

Enhancing Cyclist Safety in the EU: A Study on Lateral Overtaking Distance Across Seven Scenarios Using Lab and Crowdsourced Methods

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Cyclists face significant risks from vehicles that overtake too closely. Through crowdsourcing (N = 200) and driving simulator (N = 20) experiments, this study examines driver behaviour in seven scenarios: laser projection, road sign, road marking, car projection, centre line and side line markings (baseline), cycle lane and no road markings. Crowdsourced participants consistently underestimated overtaking distances, particularly at wider gaps, despite feeling safer with greater distances. The simulation results showed that drivers maintained an average passing distance of 3.4 m when not constrained by traffic, exceeding the 1.5 m law of the European Union. However, interventions varied in effectiveness: while laser projection was preferred, it did not significantly increase passing distance. In contrast, a dedicated cycle lane and a solid centreline led to the greatest improvements. These findings highlight the discrepancies between perceived and actual safety and provide insight for policy interventions to enhance cyclist protection in the EU.

CCS Concepts: • **Human-centered computing** → *Laboratory experiments; User studies*; • **Computing methodologies** → *Crowdsourcing*.

Additional Key Words and Phrases: Cyclist Safety, Driver Behaviour, Overtaking Distance, Simulation, Crowdsourcing, Human Factors, Vulnerable Road Users

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1 Introduction

Cycling has historically served as a vital mode of transport, particularly in countries such as the Netherlands, where a deliberate shift from car-centric to bike-centred urban design has significantly improved quality of life [12, 45, 60]. This transformation has reduced the environmental and spatial footprint of cars, making urban areas more liveable for citizens [52]. The Netherlands is a successful example of behavioural change, illustrating the potential for similar transformations in other countries such as Germany and Denmark [32]. Despite these advances, cyclists continue to face substantial risks of being involved in accidents, and in the Netherlands 25% of traffic deaths are cyclists [18, 55]. This poses a challenge to the wider adoption of cycling as a sustainable transport mode. An notable exception is Seville, Spain, where 13 years of infrastructure investment have led to the halving of the risk related to cycling (defined as the yearly ratio between the total number of collisions of bicycles with vehicles and the total number of bicycle trips) [37]. The European Union (EU) aims to reduce cycling deaths by 55% by the end of 2030 [57].

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In recent years, the urgency to reduce the carbon footprint [11] and alleviate urban traffic congestion has further elevated the importance of cycling. Since the COVID-19 pandemic, there has been a notable increase in bicycle usage and purchase [13, 38], accompanied by an increase in cycling-related deaths in the EU, accounting for 10% of all road deaths [36]. EU reports highlight that many of these accidents occur on straight roads, accounting for 66% of the total fatalities [54]. Studies have shown that drivers fail to or choose not to change lanes safely to overtake cyclists [21, 34, 62]. Additional hazards arise on narrower roads, exacerbating the risks for cyclists [54, 59]. Other factors contributing to the lack of reduction in general road fatalities include the use of mobile phones while driving. Montuori et al. (2021) demonstrated in a survey-based cross-sectional study that 69% of participants admitted to using their phones while driving [40]. In particular, distractions for cyclists caused by phone use, especially when cyclists text, significantly increase the risk [30]. The findings indicate that attention issues contribute to bicycle-car collisions [31, 49]. Habibovic & Davidsson (2011) and Bazilinskyy et al. (2022) attempted to investigate the causes of crashes between cars and cyclists at intersections [5, 29] and other studies focused on the open road [2, 48, 64].

Effective communication between drivers and motorcyclists and vulnerable road users (VRUs), such as cyclists and pedestrians, is essential to ensure everyone's safety on the roads. This is particularly critical as cycling continues to gain prominence as a sustainable transportation option. Recent studies highlight the importance of communication using external Human–Machine Interfaces (eHMIs), particularly for interaction between automated vehicles (AVs) and VRUs [4, 8, 10]. Granville et al. (2001) also emphasise the need for equitable road sharing [28]. However, few studies have focused on cyclists. The integration of technology and improved road infrastructure has significant potential to improve this communication and, consequently, cyclist safety [16]. As demonstrated by Walker et al. (2014), factors such as cyclist clothing do not significantly influence driver behaviour [63]. Notable exceptions exist: for example, when a cyclist is dressed as a police officer, drivers behave more safely, adjust their speed, and pay more attention. Chaloupka & Risser (2024) further highlighted the complexity of driver-cyclist interaction, indicating the importance of well-designed communication between the cyclist and the driver [15].

Previous studies have investigated various factors that influence driver behaviour during overtaking, as well as modelling different overtaking strategies used, such as speed and road infrastructure [25, 26, 59]. Loyola et al. (2023) investigated the effectiveness of interventions such as bicycle clothing, signage, and road markings [35].

