How does Simulation-based Testing for Self-driving Cars match Human Perception?

CHRISTIAN BIRCHLER, Zurich University of Applied Sciences & University of Bern, Switzerland
TANZIL KOMBARABETTU MOHAMMED, University of Zurich, Switzerland
POOJA RANI, University of Zurich, Switzerland
TEODORA NECHITA, Zurich University of Applied Sciences, Switzerland
TIMO KEHRER, University of Bern, Switzerland
SEBASTIANO PANICHELLA, Zurich University of Applied Sciences, Switzerland

Software metrics such as coverage and mutation scores have been extensively explored for the automated quality assessment of test suites. While traditional tools rely on such quantifiable software metrics, the field of self-driving cars (SDCs) has primarily focused on simulation-based test case generation using quality metrics such as the out-of-bound (OOB) parameter to determine if a test case fails or passes. However, it remains unclear to what extent this quality metric aligns with the human perception of the safety and realism of SDCs, which are critical aspects in assessing SDC behavior. To address this gap, we conducted an empirical study involving 50 participants to investigate the factors that determine how humans perceive SDC test cases as safe, unsafe, realistic, or unrealistic. To this aim, we developed a framework leveraging virtual reality (VR) technologies, called SDC-Alabaster, to immerse the study participants into the virtual environment of SDC simulators. Our findings indicate that the human assessment of the safety and realism of failing and passing test cases can vary based on different factors, such as the test's complexity and the possibility of interacting with the SDC. Especially for the assessment of realism, the participants' age as a confounding factor leads to a different perception. This study highlights the need for more research on SDC simulation testing quality metrics and the importance of human perception in evaluating SDC behavior.

CCS Concepts: • **Software and its engineering → Empirical software validation**.

Additional Key Words and Phrases: Software Testing, Self-driving Cars, Simulation, Human Perception

ACM Reference Format:
Christian Birchler, Tanzil Kombarabettu Mohammed, Pooja Rani, Teodora Nechita, Timo Kehrer, and Sebastiano Panichella. 2023. How does Simulation-based Testing for Self-driving Cars match Human Perception?. 1, 1 (January 2023), 34 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

In recent years, the development of autonomous systems has impacted our society in many aspects of our life [13, 18]. For instance, humans no longer rely on vacuuming their houses or mowing their grasses manually; nowadays, we have robots that do (and will do) much of our chores [9].

Authors' addresses: Christian Birchler, birc@zhaw.ch, christian.birchler@unibe.ch, Zurich University of Applied Sciences & University of Bern, Switzerland; Tanzil Kombarabettu Mohammed, tanzil.kombarabettumohammed@uzh.ch, University of Zurich, Zurich, Switzerland; Pooja Rani, rani@ifi.uzh.ch, University of Zurich, Zurich, Switzerland; Teodora Nechita, neci@zhaw.ch, Zurich University of Applied Sciences, Winterthur, Switzerland; Timo Kehrer, timo.kehrer@unibe.ch, University of Bern, Bern, Switzerland; Sebastiano Panichella, panc@zhaw.ch, Zurich University of Applied Sciences, Winterthur, Switzerland.

XXXX-XXXX/2023/1-ART $15.00
https://doi.org/XXXXXXX.XXXXXXX

(a) Failing Test: SDC driving off-lane (unsafe).

(b) Passing Test: SDC driving in-lane (safe) .

Fig. 1. Examples of simulation-based tests of an SDC.

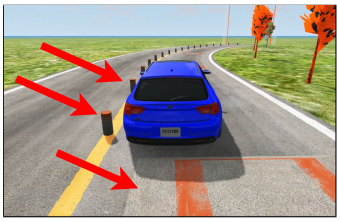
However, specific safety-critical instances of such autonomous systems such as unmanned aerial vehicles (UAVs) and self-driving cars (SDCs) [36, 37, 62, 64, 66] may experience failures that can harm humans or damage the environment [27].

Testing safety-critical autonomous systems is crucial to avoid harmful incidents in real environments [3, 11, 21, 73, 74]. To that end, simulation environments have been widely adopted to test cyber-physical systems (CPS) in general [10, 20, 49], and SDCs in particular [10, 20]. As opposed to real-world testing, simulation-based testing is easier to replicate, is more cost-efficient, and can be as effective as field testing [20, 29]. Figure 1 illustrates two test cases where an SDC model is deployed in a virtual environment, and the simulated car is expected to behave according to the control algorithms. A test case is said to pass if the car's behavior can be considered safe, while unsafe behavior constitutes a failing test case. Figure 1a shows an unsafe behavior (failing test) as the SDC drives off the lane, while Figure 1b shows a passing test.

Current research on simulation-based test case generation (STSG) of SDCs relies on an oracle that determines if a system under test is safe or unsafe based on a limited set of safety metrics [11, 23, 51], particularly the out-of-bound (OOB) metric. The metric is largely adopted for assessing the safety behavior in STSG [23, 48, 51]. Both test cases illustrated in Figure 1 are classified using the OOB metric [12] and align with the human perception of safety.

However, it is yet unclear whether STSG metrics (e.g., OOB) serve as meaningful oracles for assessing the safety behavior of SDCs. For instance, the test cases in Figure 2 are marked pass according to the OOB metric, as the SDC is keeping the lane. On the contrary, from a human standpoint, we can consider the behavior of the SDC hardly as safe. In the first test case using the BeamNG.tech simulator [25], as shown in Figure 2a, the SDC approaches solid delineators after ignoring a speed bump. Despite maintaining its lane at a speed of 50 km/h, there is a high risk of an accident in classifying this test case as a technical pass based on the OOB metric. In the second test case using the CARLA simulator [20], shown in Figure 2b, the SDC ignores the red signal. Since the car stays in the lane, it meets the OOB metric, leading to a false passing test case.

Inspecting the OOB metric reveals that it is measured at a single point in time in simulation, which is insufficient to identify unsafe behaviors. For instance, Figure 2a shows the speed bumps on the right lane, and evaluating the SDC at a single point is insufficient to assess its safety over these speed bumps. In such cases, having a time window will be more informative to assess the overall SDC behavior. Unlike real-world speed bumps, which are smooth and rounded, the test bumps have sharp edges that damage the SDC even at reasonable speeds (from a human viewpoint). Similarly, Figure 2b shows another instance where we observe the red light signal, but the SDC ignores it. It is unclear whether the red signal was already there before the SDC drove past it or the signal turned red just after the SDC analyzed the simulation scene. We hypothesize that current simulation-based testing of SDCs does not always align with the human perception of safety [23, 48, 51] and realism [5, 47, 55, 72], which are relevant aspects impacting the effective



(a) SDC in BeamNG.tech driving with 50 km/h close to obstacles

(b) SDC in CARLA crossing a red signal without stopping

Fig. 2. Examples of unsafe tests with valid OOB criteria

assessment of simulated-based test cases. Hence, our primary goal is to understand and characterize this mismatch by answering the following research question:

> When and why do safety metrics of simulation-based test cases of SDCs match human perception?

To answer our general research question (i.e., addressing the problem of *safety* and *realism* of test cases that are described in our motivating examples), we conducted an empirical study involving 50 participants using our framework named SDC-Alabaster. The framework employs virtual reality (VR) technologies [61] (i) to immerse humans in virtual SDCs so that they can sense and experience the virtual environment as similar as possible to the real world, and (ii) to enable SDC developers and researchers to analyze the human perception of *safety* and *realism* of SDC test cases. The participants in our study are asked to assess the level of *safety* and *realism* of multiple, diverse simulation-based test cases. Moreover, we provide the participants to experience simulation-based test cases in which they have the possibility to influence the behavior of (i.e., interact with) the SDC. For this purpose, we experimented with two representative SDC simulators as virtual environments, BeamNG.tech and CARLA, which are widely used in academia and industry [1, 23].

The paper contributes and complements previous research as follows:

- we propose the SDC-Alabaster framework to assess simulation-based SDC test cases from a human point of view with VR;
- we investigate the perceived level of *safety* and *realism* of simulation-based SDC test cases by conducting an empirical study with 50 participants. We publicly share a replication package with the code to reproduce our results (Section 9);
- we develop a taxonomy on impacting factors on the perceived realism of SDC simulators and provide a discussion on confounding factors and implications of our work.

The paper covers background (Section 2), study design (Section 3), our framework, experiments, and methodology. Section 4 presents our results, followed by discussions in Section 5 and threats to validity in Section 6. We discuss related work and conclusions in Section 7 and Section 8.

2 BACKGROUND

This section provides a background on existing technologies used in our study, such as simulators, test generators, and test runners for SDCs, as well as VR technology.

2.1 SDC simulators

We investigate when the safety metrics of STSG for SDCs match the human perception. To answer this question, we use two state-of-the-art SDC simulators namely BeamNG.tech, and CARLA. They are among the used SDC simulators widely used in academia and practice [20, 23, 28, 46, 51, 77]. Furthermore, they implement fundamentally different physics behaviors.

2.1.1 BeamNG.tech. We use BeamNG.tech simulator as a well-known reference technology used in recent years in several studies and software engineering competitions on testing SDCs [11, 12, 23, 26, 51]. The BeamNG.tech simulator comes along with a soft-body physics engine that allows the simulation of body deformations and therefore more realistic simulations regarding crashes and impacting forces on objects.

2.1.2 CARLA. Another widely used simulator in academia and practice is CARLA [20, 28, 33, 46, 77, 79]. The differences between CARLA and BeamNG.tech are twofold. On the one hand, CARLA comes with a rigid-body physics engine, which works differently than the soft-body physics engine of BeamNG.tech. A rigid-body simulation environment does not deform objects; e.g., when a crash happens, the objects remain rigid.

2.2 Test generators & Test Runner

Both simulators require descriptions of the test case scenarios and we use existing test generators to automatically generate test cases for them. Concretely, we use test generators from the tool competition of the *Search-Based Software Testing* workshop [23, 51]. The actual road in the simulation environments is the result of interpolating the road points that are generated by the test generator.

In order to run test cases in simulation environments, we need a test runner that manages the execution of the test cases and reports the test outcomes. We use the SDC-Scissor [11] tool, which integrates a test selection strategy for simulation-based test cases. We use SDC-Scissor since it has implemented a test runner that monitors the OOB metrics, which is suitable for our study.

2.3 Virtual reality

The notion of VR refers to the immersive experience of users being inside a virtual world. In our study, we want to provide the study participant with an immersive experience of the test cases, to have more accurate feedback on their perception of the safety and realism of SDC. We leverage VR headsets and tooling for the simulation environments to achieve this goal.

2.3.1 Headset & VR connection with simulation environments. We use the HTC Vive Pro 2 headset to provide the study participants with a 360° VR experience, which offers an unrestricted view compared to a standard monitor. The headset connects via wire to an external device with a dedicated GPU for high-resolution VR rendering. Most SDC simulators do not support VR out of the box. This is also the case for BeamNG.tech and CARLA. Therefore, for our study, we use third-party tools to enable the missing VR support for both simulators.

For BeamNG.tech, we use vorpX, a specialized tool to transform any visual output to the screen to a compatible input for VR headsets so that it provides an immersive feeling for the user. The vorpX software gives a broader view angle when wearing a VR headset. The user can move the head and can explore the virtual environment according to its head movement. In the case of the CARLA simulator, Silvera et al. [61] implemented an extension of CARLA, allowing the simulator to be compatible with the HTC Vive Pro 2 VR headset. When launching the CARLA application, passing the `-VR` flag puts the simulator into VR mode so that can be used with the headset.

3 METHODOLOGY

Overall, our research aims to explore how safety metrics, i.e., OOB, match human perception. Specifically, we investigate the factors that make simulation-based SDC test cases safe or unsafe. Hence, with SDC-Alabaster (see Section 3.3.2), we conducted an empirical study involving 50 participants (recruiting explained in Section 3.4), with several steps (summarized by Figure 3) devised to collect different types of evidence and data to answer our main question: *When and why do safety metrics of simulation-based test cases of self-driving cars match human perception?* For this purpose, the usage of SDC-Alabaster immerses the study participants in virtual SDCs within widely used virtual environments, thanks to VR technologies (as detailed in Section 3.3).

3.1 Research questions

We structured our study around three main research questions (RQs).

3.1.1 RQ_1: Human-based assessment of safety. Our first research question is:

> RQ_1: To what extent does the OOB safety metric for simulation-based test cases of SDCs align with human safety assessment?

RQ_1 explores participants' perceptions of SDC test failures and safety levels with and without VR technology. We hypothesize that the OOB safety metric in software engineering may not align with human safety perception. We evaluate alignment through Likert-scale responses from participants, correlating it with test case outcomes (Section 4.1). Statistical tests on experimental and survey data are used to investigate the impact of simulators (BeamNG.tech vs. CARLA), driving views (outside and driver's view), and test case complexity (with/without obstacles/vehicles) on SDC safety perception.

3.1.2 RQ_2: Impact of human interaction on the assessments of SDCs. Once we know how humans perceive the safety of SDC test cases and how this is related to the OOB metric (RQ_1), we investigate whether human-based interactions with the virtual SDC affect the safety perception of the test case. We argue that the safety perception of a SDC can vary when having the ability to interact, i.e., the possibility to accelerate and deaccelerate the vehicle manually, and previous VR research has shown that interactions can influence the environment positively or negatively [31, 32, 34, 39, 45, 50, 53, 57]. This aspects deserves investigation since it can help developers and researchers in designing better test cases and evaluation metrics, which lead us to our second research question:

> RQ_2: To what extent does the safety assessment of simulation-based SDC test cases vary when humans can interact with the SDC?

3.1.3 RQ_3: Human-based assessment of Realism. We argue that the level of realism of SDC simulation-based test cases is another important factor influencing the safety perception of SDCs. It is important to note that the notion of realism relates to the *Reality Gap* [5, 47, 55, 72] (see Section 7), which is a critical concern regarding the oracle problem in simulation-based testing: *"due to the different properties of simulated and real contexts, the former may not be a faithful mirroring of the latter"*. While recent studies provide solutions for addressing the reality gap, e.g., by leveraging domain randomization techniques or using data from real-world observations [15, 38, 78], in the development phase of CPS, there is no prior study that studied and/or characterized the perception of realism of SDC test cases from human participants when using VR technologies [31, 45, 53]. Hence, to complement RQ_1 and RQ_2, our study addresses the following third research question:

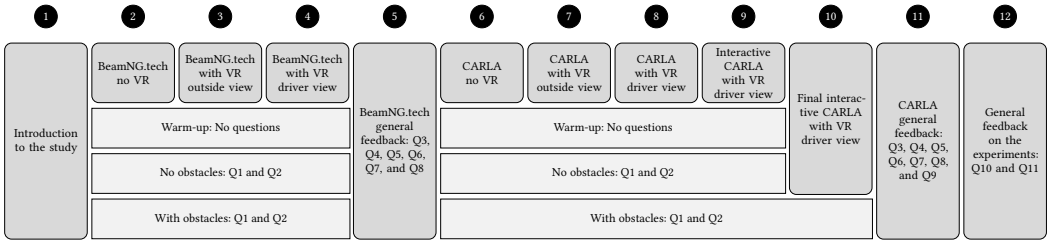


Fig. 3. Design overview with survey question IDs from Table 1

> RQ_3: What are the main reality-gap characteristics perceived by humans in SDC test cases?

Hence, after the experiments for RQ_1 and RQ_2, we ask the study participants to evaluate the level of realism for BeamNG.tech and CARLA. Then, we develop a taxonomy of aspects influencing these environments' realism to help improve simulation environments for effective testing of SDCs so that different properties of simulated and real contexts are minimized.

