to a system and the output from the system to the user [48]. The engagement of cyclists with notifications while navigating traffic frequently compromises their attention, elevating the risk of road accidents. To address this issue, Kosch et al. [25] evaluated three notification interaction modalities in Augmented Reality to investigate their impact on the interaction performance while cycling. In addition, on-bicycle feedback modalities that notify cyclists and other road users have been researched in a variety of contexts [3, 12, 52, 56]. A toolkit for rapid exploration developed by Rittenbruch et al. [47] allows users to explore different tangible and ambient interaction approaches on low-budget cycling simulators. The sudden opening of vehicle doors into the path of cyclists represents a common hazard, primarily attributed to the elevated risk of severe injury associated with such incidents. To examine the effect of hazard notifications about potential "dooring" accidents on cyclists, von Sawitzky et al. [60, 61] conducted a study in Mixed Reality to evaluate a multi-modal head-mounted cyclist hazard notification system, revealing that participants preferred visual messages and auditory cues over visual messages alone. Strohaeker et al. [54] found that warnings provided to cyclists can reduce reaction times. Furthermore, many studies focused on the use of mobile technologies while people are actively moving, ranging from notification management with smartphones [17] to text input methods reducing distraction of mobile users [33]. Matviienko et al. [31] investigated navigation systems and lane-keeping cues [30] for children and also found that uni-modal signals were the easiest to recognize and most suitable for encoding directional information [29]. Recent proposals go even beyond by suggesting the implementation of "automated driving features" for bicycles. Two independent experiments by Matviienko et al. [36] and Wintersberger et al. [66] have utilized the "Wizard-of-Oz" method on a tandem bicycle, concluding that automated driving functionality could be of interest for the cycling communities, too.

2.2 Advanced Driver Assistance Systems Supported Road Safety

Inattention to driving, as delineated in the taxonomies by Regan et al. [45] and Cunningham and Regan [10], can be defined as "insufficient or no attention to activities critical for safe driving". Comprehending the circumstances and reasons behind the potential issues of driving systems is imperative not only for accident prevention but also for enhancing the confidence of driver-passengers in partially and conditionally automated vehicles [20]. Current semi- and highly-automated driving technology consists of sensing, perception, planning, and operation [40]. The importance of factors such as trust and acceptance of ADAS has been discussed by Biassoni et al. [4], demonstrating the crucial role of information about the usage limitations and the level of automation for user acceptance. To counteract this, ADAS was developed to support drivers in different driving and traffic situations to improve driving safety [27]. A lot of research on road safety has focused on the development of notification and warning systems for vehicles [9, 11, 49, 68]. Considering today's manually driven vehicles, cruise control, and lane maintenance systems are among the most prominent ADAS for automobiles. Adaptive cruise control (ACC) is an extension of a classical cruise control system, which not only holds a specified target speed but also slows down and accelerates depending on the behavior of a preceding lead vehicle. Lane maintenance systems, in turn, aim to prevent the vehicle from leaving its designated driving lane. While passive systems, in this regard, warn the driver (lane departure warning), active systems can keep (lane keeping assist, LKA) or directly center (lane centering assist, LCA) the vehicle in the lane. The statistics show that 80% of crashes involving powered two-wheelers are collisions with other vehicles [5], and in 30% of all cases, the rider has failed to take action (due to a lack of decision time) or realize the problem ahead [26]. Despite ADAS having substantial potential to improve traffic safety [23], the implementation of such technologies into bicycles is still lacking.

3 APPARATUS: SIMULATING ADVANCED CYCLIST ASSISTANCE SYSTEMS

Given the successful implementation of ADAS in the automotive domain, we decided to bring lane maintenance features (LKA/LCA) and adaptive cruise control (ACC) systems to bicycles to become "advanced cyclist assistance systems" (ACAS), which provide "auto steering" control to keep cyclists riding on the bike path and "distance control" to maintain a safe distance between the front bicycle in cycling. We extended our VR-based bicycle simulator [65] (see Figure 1). The simulator is mounted on a Tacx Flux 2 bike trainer [1] to track the cycling performance, and a Racing Motion Platform V3 [2] to provide dynamic tilting motion with an angle of up to 10 degrees in both lateral and longitudinal axes. The bike's speed is gathered via Bluetooth and the Fitness Machine Service Protocol (FTMS) which supports both read and write [65]. To measure the handlebar's rotation and translate it to the virtual handlebar, an Oculus Quest 2 controller is attached. Furthermore, the handlebar is equipped with a Maxon EC45 flat motor [3], including a Mile Encoder [4] as well as a planetary gear [5]. This motor is mounted to the handlebar with a timing belt at a 3:1 ratio, further augmented by an intermediary 18:1 gearbox, see Figure 1. To properly and securely install the motor onto the bicycle, a customized fixation was carefully planned and created using 3D printing technology. This ensured that the motor was mounted firmly and safely onto the bicycle. To incorporate the motor into the simulator, we utilize the ESCON Module 50/5 [6], which is attached to the ESCON Module Motherboard [7]. The input and output signals from this module are then connected to an ESP32 microcontroller, which is, in turn, connected to the simulator. The Lane Keeping, Lane Centering, and Cruise Control conditions are simulated in VR scenarios, developed in Unity, and generated with the HMD Oculus 2. We designed different city cycling routines (the red cycling lanes) for both the lane maintenance features and ACC in the virtual environment (VE), see Figure 2.