1.1 Aim of Study

Cycling-related accidents are increasing, highlighting the need to better understand driver behaviour and its impact on cyclist safety, especially within the EU, where cycling cultures and infrastructure vary widely. Although interest in cycling safety is growing, key gaps remain in understanding driver-cyclist interactions. Communication technologies like light projection [23, 33] remain underexplored, and systematic comparisons of interventions—such as dedicated cycling paths, alternative road markings [56], or unprotected cycling paths [41]—are still lacking. Traditional methods such as observational studies and laboratory experiments may not fully reflect real-world EU dynamics. Building on previous work, this study focusses on overtaking scenarios to evaluate how communication technologies and infrastructure influence driver behaviour. The aim is to identify scalable safety measures using both experimental and simulation-based methodologies. The findings are intended to inform policies such as the mandatory 1.5-metre overtaking distance [17] and to support safer and more sustainable cycling infrastructure in Europe. To address these goals, the study explores the following three research questions:

- RQ1: How do different technologies, such as road infrastructure or human-machine interface (HMI), influence driver behaviour in maintaining the mandatory 1.5-meter overtaking distance from cyclists in the EU?
- RQ2: What are the most effective technological interventions to improve driver-cyclist communication among the currently available interaction concepts today?
- RQ3: How do results from crowdsourced studies compare to findings from controlled laboratory experiments, particularly in evaluating driver-cyclist communication technologies?

2 Method

Crowdsourcing is becoming a popular method for collecting data from diverse participants in a time- and cost-effective manner, particularly in transportation studies. However, the results of crowdsourced studies may need validation through controlled laboratory experiments to ensure reliability and applicability, as demonstrated by Bazilinskyy et al. (2023) [9]. This study employs a dual methodology, integrating crowdsourcing and lab-based verification, to assess the effectiveness of technological interventions to improve driver-cyclist communication.

Participants in this study were selected from the 27 EU countries (United Kingdom not included), as the research aligns with the ongoing efforts of the EU to reduce road accidents, particularly those involving VRUs, such as cyclists. The decision to focus on the EU was also motivated by the existing cycling infrastructure of the region, which, although more developed than in many other parts of the world, still faces significant safety challenges. Furthermore, choosing the EU provided a better opportunity to reach participants for the simulator experiment, allowing the results from both crowdsourcing and simulator tests to be compared and analysed together. Furthermore, to ensure meaningful comparisons between the two methodologies, the selection criteria required participants to be 18 years or older and have a valid driving licence. This approach allowed for a balanced evaluation of how drivers from diverse backgrounds responded to different scenarios in both study formats. The study was approved by the Ethics Review Board of Eindhoven University of Technology and the participants gave their informed consent to use their data.

2.1 Scenarios

Unity version 2022.1.23f1 (<https://unity.com>) was used to design seven scenarios in Table 1 that aim to analyse various technologies and road infrastructure solutions to enhance driver awareness during overtaking manoeuvres.

The city environment and the vehicle model were taken from the coupled simulator [6]. Each scenario focused on a specific intervention to assist drivers during overtaking. The seven selected scenarios took place in a 30 km/h zone, with the car travelling at a constant speed of 30 km/h (± 1 km/h) and the cyclist moving steadily at an average speed of 17 km/h varying between 12.5 and 26.5 km/h [24]. The cyclist was animated using the Male Cyclist Animated model from Code This Lab S.r.l. (<https://assetstore.unity.com/packages/3d/characters/humanoids/male-cyclist-animated-220508>). The scenarios did not include oncoming traffic to ensure that participants could focus on the distance between overtaking with the cyclist. In addition, the scenarios did not include any other road users, such as pedestrians.

2.2 Data Analysis

Paired sample t-tests and one-way repeated measures analysis of variance (ANOVA) were performed to determine significant differences between scenarios, revealing patterns in driver-cyclist communication and overtaking distances [5, 42]. The results were considered significant at $p < 0.001$, unless otherwise stated. In the laboratory experiment, additional metrics such as perceived lateral distance and stress responses were examined to verify alignment with the trends observed in crowdsourced data.

Table 1. Scenarios and view from the driver’s perspective as shown to participants. Images were taken at 8.2 s during simulation.



Laser projection: A system mounted on the bicycle handlebar that projects the safe passing distance from the bicycle onto the road similar to a solution used in London, UK [23, 58].



Vertical signage: Signs placed on the roadside to remind drivers of the 1.5-metre passing rule [20].



Road markings: Markings proposed by the Danish Cyclist Association to inform drivers of recommended overtaking distance [56].



Car projection: A system that provides the driver with visual cues to indicate the appropriate distance to overtake [1, 58].



Centre line and side-line markings: Markings on the road (base-line) .



Unprotected cycling path: A scenario simulating a cycling path without physical barriers separating it from vehicular traffic [47, 51].



No road markings: No specific road markings or signage [53].



View from driver’s perspective: Participants viewed all scenarios from this angle.

3 Crowdsourced Experiment

3.1 Method

Participants in the crowdsourced experiment were recruited through the Appen platform (<https://www.appen.com>). After joining the job, they answered demographic questions. Factors such as obtaining a driver's licence in countries with strong cycling cultures (e.g. the Netherlands) versus countries with less emphasis on cycling safety (e.g. Italy) were considered. The participants were compensated at a rate of 0.50 USD in total for their participation. See Section 7 for the materials used in the experiment.