3.2 Design overview

Figure 3 overviews the design of our study involving 12 steps:

In step ❶, we welcome and introduce the study participant by explaining the context and the procedure for the experiments. The participant in step ❷ sits before a computer screen and experiences three simulation-based test cases with the BeamNG.tech simulator. While sitting before a computer, the participant wears a VR headset for the next steps. In step ❸, the participant experiences three test cases with the BeamNG.tech simulator observing the SDC from an *outside view* perspective while in step ❹, the participant experiences three test cases with the BeamNG.tech simulator from a *driver view* perspective. The step ❺ focuses on general feedback on the experiments with the BeamNG.tech simulator. Then, the steps ❷,❸,❹ are repeated for the CARLA simulator in ❻, ❼, ❽. In step ❾, for the CARLA simulator, the participant, while wearing a VR headset from a driver's view, experiences three test cases in which they can control the SDC speed with a keyboard. In addition to step ❾, one group of participants in step ❿ will experience a crash with the SDC. The step ⓫ focuses on general feedback on the experiments with the CARLA simulator while the step ⓬ focuses on general feedback on the overall study.

For the steps ❷ - ❹, and ❻ - ❾, the participant experiences three test cases. The first test case is the warm-up so that the participant can familiarize himself or herself with the simulation environment. The second test case has no obstacles, and the third test case has obstacles (i.e., has higher complexity). At step ❿, the participant only experiences the complex test case with obstacles.

3.3 Design implementation

We implement our design by conducting experiments with our test runner called SDC-Alabaster. The test runner uses three distinct test cases created by a test generator (see Section 2.2). The participants give responses to our survey questionnaires using *Google Forms*.

3.3.1 Test cases. We use three distinct test cases generated by the *Frenetic* test generator [14] for different purposes. The first test case is the warm-up that lets the participant familiarize with the simulation environment and view setting, e.g., to get used to the VR headset and the simulator.

Table 1. Survey questions with Likert-scale (LS), Open answer (OA), and Single-choice (SC) types

ID	Question	Type
Q1	What is the perceived safety of the Scenario?	LS
Q2	Justify the perceived safety of the Scenario.	OA
Q3	How would you scale the realism of scenarios generated by test cases in the simulator?	LS
Q4	Justify the level of realism of scenarios generated by test cases.	OA
Q5	How would you scale the driving of AI of the simulator?	LS
Q6	Justify the driving of AI from the simulator.	OA
Q7	How would you scale overall experience with the simulator?	LS
Q8	Justify overall experience with the simulator.	OA
Q9	How do you compare safety with and without interaction?	OA
Q10	Did this experiment change the way you thought about the safety of self-driving cars?	SC
Q11	Please write in a few words on your experience and suggestions.	OA

Hence, no survey question for this first warm-up test case is provided. The second test case does not have obstacles, while the third involves obstacles (higher complexity).

3.3.2 SDC-Alabaster. We extend the existing test runner SDC-Scissor (see Section 2.2) by implementing SDC-Alabaster (SDC hum**A**n-in-the **L**oop simul**A**tion-**BAS**ed **T**esting s**E**lf-driving ca**R**s). Specifically, we implement an interface to run test cases with the CARLA simulator for the steps ❻ - ❿. As for BeamNG.tech, with SDC-Alabaster we can also add obstacles to the test cases in CARLA to achieve similar complexity levels for the experiments. Additionally, with SDC-Alabaster, and for steps ❾-❿, the participants could control the SDC speed with the keyboard.

Test cases generated are processed differently between BeamNG.tech and CARLA since CARLA. An automatically generated test case in BeamNG.tech (Section 2) consists of a sequence of XY-coordinates (i.e., the road points). The CARLA simulator, however, does not need all the road points defined in the test. SDC-Alabaster segments road definitions, using only the start and end points of the segments to declare scenarios in CARLA. Moreover, it enables user immersion and safety evaluation by automatically adapting test case specifications for CARLA and utilizing VR headsets for immersive experiences in its virtual environment.

3.3.3 Survey questionnaires. We employ *Google Forms* for our questionnaires, a free and user-friendly survey tool. Table 1 summarizes participant questions, having multiple choice (MC), open answer (OA), and Likert scale (LS) questions (with values from 1-5, where 1 for very unsafe, 5 for very safe, and 3 for neutral). to address our research questions (RQs). Participants answered Q1 and Q2 after the second and third test cases, respectively, with the first test case serving as a warm-up without safety assessment. For Q3-Q8, participants provide responses after all three simulator test executions, i.e., at step ❺ for BeamNG.tech and step ⓫ for CARLA. Note that at step ⓫, we include an additional question, Q9, for experiments involving CARLA, which includes interactive scenarios requiring keyboard inputs to control the SDC's speed.

3.3.4 Experimental Setting. We conducted experiments in a dedicated, soundproof room to eliminate external distractions. Participants sat at a table equipped with a desktop computer, laptop, and a VR headset. They used the laptop running the *Google Forms* application to complete survey questionnaires and the desktop computer for non-VR experiments. For VR experiments, participants used the HTC Vive Pro 2 headset, known for its high visual resolution, powered by the *nVidia GeForce RTX 3080* and *Windows 10* operating system. Additional extensions were employed to allow a full VR experience to participants, such as vorpX for BeamNG.tech's VR support and the *DReyeVR* extension for CARLA, were used. We also integrated SDC-Alabaster to facilitate testing with both BeamNG.tech and CARLA simulators. Furthermore, the participants were allowed to interact with specific SDC test cases, with the keyboard enabling them to adjust the SDC's speed.

3.4 Study participants

We recruit participants via email invitations sent to our industrial partners, university students, and researchers across departments. We target various mailing lists, including non-computer science organizations, and leverage social media platforms such as Twitter and LinkedIn. We use physical and digital flyers to attract diverse participants, ensuring a broad range of backgrounds and education levels.

3.4.1 Pre-survey. When participants sign up for our experiments, we email them a pre-survey created with *Google Forms* to collect demographic information. This survey includes an introduction to the topic, an overview of the experiment (including approximate time and location), and a recommendation to wear contact lenses. It also provides details about the simulator and VR headset used. Furthermore, the pre-survey includes a disclaimer regarding confidentiality and anonymity and a warning about potential VR-related accidents or fatalities that the participants could experience. Following this section, we gather background information on participants, as detailed in the Appendix (appx.) of our replication package (Section 9). These questions cover testing and driving experience, VR technology usage, age, and gender. This additional information helps us investigate potential confounding factors affecting safety and realism perception.

3.5 Data collection

We gather data from two primary sources: the survey (both pre-experiment and during the experiments) and the simulation logs collected during participant experiments.

3.5.1 Survey data. For both BeamNG.tech and CARLA simulators, participants evaluate test cases considering the various questions reported in Table 1. Specifically, for steps ❷ - ❹ and ❻ - ❾, Likert-scale and text data are collected for each test case except the warm-up case. For step ❿, only Likert-scale and text data are collected for test cases with obstacles. Additionally, at steps ❺ and ⓫, general feedback on the simulators is collected after the test executions with all viewpoints. Complementary, participants rate the perceived safety and realism of each simulator using Likert-scale values based on their own driving experiences. Finally, general feedback on the experiments is collected at step ⓬. In total, we collected 21 Likert-scale, 23 open, and 1 single-choice response per participant during the experiments. In addition to the experimental survey, we gather data from the pre-survey (Section 3.4.1) to obtain participant demographics, mainly through single-choice and open-text responses.

3.5.2 Simulation data. For each test case in each participant's experiment, we collect relevant data, saving logs (see Section 9) in JSON files of SDC-Alabaster. These logs include timestamped vehicle position coordinates, sensor data (e.g., fuel, gear, wheel speed), and OOB metric violations (i.e., driving off the lane), categorizing the test as pass or fail based on this metric. Additionally, on CARLA, the log structure includes also weather condition details. It is important to note that to enhance our findings further, we also analyze participants' quantitative and qualitative insights both with and without VR headsets as well as when experiencing different driving views.

3.6 Data analysis

3.6.1 RQ_1 & RQ_2: Perceived level of safety. We utilize various visualizations, including stacked barplots and boxplots, to assess safety and realism perceptions. We apply statistical tests: Wilcoxon rank-sum, and Vargha-Delaney to determine the effective size. For RQ_1, we mainly analyze responses from the test cases where the participant has no interaction with the SDC; for RQ_2, we analyze the data where the participant has some direct interactions with the SDC by a keyboard to control the vehicle's speed. In RQ_2, we explore how SDC interactions affect the safety and realism perceptions

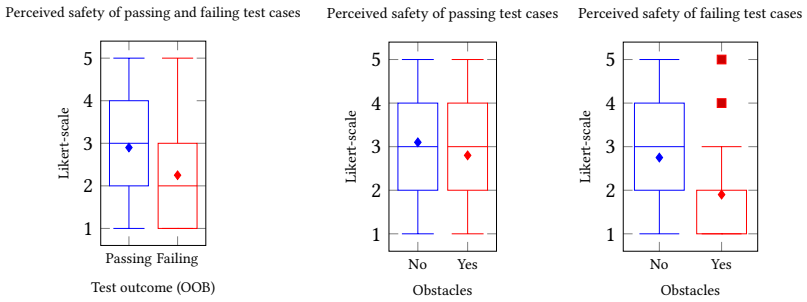


Fig. 4. Perceived safety of failing and passing tests grouped by scenario's complexity

of participants. For this, we analyze Likert-scale scores and qualitative feedback. We employ stacked bar plots to examine data spread across the two categories in steps ❽ and ❾.

3.6.2 RQ_3: Taxonomy on realism. With RQ_3, we examine the realism of SDC test cases and their correlation with human safety assessments. We identify and categorize factors affecting test case realism in a taxonomy based on the participant responses in question Q4 at steps ❺ and ⓫.

We adopt a two-step approach for the initial taxonomy creation. Initially, two authors analyze responses grouped by the simulators: one author focuses on Q4 from step ❺ with the BeamNG.tech simulator, and the other on Q4 from step ⓫ with the CARLA simulator. Each author proposes categories via an open-card sorting method [63]. In the second step, both authors collaboratively define a meta-taxonomy by discussing their proposed categories. Subsequently, this meta-taxonomy is employed to label all Q4 responses for BeamNG.tech and CARLA (steps ❺ and ⓫). To do this, the two authors responsible for the meta-taxonomy and a third author conduct a hybrid card sorting labeling process using online spreadsheets. They individually assign each response to the meta-taxonomy categories or create new categories when necessary. A collaborative approach is employed for validation, where each of the three co-authors reviews and addresses any disagreements in assignments during an online meeting.

4 RESULTS

In this section, we present the survey results for RQ_1, focusing on participants' safety perception of the test cases, and RQ_2, examining how this perception changes when participants can interact with the SDC. For RQ_3, we developed a taxonomy by classifying participants' comments on test case realism.

4.1 RQ_1: Human-based assessment of safety metrics

To address RQ_1, we analyzed Likert scale values across various data subgroups. These subgroups included comparisons between test outcomes (failures and successes based on OOB metrics) and different test case complexities (with and without obstacles). This allowed us to identify factors influencing perceived safety among participants. We present boxplots and statistical tests (appx. B.1) for each subgroup.

4.1.1 Safety perception of failing vs. passing test cases. Figure 4 illustrates perceived safety distributions for test cases grouped by test outcome (OOB metric). We found a significant difference (Table 5) in how participants rate safety for failing and passing test cases on a Likert scale.

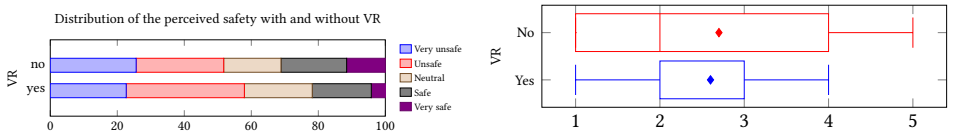


Fig. 5. VR vs. no VR

> *Finding 1:* The passing test cases (i.e., the cases where the OOB metric is not violated) have a higher perception of safety from the participants than those failing (OOB metric is violated).

The aforementioned Finding 1 is somewhat expected and is aligned with comments from study participants (appx. C.1). These comments pertain to the BeamNG.tech simulator, excluding VR and obstacles. We selected these comments for their exclusive focus on SDC lane-keeping, providing qualitative insights into the OOB metric without obstacle influence. Notably, among comments where the SDC violates the OOB metric (test case failure), safety concerns are recurrent: *"As the car did not drive all the time on the street, I felt unsafe. [...]."- (P3/B1/S1)*"; *"When the car starts to go off the road when driving in a curve, it feels pretty unsafe."- (P31/B1/S1)*"; *"Not Very Safe since the car sometimes drove a bit from the road."- (P45/B1/S1).*

On passing test cases where the OOB metric is not violated, we can find that the participants gave consistent comments in terms of safety: *"The car was driving in lane and at a safe speed considering the road is empty." - (P16/B1/S1)*; *"The car was following the path in a safe way and was not speeding up too much." - (P25/B1/S1).*

All comments that support Finding 1 are listed in appx. C.1.

4.1.2 Safety perception With and Without obstacles. Additionally, participants assessed test cases with varying complexity, including additional obstacles. Figure 4 displays differences in perceived safety, with statistical significance reported in appx. B.1. Concretely, failing test cases are generally seen as less safe, but those with added obstacles are perceived as even less safe. In contrast to passing test cases, perceived safety remains largely unaffected by the higher complexity of scenarios (e.g., additional obstacles). As shown in appx. B.1, no significant statistical differences were observed in the samples, leading us to conclude:

> *Finding 2:* There is no statistical difference in safety perception between scenarios with and without obstacles when the OOB metric is not violated. However, when the car goes out of bounds, the scenario is perceived as significantly less safe with obstacles ($p = 3.52 * 10^{-16}$).

From participants, we received qualitative support for Finding 2. For those feeling unsafe with scene obstacles, here are representative answers: *"The car crashed toward an obstacle and even running over bumps was not so smooth as humans would do. Definitively more unsafe than the previous scenario."- (P1/B1/S2)*; *"Ran off the road in a curve and hit obstacles without slowing down, which resulted in flat tires."- (P24/B1/S2).*

In participants who felt safe or neutral when obstacles were present, consistent comments were reported: *"It car was running smooth with obstacles, there was a moment when it was too close to one of the obstacle" - (P16/B1/S2)*; *"The vehicle does well to avoid obstacles while maintaining the safe speed" - (P18/B1/S2)*; *"The driver accelerated over all the obstacles and did not have a perfect finish." - (P40/B1/S2)*; *"Car was driving well. Only at the end it went off the road, but there was no object it bumped into." - (P45/B1/S2).*

All comments that support Finding 2 are reported in appx. C.1.

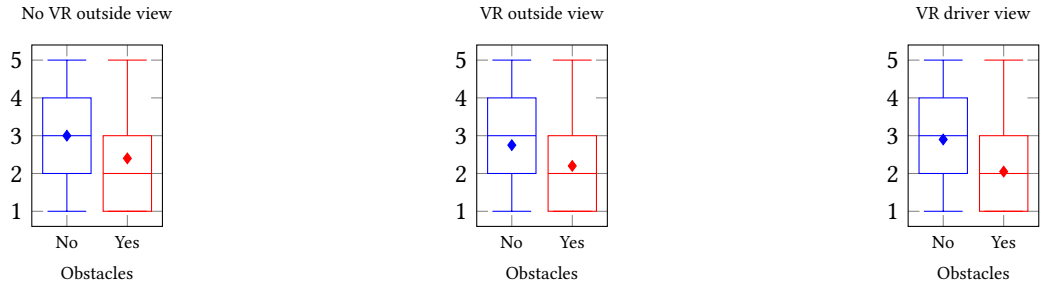


Fig. 6. Different VR-related views grouped by scenario's complexity

4.1.3 Safety perception, with VR and without VR. To assess the impact of VR on safety perception, we categorized data into *with VR* and *without VR* groups. Appx. B.1 shows no statistically significant difference. However, Figure 5 reveals that *without VR* has more *very unsafe* and *very unsafe* responses. This is also evident from the smaller interquartile range in *with VR* (compared to the *without VR*).