3.1 Lane Keeping and Lane Centering Implementation

The lane maintenance features are realized with a control system on the handlebar of the bicycle, which contains a Maxon EC45 brushless DC motor with an integrated encoder for precise torque transmission. Subsequently, the handlebar is actuated through an open-loop current control mechanism, managed via the game engine Unity. When the steering control is active, the motor will provide an impulse in a particular direction to adjust the rotation angle of the handlebar to keep the bicycle traveling in the correct direction on the lane. Under the LCA condition, the direction and force of the motor are calculated based on the angle between the cycling direction and the center of the lane (based on a reference point 4.5 meters ahead of the bicycle). Within the LKA condition, the motor control is active when the cycling direction collides with either side of the cycling lane. In the LCA condition, the motor control is constantly active if the user is not in the middle of the lane. The motor-generated force was computed based on the deviation between the cycling direction and the center of the path. This computation involved interpolation between a range of the pulse width manipulation signals based on the handlebar rotation

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[1] https://www.garmin.com/en-US/p/690887

[2] https://nextlevelracing.com/products/next-level-racing-motion-platform-v3

[3] https://www.maxongroup.ch/maxon/view/product/motor/ecmotor/ecflat/ecflat45/651613

[4] https://www.maxongroup.ch/maxon/view/product/sensor/encoder/Induktive-Encoder/Encoder-MILE-256-2048-/673031

[5] https://www.maxongroup.ch/maxon/view/product/gear/planetary/gp32/166159

[6] https://www.maxongroup.ch/maxon/view/product/control/4-Q-Servokontroller/438725

[7] https://www.maxongroup.ch/maxon/view/product/accessory/Starter-kitsEva-BoardsMotherboards/438779

angle. The range of these signals, which determines the motor force, was carefully assessed through comprehensive analysis during the developmental phase. This process involved testing and evaluating the optimal range that balances efficacy and sensitivity. In contrast, for the LKA condition, the force was calculated based on the deviation between the cycling direction and the edge of the cycling lane. In the LCA condition, the assist intends to keep the cyclist in the center of the bike path, and it was triggered when the rotation angle deviated from the central direction on the path. Compared to LCA, LKA is activated to adjust the cycling direction only when the cyclist is leaving the lane (Figure 2a).

3.2 Adaptive Cruise Control Implementation

The implementation of Adaptive Cruise Control, integrated within the VR simulation in Unity, facilitates a controlled cycling experience on a pre-designed cycling lane, requiring cyclists to follow a lead bicycle that consistently travels at the center of the lane, see Figure 2b. The speed of this lead bicycle is dynamically adjusted based on environmental conditions: it maintains a velocity of 10.8 km/h on standard road sections, reduces to 7.2 km/h at intersections of the road, and further decreases to 3.6 km/h when the bike getting close to other vehicles. The basic velocity of 10.8 km/h is based on the average VR cycling speed in a previous study [65], which is slightly below the average cycling speed in natural urban environments as determined by Dozza and Fernandez [15]. The lower velocities were only present in turns or evasive maneuvers for a short time. ACC activates when the cyclist's bike reaches a 4.5-meter threshold distance from the preceding bike, with the cyclist's speed being automatically adjusted to match that of the preceding bike. This 4.5-meter threshold was chosen based on the distance traveled at a speed of 10.8 km/h given a reaction time of 1.5 seconds [55]. Cyclists can disengage from using ACC by stopping to pedal and pressing the brakes, allowing the distance between their bike and the leading bike to extend naturally. Should the cyclist again come within the threshold distance proximity to the preceding bike, the cruise control feature is re-engaged. A pedestrian obstructing the path is designed as a critical situation. Here, the ACC would automatically stop based on the behavior of the lead bike. Conversely, in the absence of cruise control functionality, participants are required to manually decelerate and stop their bicycles upon approaching the stationary pedestrian. It should be noted that a real implementation can only work with electric bicycles. Here, the pedals would be disconnected from the motor and the rider would either drain (ACC faster than the user pedaling) or load (user pedaling faster than the ACC drives) the battery.

4 USER STUDY: EVALUATION OF ADVANCED CYCLIST ASSISTANCE SYSTEMS

We conducted a controlled VR experiment on the bicycle simulator supported by the advanced cyclist assistance systems to investigate the impact of the lane maintenance features (LKA and LCA) and ACC on cycling experience and safety. We evaluated the efficiency of ACAS by measuring the objective and subjective data collected from the experiment and interviewed the participants after they completed all the trials.