The participants were shown videos of one scenario at a time, presented in random order. Each of the seven scenarios was tested with three different lateral overtaking distances: 0.8 m, 1.6 m, and 2.4 m from the cyclist, resulting in a total of 21 tests. The 1.6 m distance was used as a control to align with the EU's minimum legal overtaking distance of 1.5 m, making it harder for participants to guess the purpose of the study. The other two distances were chosen by increasing and decreasing the control distance by 0.8 m, creating a noticeable variation while ensuring that the shortest distance was close enough to feel risky but not excessively unsafe.

During each trial, participants were asked to *"PRESS and HOLD Fkey when you experience any discomfort with the overtaking scenario. Release it when you feel comfortable again"* [7, 39, 43]. This input served as a method for capturing participants' responses rather than reflecting direct behaviour. Performance scores were computed for each scenario by calculating the percentage of participants who pressed the key during the 100-ms periods, scaled from 0 to 100. After the video, the participants responded to two questions shown with sliders. The first asked: *"The space between the car and the bicycle during the overtaking manoeuvre was adequate"*. Responses were given on a 5-point Likert scale ranging from "Strongly disagree" to "Strongly agree". The second question was *"Estimate the lateral distance between the car and the bicycle during the overtaking manoeuvre. The distance between the car and the bicycle was approximately"*. The slider ranged from 0.5 to 2.5 m.

At the end of the experiment, participants were polled to respond to three statements on the 5-point Likert scale ranging from "Strongly disagree" to "Strongly agree": (1) *After experiencing the videos in the experiment, I will change my attitude towards maintaining a safe overtaking distance from cyclists.*, (3) *I felt safe while overtaking the cyclist in the videos.*, (3) *Based on my experience, I support the introduction of the technology used in the scenarios on real roads.* On the next page, they were asked to indicate the most preferred scenario as *Which scenario was most helpful in choosing the overtaking distance from cyclists?* and provide feedback on the level of stress during the experiment *I experienced a high level of stress during all scenarios.* (5-point Likert scale ranging from "Strongly disagree" to "Strongly agree").

3.2 Results

A total of 200 participants joined, 71 participants were filtered because 67 of them completed the study in under 900 s, 3 used the same IP, one used the same worker code and two people did not have a valid worker ID. A total of 120 (52 female and 68 male) persons participated in the crowdsourced experiment. The average age of the participants was 34.54 years (SD = 10.01), and the average year of obtaining a driving licence was 21.49 years (SD = 6.13). The participants came from Italy (n = 35), Portugal (n = 14), Hungary (n = 13), France (n = 12), Spain (n = 10), Germany (n = 8), Poland (n = 7), Romania (n = 6), the Netherlands (n = 6), Belgium (n = 3), Greece (n = 2), Croatia (n = 2), Denmark (n = 1) and Ireland (n = 1). Given the focus on the EU context, we aimed to cover all of the EU, but participation from some of the member states, such as certain Baltic and Central European countries (e.g., Estonia and Austria), was not achieved.

Background questions indicated that participants perceived the average EU overtaking distance rule as 1.88 m (SD = 1.82), which implies that, in general, the governments of the EU countries did not inform on such rules correctly.

The participants demonstrated behaviour aligned with the distance of the overtaking manoeuvre, which appears to be influenced by their level of discomfort, as shown in Figure 1. The 1€ filter [14] was applied to the data in this graph and other plots (frequency = 120, mincutoff = 0.1, beta = 0.1). Closer overtaking distances, such as 0.8 m, elicited the highest keypress, indicating the most discomfort. The overtaking distance of 2.4 m produced the lowest keypress, suggesting a greater sense of safety and comfort. The results of the t-test revealed significant differences between distances, particularly between 0.8 and 1.6 m and between 0.8 and 2.4 m. These findings highlight that participants could clearly distinguish between the levels of safety at varying distances of overtaking.