> *Finding 3:* The utilization of VR had a minor impact on safety perception. However, participants using VR tend to perceive scenarios as somewhat less safe, though this difference was not statistically significant (Wilcoxon rank-sum test, $p = 0.16$).

Certain participant comments support Finding 3. For instance, a neutral participant stated: *"The prespective doesnt change much with the vr" - (P22/B2/S1).* Another example is a comment from a participant who felt very unsafe: *"The same as without the VR glasses. The car was not able to keep the middle of the lane and was driving badly compared to a human." - (P28/B2/S1).*

4.1.4 Different views with different complexity. In Figure 6, we note a decrease in test case safety perception across various viewpoints. Statistical differences are evident in appx. B.1, supporting the following general finding:

> *Finding 4:* Overall, participants found the test cases less safe with obstacles.

Participants' general comments during the experiment for each simulator qualitatively support Finding 4. Representative comments on BeamNG.tech driving behavior include: *"It did not look at safety lines, which is very dangerous if other traffic is involved. It also ran off the road multiple times, which can easily lead to a loss of control. Also, the car rashed into easily avoidable obstacles." - (P24/B)*; *"At least the AI seems to have an understanding of the general elements of the simulation, like the road. However, it seems to struggle with bumps in the middle of the road and also seems to drive too fast in curvy situations." - (P31/B).*

In the case of CARLA, we got the following representative comments on the driving behavior with regard to different complexity of the scenario: *"Except at the roundabouts, the car followed traffic rules, signals, and speed limits. However, it kept crashing and losing control in the roundabouts." - (P27/C)*; *"In most scenarios, the AI did well. From what I have seen during the simulations, it is not able to drive around roundabouts and does not stop at stop signs." - (P31/C)*; *"very slow driving, unsmooth behavior, always too close to roundabout and abrupt stopping in front of obstacles." - (P41/C).*

We observe that the perception of safety drops when increasing the complexity (i.e., adding obstacles to the scenario). This observation is coherent among both simulators, BeamNG.tech and CARLA, as reported by the participants during the experiment.

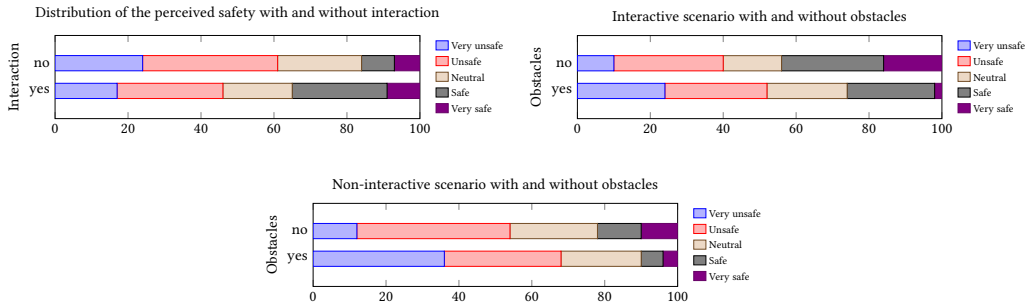


Fig. 7. Safety perception with and without interaction with the SDC (grouped by complexity)

4.2 RQ_2: Impact of human interaction on the assessments of SDCs

To assess the safety perception of test cases with human interaction with the SDC, participants controlled SDC speed during the test execution. Figure 7 shows the Likert scale of responses. We compare responses when participants can or cannot control the car and when obstacles are present.

4.2.1 Safety perception with and without interaction with the SDC. In general, interacting with the SDC enhances participants' perception of safety. From appx. B.2, we observe a statistically significant difference, leading to the following finding:

> *Finding 5:* Safety perception of test cases is not static: When users can interact with the SDC, participants feel significantly safer ($p = 0.013$) compared to when they cannot.

The participants' justification supports Finding5, e.g., controlling the SDC speed enhances safety perception, as P1 reported: *"The fact I could control the car when needed gave me a safer perception of the driving experience. Moreover, I could speed up the car when I wanted to." - (P1).* However, not all participants perceive interaction-based test cases as inherently safe. For instance, participant P4 comments: *"With a bit of control, it feels safer, especially being able to adjust the speed in dangerous situations. However, it is still not safe since the car ends up going off-road at the end of the scenario." - (P4).* While the SDC remains self-steering, it may still crash despite having speed control capability.

4.2.2 Safety perception for with and without obstacles. When interactive test cases involve obstacles, participants perceive them as less safe than obstacle-free scenarios, a statistically significant difference, leading to the following finding:

> *Finding 6:* Incorporating obstacles into the simulation, where participants interact with the SDC, leads to significantly lower perceived safety in test cases ($p = 0.026$) compared to obstacle-free interactive scenarios.

This finding is also coherent with the answers of the study participants, e.g., by P4: *"It felt safer, especially since it was stopping the speed when it had another car in front. However, it still went to the footpath, making it not safe" - (P4).* From the comment, we observe safer perception through speed control. P20 also states: *"it could have stopped before hitting the camion" - (P20).*

However, as the study participant cannot control the SDC's steering, some accidents remain unavoidable, as reported by P19: *"Hit the bike driver" (P19).* P40 gives a clearer comment: *"Two matters: 1) driver keeps its distance to the can in the front, but with sharp breaks instead of slowing down the car. 2) unable to avoid strange behaviors and drove next to a car with unstable drive and*

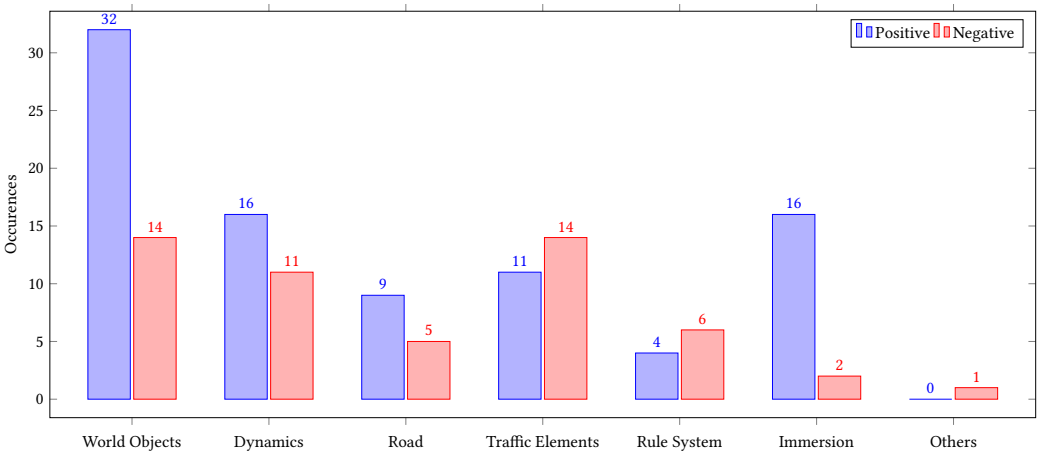


Fig. 8. Taxonomy of positive and negative factors impacting the perceived test cases' realism.

had an accident" (P40). The participant can maintain distance by adjusting speed, but accidents can occur during lane changes.

In non-interactive test cases, obstacles induce insecurity among participants. However, the level of how they feel unsafe when obstacles are included is higher in the case where the participants can interact with the SDC. This leads to the following finding:

> *Finding 7:* In the simulation, obstacles in non-interactive SDC test cases reduce safety perception ($p = 0.013$). Yet, the ability to interact with the car raises more discomfort (making participants feel less safe) when obstacles are present.

Besides the statistical tests, we also note participant comments supporting Finding 7. Some express discomfort in obstacle scenarios without the ability to control the car, as evident in the following example: *"The car was breaking and accelerating a lot while being behind the other car, and also the other car was not behaving safely on the road, ending the simulation with an accident between the two, so it felt quite unsafe overall." (P25).* Some participants also experience the worst-case scenario without control, as reported by P28: *"It drove extremely close up to the ambulance car and finally crashed into it. therefore, the worst case happens." (P28).*

4.3 RQ$_3$: Taxonomy on realism

Realism is a crucial aspect to consider when evaluating test case *safety*. We created a taxonomy to gauge the perceived realism of study participants. Two coders used open card sorting on 50 comments each to establish categories, which were later reviewed by a third coder. Table 2 presents the seven resulting categories with their descriptions.

Next, two coders independently classified 100 comments using the designed taxonomy. Disagreements were resolved by a third coder. Table 2 and Figure 8 show the classification of comments related to question Q4 in steps ❺ and ⓫. We categorized comments as *positives* (increasing realism) and *negatives* (decreasing realism) in the taxonomy. We observe that most classifications fall under *World Objects*, totaling 46, with 32 positives and 14 negatives.

Table 2. Taxonomy description including # of positive and negative comments on the perception of realism

Category	Description	Occurrences		
		Positive	Negative	Total
World Objects	This category relates to comments of participants on the accuracy of visual looks and design of all elements in the virtual environment, such as the weather, landscape, car design, traffic objects, etc., and how the graphical resolution is perceived.	32	14	46
Dynamics	This category relates to participants' comments on the physical dynamics of the elements in the virtual environment. For example, if the movement of the cars is physically realistic and reasonable or if crashes are realistically simulated from a physical perspective.	16	11	27
Road	This category relates to participants' comments on the road itself; to what extent the shape, surface, and structure are reasonably expected in the real world.	9	5	14
Traffic Elements	This category relates to participants' comments on the placement of the elements in the virtual environment. Furthermore, this category considers comments on the location and scale of the placed elements but also the quantity of the elements.	11	14	25
Rule System	This category relates to participants' comments on the traffic laws and the common sense of humans for resolving certain issues in specific traffic situations. A car should, for example, stop at a red signal and stop signs. Furthermore, the car should not drive recklessly and avoid dangerous situations (e.g., driving too close to other vehicles).	4	6	10
Immersion	This category relates to participants' comments on the immersive experiences. It applies to comments where participants express their feelings on how they experience the virtual environment and how they acoustically, visually, physically, and haptically sense it.	16	2	18
Others	This category relates to participants' comments that do not fit into the above categories.	0	1	1

Finding 8: Several factors (e.g., the surroundings, car design, and object scale) impact the participants' perceived realism. The *World Objects* category dominates with 32 *positive* (e.g., car design) and 14 *negative* (e.g., traffic objects) aspects affecting realism perception.

Examples of positive comments with the BeamNG.tech simulator: *"The realism is quite good, especially in the car design. The car structure was damaged after crashing; the wheels were getting broken, and there was smoke coming out. The inside view of the car was also pretty real, with the driver's hand moving the steering wheel and all the car panel commands. [...] ." - (B/P4)*; *"They respect the scale from the objects." - (B/P22)*. Examples of positive comments for the CARLA simulator: *"The surroundings have more detail, which made it feel more realistic." - (C/P31)*; *"The environment (lighting, obstacles) feels quite real." - (C/P17)*. An example of a negative comment: *"The grass, the horizon as well, and the red vertical lines do not look very realistic." - (B/P3)*. Besides finding in Section 8, we noted that the *Immersion* category generally received positive comments about perceived realism.

Finding 9: The *Immersion* category primarily comprises comments on factors that affect realism (e.g., view, perspective). It includes 16 *positive* (e.g., the realism of driver's seat) and 2 *negative* (e.g., low realism outside the vehicle) comments influencing participants' perceived realism.

This finding is reasonable since a driver sits in the driver's seat, unlike the perspective in a video game. The following quotes support this: *"The driver seat simulator felt very realistic." - (B/P14)*; *"It was different when I sat in the car than from outside, so it felt more real. But still looked like a game, so not that realistic." - (B/P21)*. In summary, comments on *Immersion* were positive, indicating that the driver seat viewpoint and VR usage enhanced perceived realism.

5 DISCUSSION

We first discuss safety considerations for simulation-based tests, including RQ_1 and interactive test cases RQ_2. Then, we delve into realism by discussing the taxonomy of influencing factors.

5.1 RQ_1 & RQ_2: Human-based safety assessment of simulation-based test cases

The study participants perceived passing test cases (OOB metric not violated) as safer than failing ones (Finding 1), aligning with the OOB metric-based test oracle. This observation is supported by [36], where participants' assessment of driving quality correlates with metrics related to the SDC's lateral position. The OOB metric generally reflects test case safety. However, the extent to which the safety perception varies depending on certain simulation factors (e.g., obstacle inclusion) remains unclear. Hence, we conducted experiments with test cases featuring additional obstacles.

In Section 2, we found that adding obstacles to a passing test case does not significantly affect safety perception. However, participants perceive failing test cases as less safe with additional obstacles. Therefore, human safety perception does not proportionally align with the OOB metric. The OOB metric can be violated, but it still does not distinguish the case if there are additional obstacles in the test case, but the human does and perceives the test case unsafer.

We experimented with different immersion levels (i.e., various viewpoints), and as reported in Finding 3, participants using VR headsets perceived test cases as slightly less safe. This perception change is minimal when evaluating VR. Consequently, when using humans as oracles, outcomes vary based on immersion levels in virtual environments. Hence, similar human-based studies on simulation-based test cases for SDCs [36] may exhibit a slight bias if immersion is not considered. When grouping safety perceptions of test cases by their assessed viewpoints, cases with obstacles were generally perceived as less safe than those without obstacles (Finding 4). Thus, using the OOB metric as an oracle may not always accurately represent safety perceptions from a human perspective. This observation aligns with the example illustrated by Figure 2a and Figure 2b.

As shown in Finding 5, participants perceived test cases as safer when they could control the vehicle's speed (i.e., they express a higher trust level in the SDC behavior), which means that the safety perception of simulation-based test cases depends on the user interaction levels. Having control over the vehicle impacts safety perception, which may not align with the OOB metric. In the case of test cases involving participant interaction, safety perception generally decreases when obstacles are present, as indicated by Finding 6. This aligns with the findings for non-interactive test cases, as highlighted in Finding 7.

5.2 RQ_3: Taxonomy on test cases' realism

As shown in Finding 8, most participants' comments on Question Q4 fall under the *World Objects* category. As discussed in Section 1, we conjecture that assessing test case safety should also consider realism. The importance of *World Objects*, with respect to realism, confirms the fact that pure lane-keeping (as it is the focus of OOB) is not enough for doing a realistic safety assessment. Given that most comments related to test case realism are categorized as *World Objects*, it becomes essential to prioritize when evaluating test case safety. The *Immersion* category predominantly features comments expressing a positive or heightened sense of realism, as revealed in Finding 9. Participants' immersion, particularly their viewpoint, influences perceived realism. Notably, the driver seat perspective yields a higher realism perception, as evident in comments on Finding 9, consequently impacting safety perception. The importance of immersion, with respect to realism, confirms that static 2D assessment (again, as it is the focus for OOB) is not enough for doing a realistic safety assessment.