4.1 Hypotheses

To evaluate our developed ACAS, we propose the following hypotheses (all in comparison to a baseline without the corresponding features):

- **H1:** The lane maintenance features (i.e., LKA and/or LCA functionalities) can improve cycling performance.
- **H2:** Adaptive Cruise Control can improve cycling performance.
- **H3:** Cyclists will show a lower cognitive load when utilizing the lane maintenance features and highly accept the LKA/LCA technologies.
- **H4:** Cyclists will show a lower cognitive load when utilizing ACC and highly accept the technology.

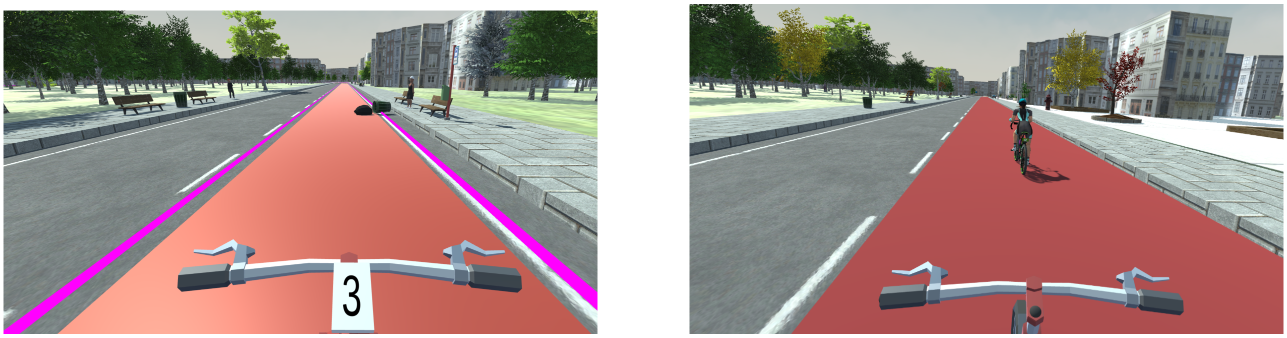
4.2 Method

The research employed a within-subject design structured around two principal blocks: The first was dedicated to lane maintenance features, which included Lane Keeping Assistance (LKA), Lane Centering Assistance (LCA), and a baseline scenario. The other block focused on Adaptive Cruise Control (ACC) in comparison to a baseline scenario. Within each block, the sequence of conditions was quasi-randomized to mitigate order effects. Furthermore, the arrangement of the two blocks was alternated to anticipate order effects and potential participant dropouts attributable to simulator sickness.

4.3 Participants and Procedures

In total, 41 participants (29 male, and 12 female) took part in the experiment. All participants stated having the capability to operate bicycles. Regarding their daily transportation habits, four participants ride a bike several times a week or even daily, five ride a bike about 1 to 3 times a week, and five cycle 1 to 3 times a month. Fourteen participants cycle several times a year, and five never cycle. Some participants dropped out midway because of the strong sickness. In the end, 24 participants completed the study completely, 7 additional participants finished the lane maintenance block, and 9 additional participants only finished the cruise control block. We only collected full datasets from each participant. After removing all participants who dropped out because of simulator sickness, we had 31 participants (22 male, and 9 female) aged between 20 and 32 (M=22.775, SD=2.92) who completed the lane maintenance block, and 33 participants (23 male, and 10 female) aged between 20 and 32 (M=22.63, SD=2.89) who accomplished the cruise control block.

After obtaining informed consent, we collected participants' demographic data. We provided a brief overview of the bicycle simulator with ACAS and tasks in the lane maintenance and cruise control blocks. Once the participants were prepared, we started the experiment, in which they needed to cycle three rounds for the lane maintenance block (LKA, LCA, and Baseline), or two rounds for cruise control (ACC and Baseline). Additionally, in the lane maintenance block, participants had to perform a distraction task in the virtual environment. A simulated display on the handlebar randomly generates numbers between 1 and 9, see Figure 2a. Participants were instructed to verbally report the occurrence of the number 7 when it appeared. Participants were informed of the next experimental condition before they started to cycle. Each round



(a) Scenario of Lane Maintenance Features

(b) Scenario of Cruise Control

Figure 2: The virtual scenarios of the Lane Maintenance and Cruise Control features in the cycling simulation.

took around 5 minutes of cycling, and the subsequent questionnaire took approximately 10 minutes after each trial. The sequence of experimental conditions was quasi-randomized. Some participants dropped out midway, and only the completely accomplished blocks were included in the evaluation.