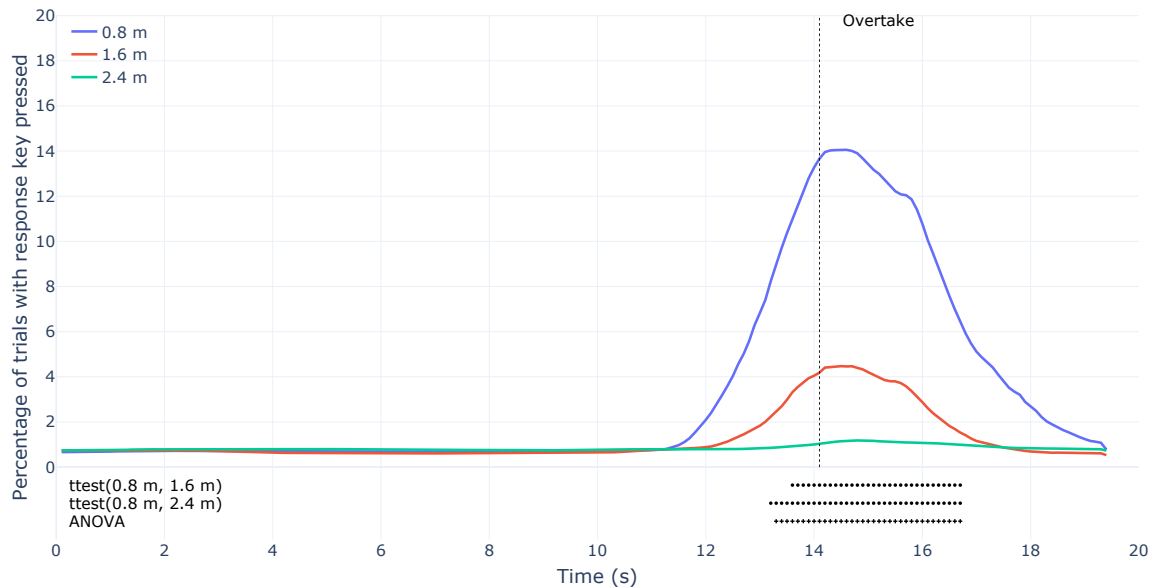


Fig. 1. Mean discomfort level in the crowdsourced experiment for the three distances. The vertical line represents the overtaking moment. The asterisks and crosses at the bottom indicate significant differences, $p < 0.001$.

Additionally, the shape of the curves provides valuable information on participants' behaviour. The curve for 0.8 metres has the steepest gradient and the highest peak, suggesting increased discomfort and urgency at this distance. In contrast, the flatter and narrower curve for 2.4 m indicates that discomfort was both lower in magnitude and shorter in duration. All curves peak around the same time (~14.5 s), which reflects a specific moment in the overtaking manoeuvre that participants consistently identified as critical. This specific moment was when the car was side-to-side with the cyclist. The results of the t-test highlight significant differences between the scenarios, particularly in the duration of the reported discomfort. On average, participants reported feeling discomfort for a longer period when the overtaking distance was 0.8 m, compared to distances of 1.6 and 2.4 m. The shorter duration of discomfort reported for the 2.4-m condition suggests that larger overtaking distances contribute to a greater sense of safety and reduced stress.

The results confirm that closer overtaking distances increase discomfort, whereas larger distances improve safety perceptions. The statistical significance of these findings, as demonstrated by the t-test, validates the reliability of

the observed trends. These results underscore the importance of maintaining safe overtaking distances to minimise discomfort and ensure cyclist safety.

Figure 2 highlights the levels of discomfort reported by participants during overtaking scenarios in seven scenarios. The results indicate that the participants felt more comfortable in scenarios where some form of communication was provided, particularly with the Car projection. Interestingly, participants also appeared to feel relatively at ease in scenarios that involved an unprotected cycling path. The t-tests demonstrate marginal differences under these conditions.

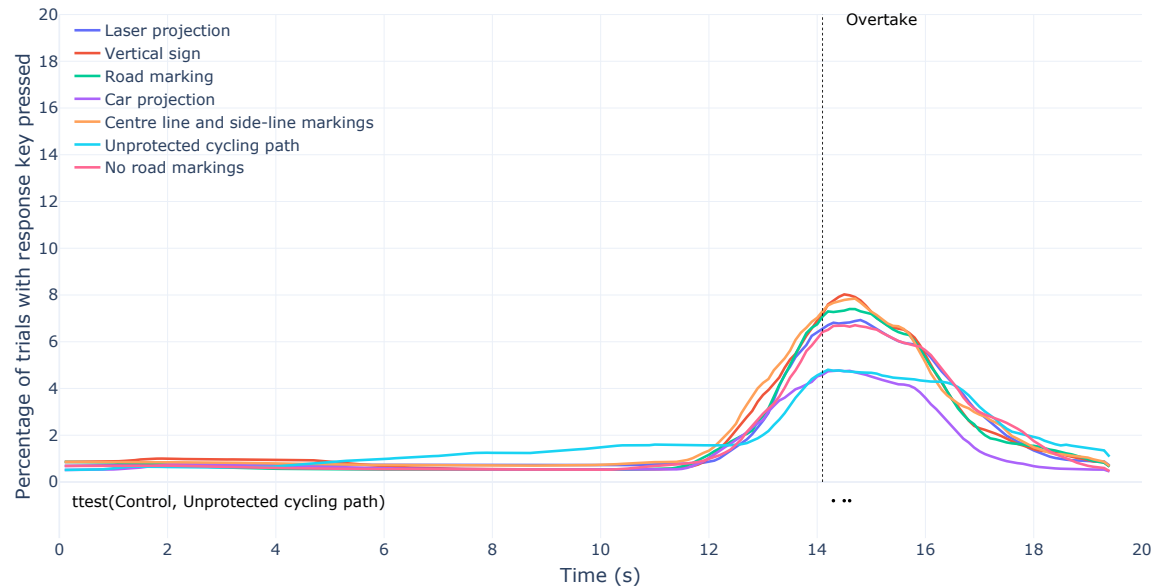


Fig. 2. Mean discomfort level in the crowdsourced experiment for the seven scenarios. The vertical line represents the overtaking moment. The asterisks at the bottom indicate significant differences, $p < 0.001$.