When we take a closer look at the participants' demographics and how they assess the level of realism, we observed that the participants in the age range between 18 and 30 years tend to assess the test cases 17% more realistically (Likert scale) than the older participants. Another insight is that we do not observe a different assessment of realism among the genders. Hence, there are confounding factors that influence the perception of realism, such as the age of the participant. This aspect suggests that the reality-gap characteristics are not deterministic measures as they depend on the human perception that might vary, as for the case of the participants'age.

5.3 Implications & Lessons learned

The oracle definition for SDCs is many-fold as the safety has different aspects characterizing it. The OOB metric may not always reflect human safety perception in test cases due to various unaccounted factors. To enhance simulation-based testing, SDC testers and practitioners should consider devising alternative metrics that better align with human safety perception. Interacting with the car boosts perceived safety, potentially due to distrust in the AI driving the SDC. Future research should explore this further, ruling out other influencing factors. If low trust in AI is the main issue, this suggests shaping the direction of autonomous driving research toward increasing the level of trustworthiness of SDCs, which represents an important limiting factor to SDC real-world adoption.

As motivated in Section 1, realism significantly influences the safety perception of SDCs, as reflected in participants' comments on Q4. For this reason, we have created a taxonomy of factors that affect realism in simulation-based SDC testing, to guide future research in the field. The taxonomy provides an overview of factors impacting the realism of SDC simulation-based testing. We argue that our taxonomy is instrumental in supporting future research on the *perceived reality-gap*, which is critical to bridge the gap between the simulation-based outcome of a test case and what happens eventually in the real world. Furthermore, we think the taxonomy provides a base for investigating similar limitations in other CPS application domains, which leverage simulation environments and target to improve the human perception of the realism and safety of CPSs.

6 THREATS TO VALIDITY

6.1 Threats to internal validity

The study participants rated safety and realism based on their immersion into the scenario. To limit the risks of unbiased assessments, we employed modern VR technology (HTC Vive Pro 2) to enhance immersion. The simulators, BeamNG.tech and CARLA, utilize distinct predefined maps. BeamNG.tech employs a flat map from the SBST tool competition [51], while CARLA uses built-in urban-like maps, which impose some constraints on road definition. These differing maps may lead to varying perceptions of test case safety and realism due to their distinct natures. This is something we plan to investigate for future work.

The different personal interactions with the study participants might influence the participants' focus during the experiments. To limit this risk, we used a protocol sheet during the experiments to ensure that all steps of the experiments were equally performed to minimize this threat.

6.2 Threats to external validity

We recruited study participants primarily from an academic computer science background, which may not represent the general population. To address this potential bias, we ensured diversity in terms of age, gender, and driving experience, reducing the influence of factors beyond professional background. Another concern is the focus on the OOB metric, which may introduce bias as there are various metrics for evaluating SDCs in simulation environments. We chose OOB due to its

widespread use among researchers and practitioners, as documented in recent studies [12, 23, 26, 36, 51]. Our study's limited use of only two simulators, BeamNG.tech and CARLA, restricts the generalizability of our findings to these specific platforms. However, we selected them because they are widely adopted in academia and industry, ensuring the reproducibility of our results compared to less-maintained options such as Udacity[1] and SVL [56].

7 RELATED WORK

In this section, we elaborate on related work on testing in virtual environments and assessing the quality of oracles in the context of CPS. We group the recent and ongoing research concerning topics that are relevant to our investigation such as (i) simulation-based testing, (ii) the testing metrics adopted, the oracle problem, and (iii) VR in software engineering.

7.1 Simulation-based testing

The automated testing of Cyber-Physical Systems (CPSs) remains an ongoing research challenge [62]. In this context, simulation-based testing emerges as a promising approach to enhance testing practices for Safety-Critical Systems (SDC) [11, 12, 48, 54] and to support test automation [5, 6, 71, 72, 75]. Past research on testing CPS in simulation environments focused on monitoring CPS and predicting unsafe states [62, 66] of the systems using simulation environments [66, 76] as well as generating scenarios programmatically [52] or based on real-world observations [22, 65]. Recent research also proposed cost-effective regression testing techniques, including test selection [11], prioritization [8, 12] and minimization techniques to expose CPS faults or bugs earlier in the development and testing process. This research effort fundamentally contributed toward more robust and reliable simulation-based testing practices. However, it remains challenging to replicate the same bugs observed in physical tests within simulations [4, 72] and generate representative simulated test cases that uncover realistic bugs [5]. Hence, previous research in the field was conducted on the premise that simulation environments sufficiently represent, with high fidelity, safety-critical aspects of the real world according to human judgments. In our paper, we hypothesize that the current simulation-based testing of SDCs (and general CPSs) does not always align with the human perception of safety and realism, which heavily impacts the effectiveness of simulation-based testing in general. To that end, in our research, we investigated when and why the safety metrics of simulation-based test cases of SDCs match human perception.

7.2 Testing metrics & the Oracle Problem

To automatically infer the expected test outcome from a given input remains an unsolved challenge, which is known as the oracle problem. Many research papers propose some techniques to address this problem into the context of traditional software systems such as generating oracles [7] or improving already existing test oracles [35, 68–70]. In either case, the previous research do not show an approach that produce fully optimal and effective oracles. However, while the oracle problem still remains an open challenge which requires humans to define the oracle, for the sake of test automation, several code coverage and mutation score metrics have been proposed for for quantitatively assessing the quality of traditional software systems.

Software engineering for CPS is increasingly explored, with recent efforts mainly focused on bug characterization [24], testing [2, 19, 80], and verification [16] of self-adaptive CPSs. Another emerging area of research is related to the automated generation of oracles for testing and localizing faults in CPSs based on simulation technologies. For instance, Menghi *et al.* [43] proposed SOCRaTes, an approach to automatically generate online test oracles in Simulink able to handle CPS Simulink

[1] https://github.com/udacity/self-driving-car

models featuring continuous behaviors and involving uncertainties. The oracles are generated from requirements specified in a signal logic-based language. In this context, for the sake of test automation, just like traditional software testing, simulation-based testing of SDCs relies on an oracle that determines whether the observed behavior of a system under test is safe or unsafe. To that end, current research on automated safety assessment focuses primarily on a limited set of temporal and non-temporal safety metrics for SDCs [11, 23, 51, 67]. In particular, the out-of-bound (OOB) non-temporal metric is largely adopted for assessing SDCs in simulation-based testing [23, 48, 51], to determine if a test case fails or passes. However, it is yet unclear whether this metric serves as a meaningful oracle for assessing the safety behavior of SDCs in simulation-based testing in general.

This study is built on our hypothesis that current simulation-based testing of SDCs does not always align with the human perception of safety and realism, and for this reason, we focus on understanding and characterizing this mismatch in our research. Close to our work, a recent study [36] conducted a human-based study and observed that correlations between the computed quality metrics and the perceived quality by humans are meaningful for assessing the test quality for SDCs. However, such previous work did not investigate the factors that define the test quality and realism of the simulation environments from a human point of view with the use of virtual reality [61] as done in our work.

A critical concern concerning the oracle problem in simulation-based testing is represented by the *Reality Gap* [5, 47, 55, 72]. Due to the different properties of simulated and real contexts, the former may not be a faithful mirroring of the latter. Simulations are necessarily simplified for computational feasibility yet reflect real-world phenomena at a given level of veracity, the extent of which is the result of a trade-off between accuracy and computational time [17]. Robotics simulations rely on the replication of phenomena that are difficult to accurately replicate, e.g., simulating actuators (i.e., torque characteristics, gear backlash), sensors (i.e., noise, latency), and rendered images (i.e., reflections, refraction, textures). This gap between reality and simulation is commonly referred to as the *reality-gap*[17]. A closely related problem concerns the concrete realistic *bug reproduction* and exposure in simulation environments [5, 72]. It is indeed challenging to capture the same bugs as physical tests [4, 72] and to *generate effective test cases* that can expose real-world bugs in simulation [5]. While recent studies provide solutions for addressing the reality gap (e.g., leveraging domain randomization techniques or using data from real-world observations) [15, 17, 38, 40, 58, 78] in the development phase of CPS, there is no prior study that investigated and/or characterized the perception of realism of SDC test cases from human participants. This study focuses on addressing this specific open question in the context of RQ3.

7.3 Immersion Technology in Software engineering

Furthermore, using VR for software engineering was also considered by [30, 42] but with another focus as well. They used VR to gain design knowledge from legacy systems by using diferent visualization approaches using immersion technologies. Furthermore, most papers [41, 59, 60] referring to the potential use of VR and AR for the workspace of software development teams. In general, the use of VR and AR in software engineering is not well studied yet, and the only papers available or mainly vision papers for future research [44]. However, in our work, we present a practical application of VR for assessing the test oracles with a Human-in-the-Loop approach.

8 CONCLUSION

Testing self-driving car (SDC) software, such as traditional software, relies on safety and quality oracles. However, depending solely on metrics such as the OOB for simulation-based SDC testing can be limited in terms of reliability and perceived realism from a human standpoint. In this study, we explored when and why safety metrics align with human perception in SDC testing. We conducted

an empirical study with 50 participants from diverse backgrounds, evaluating their perception of test case safety and realism. We observed that the safety perception of SDC significantly decreases as test case complexity rises. Interestingly, safety perception improves when participants can control the SDC's speed, indicating that OOB metric is not sufficient to match/model human (more subjective) factors. Additionally, realism perception varies with the complexity of scenarios (i.e., object additions) and different participant viewpoints. These findings emphasize the need for more meaningful safety metrics that align with human perception of *safety* and *realism* to bridge the current problem of the *reality-gap* in simulation-based testing. Future work should also consider other safety metrics, as suggested by recent studies [67], to enhance SDC software testing in simulation environments and improve safety and realism.

9 DATA AVAILABILITY

A replication package with data, code, and appendices is privately available for reviewers and openly available upon acceptance by a DOI: https://figshare.com/s/b3c9a7997a1233d26ae9

REFERENCES

[1] 2022. *International Conference on Intelligent Transportation Systems*. IEEE. https://doi.org/10.1109/ITSC55140.2022

[2] Raja Ben Abdessalem, Shiva Nejati, Lionel C. Briand, and Thomas Stifter. 2018. Testing vision-based control systems using learnable evolutionary algorithms. In *International Conference on Software Engineering*. 1016–1026. https://doi.org/10.1145/3180155.3180160

[3] Raja Ben Abdessalem, Annibale Panichella, Shiva Nejati, Lionel C. Briand, and Thomas Stifter. 2020. Automated repair of feature interaction failures in automated driving systems. In *International Symposium on Software Testing and Analysis*. ACM, 88–100. https://doi.org/10.1145/3395363.3397386

[4] Afsoon Afzal, Deborah S. Katz, Claire Le Goues, and Christopher Steven Timperley. 2020. A Study on the Challenges of Using Robotics Simulators for Testing. arXiv:2004.07368 https://arxiv.org/abs/2004.07368

[5] Afsoon Afzal, Deborah S. Katz, Claire Le Goues, and Christopher Steven Timperley. 2021. Simulation for Robotics Test Automation: Developer Perspectives. In *Conference on Software Testing, Verification and Validation*. IEEE, 263–274. https://doi.org/10.1109/ICST49551.2021.00036

[6] Miguel Alcon, Hamid Tabani, Jaume Abella, and Francisco J. Cazorla. 2021. Enabling Unit Testing of Already-Integrated AI Software Systems: The Case of Apollo for Autonomous Driving. In *Conference on Digital System Design*. IEEE, 426–433. https://doi.org/10.1109/DSD53832.2021.00071

[7] Aitor Arrieta, Maialen Otaegi, Liping Han, Goiuria Sagardui, Shaukat Ali, and Maite Arratibel. 2022. Automating Test Oracle Generation in DevOps for Industrial Elevators. In *International Conference on Software Analysis, Evolution and Reengineering*. IEEE, 284–288. https://doi.org/10.1109/SANER53432.2022.00044

[8] Aitor Arrieta, Shuai Wang, Goiuria Sagardui, and Leire Etxeberria. 2019. Search-Based test case prioritization for simulation-Based testing of cyber-Physical system product lines. *J. Syst. Softw.* 149 (2019), 1–34. https://doi.org/10.1016/j.jss.2018.09.055

[9] BBC. 2023. Robots to do 39% of domestic chores by 2033, say experts. https://www.bbc.com/news/technology-64718842. Accessed: 2023-01-04.

[10] BeamNG.tech. [n. d.]. BeamNG.research. https://documentation.beamng.com/beamng_tech/. Accessed: 2022-07-31.

[11] Christian Birchler, Sajad Khatiri, Bill Bosshard, Alessio Gambi, and Sebastiano Panichella. 2023. Machine learning-based test selection for simulation-based testing of self-driving cars software. *Empir. Softw. Eng.* 28, 3 (2023), 71. https://doi.org/10.1007/s10664-023-10286-y

[12] Christian Birchler, Sajad Khatiri, Pouria Derakhshanfar, Sebastiano Panichella, and Annibale Panichella. 2023. Single and Multi-objective Test Cases Prioritization for Self-driving Cars in Virtual Environments. *ACM Trans. Softw. Eng. Methodol.* 32, 2 (2023), 28:1–28:30. https://doi.org/10.1145/3533818

[13] Tim Bohne, Gurunatraj Parthasarathy, and Benjamin Kisliuk. 2023. A systematic approach to the development of long-term autonomous robotic systems for agriculture. In *43. GIL-Jahrestagung, Resiliente Agri-Food-Systeme (LNI, Vol. P-330)*. Gesellschaft für Informatik e.V., 285–290. https://dl.gi.de/20.500.12116/40260

[14] Ezequiel Castellano, Ahmet Cetinkaya, Cédric Ho Thanh, Stefan Klikovits, Xiaoyi Zhang, and Paolo Arcaini. 2021. Frenetic at the SBST 2021 Tool Competition. In *International Workshop on Search-Based Software Testing*. IEEE, 36–37. https://doi.org/10.1109/SBST52555.2021.00016

[15] Yevgen Chebotar, Ankur Handa, Viktor Makoviychuk, Miles Macklin, Jan Issac, Nathan D. Ratliff, and Dieter Fox. 2019. Closing the Sim-to-Real Loop: Adapting Simulation Randomization with Real World Experience. In *International*

Conference on Robotics and Automation. IEEE, 8973–8979. https://doi.org/10.1109/ICRA.2019.8793789

[16] Shafiul Azam Chowdhury, Sohil Lal Shrestha, Taylor T. Johnson, and Christoph Csallner. 2020. SLEMI: equivalence modulo input (EMI) based mutation of CPS models for finding compiler bugs in Simulink. In *International Conference on Software Engineering*. 335–346. https://doi.org/10.1145/3377811.3380381

[17] Jack Collins, Ross Brown, Jurgen Leitner, and David Howard. 2020. Traversing the reality gap via simulator tuning. *arXiv preprint arXiv:2003.01369* (2020).