4.4 Measurements

We quantified relevant dependent variables within each experimental segment to assess the influence of the developed ACAS. Subsequently, participants completed the NASA Task Load Index (NASA TLX), which covers the workload in terms of mental demand, physical demand, temporal demand, overall performance, effort, and frustration level [19], and the Technology Acceptance Model (TAM) [28], which includes factors that influence people's intention to use a product. The TAM is based on the psychological attitude paradigm and consists of the four dimensions *perceived usefulness* (PU), *perceived ease of use* (PeoU), *attitude towards using the system* (Attitude) and *intention to use the system* (Intention). Additional questions addressed subjective risk and trust in the form of single-item ratings. All the measured dependent variables for both blocks are described below:

Lane Maintenance Features: For the *Steering Angle*, we measure the rotation angle of the bicycle handlebar. For *Deviation from lane center*, we measured how much the cyclist deviated from the center of the cycling lane (similar to the standard deviation of lateral position, SDLP in automotive research [24]) to detect whether the lane maintenance features could help cyclists ride in the middle of the path. The *velocity* was used to detect the speed of users' cycling in the simulation in VR. The *Number Seven Detection Times* evaluates the secondary task. Participants were required to orally report whenever the number seven was presented on the screen during cycling. We implemented the secondary task to assess attention distribution during cycling and to investigate whether the lane maintenance features would promote efficient support for multitasking while riding a bike. The secondary task is a visual detection response task that has been used in driving studies to investigate distraction [64]. To assess participant's *Subjective Perception*, we measured NASA TLX, TAM, risk, and trust as described above.

Cruise control: For the *Following Deviation*, we measured the angular deviation between the lead and the user's bike's driving direction, which indicates the consistency of the following performance between both bicycles. The *Following Distance* represents the distance between the user bike and the lead bike, which indicates the maintenance of a stable safety distance (i.e., headway). The *Velocity* refers to the speed of the cycling in the simulation in VR. We also detected the velocity of the Tacx trainer (*Tacx Velocity*), which is the physical speed of the participants' pedaling. For *Subjective Perception*, we again measured NASA TLX, TAM, risk, and trust.

5 RESULTS

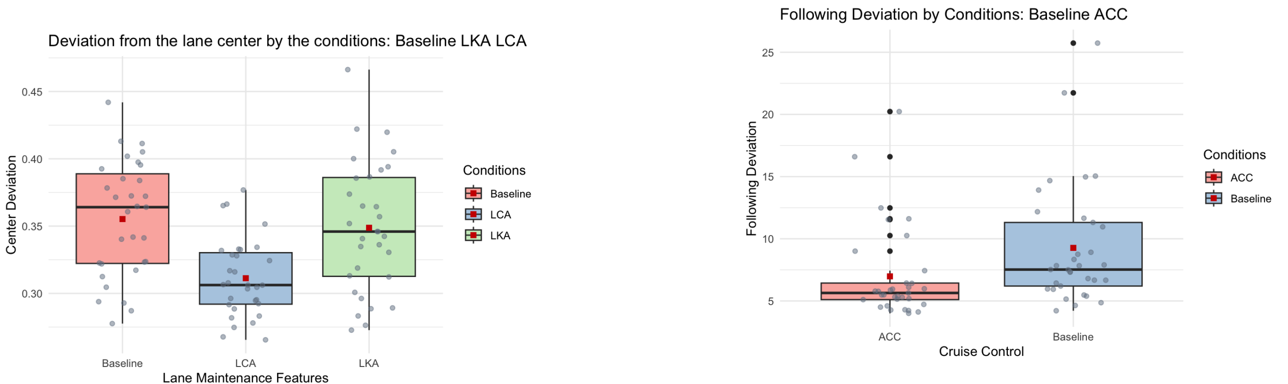
In the following, we present the results of both blocks in dedicated subsections. The results of lane maintenance features (LKA, LCA, and Baseline) and cruise control (ACC and Baseline) are shown in Table 1. For the analysis, we utilized parametric tests, as our sample satisfied the central limit theorem. In the lane maintenance block, we used Repeated Measures ANOVAs and Bonferroni-corrected post hoc tests to analyze our data; in the cruise control block, we used paired-sample T-tests. In addition, this section presents the major themes that were identified through thematic analysis, which included two coders and two rounds of iteration, based on the semi-structured interviews conducted after the study. The data extracts have been translated from German.

5.1 Evaluation of Lane Maintenance Features

5.1.1 Cycling Performance. When comparing the effectiveness of LKA, LCA, and the baseline, it was found that LCA significantly reduced the deviation from the lane center (Center Deviation) compared to both the Baseline and LKA systems ($F = 19.333$, $p < .001$, $\eta^2 = .392$). Post hoc comparisons revealed that LCA improved lane centering significantly more than the Baseline ($Md = .044, p < .001$) and LKA ($Md = .037, p < .001$), shown in Figure 3a. For the steering angle, the mean difference between the baseline and LKA was 0.090 ($p = .891$), the difference between the baseline and LCA was 0.041 ($p = 1.000$). The comparison between LKA and LCA also showed no significant difference ($Md = -.049, p = 1.000$). It was observed that the lane maintenance features significantly impacted the cycling velocity ($F = 5.057$, $p = .009$, $\eta^2 = .144$). Post hoc comparisons indicated a significant reduction in cycling velocity with LCA in comparison to the baseline ($Md = .758, p = .007$), as well as a non-significant trend towards a reduction when compared