The levels of discomfort varied between different scenarios, with some interventions leading to a more sustained perception of safety, while others resulted in momentary spikes in discomfort. The unprotected cycling path and the Car projection showed a more uniform distribution of discomfort reports over time, suggesting that participants did not experience a specific moment of increased discomfort, but rather a more stable perception of safety or unease.

Interestingly, the *Laser projection* did not perform as effectively as the *Car projection*, with participants reporting levels of discomfort similar to those of other solutions rather than demonstrating a clear improvement. Furthermore, the *Vertical signage* and the *Road markings* resulted in momentary increases in discomfort, suggesting that participants felt uneasy at specific points in the overtaking process. The absence of road markings showed results similar to the *Centre line and side-line markings* (baseline), indicating that the lack of additional visual guidance did not provide substantial safety improvements.

These findings highlight the importance of further investigating technological interventions, particularly *Car projection*, which demonstrated more consistent results in promoting a sense of safety for both drivers and cyclists. Given its potential to improve driver awareness during overtaking manoeuvres, this approach deserves further examination as a possible alternative to traditional infrastructure-based solutions.

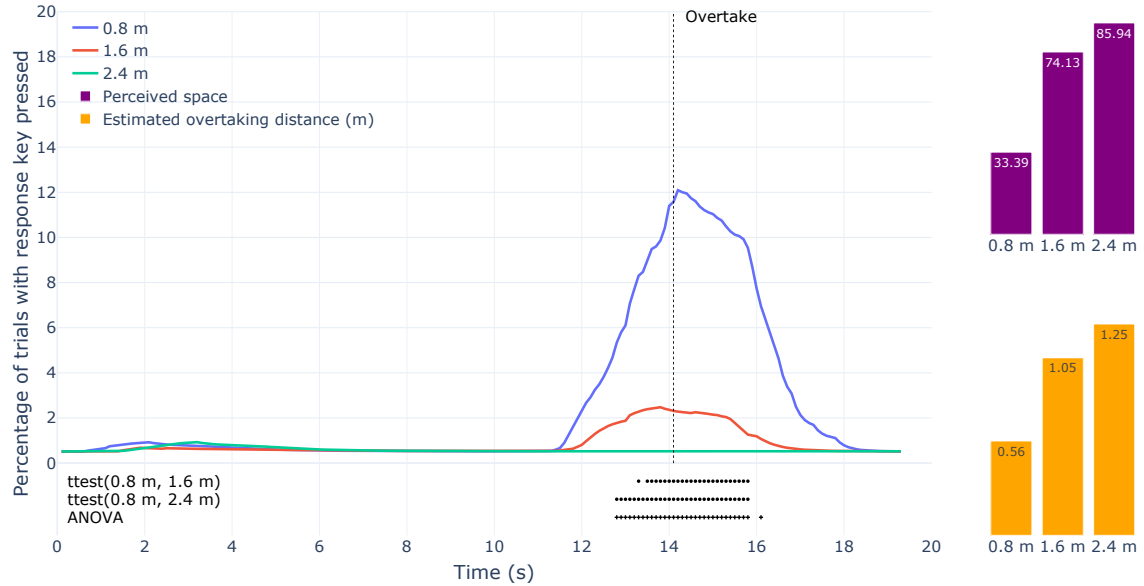


Fig. 3. Participants' discomfort responses and post-stimulus questionnaire results for the perceived adequate overtaking distance and the estimated lateral distance for the *Car projection*. The purple bars represent the adequate overtaking distance reported by participants, while the orange bars indicate the estimated lateral distance of the overtaking manoeuvre. The vertical line represents the overtaking moment. The asterisks and crosses at the bottom indicate significant differences, $p < 0.001$.

Figure 3 provides information on results related to the *Car projection*. The results of the t-test highlight significant pairwise differences between specific scenarios, reinforcing the findings of the ANOVA, which confirmed that the differences between perceived discomfort in the three stimuli (overtaking distance of 0.8 m, 1.6 m, and 2.4 m) were statistically significant during the overtaking manoeuvre. The t-test revealed significant differences between individual pairs of scenarios, such as between trials with distance of 0.8 m and 2.4 m, where the smaller overtaking distance of 0.8 m elicited a higher keypress rate, indicating greater discomfort. Similarly, the ANOVA test validates these findings by showing that the differences in all three videos are not due to random variation, but reflect meaningful patterns in participant responses. Specifically, the trial with 0.8 m distance recorded the highest keypress rate, suggesting that the participants experienced the greatest discomfort or felt the least safe. The trial with the 2.4 m distance showed the lowest keypress rate, reflecting increased comfort and perception of safer overtaking conditions. The range of keypress data in the trial with the 1.6 m distance fell in between, with moderate keypress rates, reflecting a gradual improvement in perceived safety.

Participants generally felt safer and more comfortable with longer overtaking distances. However, they consistently underestimated the actual gap. This trend suggests a misalignment between perception and reality in driver behaviour. The results confirm that shorter overtaking distances lead to significantly higher discomfort, while larger gaps were associated with a greater sense of adequacy and safety.