[18] Hugo Leonardo da Silva Araujo, Mohammad Reza Mousavi, and Mahsa Varshosaz. 2023. Testing, Validation, and Verification of Robotic and Autonomous Systems: A Systematic Review. *ACM Trans. Softw. Eng. Methodol.* 32, 2 (2023), 51:1–51:61. https://doi.org/10.1145/3542945

[19] Jyotirmoy V. Deshmukh, Marko Horvat, Xiaoqing Jin, Rupak Majumdar, and Vinayak S. Prabhu. 2017. Testing Cyber-Physical Systems through Bayesian Optimization. *ACM Trans. Embed. Comput. Syst.* 16, 5s (2017), 170:1–170:18. https://doi.org/10.1145/3126521

[20] Alexey Dosovitskiy, Germán Ros, Felipe Codevilla, Antonio M. López, and Vladlen Koltun. 2017. CARLA: An Open Urban Driving Simulator. In *Annual Conference on Robot Learning (Proceedings of Machine Learning Research, Vol. 78)*. PMLR, 1–16. http://proceedings.mlr.press/v78/dosovitskiy17a.html

[21] Alessio Gambi, Tri Huynh, and Gordon Fraser. 2019. Automatically reconstructing car crashes from police reports for testing self-driving cars. In *International Conference on Software Engineering: Companion Proceedings*. IEEE / ACM, 290–291. https://doi.org/10.1109/ICSE-Companion.2019.00119

[22] Alessio Gambi, Tri Huynh, and Gordon Fraser. 2019. Generating effective test cases for self-driving cars from police reports. In *Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. ACM, 257–267. https://doi.org/10.1145/3338906.3338942

[23] Alessio Gambi, Gunel Jahangirova, Vincenzo Riccio, and Fiorella Zampetti. 2022. SBST Tool Competition 2022. In *International Workshop on Search-Based Software Testing*. IEEE, 25–32. https://doi.org/10.1145/3526072.3527538

[24] Joshua Garcia, Yang Feng, Junjie Shen, Sumaya Almanee, Yuan Xia, and Qi Alfred Chen. 2020. A comprehensive study of autonomous vehicle bugs. In *International Conference on Software Engineering*. ACM, 385–396. https://doi.org/10.1145/3377811.3380397

[25] BeamNG GmbH. 2023. BeamNG.tech. https://beamng.tech/

[26] BeamNG GmbH. 2023. Publications based on BeamNG.tech. https://beamng.tech/research/

[27] The Guardian. 2018. Self-driving Uber kills Arizona woman in first fatal crash involving pedestrian. https://www.theguardian.com/technology/2018/mar/19/uber-self-driving-car-kills-woman-arizona-tempe

[28] Rodrigo Gutiérrez-Moreno, Rafael Barea, Elena López Guillén, Javier Araluce, and Luis Miguel Bergasa. 2022. Reinforcement Learning-Based Autonomous Driving at Intersections in CARLA Simulator. *Sensors* 22, 21 (2022), 8373. https://doi.org/10.3390/s22218373

[29] Carl Hildebrandt and Sebastian G. Elbaum. 2021. World-in-the-Loop Simulation for Autonomous Systems Validation. In *International Conference on Robotics and Automation*. IEEE, 10912–10919. https://doi.org/10.1109/ICRA48506.2021.9561240

[30] Adrian Hoff, Michael Nieke, and Christoph Seidl. 2021. Towards immersive software archaeology: regaining legacy systems' design knowledge via interactive exploration in virtual reality. In *Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. ACM, 1455–1458. https://doi.org/10.1145/3468264.3473128

[31] Jiawei Huang and Alexander Klippel. 2020. The Effects of Visual Realism on Spatial Memory and Exploration Patterns in Virtual Reality. In *Symposium on Virtual Reality Software and Technology*. ACM, 18:1–18:11. https://doi.org/10.1145/3385956.3418945

[32] Jiawei Huang, Melissa S. Lucash, Mark B. Simpson, Casey Helgeson, and Alexander Klippel. 2019. Visualizing Natural Environments from Data in Virtual Reality: Combining Realism and Uncertainty. In *Conference on Virtual Reality and 3D User Interfaces*. IEEE, 1485–1488. https://doi.org/10.1109/VR.2019.8797996

[33] Carlos Gómez Huélamo, Javier del Egido, Luis Miguel Bergasa, Rafael Barea, Elena López Guillén, Juan Felipe Arango, Javier Araluce, and Joaquín López. 2022. Train here, drive there: ROS based end-to-end autonomous-driving pipeline validation in CARLA simulator using the NHTSA typology. *Multim. Tools Appl.* 81, 3 (2022), 4213–4240. https://doi.org/10.1007/s11042-021-11681-7

[34] Jonatan S. Hvass, Oliver Larsen, Kasper B. Vendelbo, Niels C. Nilsson, Rolf Nordahl, and Stefania Serafin. 2017. The effect of geometric realism on presence in a virtual reality game. In *Virtual Reality*. IEEE Computer Society, 339–340. https://doi.org/10.1109/VR.2017.7892315

[35] Gunel Jahangirova, David Clark, Mark Harman, and Paolo Tonella. 2016. Test oracle assessment and improvement. In *International Symposium on Software Testing and Analysis*. ACM, 247–258. https://doi.org/10.1145/2931037.2931062

[36] Gunel Jahangirova, Andrea Stocco, and Paolo Tonella. 2021. Quality Metrics and Oracles for Autonomous Vehicles Testing. In *Conference on Software Testing, Verification and Validation*. IEEE, 194–204. https://doi.org/10.1109/ICST49551.

2021.00030

[37] Sajad Khatiri, Sebastiano Panichella, and Paolo Tonella. 2023. Simulation-based Test Case Generation for Unmanned Aerial Vehicles in the Neighborhood of Real Flights. In *International Conference on Software Testing, Verification and Validation*. IEEE, 281–292. https://doi.org/10.1109/ICST57152.2023.00034

[38] Sylvain Koos, Jean-Baptiste Mouret, and Stéphane Doncieux. 2013. The Transferability Approach: Crossing the Reality Gap in Evolutionary Robotics. *IEEE Trans. Evol. Comput.* 17, 1 (2013), 122–145. https://doi.org/10.1109/TEVC.2012.2185849

[39] Joung Huem Kwon, John A. Powell, and Alan Chalmers. 2013. How level of realism influences anxiety in virtual reality environments for a job interview. *Int. J. Hum. Comput. Stud.* 71, 10 (2013), 978–987. https://doi.org/10.1016/j.ijhcs.2013.07.003

[40] Timothy E Lee, Jonathan Tremblay, Thang To, Jia Cheng, Terry Mosier, Oliver Kroemer, Dieter Fox, and Stan Birchfield. 2020. Camera-to-robot pose estimation from a single image. In *International Conference on Robotics and Automation*. IEEE, 9426–9432.

[41] Rohit Mehra, Vibhu Saujanya Sharma, Vikrant Kaulgud, Sanjay Podder, and Adam P. Burden. 2020. Immersive IDE: Towards Leveraging Virtual Reality for creating an Immersive Software Development Environment. In *International Conference on Software Engineering, Workshops*. ACM, 177–180. https://doi.org/10.1145/3387940.3392234

[42] Rohit Mehra, Vibhu Saujanya Sharma, Vikrant Kaulgud, Sanjay Podder, and Adam P. Burden. 2020. Towards Immersive Comprehension of Software Systems Using Augmented Reality - An Empirical Evaluation. In *International Conference on Automated Software Engineering*. IEEE, 1267–1269. https://doi.org/10.1145/3324884.3418907

[43] Claudio Menghi, Shiva Nejati, Khouloud Gaaloul, and Lionel C. Briand. 2019. Generating automated and online test oracles for Simulink models with continuous and uncertain behaviors. In *Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. 27–38. https://doi.org/10.1145/3338906.3338920

[44] Leonel Merino, Mircea Lungu, and Christoph Seidl. 2020. Unleashing the Potentials of Immersive Augmented Reality for Software Engineering. In *International Conference on Software Analysis, Evolution and Reengineering*. IEEE, 517–521. https://doi.org/10.1109/SANER48275.2020.9054812

[45] Elena Molina, Alejandro Ríos Jerez, and Núria Pelechano Gómez. 2020. Avatars rendering and its effect on perceived realism in Virtual Reality. In *International Conference on Artificial Intelligence and Virtual Reality*. IEEE, 222–225. https://doi.org/10.1109/AIVR50618.2020.00046

[46] Saasha Nair, Sina Shafaei, Daniel Auge, and Alois C. Knoll. 2021. An Evaluation of "Crash Prediction Networks" (CPN) for Autonomous Driving Scenarios in CARLA Simulator. In *Workshop on Artificial Intelligence Safety (CEUR Workshop Proceedings, Vol. 2808)*. CEUR-WS.org. http://ceur-ws.org/Vol-2808/Paper_10.pdf

[47] Anthony Ngo, Max Paul Bauer, and Michael Resch. 2021. A Multi-Layered Approach for Measuring the Simulation-to-Reality Gap of Radar Perception for Autonomous Driving. In *International Intelligent Transportation Systems Conference*. IEEE, 4008–4014. https://doi.org/10.1109/ITSC48978.2021.9564521

[48] Vuong Nguyen, Stefan Huber, and Alessio Gambi. 2021. SALVO: Automated Generation of Diversified Tests for Self-driving Cars from Existing Maps. In *International Conference on Artificial Intelligence Testing*. IEEE, 128–135. https://doi.org/10.1109/AITEST52744.2021.00033

[49] Nvidia 2020. NVIDIA DRIVE Constellation. https://developer.nvidia.com/drive/drive-constellation

[50] Nami Ogawa, Takuji Narumi, and Michitaka Hirose. 2018. Object Size Perception in Immersive Virtual Reality: Avatar Realism Affects the Way We Perceive. In *Conference on Virtual Reality and 3D User Interfaces*. IEEE Computer Society, 647–648. https://doi.org/10.1109/VR.2018.8446318

[51] Sebastiano Panichella, Alessio Gambi, Fiorella Zampetti, and Vincenzo Riccio. 2021. SBST Tool Competition 2021. In *International Workshop on Search-Based Software Testing*. IEEE, 20–27. https://doi.org/10.1109/SBST52555.2021.00011

[52] Mingyu Park, Hoon Jang, Taejoon Byun, and Yunja Choi. 2020. Property-based testing for LG home appliances using accelerated software-in-the-loop simulation. In *International Conference on Software Engineering*. ACM, 120–129. https://doi.org/10.1145/3377813.3381346

[53] Yi-Hao Peng, Carolyn Yu, Shi-Hong Liu, Chung-Wei Wang, Paul Taele, Neng-Hao Yu, and Mike Y. Chen. 2020. WalkingVibe: Reducing Virtual Reality Sickness and Improving Realism while Walking in VR using Unobtrusive Head-mounted Vibrotactile Feedback. In *Conference on Human Factors in Computing Systems*. ACM, 1–12. https://doi.org/10.1145/3313831.3376847

[54] Andrea Piazzoni, Jim Cherian, Mohamed Azhar, Jing Yew Yap, James Lee Wei Shung, and Roshan Vijay. 2021. ViSTA: a Framework for Virtual Scenario-based Testing of Autonomous Vehicles. In *International Conference on Artificial Intelligence Testing*. IEEE, 143–150. https://doi.org/10.1109/AITEST52744.2021.00035

[55] Fabio Reway, Abdul Hoffmann, Diogo Wachtel, Werner Huber, Alois C. Knoll, and Eduardo Parente Ribeiro. 2020. Test Method for Measuring the Simulation-to-Reality Gap of Camera-based Object Detection Algorithms for Autonomous Driving. In *Intelligent Vehicles Symposium*. IEEE, 1249–1256. https://doi.org/10.1109/IV47402.2020.9304567

[56] Guodong Rong, Byung Hyun Shin, Hadi Tabatabaee, Qiang Lu, Steve Lemke, Martins Mozeiko, Eric Boise, Geehoon Uhm, Mark Gerow, Shalin Mehta, Eugene Agafonov, Tae Hyung Kim, Eric Sterner, Keunhae Ushiroda, Michael Reyes, Dmitry Zelenkovsky, and Seonman Kim. 2020. LGSVL Simulator: A High Fidelity Simulator for Autonomous Driving. (2020), 1–6. https://doi.org/10.1109/ITSC45102.2020.9294422

[57] Daniel Roth, Jean-Luc Lugrin, Dmitri Galakhov, Arvid Hofmann, Gary Bente, Marc Erich Latoschik, and Arnulph Fuhrmann. 2016. Avatar realism and social interaction quality in virtual reality. In *Virtual Reality*. IEEE Computer Society, 277–278. https://doi.org/10.1109/VR.2016.7504761

[58] Erica Salvato, Gianfranco Fenu, Eric Medvet, and Felice Andrea Pellegrino. 2021. Crossing the Reality Gap: A Survey on Sim-to-Real Transferability of Robot Controllers in Reinforcement Learning. *IEEE Access* 9 (2021), 153171–153187. https://doi.org/10.1109/ACCESS.2021.3126658

[59] Vibhu Saujanya Sharma, Rohit Mehra, Vikrant Kaulgud, and Sanjay Podder. 2018. An immersive future for software engineering: avenues and approaches. In *International Conference on Software Engineering: New Ideas and Emerging Results*. ACM, 105–108. https://doi.org/10.1145/3183399.3183414

[60] Vibhu Saujanya Sharma, Rohit Mehra, Vikrant Kaulgud, and Sanjay Podder. 2019. An extended reality approach for creating immersive software project workspaces. In *International Workshop on Cooperative and Human Aspects of Software Engineering*. IEEE / ACM, 27–30. https://doi.org/10.1109/CHASE.2019.00013

[61] Gustavo Silvera, Abhijat Biswas, and Henny Admoni. 2022. DReyeVR: Democratizing Virtual Reality Driving Simulation for Behavioural & Interaction Research. In *International Conference on Human-Robot Interaction*, Daisuke Sakamoto, Astrid Weiss, Laura M. Hiatt, and Masahiro Shiomi (Eds.). IEEE / ACM, 639–643. https://doi.org/10.1109/HRI53351.2022.9889526

[62] Andrea Di Sorbo, Fiorella Zampetti, Aaron Visaggio, Massimiliano Di Penta, and Sebastiano Panichella. 2023. Automated Identification and Qualitative Characterization of Safety Concerns Reported in UAV Software Platforms. *ACM Trans. Softw. Eng. Methodol.* 32, 3 (2023), 67:1–67:37. https://doi.org/10.1145/3564821

[63] Donna Spencer. 2009. *Card sorting: Designing usable categories*. Rosenfeld Media.

[64] Jack Stilgoe. 2021. How can we know a self-driving car is safe? *Ethics Inf. Technol.* 23, 4 (2021), 635–647. https://doi.org/10.1007/s10676-021-09602-1

[65] Andrea Stocco, Brian Pulfer, and Paolo Tonella. 2023. Mind the Gap! A Study on the Transferability of Virtual Versus Physical-World Testing of Autonomous Driving Systems. *IEEE Trans. Software Eng.* 49, 4 (2023), 1928–1940. https://doi.org/10.1109/TSE.2022.3202311

[66] Andrea Stocco, Michael Weiss, Marco Calzana, and Paolo Tonella. 2020. Misbehaviour prediction for autonomous driving systems. In *International Conference on Software Engineering*. ACM, 359–371. https://doi.org/10.1145/3377811.3380353

[67] Shuncheng Tang, Zhenya Zhang, Yi Zhang, Jixiang Zhou, Yan Guo, Shuang Liu, Shengjian Guo, Yan-Fu Li, Lei Ma, Yinxing Xue, and Yang Liu. 2023. A Survey on Automated Driving System Testing: Landscapes and Trends. *ACM Trans. Softw. Eng. Methodol.* 32, 5 (2023), 124:1–124:62. https://doi.org/10.1145/3579642

[68] Valerio Terragni, Gunel Jahangirova, Mauro Pezzè, and Paolo Tonella. 2021. Improving assertion oracles with evolutionary computation. In *Genetic and Evolutionary Computation Conference, Companion Volume*. ACM, 45–46. https://doi.org/10.1145/3449726.3462722

[69] Valerio Terragni, Gunel Jahangirova, Paolo Tonella, and Mauro Pezzè. 2020. Evolutionary improvement of assertion oracles. In *Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. ACM, 1178–1189. https://doi.org/10.1145/3368089.3409758

[70] Valerio Terragni, Gunel Jahangirova, Paolo Tonella, and Mauro Pezzè. 2021. GAssert: A Fully Automated Tool to Improve Assertion Oracles. In *International Conference on Software Engineering: Companion Proceedings*. IEEE, 85–88. https://doi.org/10.1109/ICSE-Companion52605.2021.00042

[71] Christopher Steven Timperley, Afsoon Afzal, Deborah S Katz, Jam Marcos Hernandez, and Claire Le Goues. 2018. Crashing simulated planes is cheap: Can simulation detect robotics bugs early?. In *International Conference on Software Testing, Verification and Validation*. IEEE, 331–342.