Lane Maintenance Features							Cruise Control				
Measure	Baseline		LKA		LCA		Measure	Baseline		ACC	
	M	*SD*	*M*	*SD*	*M*	*SD*		*M*	*SD*	*M*	*SD*
Cycling Performance											
CenterDeviation (°)	0.355	0.043	0.349	0.048	0.311	0.029	Velocity (km/h)	10.761	0.274	10.760	1.850
SteeringAngle (°)	0.326	0.982	0.236	1.242	0.285	1.239	FollowingDeviation (°)	9.269	4.864	6.979	3.724
Velocity (km/h)	13.036	2.462	12.632	2.291	12.277	2.040	FollowingDistance (cm)	612.970	124.154	800.363	108.330
NumberDetection (times)	9.484	1.998	10.065	2.250	9.935	2.016	TacxVelocity (km/h)	10.652	0.242	10.467	2.194
NASA TLX											
MentalDemand	2.032	1.080	2.387	1.334	2.710	1.216	MentalDemand	2.333	1.137	1.848	0.906
PhysicalDemand	2.032	1.110	1.839	1.036	2.065	1.153	PhysicalDemand	1.939	1.116	1.606	0.704
TemporalDemand	1.129	0.341	1.323	0.702	1.161	0.374	TemporalDemand	1.818	1.131	1.485	0.834
Performance	4.419	0.672	4.161	1.003	4.194	0.749	Performance	4.121	0.893	4.182	0.882
Effort	2.065	1.153	2.194	1.138	2.419	1.259	Effort	2.030	1.075	1.636	0.822
Frustration	1.484	0.890	1.839	1.003	2.548	1.480	Frustration	1.848	1.093	1.333	0.540
TAM/Intention/Trust/Risk											
PU	3.839	0.595	3.226	1.023	2.441	1.107	PU	3.616	0.667	3.616	0.683
PeoU	4.183	0.601	3.882	0.791	3.301	1.136	PeoU	4.253	0.656	4.364	0.580
Attitude	3.774	0.658	3.677	0.805	3.183	1.064	Attitude	3.727	0.738	4.051	0.547
Intention	3.871	0.763	3.097	1.106	2.387	1.256	Intention	3.788	0.820	3.394	0.966
Trust	4.065	0.929	3.161	1.128	2.613	1.086	Trust	4.030	0.984	3.667	0.957
Risk	2.032	0.912	2.258	1.237	2.516	1.262	Risk	2.030	1.015	1.788	0.740

Table 1: Objective and subjective data results in Lane Maintenance Features and Cruise Control conditions. The lane maintenance features are comprised of conditions LKA and LCA and also include a corresponding Baseline condition. Cruise Control contains the ACC condition and the corresponding Baseline condition.



(a) Deviation from the lane center in Lane Maintenance Features

(b) The deviation of following direction between the preceding bike and the user bike in Cruise Control

Figure 3: The figures from (a) to (b) show the data analysis results of cycling deviation from the lane center in Lane Maintenance Features (Baseline/LKA/LCA) and the deviation of following direction of the user bike from the preceding bike in Cruise Control.

to LKA ($Md = .404, p = .287$). The number of times the number seven was detected in the secondary task indicated no significant difference between the baseline, LKA, and LCA ($F = 1.531$, $p = .225$, $\eta^2 = .049$).

5.1.2 Subjective Scales. The results of the NASA TLX for the different lane maintenance features revealed a significant impact on drivers' mental demand ($F = 3.711$, $p = .03$, $\eta^2 = .110$) and the frustration level ($F = 9.349$, $p < .001$, $\eta^2 = .238$). Post hoc tests show that the LKA condition did not significantly affect the mental demand in comparison to the baseline ($Md = -.355, p = .477$). The LCA ($Md = -.677, p = .025$) condition significantly increased the cognitive demand during cycling. In terms of frustration level, both LKA and LCA resulted in higher frustration levels compared to the baseline, with the LCA showing a more noticeable increase ($Md = -1.065, p < .001$) than LKA ($Md = -.355, p = .48$). No significant differences were found in the physical demand ($F = .856$, $p = .430$, $\eta^2 = .028$), temporal demand ($F = 1.875$, $p = .162$, $\eta^2 = .059$), performance ($F = 1.829$, $p = .169$, $\eta^2 = .057$), and effort ($F = 2.250$, $p = .114$, $\eta^2 = .070$). These findings suggest that Lane Maintenance Features, especially LCA, can potentially increase the mental demand and frustration commonly associated with cycling, without affecting other aspects of the cycling experience.