When comparing the *Car projection* with the *Unprotected cycling path*, the results reveal a misalignment between perceived comfort and actual overtaking distance. See Section 7 for additional visualisations and analysis. Although participants reported feeling more comfortable with *Unprotected cycling path*, they were unable to achieve adequate

overtaking distances or high safety ratings. This contrast underscores the importance of designing interventions that balance subjective perceptions with measurable safety outcomes.

Figure 4 compares the discomfort responses and spatial estimates between the Car projection and the *Unprotected cycling path*. Although both show a trend of increasing comfort and distance perception with wider overtaking margins, the *Car projection* condition yielded consistently lower discomfort levels and higher perceived adequacy scores. In particular, although participants reported feeling safer under the *Unprotected cycling path* condition, their estimated overtaking distances remained lower than actual values, reinforcing the idea that perceived safety does not always align with objective spatial behaviour.

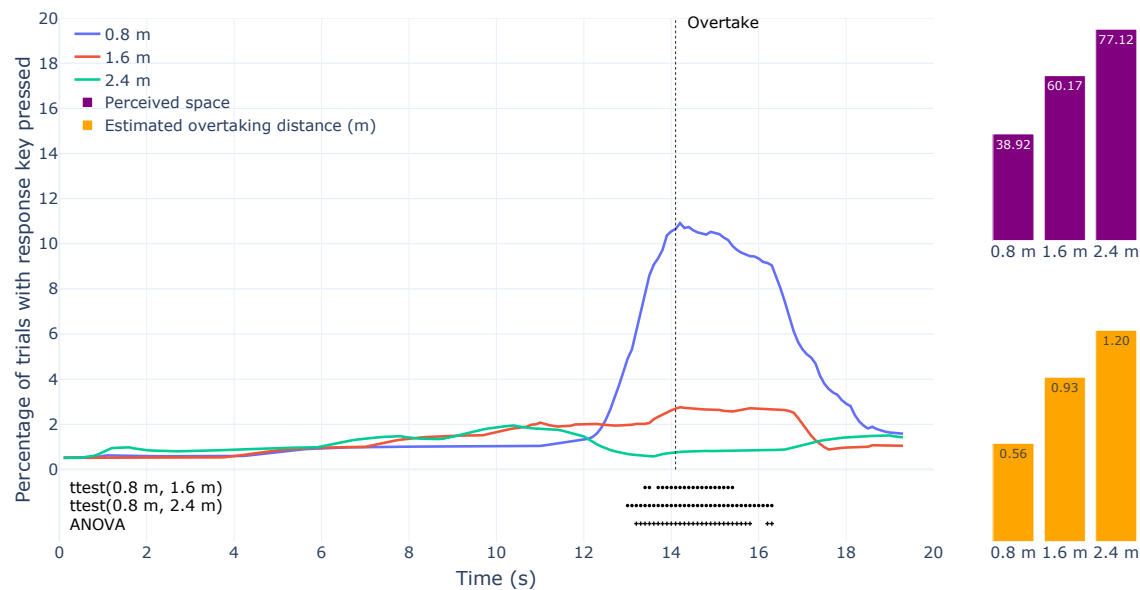


Fig. 4. Participants' discomfort responses and post-stimulus questionnaire results for the perceived adequate overtaking distance and the estimated lateral distance for the *Unprotected cycling path*. The purple bars represent the adequate overtaking distance reported by participants, while the orange bars indicate the estimated lateral distance of the overtaking manoeuvre. The vertical line represents the overtaking moment. The asterisks and crosses at the bottom indicate significant differences, $p < 0.001$.

The *Car projection* demonstrated its effectiveness in improving overtaking behaviour, particularly at greater distances, as evidenced by lower keypress rates, higher perceived space, and better adequacy scores in the trial with the 2.4 m distance. The combined validation from the t-test and ANOVA confirms the reliability of these findings and underscores the potential of the Car projection as an effective communication tool to improve driver-cyclist interactions.

Participants were asked to choose the most helpful interaction to maintain the overtaking distance. The scenarios were chosen in this order: *Car projection* ($n = 38$), *Laser projection* ($n = 36$), *Unprotected cycling path* ($n = 22$), *Road markings* ($n = 19$) and *Vertical signage* ($n = 1$). These preferences align with keypress data, which indicated lower levels of discomfort in such scenarios.

4 Laboratory Experiment

4.1 Method

The setup, consisting of a screen, a gaming steering wheel, and paddles for speed control, was used to evaluate the scenarios more thoroughly, focussing on whether they contributed to improving the lateral overtaking distance rather than assessing distance perception. Participants could freely control the car's steering with the wheel and adjust the speed using the pedals, allowing for a detailed analysis of their actions while overtaking the cyclist. The speed of the car and the lateral distance from the cyclist were recorded every 0.1 s [22, 61]. In addition, the coordinates of the car, time, speed, and the closest distance between the bicycle and the car box colliders were also recorded [50].

The tests were carried out in a controlled environment, the light level was kept the same, and the shades were closed during the experiment. There was no noise during the experiment. To closely mimic a real driving experience, the participants used a 27-inch screen set-up equipped with a steering wheel, accelerator, and braking pedals (see Figure 5). To run the simulation, a Microsoft Surface Book 2 with Intel I7, 8GB of RAM, and a dedicated graphics card, Nvidia 1050ti, was used. In this setup, the cyclist maintained a constant speed of 17 km/h along a set path, while the car's speed was controlled by the participant, allowing variations in speed and lateral distance.