[72] Dinghua Wang, Shuqing Li, Guanping Xiao, Yepang Liu, and Yulei Sui. 2021. An exploratory study of autopilot software bugs in unmanned aerial vehicles. In *Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. ACM, 20–31. https://doi.org/10.1145/3468264.3468559

[73] Lingfeng Wang and K.C. Tan. 2005. Software testing for safety critical applications. *IEEE Instrumentation & Measurement Magazine* 8, 2 (2005), 38–47. https://doi.org/10.1109/MIM.2005.1438843

[74] Franz Wotawa. 2019. On the Importance of System Testing for Assuring Safety of AI Systems. In *Workshop on Artificial Intelligence Safety 2019 co-located with the 28th International Joint Conference on Artificial Intelligence (CEUR Workshop Proceedings, Vol. 2419)*. CEUR-WS.org. https://ceur-ws.org/Vol-2419/paper_29.pdf

[75] Franz Wotawa. 2021. On the Use of Available Testing Methods for Verification & Validation of AI-based Software and Systems. In *Workshop on Artificial Intelligence Safety (CEUR Workshop Proceedings, Vol. 2808)*. CEUR-WS.org.

http://ceur-ws.org/Vol-2808/Paper_29.pdf

[76] Qinghua Xu, Shaukat Ali, and Tao Yue. 2021. Digital Twin-based Anomaly Detection in Cyber-physical Systems. In *Conference on Software Testing, Verification and Validation*. IEEE, 205–216. https://doi.org/10.1109/ICST49551.2021.00031

[77] Eleni Zapridou, Ezio Bartocci, and Panagiotis Katsaros. 2020. Runtime Verification of Autonomous Driving Systems in CARLA. In *Runtime Verification - International Conference (Lecture Notes in Computer Science, Vol. 12399)*. Springer, 172–183. https://doi.org/10.1007/978-3-030-60508-7_9

[78] Fangyi Zhang, Jürgen Leitner, Zongyuan Ge, Michael Milford, and Peter Corke. 2019. Adversarial discriminative sim-to-real transfer of visuo-motor policies. *Int. J. Robotics Res.* 38, 10-11 (2019). https://doi.org/10.1177/0278364919870227

[79] Wei Zhang, Siyu Fu, Zixu Cao, Zhiyuan Jiang, Shunqing Zhang, and Shugong Xu. 2020. An SDR-in-the-Loop Carla Simulator for C-V2X-Based Autonomous Driving. In *Conference on Computer Communications*. IEEE, 1270–1271. https://doi.org/10.1109/INFOCOMWKSHPS50562.2020.9162743

[80] Husheng Zhou, Wei Li, Zelun Kong, Junfeng Guo, Yuqun Zhang, Bei Yu, Lingming Zhang, and Cong Liu. 2020. DeepBillboard: systematic physical-world testing of autonomous driving systems. In *International Conference on Software Engineering*. 347–358. https://doi.org/10.1145/3377811.3380422

A STUDY PARTICIPANTS

Table 3. Education level of participants

Field/Profession	Education level						Total
	Senior researcher	*Postdoc*	*PhD*	*Master*	*Bachelor*	*other education*	
Artificial intelligence (AI)	-	-	-	1	-	-	1
AI ethics / Political science	-	-	1	-	-	-	1
Biology	-	1	2	-	-	-	3
Business administration	-	-	-	-	2	-	2
Computer science	1	2	5	22	6	1	37
Robotics	-	-	-	1	-	-	1
Mechanical engineering	-	-	-	-	1	-	1
Industrial engineering	-	-	-	1	-	-	1
Architecture	-	-	-	1	-	-	1
Law	-	-	1	-	-	-	1
Commercial clerk	-	-	-	-	-	1	1
Total	1	3	9	26	9	2	**50**

Table 4. (with *High Educ.* refers to Faculty and/or Senior Researcher)

Participant	Gender	Age	Driving Experience	Field/Profession	Educational Level
P1	man	31-35	>10 years	Computer Science	Higher Professional Education
P2	man	26-30	>10 years	Computer Science	Masters
P3	man	31-35	>10 years	Computer Science	Masters
P4	man	26-30	6-10 years	Computer Science	PhD
P5	woman	26-30	6-10 years	Computer Science	Masters
P6	woman	26-30	1-2 years	Computer Science	Masters
P7	man	31-35	3-6 years	Computer Science	Masters
P8	man	26-30	1-2 years	Computer Science	Masters
P9	man	>55	>10 years	Computer Science	Bachelors
P10	woman	31-35	3-6 years	Computer Science	Masters
P11	man	31-35	>10 years	Computer Science	Bachelors
P12	man	26-30	3-6 years	Business administration/ Banking and Finance/ Economics	Bachelors
P13	man	18-25	3-6 years	Computer Science	Bachelors
P14	woman	18-25	less than one year	Computer Science	Masters
P15	man	18-25	3-6 years	Computer Science	Masters
P16	man	18-25	6-10 years	Computer Science	Masters
P17	man	26-30	3-6 years	Computer Science	Masters
P18	man	26-30	3-6 years	Computer Science	Masters
P19	man	26-30	6-10 years	Computer Science	Masters
P20	man	26-30	6-10 years	Computer Science	PhD
P21	woman	18-25	1-2 years	Business administration/ Banking and Finance/ Economics	Bachelors
P22	woman	18-25	3-6 years	Computer Science	Bachelors
P23	man	26-30	3-6 years	Computer Science	Masters
P24	man	18-25	3-6 years	Computer Science	Masters
P25	woman	26-30	less than one year	Biology	Postdoc
P26	man	18-25	3-6 years	Computer Science	PhD
P27	man	31-35	>10 years	Computer Science	Masters
P28	man	31-35	>10 years	Computer Science	Masters
P29	man	18-25	3-6 years	Computer Science	Masters
P30	man	31-35	>10 years	Robotics	Masters
P31	man	26-30	>10 years	Computer Science	Masters
P32	man	26-30	3-6 years	Computer Science	Bachelors
P33	woman	26-30	3-6 years	Computer Science	Postdoc
P34	man	26-30	3-6 years	Computer Science	Masters
P35	man	18-25	3-6 years	Computer Science	Masters
P36	man	26-30	3-6 years	Computer Science	PhD
P37	woman	26-30	6-10 years	AI ethics / Political science	PhD
P38	man	>55	>10 years	Computer Science	Postdoc
P39	man	26-30	1-2 years	Computer Science	Masters
P40	man	31-35	>10 years	Computer Science	PhD
P41	woman	31-35	less than one year	Artificial Intelligence	Masters
P42	man	18-25	3-6 years	Mechanical Engineering	Bachelors
P43	woman	26-30	6-10 years	Computer Science	other
P44	woman	31-35	1-2 years	Industrial engineering	Masters
P45	woman	31-35	less than one year	Architecture	Masters
P46	woman	31-35	>10 years	Law	PhD
P47	woman	51-55	>10 years	Commercial Clerk	other
P48	woman	26-30	6-10 years	Biology	PhD
P49	woman	18-25	6-10 years	Biology	PhD
P50	woman	26-30	less than one year	Computer Science	Bachelors

B STATISTICAL RESULTS ON SAFETY PERCEPTION

B.1 RQ_1

Table 5. Statistical test results for RQ_1

Method	Test statistic	p-value Effect size A_{12}
Failing vs. Passing (Figure 4):		
Shapiro-Wilk	0.86	** $3.69 * 10^{-18}$
	0.90	** $4.41 * 10^{-13}$
Vargha-Delaney		0.34
Wilcoxon rank-sum	40461.5	** $6.2 * 10^{-14}$
Failing: No obstacles vs. with obstacles (Figure 4):		
Shapiro-Wilk	0.90	** $4.71 * 10^{-9}$
	0.79	** $2.15 * 10^{-16}$
Vargha-Delaney		0.71
Wilcoxon rank-sum	26507.0	** $3.52 * 10^{-16}$
Passing: No obstacles vs. with obstacles (Figure 4):		
Shapiro-Wilk	0.89	** $5.08 * 10^{-10}$
	0.90	** $1.56 * 10^{-7}$
Vargha-Delaney		0.56
Wilcoxon rank-sum	12719.5	0.06
VR vs. No VR (without interactive scenarios) (Figure 5):		
Shapiro-Wilk	0.89	** $1.77 * 10^{-16}$
	0.88	**$2.26 * 10^{-11}$
Vargha-Delaney		0.47
Wilcoxon rank-sum	36817.5	0.16
No VR outside view: No obstacles vs. with obstacles (Figure 6 and 5):		
Shapiro-Wilk	0.89	** $5.48 * 10^{-7}$
	0.82	**$1.02 * 10^{-9}$
Vargha-Delaney		0.66
Wilcoxon rank-sum	6591.5	** $6.74 * 10^{-5}$
VR outside view: No obstacles vs. with obstacles (Figure 6):		
Shapiro-Wilk	0.89	** $4.97 * 10^{-7}$
	0.85	** $1.17 * 10^{-8}$
Vargha-Delaney		0.65
Wilcoxon rank-sum	6460.0	** $2.075 * 10^{-4}$
VR driver view: No obstacles vs. with obstacles (Figure 6):		
Shapiro-Wilk	0.90	** $2.21 * 10^{-6}$
	0.83	** $2.23 * 10^{-9}$
Vargha-Delaney		0.71
Wilcoxon rank-sum	7082.5	** $1.45 * 10^{-7}$

B.2 RQ_2

Table 6. Statistical test results for RQ_2 on the safety perception with interactive scenarios (*:$\alpha < 5\%$, **:$\alpha < 1\%$)

Method	**Test statistic**	**p-value** **Effect size** A_{12}
Interactive vs. non-interactive scenario:		
Shapiro-Wilk	0.90	$^{**}1.43 * 10^{-6}$
	0.87	$^{**}9.89 * 10^{-8}$
Vargha-Delaney		0.60
Wilcoxon rank-sum	5983.5	*0.013
Interactive scenario: No obstacles vs. with obstacles (Figure 4):		
Shapiro-Wilk	0.89	**0.0003
	0.88	**0.0001
Vargha-Delaney		0.626
Wilcoxon rank-sum	1565.0	*0.026
Non-interactive scenario: No obstacles vs. with obstacles (Figure 4):		
Shapiro-Wilk	0.877	$^{**}9.022 * 10^{-5}$
	0.846	$^{**}1.223 * 10^{-5}$
Vargha-Delaney		0.6392
Wilcoxon rank-sum	1598.0	*0.013

C COMMENTS ON SAFETY PERCEPTION

C.1 RQ_1: Without interaction

Table 7. Color-coded comments by safety perception on BeamNG.tech (no VR, without obstacles) of participants supporting Finding 1

Code	Perceived Safety	Comment
P3/B1/S1	very unsafe	"As the car did not drive all the time on the street I felt unsafe. Especially if there would be some obstacles."
P4/B1/S1	unsafe	"While the car managed to detect the road correctly, it deviated a bit from it on a couple occasions. Even though it rightly reached the end, in a real-life scenario deviating from the road could cause a fatality."
P5/B1/S1	unsafe	"The car was fast and did not stay on track."
P7/B1/S1	unsafe	"Cannot term it safe as car drove off the road and into the grass. But since there was no threat by driving on the grass, I won't term it very unsafe."
P11/B1/S1	safe	"The car was on track all the time."
P13/B1/S1	neutral	"The car wasn't on the middle of the lane and there were a few moments in which it almost went of but didnt."
P16/B1/S1	safe	"The car was driving in lane and at a safe speed considering the road is empty."
P17/B1/S1	unsafe	"The car is not lane keeping properly and even seems to steer off the road at the end."
P19/B1/S1	unsafe	"Not exactly following the road. Unsafe for narrow passages of roads."
P20/B1/S1	unsafe	"It drives on the grass and does the curves with too much speed."
P24/B1/S1	very unsafe	"Ran off the roads multiple times and did not follow safety lines in curves."
P25/B1/S1	very safe	"The car was following the path in a safety way and was not speeding up too much"
P26/B1/S1	unsafe	"The car went out of the way in at least 2 times."
P26/B1/S1	very unsafe	"The car veered off the path multiple times crossing the hard white and yellow lines. It also seemed too fast while turning."
P29/B1/S1	unsafe	"Outside of the lines."
P30/B1/S1	unsafe	"Drive out of the road and not in the middle of the lane"
P31/B1/S1	unsafe	"When the car starts to go off the road when driving in a curve it feels pretty unsafe."
P33/B1/S1	unsafe	"it went out of the road twice."
P34/B1/S1	unsafe	"exited lane twice."
P35/B1/S1	unsafe	"The car cut two corners and was off the road with 2 wheels at a time."
P36/B1/S1	unsafe	"car went out of the road partially on curves, could be harmful if the road sides have different level"
P37/B1/S1	safe	"Overall, I do not think I would be in danger in this scenario, but I would still feel anxious because the car drove overboard and the wheels were in the grass. If a driver would do that I would ask him or her whether he or she is feeling ok."
P40/B1/S1	unsafe	"The car crossed the lines on the both side of the road a few times."
P41/B1/S1	unsafe	"slightly got off the road, somewhat crash to pile in the end."
P43/B1/S1	unsafe	"Road side was not kept well, so it would seem like the driver would not have full control of the car, had it been a human driving."
P44/B1/S1	unsafe	"unsafe - crossing the line and invading the other lane."
P45/B1/S1	unsafe	"Not Very Safe since the car sometimes drove a bit from the road."
P49/B1/S1	neutral	"Does not drive exactly between the lines, so not super safe."
P50/B1/S1	unsafe	"The car went off the lanes multiple times."