Considering technology acceptance (TAM), the lane maintenance features significantly affect the perceived usefulness ($F = 20.011$, $p < .001$, $\eta^2 = 0.400$), and the post hoc tests showed that LCA significantly decreased PU ($Md = 1.398, p < .001$) compared to the baseline and LKA ($Md = .785, p = .002$). Meanwhile, the Perceived Ease of Use was also affected significantly ($F = 10.804$, $p < .001$,

$\eta^2 = .265$). LCA reduced the PeoU ($Md = .882, p < .001$) significantly compared to the baseline condition. The sub-dimension attitude towards using the system was significantly affected, yielding lower ratings for the lane maintenance features in comparison to the baseline ($F = 5.694$, $p = .005$, $\eta^2 = .160$). The post hoc tests showed that, compared to LKA ($Md = .097, p = 1.000$), LCA ($Md = .591, p = .008$) significantly reduced users' attitudes towards using the system. Also, the intention dimension was significantly affected ($F = 18.566$, $p < .001$, $\eta^2 = .382$), where LCA received significantly lower ratings ($Md = 1.484, p < .001$) than the baseline. In addition, the results indicate little trust in the lane maintenance features ($F = 18.499$, $p < .001$, $\eta^2 = .381$) – compared to the baseline, both LKA ($Md = .903, p = .001$) and LCA ($Md = 1.452, p < .001$) show noticeably lower trust. No significant effect was detected for perceived risk ($F = 1.643$, $p = .202$, $\eta^2 = .052$).

5.1.3 *Thematic Analysis.*

Attention. When asked about their perception of the lane maintenance systems, participants reported that it either reduces the required attention or causes distraction (n=7). P34 stated *"[it] makes it easier to stay in the lane and you don't have to pay much attention to keeping in line"*. Another supportive argument was expressed by P37, who argued that *"in real life it's often the case, that I have to look backward to check for cars. While doing this, it's harder to keep the lane [...] this is useful in an area with busy traffic"*. Others, however, argued the systems are distracting (P40: *"was a bit distracting as often I don't even want to keep my bike in the center."*, n=2).

Use Cases. The dominant themes where participants can imagine the lane maintenance systems to be of use were for long trips or elderly users (n=5). Participants imagine it beneficial on longer rides where attention to traffic and surroundings is crucial, as it requires less focus. P34 mentioned that *"lane keeping improves the feeling of control over the bike, which is especially useful for older people"*. Other participants, such as P2, perceived this as *"annoying in the city when there are not always bicycle roads"* (n=2).

Loss of Control. The participants' main concern was losing control of the bike (n=4). P1 argued *"[...] it felt kind of strange and insecure if the bike/computer decides whether to go right or left or how to bypass an obstacle"*. Participants also compared it to lane maintenance systems in cars and stated it *"would not be a preferred choice to me, tho I also have to say that I neither enjoy the assistant in cars. It just feels like giving up control [..]"* said P35.

Feedback. Participants gave feedback on the current implementation. They reported that the motor's correction on the handlebar was too strong or frequent (n=6). P19 argued that *"[..] it was a bit overwhelming because the bike took so much steering responsibility"*; P10 said that the *"impulses too strong, weaken impulses or vibration instead"*. This can lead to frustration, as mentioned in my P20 *"The impulses can be frustrating if you think you are already in the middle but it still tries to correct"*.

5.2 Evaluation of Adaptive Cruise Control

5.2.1 *Cycling Performance.*

In the assessment of cruise control, the findings indicated that although velocity ($t = -.004, p = .997$) and Tacx velocity ($t = -.499, p = .621$) remained unchanged between ACC and Baseline conditions, significant improvements were observed in terms of the deviation of the following direction ($t = -2.694, p = .011$). As shown in 3b, the angular deviation between the lead bike and the user bike ($t = 8.432, p < .001$) was shorter and more stable with ACC activated. Moreover, ACC significantly increased the following distance between the user's bike and the preceding bike compared to the baseline ($t = 8.432, p < .001$), and a lower deviation indicates a more stable headway (this stems from the fact that, with ACC active, the headway could never fall below 4.5 meters). These improvements underscore the benefits of utilizing adaptive cruise control in cycling.

5.2.2 *Subjective Scales in Cruise Control.*

The analysis of the NASA TLX for ACC compared to the Baseline condition revealed that the use of ACC significantly reduced cognitive demand ($t = -2.617, p = .013$) and frustration ($t = -2.576, p = .015$), indicating an improved cycling experience in terms of mental workload. There was also a reduction in physical demand ($t = -1,935, p = .062$) and temporal demand ($t = -1.935, p = .062$), but without statistical significance. ACC did not significantly affect performance ($t = .571, p = .572$), but the effort ($z = -2.132, p = .029$) indicated that participants felt they needed less effort when cycling with activated ACC. Also, a lower frustration level was detected in ACC ($t = -2.576, p = .015$). These results suggest that ACC reduces the mental load and frustration associated with cycling, and also requires less effort. The statistical analysis of the TAM measurements for ACC compared to the baseline condition showed that there was no significant difference in Perceived Usefulness ($t = 2.148 * 10^{-8}, p = 1.000$) and Perceived Ease of Use ($t = .864, p = .394$). However, attitudes towards using the system ($t = 2.047, p = .049$) suggested a favorable reception for ACC. Intentions to use ACC did not change significantly ($t = -1.602, p = .119$), nor did trust in the system ($t = -1.481, p = .148$). Furthermore, the perceived risk associated with ACC had no significance from the baseline ($t = -1.215, p = .233$), indicating that participants did not feel that ACC was riskier than manual control. These findings underscore the positive perception of the ACC system.