Fig. 5. Experimental setup used during the laboratory experiment. Participants controlled a vehicle using a gaming steering wheel and paddles for speed adjustments with the simulation on a monitor.

The laboratory experiment was conducted by first providing participants with information about the project and requiring them to complete the demographic survey, which included questions on driving experience and familiarity with cycling safety. They were then asked to read the instructions. Before the first actual trial, the participants were given a demonstration in which only the car and the city environment were used without the cyclist to allow the participants to practice. Participants were allowed as much time as needed until they felt confident driving the car. Section 7 for the materials used in the laboratory experiment.

The scenarios were randomised. After each scenario, participants were required to answer two questions based on the survey: (1) *After the simulation, to what extent do you agree with the following statement: The space between the car and the bicycle during the overtaking manoeuvre was adequate* and (2) *Could you estimate the lateral distance between the car and the bicycle during the overtaking manoeuvre. Give your answer in meters. The distance between the car and the bicycle was approximately.....* Participants at the end of the study were asked to express their preferences for the scenario *Which of the seven scenarios, featuring various technologies such as road markings or laser projections, was the most helpful in accurately determining the distance between the car and the cyclist?* They could select only one of the seven scenarios.

The total number of participants in the laboratory study was 20 (7 female and 13 male). The average age of the participants was 21 years (SD = 3.0), with an average driving licence holding period of 2 years (SD = 2.3). The participants were from Estonia (n = 4), the Netherlands (n = 4), Bulgaria (n = 3), Italy (n = 2), Poland (n = 2), Spain (n = 1), Germany (n = 1), Romania (n = 1), Latvia (n = 1), and Cyprus (n = 1)

4.2 Results

The results of the laboratory experiment showed that there was a variation between the different scenarios. The results of this experiment provide support for what can be observed in the crowdsourced experiment. The first insight from the general result has shown that participants demonstrated difficulty in accurately estimating the lateral overtaking distance, with an estimation error of 1.63 m in all of the scenarios by comparing the estimation with the actual overtaking distance.

The distance between the car and the cyclist was also observed to be on average high compared to expectation, regardless of the scenario. The average overtaking distance was 3.40 m. This is likely due to the absence of incoming traffic as some comments that the participants provided suggested, which made the participants feel comfortable taking a greater distance than required by regulations.

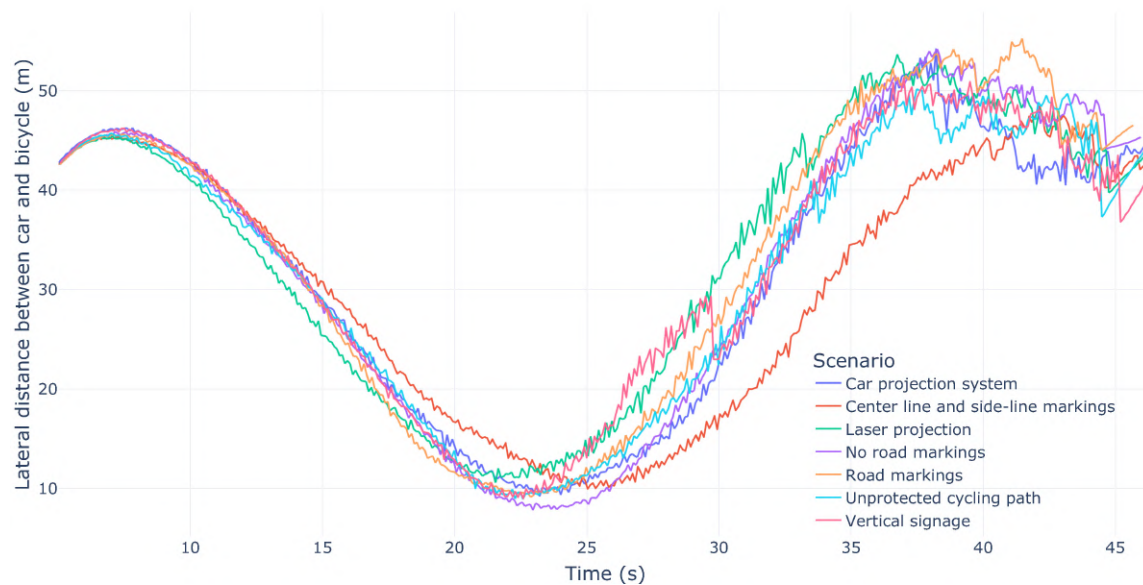


Fig. 6. Lateral distance between car and bicycle across scenarios. Data is shown from the 5th second.