Table 8. Color-coded comments by safety perception on BeamNG.tech (no VR, with obstacles) of participants supporting Finding 2

Code	Perceived Safety	Comment
P1/B1/S2	very unsafe	"The car crashed toward an obstacle and even running over bumps was not so smooth as humans would do. Definitively more unsafe that the previous scenario."
P3/B1/S2	very unsafe	"so the same feeling as in scenario 1 as the car was not able to follow the street proberly. In the end car even crashed into a bin"
P4/B1/S2	unsafe	"From an AI standpoint, the car's driving technique was similar to scenario 1. While it managed to follow the road, it deviated from it in some occasions, finally crashing with some obstacles. It also surprised me that the car didn't stop accelerating after crashing. As such, I perceive it as unsafe (I would not use such a car in real life)."
P7/B1/S2	unsafe	"Hitting the barricade is what makes the scenario unsafe."
P8/B1/S2	very unsafe	"The initial drive was good, but the car quickly rammed into the obstacle, potentially coming to a halt and unable to recover, and the accident itself was very rough"
P9/B1/S2	neutral	"Eindruck das eher schnell gefahren wurde, am Schluss die Strasse verlassen :-("
P10/B1/S2	very unsafe	"easily distracted by obstacles in the path"
P13/B1/S2	very unsafe	"the car was wobbly. didnt stick to the lane. ran into obstacles and didnt take proper measures to get out of the same"
P14/B1/S2	neutral	"Safe because of the dividers. Unsafe for unqualified drivers"
P15/B1/S2	unsafe	"Car crashed and the tront wheels and suspension were damaged, also it was going too fast for the bumps"
P16/B1/S2	neutral	"It car was running smooth with obstacles, there was a moment when it was too close to one of the obstacle."
P17/B1/S2	very unsafe	"The car is hitting an obstacle in the road and seems to be unable to progress any further making it very dangerous."
P18/B1/S2	very safe	"The vehicle does well to avoid obstacles while maintaining the safe speed"
P19/B1/S2	unsafe	"It seemed the car was not in control. With the turns and very narrowly escaping the obstacles. Wouldn"t feel safe in it"
P20/B1/S2	very unsafe	"it bumped on an easily avoidable side object and couldn't even get out of it"
P21/B1/S2	very unsafe	"the car hit an obstical and wanted to go on without stopping"
P24/B1/S2	very unsafe	"Ran off the road in a curve and hit obstacles without slowing down, which resulted in flat tires."
P25/B1/S2	neutral	"Car was a bit bumpy along the way and actually hit one of the obstacle on the left even if was controlling the speed well along the way it still felt a bit unsafe"
P27/B1/S2	very unsafe	"The car started too fast and did not seem to have any control over its speed or direction. It crashed onto the pylons multiple times as well."
P28/B1/S2	very unsafe	"The car did not take the speed bumps into account and was not driving in the middle of the lane. At the very end it even drove completely off..."
P30/B1/S2	very unsafe	"Hit the obstacles in the middle of the lane. Car had an accident."
P31/B1/S2	very unsafe	"Despite the relatively narrow road, the car was going pretty fast. Therefore, it felt a bit unsafe. The AI even hit a bump which is the main reason that it feels unsafe."
P32/B1/S2	unsafe	"Going fast on bumps and offroad multiple times. Parked offraod at the end."
P33/B1/S2	very unsafe	"The car went out of the road once and creashed due to one obstracle. It could not recover fom the crash."
P34/B1/S2	very unsafe	"hit obstacle, fast over bumps"
P35/B1/S2	very unsafe	"Went over the speed bumps to fast and crashed."
P36/B1/S2	very unsafe	"no speed change on the speed bumps, partiall loss of controll after some hard crush in the end."
P37/B1/S2	neutral	"Still not feeling in danger, but the car went faster and drifted a little bit in the curve whereas driving should be smoother than that."
P38/B1/S2	unsafe	"Touched obstacles"
P39/B1/S2	unsafe	"car was trying to avoid obstacle which caused it to go wide on road"
P40/B1/S2	neutral	"The driver accelerated over all the obsticles and did not have a perfect finish."
P41/B1/S2	very unsafe	"collision with obstacles, jumps on road and changes of trajectory"
P43/B1/S2	unsafe	"Car was not staying on the road, as well as driving to fast for the given conditions. It was again not stayingon the right side of the road during corners."
P44/B1/S2	very unsafe	"crashing the obstacle and having a crash"
P45/B1/S2	safe	"Car was driving well. Only at the end it went off the road, but there was no object it bumped into."
P46/B1/S2	very unsafe	"the car was driving too fast and thus hit obstacles. and in order to get back on the road, it went on the wrong side of the road, which made me feel unsafe as a passenger."
P48/B1/S2	unsafe	"car did not hold the line"
P49/B1/S2	very unsafe	"does not drive exactly between the lines and then hit the pole. gives a scary feeling."
P50/B1/S2	very unsafe	"The car went off the lane and crashed into multiple obstacles. It got stuck at one obstacle and tried to drive through it, which didn't succeed."

C.2 RQ_2: With interaction

Table 9. Interactive scenario without obstacles

Code	Perceived Safety	[C3] Justify the perceived safety of the interactive scenario 1?
P1	Neutral	the fact i could control the car when needed, gave me a safer perception of the driving experience. Moreover, i could speed up the car when i wanted to.
P2	Safe	I could still stop or slow down the car at the stop signs.
P3	Very Unsafe	anticipation of bad happening in the same circle from previous scenarios
P4	Unsafe	With a bit of control it feels safer, especially being able to adjust the speed in dangerous situations. However, it is still not safe since the car ends up going off road at the end of the scenario.
P5	Safe	it was okay
P6	Very Unsafe	had accident
P7	Unsafe	It was unsafe as it ran on the sidewalk of roundabout.
P8	Safe	Safe overall, nothing to complain about. Even after making it extremely safe, the car followed all the road rules.
P9	Unsafe	konnte beim Stop die Geschwindigkeit verringern, im Roundabout dann wieder unsicher da zu schnell
P10	Very Unsafe	car crashed
P11	Neutral	the car complted the track without issue
P12	Neutral	Turing have a big issue.
P13	Very Unsafe	ran into an accident. the interaction wasnt very responsive hence it made me feel even more unsafe than i usually would
P14	Safe	Decent control of speed
P15	Safe	Follows the road well.
P16	Very Safe	no accident and smooth
P17	Unsafe	The car ignore stop markings on the road.
P18	Neutral	The car follows the traffic rules and speed limit well but misses the lane while turning at the end.
P19	Unsafe	majoity of the drive was safe. but again hit the sideways while taking left in the roundabout.
P20	Safe	it is safer when controlling safety zones
P21	Safe	it slowed down at the stop sign when i clicked unsafe
P22	Neutral	It feels better because I feel I have control but still its not as resposibe as I want it to be
P23	Unsafe	The car does not stop at stop markings. It had problems at the roundabout.
P24	Unsafe	drove well, but still hit the curb in the roundabout
P25	Safe	Till the roundabout the scenario was very safe but when it had to turn there the safety and stabilty of the car decreased quite a lot, but overall it was still quite positive experience.
P26	Neutral	The safety is betteer since I can control the speed of the car. But still the car crashed.
P27	Unsafe	It was safe for the most part, except at the end when the car mounted the curb at the round-about.
P28	Safe	I knew where the pain points are, so I could counteract the bad behaviour of the AI. Nevertheless it crashed.
P29	Unsafe	Car didn't respect the stops on its own
P30	Very Safe	Having control over the speed makes it much safer.
P31	Very Safe	I was feeling save during the whole time.
P32	Unsafe	Car went over the roundabout.
P33	Unsafe	The car changed lane in middle of the road in the start. It went above the roundabout at the end.
P34	Neutral	Better than without, but in the end its still close with the curb
P35	Very Safe	I was able to slow down the car in front of the intersection and in front of the roundabout
P36	Safe	I could fix the mentioned issues at the first turn with the use of speed limit controll.
P37	Safe	Everything was fine. At the end the car still did go on the sidewalk, so not so good, but there was no sound, so it felt not as bad ahah.
P38	Very Safe	Influence of the speed is good
P39	Very Safe	It was safe and easy to control
P40	Unsafe	I could not stop the agent to move up the square at the end even with my feedback and I felt unsafe for this reason.
P41	Unsafe	Felt okay in the beginning (still rather too slow), felt unsafe in direction of roundabout, went way too close
P42	Very Safe	Responsive yet issues with the roundabout.
P43	Unsafe	Ignored stop sign, crashed into roundabout because driving with too much speed
P44	Neutral	slowing down before the STOP sign and moderate the speed in the roundabout
P45	Unsafe	Did not break at the stop sign and drove too hard at the roundabout where there is no view what comes around the corner.
P46	Safe	i was able to adjust the speed and make the car stop at stop signs which made me feel safe and gave me back some control.
P47	Very Unsafe	-
P48	Safe	More control feels safer
P49	Very Safe	felt safe, especially since i can regulate the speed myself. gives control over the car back which is good. especially for roundabouts where everyone has a different preferred speed to go over it.
P50	Safe	The car drove nicely and steadily. I only reduced the speed in the end when entering the roundabout.

Table 10. Interactive scenario with obstacles

Code	Perceived Safety	[C3] Justify the perceived safety of the interactive scenario 1?
P1	Unsafe	even if i was able to control the car, the vehicle was not able to have smooth driving actions close to the other car (e.g., fast acceleration and quick stop). It is also true that this happen in real time, depending on the driver. The final incidents made the whole scenario unsafe.
P2	Neutral	I could not react to all obstacles but the AI could manage it.
P3	Very Unsafe	anticipation of bad happening in the same circle from previous scenarios
P4	Unsafe	It felt safer, especially since it was stopping the speed when it had another car in front. However, it still went to the foot-path making it not safe.
P5	Very Unsafe	the car in the front which was always stopping was annoying
P6	Unsafe	had accident
P7	Very Unsafe	It collided with the vehicle in the end. SDC should be able to identify these kind of day to day aberrations.
P8	Safe	The speed control with ctrl and right enter was good, I was able to control the car not climbing on top of the roundabout at the end.
P9	Neutral	Ich habe versucht zu lernen, wie die AI auf meine Befehle betreffs Sicherheitsgefuehl reagiert. Konnte dadurch im Roundabout auch genuegend verzoegern, wodurch im mich sicherer fuehlte.
P10	Unsafe	not able to follow path
P11	Very Unsafe	the car meet with an accident
P12	Unsafe	unstable at turning
P13	Safe	was good. felt like i followed the lane properly and the rules too
P14	Safe	Decent drive with good speed control
P15	Safe	It does foolow the saf/unsafe instructions well.
P16	Unsafe	it hit a car
P17	Unsafe	The car ignores stop markings on the road, turns too aggressively and veeres of the road.
P18	Neutral	The car does a good job of avoiding other vehicles and following traffic lights but a little shaky at the end
P19	Very Unsafe	Hit the bike driver
P20	Unsafe	it could have stopped before hitting the camion
P21	Very Unsafe	at the end I felt verzy unsafe beacause I had the feeling I am not controlling it like in the beginning I coud not do anything
P22	Neutral	Also I feel more in control with the Interactive one but I was not able to prevent the crash
P23	Very Unsafe	The car was simply not operaing well, I felt very unsafe.
P24	Safe	slowed down at stop sign, kept proper distance and I was able to tell the car to slow down
P25	Unsafe	The behaviour of the car in the presence of the other car was quite unsafe, with a lot of breaking and accelerating. The behaviour in the absence of the other car but with heavy rain was much better even still having problems dealing with the roundabout.
P26	Safe	Having the controll is better for safe perception
P27	Unsafe	It was safe for the most part, except at the end when the car mounted the curb at the round-about and lost control.
P28	Neutral	I was finally able to stop at the stop sign and but still not able to avoid the crash. Therefore overall safe, but due to the crash neutral. And this crash was more severe than the one in the empty roundabout.
P29	Unsafe	Car didn't respect the stops on its own
P30	Neutral	I had to interract to many times becaus I did not feel so safe
P31	Neutral	Except during the situation whe the car in front behaved strangely (which caused an accident), i felt save the whole time. Since I did not have control in previous situations, I already trusted the AI.
P32	Unsafe	Better decisions needed when other cars are around,
P33	Unsafe	The car changed lane in middle of the road in the start. It went above the roundabout at the end.
P34	Neutral	Better, but in the end it still hit the curb
P35	Neutral	I was again able to slow down the car. But it still didnt manage to drive the roundabout.
P36	Safe	i could controll the speed, so less suddent breaks with the slow car in front
P37	Safe	It was safe because I could intervene when the car was making mistakes and I could avoid the usual collision at the round about.
P38	Very Safe	Speed Influence enhances safety feeling
P39	Safe	safe and easy to use
P40	Very Unsafe	Two matters: 1) driver keeps its distance to the can in the front, but with sharp breaks instead of slowing down the car. 2) inable to avoid strange behaviors and drove next to a car with unstable drive and had an accident.
P41	Neutral	no irritation because of other obstacles or weather, but still unsteady/unsafe behaviour in the end, lots of intervention from me
P42	Very Unsafe	Caused a collision
P43	Unsafe	Crashed in roundabout and drove with too much speed in it, ignored stop signal
P44	Neutral	slowing down before the STOP, moderating the speed when the rain starts and when entering the roundabout
P45	Very Unsafe	car doesnt drive safely without adjusting the max speed yourself
P46	Safe	i was able to control the speed and thus avoid a person on the bicycle. this gave me back some control.
P47	Very Unsafe	-
P48	Safe	having the control to react to different situations feels safe
P49	Safe	regulating the speed of the car gives a strong sense of safety because i can keep distance from an unpredictable driver, this way i was not so much disturbed by the bad driving and just slowly followed. after that i could speed up again and slow down again at the roundabout.
P50	Very Unsafe	The car left the road and drove over the sidewalk. Afterwards, it crashed into a streetlight. It seemed like it wanted to avoid the other car that had crashed, but overcorrected and left the road.

C.3 RQ_2: Without interaction

Table 11. Non-interactive scenario without obstacles

Code	Perceived Safety	[C3] Justify the perceived safety of scenario 1?
P1	Unsafe	the car, as mentioned before has to fast steering actions time to time. Going in vertical path is safe in general, mainly at the end the car bumped on the merging of the road this made this scenario unsafe
P2	Neutral	The car drove more moderate but the turns were a bit too sharp.
P3	Very Unsafe	the car took strange ways and it crashed in the end
P4	Neutral	It felt safe all the path except the roundabout where the car went off-road.
P5	Unsafe	it was too fast in the circle
P6	Unsafe	unsafe
P7	Unsafe	Vehicle struck the side area of roundabout. Didn't lookedsafe
P8	Neutral	Safe in the beginning, but again climbed the roundabout at the end. The sound of glass breaking when the car mount the roundabout is a nice touch.
P9	Unsafe	am Ende des Tests: Glass ging zu Bruch
P10	Unsafe	it follows traffic light but got distracted on square and not able to follow path
P11	Unsafe	the car ran on the foot path
P12	Unsafe	Followed rule but have issue at roundabout.
P13	Neutral	Was good until it went on the curb aat the end
P14	Safe	Overall a smooth driving experience except on the round about
P15	Neutral	Soft crash in the end, everything was good until then.
P16	Neutral	not smooth with obstacles at a very few moments.
P17	Unsafe	The car only stops at some red light and ignores some stop markings on the road.
P18	Safe	The car did a good job of staying within the limits and following the traffic rules
P19	Unsafe	Overall turning was good but again as in the previous two scenarios, the car would hit the sideways while moving left in the roundabout
P20	Neutral	in the end it hits the side of the roundabout
P21	Unsafe	He didnt stop at the STOP sign and at the end I heard the sound of crashing behind
P22	Unsafe	It felt pretty safe until something crashed on the back of the car, it also stopped in the middle of the road after it
P23	Very Unsafe	The car did not stop at a stop marking, it also had problems at the randabout.
P24	Unsafe	ran over stop sign; hit the curb
P25	Neutral	The car was keeping a low speed so it felt quite ok the overall experience even if it had problem with the roundabout were it hits the obstacle with the left side of the car. The feeling of being in the car it feels quite real.
P26	Unsafe	The car hitted at the end.
P27	Unsafe	Although the car seemed to follow the traffic rules and speed limits, it was not able to navigate the round-about, crashed on to the curb and lost control in the end.
P28	Very Safe	driving extremely slow through an empty city, nothing to be worried about.
P29	Very Unsafe	Car didn't respect the stops and and been damaged
P30	Safe	It was not so bad even when the car hit the border in the circle
P31	Very Safe	From within the car, it felt more realistic. The car did keep on track well and stopped at the road crossings and signals. Since it did not drive too fast, it felt really save.
P32	Safe	Moderate. Safelz driven.
P33	Very Unsafe	The car changed lane in middle of the road in the start. It hit the roundabout at the end and got into an accident (based on sound experience but could not see anything).
P34	Unsafe	drove on curb, too slow, ignored stop
P35	Neutral	No slowing down for the intersection and later crashed in the roundabout
P36	Unsafe	this time i was more concerned about the first turn, car did not really stop at the intersection to look for other cars crossing. also the hit to the round about in the last second, felt reallt unsafe.
P37	Unsafe	Driving is smooth, but I took the sidewalk and apparently something broke.
P38	Very Safe	Altought the steering is not very smoothly, it was very relaxing to drive
P39	Safe	it was smooth experience
P40	Neutral	I heard a crash towards end of the experiment, but I felt safe since there was not only other objects around.
P41	Neutral	most of the time correct in line behaviour, but very slow feeling (maybe due to latency of simulation), touching of roundabout in the end made it somewhat unsafe again
P42	Very Safe	Weird roundabout interaction, otherwise very safe.
P43	Very Unsafe	Car crashed and ignored stop sign.
P44	Unsafe	skipping the STOP sigh and invading the vegetation in the roundabout
P45	Unsafe	At the end the car bumped into the roundabout.
P46	Unsafe	the car did not stop on stop sign. the car crashed in the roundabout. this made me feel unsafe.
P47	Very Unsafe	-
P48	Neutral	safe until the end, but no other traffic members are involved
P49	Safe	waas quite okay, respects all the traffic rules. just the roundabout is a bit stressful and would have liked to be able to control the steering wheel
P50	Very Safe	The car drove correctly and followed the rules.