5.2.3 *Thematic Analysis in Cruise Control.*

Comfort. When asked about their experience with ACC, participants mentioned comfort combined with helpfulness (n=8). One of the participants, P33, described it as a *"great experience that seems helpful"*. Moreover, the participants highlighted the potential of cruise control to enhance the overall riding experience in different situations. P12 argued *"I would use it in the city or on bikeways. It makes riding a little more calm."* Or as P25 states, *"I felt the cruise control was comfortable, but I would only use it in certain scenarios like a straight path like a car on the highway"*. Some participants also mentioned discomfort and would, like P7, *"[...] not use it"* (n=3).

Safety. Since cyclists are more vulnerable than drivers of conventional vehicles, safety was discussed (n=3). The participants compared the safety aspects of current bikes to adaptive cruise control. P21 stated that having a *"more safety feeling with cruise control"*. Participants also reflected on the safety of their driving behaviors. P15 said that *"I tend to follow people quite closely so it is not always too safe [...] with cruise control it was pretty helpful to keep a safe distance, especially in the city or when many people are cycling"*.

Attention. This was a dominant theme in the analysis (n=6). Driving a bike, especially with many other road users, takes a lot of attention. *"Without cruise control more attention on driving is necessary"* said P20. On the other hand, driving with cruise control was perceived as reducing the workload and needed attention to traffic. P32 argued it was *"[..] really nice not to worry about speed and crashing"*, or P6 mentioned that *"[...] if the person in front of you is slower and you do not pay that much attention, it could lead to a crash."*

Feedback. Participants also gave feedback on the current implementation. They stated that the system was not intuitive enough and wished for feedback on whether the assistance system was activated (n=11). *"Cruise control is useful but there was no feedback when it is on or off"* said P29. P13 mentioned that *"[...] finding the distance of when cruise control is active was not intuitive"*. Furthermore, participants would also prefer to regulate the distance to the bike in front on their own, rather than on a fixed distance. Like *"[..] the distance to the bike in front was too short to feel safe"* from P1.

6 DISCUSSION

Our experiment yielded quite contradicting results. Although both ACAS could improve participants' cycling performance, they received differing ratings regarding workload and user acceptance.

6.1 Lane Maintenance Systems (LKA/LCA)

Typically, LKA and LCA affect lateral control, and a main criterion for assessment is the accuracy of the yaw angle in the lane [21]. Therefore, we measured the deviation from the lane center, and the results show that the LCA yielded the best result in terms of cyclists' standard deviation of lateral position (average deviation from the lane center), while LKA performed similarly to the baseline condition without support. We accept **H1** since LCA improved participants' lane-keeping performance. However, participants' perception of lane centering and lane keeping was not very satisfactory. The LCA was rated significantly worse than the other conditions in terms of mental demand, and the baseline received better ratings than both system versions regarding participants' frustration levels. In addition, the baseline received significantly better ratings for some TAM dimensions. Finally, participants expressed the highest trust and lowest risk in the baseline condition without any support. These qualitative findings rather suggest that LKA/LCA made participants feel overwhelmed and sometimes even hindered by these systems. Consequently, **H3** must be rejected. We expected a more positive result, since previous works have suggested that people have positive perceptions of "self-driving" features for bicycle systems [36, 67]. A major difference between these works is that they utilized the "Wizard-of-Oz" (WoZ) method to simulate fully automated bicycle steering, while our experiment addressed an implementation using a motor controlling the handlebar of a bicycle further simulated in VR. Our prototype must be considered an assistance system and not a "fully automated bicycle". Participants could not fully release control and had to operate the bicycle at all times, even when the LKA/LCA systems were activated. Additionally, this paper aimed to evaluate the effect of the tested lane maintenance systems on a conceptual level, while other recent studies into steering assistance rather focused on increasing stability by active steering into the fall [1, 18]. The steering interventions of the LKA, and especially the LCA, could not be implemented on an actual bicycle without an additional control layer that mitigates the adverse effects on the stability of the bicycle as a dynamic system. The simulated bicycle did not exhibit the balancing dynamics cyclists are used to feeling (and that makes bicycles inherently unstable at most velocities [1]). This is potentially a strong source adding to the user's discomfort and distrust regarding the unfamiliar steering interventions, resulting in the rider counteracting the controller more than otherwise expected or wanting to while rationally knowing that the interventions are meant to be helpful. Such a conflict in response could explain the observed increase in mental demand. It will be worthwhile to examine if a more realistic simulation of the balancing of the bicycle will result in increased user trust, reduced mental demand, and perceived risk of interventions that affect the rider's balance, such as the steering interventions. If that is the case, LKA/LCA systems in cycling may yet be perceived as beneficial. On the other hand, we see even in the automotive domain, lane maintenance systems are perceived as less useful than other assistance systems. According to a study by Reagan et al. [44], only half of drivers with such systems in their vehicles activate them, and these drivers argued that such systems are distracting and (at least compared to other assistance systems) unnecessary.