Figure 6 presents the recorded overtaking distances in different scenarios, illustrating both how the mean distance varies over time in the scenarios. Although scenarios such as the *Laser projection* demonstrated the highest recorded overtaking distances, there is significant variation between scenarios. The *Unprotected cycling path*, which participants in the crowdsourced experiment associated with high comfort and high perceived adequacy 2, also resulted in shorter overtaking distances, reinforcing its limitations 6. The results of the t-test indicated that there were no statistically significant differences between conditions, highlighting the need for more research to better understand the relationship between perceived safety and actual driver behaviour in overtaking situations.

Participants were polled to indicate their most preferred interaction concept. The scenarios preferred by the participants did not always correspond to those that maintained the highest overtaking distances. The *Unprotected cycling path* received the highest number of participant votes, with 10 in total. This was followed by the *Laser projection* with 5 votes, the *Car projection* with 3, and the *Road marking* with 2. The remaining options did not receive any votes. However, Figure 6 shows that the *Unprotected cycling path* did not result in the highest overtaking distances, as other conditions, such as the *Laser projection*, led to greater actual clearance. This discrepancy between perceived safety and actual driver behaviour suggests that the participants' sense of security does not necessarily align with objective overtaking behaviour, which warrants further investigation.

5 Discussion

This study examined seven interventions aimed at increasing the lateral overtaking distance for cyclist safety in the EU. A crowdsourced (N = 120) and a laboratory (N = 20) experiments evaluated technologies and infrastructure-based solutions. While *Laser projection* and *Car projection* were preferred, they were not always the most effective in measured results. The results highlight a gap between perceived comfort and actual overtaking distances, which underlines the need to align driver perception with real safety (RQ1). Previous studies have shown that drivers often underestimate the distance they leave when overtaking cyclists, particularly when they perceive the road to be wide or the cyclist to be predictable [61]. This misalignment suggests that effective HMI or infrastructure interventions must not only influence behaviour but also enhance spatial awareness during overtaking.

Car projection emerged as the most effective, increasing overtaking distance and reducing discomfort through intuitive visual cues. *Laser projection* was the most preferred, valued for its clarity. Similarly, automotive projection systems offer real-time feedback, reducing stress and improving decision making [19]. Advanced technologies were favoured, but simpler interventions, such as *Vertical signage* and *Road markings*, performed comparably in measured behaviour. Although less preferred, *Vertical signage* achieved similar results in terms of measured overtaking distances, highlighting its potential as a lower-cost alternative [20]. *Road markings* showed moderate effectiveness, providing further support for their applicability in resource-constrained settings. Interestingly, the *Unprotected cycling path* was rated as comfortable, but resulted in the smallest overtaking distances, exposing a misalignment between subjective comfort and actual safety (RQ2) [44].

The behavioural results confirm that drivers often misjudge safe passing distances [27], reinforcing the need for interventions that improve spatial awareness. Technologies such as bicycle and car projections help reduce uncertainty, but the diversity of responses indicates that no single intervention is universally effective. Context-specific solutions are likely to be needed to account for environmental and cultural variation.

The combination of crowdsourcing and simulation provided complementary insights (RQ3). Crowdsourcing enabled broad participation across the EU but was limited by its use of pre-recorded videos. The controlled study, although lacking traffic complexity, offered real-time behavioural data. The laboratory simulation showed greater overtaking

distances, probably due to the absence of oncoming traffic or distractions. This difference underscores the importance of validating the findings in real-world settings to ensure broader applicability.

5.1 Limitations and Future Work

While this study provides valuable information, several limitations must be acknowledged. Although this study focused on drivers, future work should explore how these interventions affect cyclists' perceived safety. A more immersive simulator, such as the one in Petermeijer et al. (2017) [46], or the use of VR headsets could better replicate real-world driving [8]. Furthermore, conducting tests in live traffic would improve the ecological validity by capturing more natural driver behaviour. The current simulation lacked dynamic elements, such as pedestrians and opposing traffic, which can influence decisions. The crowdsourced approach offered broad perspectives but relied on subjective interpretations of 2D video, potentially limiting realism. The sample size was also small compared to similar studies (e.g., Onkhar et al. (2022) [42] and Bazilinskyy et al. (2022) [5] with 2000 participants each), suggesting that future work should scale up, ideally across all EU member states. The selected overtaking distances (0.8 m, 1.6 m, 2.4 m) could be expanded to a continuous range for richer behavioural insights [3]. Similarly, while seven interventions were tested, future research should assess whether they represent the entire design space or if additional concepts should be explored. Regional and infrastructural differences across the European Economic Area (EEA) and beyond may influence effectiveness, especially since the current scenario reflected a US-style layout. Future work should also consider other VRUs, such as scooter riders, which face similar risks. Lastly, although participants had driver's licences, a further detailed analysis of the driving experience, particularly among crowdsourced population, could clarify its impact on overtaking behaviour. Real-world studies, integration with connected vehicles, and the development of real-time feedback systems can provide deeper insights and improve cyclist-driver communication.

6 Acknowledgments

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7 Supplementary Material

Supplementary material containing anonymous questionnaire data, user test forms and VR and analysis code is available at: <https://drive.google.com/drive/folders/1MioioNDYjwnr9ez8nuBy6qMcAPb7Abjj>. The maintained version of the code is available at <https://github.com/gip58/cyclist-distance-crowdsourced>.

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