Table 12. Non-interactive scenario with obstacles

Code	Perceived Safety	[C3] Justify the perceived safety of 2?
P1	Unsafe	similar level of unsafety. main difference was that the not so smooth behavior of the car happens also in the proximity of other cars (fast restarts followed by rapid stops, a more safe driving would be ideal). However, without obstacles i felt in some cases the car was too slow compared to the one of BEAMNG
P2	Unsafe	The car should drive more conscious in the dark.
P3	Very Unsafe	the car drove really strange, it sped up and down and did not drive consistently
P4	Neutral	It felt very safe all the way, except the roundabout where it went off-road. The fact that it stops when there is a motorbike in front and that it obeys traffic lights makes it increase the safety perceived.
P5	Unsafe	it was too fast in the circle
P6	Neutral	not very safe
P7	Very Unsafe	It was very unnsafe. The vehicle was not able to take turn on the roundabout and there was accident.
P8	Neutral	Good in the beginning, the turn when the weather was dark was a bit unnatural, climbed the pavement at the end
P9	Unsafe	am Ende des Tests: Glass ging zu Bruch, es regnete IM Auto, zu nahe auf Feuerwehrfahrzeug aufgefahren
P10	Very Unsafe	car crashed in another car when other car does not follow usual path and after crash not able to identify the traffic light
P11	Neutral	the car complted the track
P12	Very Unsafe	Cannot handle sudden change of situation.
P13	Very Unsafe	didnt properlz assess the vehicle in front and didnt brake when the vehicle came in front of it not did it stop
P14	Safe	Decent work despite challenging obstacles
P15	Neutral	Soft crash in the end, everything was good until then. Also, close call with another car.
P16	Unsafe	Did not hit any other car/ person but at a round about it hit the ramp and ended in a bush.
P17	Unsafe	The car ignores stop markings on the street and veeres off the road.
P18	Neutral	The did a good job of being within the speed limits but lost control at a turn and crashed the rear end
P19	Unsafe	for the majoity of the ride, the drive was safe. It was responding well to the abnormal behaviour of bike applying brakes abruptly. Towards the end, it again hit the sideways at the roundabout. This made it unsafe.
P20	Neutral	it had an accident but it was not its fault
P21	Very Unsafe	Because he didnt slow down smothly for the bycicle and at teh end the crashing sound was uncomfortable
P22	Unsafe	Same as in scenario 1, it was safe at the beginning with the other cars also but at the end it crashes and it stops in the middle of the road
P23	Unsafe	The car accelerates and stops abruptly. I know it is because the care in front was doing exactly the same. In such situations, I would simply drive at a safer distance from the driver in front of me.
P24	Very Unsafe	instantly crashed into curb and lamp post
P25	Very Unsafe	The car was breaking and accelerating a lot while being behind the other car and also the other car was not behaving safely on the road, ending the simualtion with an accident between the two, so it felt quite unsafe overall.
P26	Very Unsafe	The distance betweent the car and the obstacles was very close.
P27	Unsafe	It was safe for the most part, but the car lost control in the round-about and crashed on to the curb.
P28	Very Unsafe	it drove extremely close up to the ambulance car and finally crashing into it. therefore, the worst case happen.
P29	Very Unsafe	Car didn't stop at stops and was outside the lines in the curves, brakes were very abrupt
P30	Neutral	Turning around was to fast. I was still looking to the left if there is a car coming and looking out infront of the car it was a big surpise seeing alt he cars infront of me. Then we had a nice accident xD
P31	Neutral	From within the car, it felt more realistic. The car did keep on track well and stopped at the road crossings and signals. Since it did not drive too fast, it felt really save.
P32	Very Unsafe	Car overturned.
P33	Very Unsafe	The car changed lane in middle of the road in the start. It hit the roundabout at the end and got into an accident (based on sound experience but could not see anything).
P34	Unsafe	drove on curb, too slow, ignored stop
P35	Neutral	No slowing before the intersection and crash in the roundabout. But did stop for red light.
P36	Safe	safe, but still it could handle the slow dirver in front better, too much use of hard break.
P37	Unsafe	"I only feel unsafe because something broke again at the end. I do not feel unsafe that it stops all the time because of the motorcycle, but the guy on the motorcycle obviously does not know how to drive and the car should double cross him. "
P38	Very Safe	The only thing was, that the car moves not precise enought
P39	Very Unsafe	taking turn was poor and car crashed
P40	Unsafe	There was a motobycle with very strange behavior which was ignored by the drive until the accident happened.
P41	Very Unsafe	started okay, but the unsteady behaviour of other vehicles made me feel uncomfortable, late stopping of ego vehicle also, very unsafe behaviour around roundabout
P42	Very Safe	Except the roundabout issue, very safe.
P43	Very Unsafe	Ignored stop sign, had a crash into roundabout.
P44	Very Unsafe	not smooth STOP and GO, entering the lane with other road users in unsafe manner,
P45	Unsafe	Car drove into roundabout at the end.
P46	Unsafe	the car did crash with an ambulance and did not stop on stop sign. in the end it crashed in the round about.
P47	Very Unsafe	-
P48	Neutral	rather safe, no reaction to other cars though
P49	Unsafe	the car crashing felt unsafe and i would have liked that the car would make a bigger curve around it. and then crashing in the house was not great either
P50	Safe	The car drove correctly, however, at one point, it was moving wobbly, which it immediately course corrected.

D RQ_3: COMMENTS ON REALISM

D.1 Realism for BeamNG.tech

Table 13. Comments on realism of the test cases in BeamNG.tech

Code	Perceived realism	Justify level of realism of scenarios generated test cases?
P1	3	"With the road including obstacles the realist of the scenario was ok. The level of realism of the experience drastically improved when I am within the car. perceived level of safety reduced drastically with the increase level of realism."
P2	4	"The simulation was smooth and there was a high resolution."
P3	2	"the grass the horizon as well as the red vertical lines do not very realistic"
P4	4	"The realism is quite good, especially in the car design. The car structure was damaged after crashing, the wheels were getting broken, and there was smoke coming out. The inside view of the car was also prety real, with the driver's hand moving the steering wheel, and all the car panel commands. The reason I don't put it a 5 is that the landscape and road design was not as real, especially when compared to some videogames such as GTA5 or red-dead redemption."
P5	2	"Driving was too careless"
P6	4	"normal"
P7	4	"Being in simulator, I can see that simulator took care of all the aspects of real life scenario like when it crashed carswerved. Inside the car view was also very as per driver reference and it felt safe and like how driver will drive"
P8	4	"It was not too realistic, but it was also not too shabby. The roads specifically felt very real, but the environment itself did not feel too polished."
P9	4	"good genough for this test"
P10	3	"without obstacles path felt more real. Obstacles realism can be improved"
P11	4	"the test cases has obsticals and real word road conditions"
P12	2	"They didnt have any difference in scenarios."
P13	2	"the roads were as thez would be in actual life."
P14	4	"The driver seat simulator felt very realistic"
P15	5	"Good real-life simulation"
P16	4	"with empty road, it felt very real."
P17	3	"the car seems to behave realisticly, but the environment isn't very real life-like yet."
P18	4	" It replicates real world scenarios quite well"
P19	4	"the view was realistic and not distorted."
P20	4	"the crashes are more realistic, a physical object got stuck between the wheel and the engine for example."
P21	4	"it was diffrent when I sit in the car than from outside so it felt more real. But still looked like a game so not that realistic."
P22	4	"They respect the scale from the objects"
P23	4	"I think that the roads generated and the obstacles were pretty realistic."
P24	3	"The car didnt bechave as expected when driving on grass, other than that it was quite realistic"
P25	3	"The scenario felt ok, especially the one with the obstacles and the bumps of the car on the obstacles on the road. Same for the quality of the perception in the simulation inside the car. It would be nice to add the sound to the scenario to increase realism."
P26	2	"The obstacles are static. Also, the way seems unrealistic."
P27	4	"The movement of the car, speeding up and down, reaction to going over bumps etc. seemed very realistic."
P28	1	"It looks like a computer game to me and I can differentiate clearly between reality and fiction as far as I know."
P29	4	"Very simple scene, few details"
P30	2	"The steets were not so realistic"
P31	4	"The overall level of realism regarding the behaviour of the car is quite good from the perspective inside the car. The surroundings in the environment do not look very realistic compared to state-of-the-art computer games that focus on car driving."
P32	3	"good"
P33	4	"Someitme it is hard to know the expected outcome."
P34	5	"good length of the curves and good obsticals, that would be a challange for humans as well"
P35	3	"The environment with the obstacles had way to many speed bumps for it to be realistic. The other environment was ok."
P36	2	"the road was not realisitic in some cases, like a very small side road in warmup scenario. speed bumps are too close to each other, and the obstacles in the middle feel artificial."
P37	2	"There is nothing in the environment, it feels like a test route for car industry."
P38	4	"In real the steering is much more precise"
P39	4	"It seems good enough and can feel the environment"
P40	3	"Low graphics from the environment, no other cars or people around, car feels quite regid and going over the obsticles is not bumpy."
P41	3	"testcase without obstacles seems more realistic, second one has quite a lot bumps, but might be realistic for some roads"
P42	4	"Real life scenarios with bumpy or uneven roads and obstacles."
P43	3	"Movement is not as smooth as one would usually associate with a car, it moves quite jerkily. The general feel of the simulation is slightly animated and not as real looking"
P44	4	"good visibility of the lines and realism of the speed"
P45	3	"Looks like a game, not the real world."
P46	3	"there ar no other cars on the street. basic surroundings."
P47	3	"Bin ??berfragt."
P48	3	"realistic scenarios"
P49	4	"when i was sitting in the drivers seat i was actually quite uncomfortable and it did feel like it was real, except that my body of course does not move similarly. but i noticed that i was physically reacting to the things happening on the screen."
P50	4	"It is realistic to have curvy roads, and the obstacles simulate other cars decently enough for testing whether the car would be a hazard for other cars."

D.2 Realism for CARLA

Table 14. Comments on realism of the test cases in CARLA

Code	Perceived realism	Justify level of realism of scenarios generated test cases?
P1	5	It was possible to observe almost anything you see in a city (pedestrian, cars, other vehicles, traffic signs, etc.). It was also way more realistic driving style.
P2	2	The simulation was very haltingly and it felt in general very artificial. The sound of the car was just weird, especially for an electrical car.
P3	4	it had sounds and a lot of world objects
P4	4	Very good actually. I don't put a 5 because there is always room for improvement and I've seen game engines with more realistic results, but I was positively surprised. While the car was designed as a single box, the landscape was much more realistic, which made you more immerse in the scenario. Also the fact that it uses full VR (3D) makes a big difference.
P5	4	it was good but didnt stop on the stop signals
P6	5	good
P7	5	The scenario was very real along with traffic lights, day and night, foggy and it looked like high quality graphics.
P8	5	This level was more realistic compared to the previous simulator.
P9	4	goo for this test
P10	4	scenarios seems very real
P11	3	it covered the scenarions like trafic light, city limit
P12	5	AI was very responsive
P13	5	the world and the objects in it were very realistic including the sounds
P14	4	It gave a clear sense of traffic rules and turns although you can expect much more traffic and dangers in the real world.
P15	5	It was very realistic
P16	5	The city graphics look very real.
P17	4	The environment (lighting, obstacles) feel quite real.
P18	5	Replicates the real world scenario very well.
P19	3	reality seemed okay
P20	4	best than BeamNG t generate realistic environments and scenarios, as well as a better graphical aspect
P21	5	Compared to the first simulation it was better and more realistic because of the enviroment.
P22	5	The scale of the objects and details are really good
P23	5	It was very realistic, because it was in a city, there were other vehicles and the weather was changing.
P24	1	The movements were very abrupt, the physics did not feel too realistic
P25	5	The scenario it quite realistic probably also because it consider the simulation inside a city in which the car has to deal with traffic signs and other cars, but also people.
P26	3	Better for shadows, textures, and realistic obstacles. However, phisics still not realistic enough.
P27	3	There were some lags in the animation and the movement of the car did not seem realistic at times. During the rainy weather scenarios, raindrops were falling inside the car even though everything was closed.
P28	3	still perceivable as a computer simulation, but with much more details and therefore kind of comparable to reality.
P29	4	Scene isn't too detailed
P30	4	It was a good scenario expect some cars which where driving in a snale line.
P31	5	The surroundings have more detail which made it feel more realistic.
P32	4	OK
P33	4	Changing lane was not safe
P34	5	Very nice with the real city map
P35	4	It was more realistic than BeamNG since it was an actual city. The car was also driving smoother which helped for the realism.
P36	4	the city environment and the obstacle, cars, etc. were realitic. just the drivers of bicycle and cars were too artifically crazy in some cases. you don't expect that level of crazyness on the real streets normally
P37	5	there are cars and environment on the side and there are street lights and stop signs. Too bad there are no bytanders
P38	4	They were very interactive and quite realistic
P39	4	scenes are really good
P40	4	The simulation is quite realistic including sound. The resolution of traffic signs and lights (far objects) are too low and direction lines on trafic lights and sometime on the streets are missing.
P41	4	it has some latency, which gives an akward feeling, but was better than the other simulator
P42	5	Great generation and simulation
P43	3	Cars do not follow all traffic rules. They ignore stop signs and do not indicate when to turn. But the being driven feels realistic to me, just like being a passenger.
P44	4	well reproduced city conditions (infrastructure, buildings, vegetation, etc). Not always well understood behaviours of other vehicles, weather conditions included
P45	4	Quite a lot of details but you can see it is obviously not real world.
P46	4	the buildings, different cars / bicycles / persons. the street marking etc.
P47	3	Umgebung war ziemlich realistisch. Jedoch fehlt das grosse Verkehrsaufkommen.
P48	4	very realistic environment
P49	5	felt real, because it is really what a city or village could look like so i really reacted to what was happening on screen.
P50	5	The scenarios were very realistic, complete with other vehicles that weren't driving correctly all the time (which is accurate to real life).