6.2 Adaptive Cruise Control

In contrast, the results for the proposed ACC system were much more positive. Participants were significantly better at maintaining the speed of the front bicycle compared to the baseline condition where they had to continuously adjust their speed using pedals and breaks; therefore **H2** is accepted. With ACC, the distance between the user's bike and the lead bike is significantly increased, indicating more safer headways. Meanwhile, the deviation of the following direction of the front is reduced with the ACC, suggesting a more stable lane position. We measured the Tacx velocity to evaluate whether cyclists would consciously spend less physical effort during cycling with the ACC support, and the results indicate the cyclists' physical effort of cycling with ACC is close to the baseline. In addition, the unchanged velocity shows the ACC has less impact on the cycling speed. We also accept the **H4**, since the cruise control feature lowered participants' subjective workload in terms of cognitive demand, effort, and frustration, and participants reported a significantly higher user acceptance regarding their attitude towards using the bicycle with ACC, while they rated the risk of using such a system similar to the baseline condition. Despite our participants naming a couple of improvements for the system (such as an option to regulate the headway themselves) in the semi-structured interview, most felt safer and argued that ACC would be a comfortable support system for urban cycling. This resembles investigations conducted in the automotive domain, where more than 90% of drivers reported positive attitudes towards this feature [53].

7 LIMITATIONS AND FUTURE WORK

Although the advanced cyclist assistance systems supported a perceived improvement in the cycling experience, the cycling simulation in VR does not reflect the balancing dynamics of an actual bicycle, nor does it reflect the high level of complexity of an urban traffic system. Adapting the tilt to reflect the dynamic principles of bicycle balancing will aid in the design of advanced cyclist assistance systems because implementations will more closely resemble an actual prototype implementation that could work on a real bicycle. Additionally, an urban scenario with a more complex traffic environment, for instance, a more comprehensive public transportation system, traffic light system, and bystanders with dynamic movements could improve the perception of the ACAS' practicability in real traffic scenarios. The supportive features LKA, LCA, and ACC are all activated automatically in the cycling process, cyclists might be over-controlled when the assists start, and the participants requested options to better control these features. The cycling simulation in our study was implemented in VR, and participants had different experiences with this technology. Therefore, the immersion, perception, and simulator sickness of participants in VR could also impact their cycling experience to some extent. On the other hand, if participants are permitted to activate or deactivate the systems at will, it could mitigate concerns regarding the system's operation in unnecessary scenarios. Further, the recruited participants are from a younger age group; considering the physical limitations of people of different ages, the ACAS might exert more efficiency for older cyclists in urban traffic. The systems could help certain groups of people, such as the elderly, people with lower physical strength, and cyclists, perform additional tasks.

Our study highlights research possibilities for future (semi- automated) bicycle design. However, the realization of these functions also requires the development of sophisticated technologies. For instance, radars and cameras for correctly identifying other bicycles. In addition, dedicated bike lanes are crucial for cycling in urban traffic. For future research on cycling assistance systems, incorporating better feedback mechanisms that alert users about system interventions could reduce perceived risk and discomfort. Considering that different systems were rated differently (e.g., ACC was received more positively than LKA/LCA), exploring other potential assistance features that might be more intuitive and less intrusive could also be beneficial. Based on feedback on high mental demand and frustration, design changes focusing on reducing cognitive load could be beneficial. Additionally, allowing more customization and control to the users, such as adjustable intervention levels, might enhance user acceptance. To assess long-term adaptation and acceptance, longitudinal studies could be accepted where users are given more time to acclimatize to the systems in a variety of cycling conditions. Finally, we want to emphasize that ADAS is only an additional safety and comfort concept and no substitution for dedicated cycling infrastructure, which should still be prioritized by policymakers and city planners.

8 CONCLUSION

In this paper, we developed advanced cyclist assistance systems to support cyclists with LKA, LCA, and ACC. Our aim was an improvement in the cycling experience and safety, gradually climbing the ladder towards "(semi) automated cycling". We extended a motion-based bicycle simulator to evaluate the efficiency of LKA, LCA, and ACC. A VR cycling simulation supported by the advanced cyclist assistance systems was used to facilitate a user study, which evaluated the impacts of LKA, LCA, and ACC on cycling safety and experience. From the experiment, we discovered that LCA is effective in keeping cyclists riding in the center of the cycling path, but also significantly slowing down the cycling velocity and increasing the round time of cycling. Meanwhile, LCA also increases the cognitive load of cycling compared to LKA, and both lane maintenance features (LCA and LKA) increased the frustration level of cyclists. Compared to the Baseline condition, cyclists' trust in both LKA and LCA is significantly decreased. People also consider LKA to be easier to use than LCA. In contrast, with ACC, the deviation of the following direction from the preceding bike was significantly reduced, and the safe distance between the preceding bike was notably increased. ACC assistance improves the cycling experience by reducing the cognitive demand and frustration of cyclists. Meanwhile, cyclists spend less effort when riding a bike equipped with ACC assistance. Participants have shown a positive attitude toward ACC in this study, indicating promising prospects for its future acceptance and adoption in the development and design of advanced cyclist assistance systems.

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