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UX Assessment Protocol for Automotive HMIs: From Real-Vehicle Evaluation to Digital Simulation Environments

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Abstract

This study presents the development and application of a human-centered assessment protocol for in-vehicle Human–Machine Interfaces (HMIs), suitable for real-vehicle evaluation and designed to support future implementation in simulated environments. The objective is to define a structured protocol to assess user experience (UX) in physical testing environments and simulated virtual scenarios. The protocol evaluates user performance and subjective perceptions while interacting with key interface components, including the instrument cluster, central display, steering-wheel controls, and ergonomic adjustment commands, establishing a methodological baseline for future digital and simulation-based evaluations. The work describes the process from requirement analysis to protocol design and user testing, conducted in collaboration with an automotive manufacturer. Participants performed predefined interaction tasks reflecting typical phases of vehicle use. Objective metrics, including task completion times and error rates, were collected alongside subjective evaluations of perceived usability, perceived quality, and satisfaction. Data were analyzed through *t*-tests and ANOVAs to investigate differences across user groups and interface elements. Beyond the empirical findings, the main contribution of this work lies in delivering a reusable human-centered evaluation framework supporting both current in-vehicle assessments and future simulated environments through automated interaction logging, behavioral tracking, and multimodal data capture while preserving methodological continuity and human-centered validity.

Keywords: automotive HMI; Human-Centered Design; user experience evaluation; driving simulator; usability testing; human factors; simulation-based assessment; automotive ergonomics

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1. Introduction

The design of Human–Machine Interfaces (HMIs) have become a central aspect of automative, driven by the increasing complexity of interactions between drivers and advanced vehicle systems. The rapid digitalization of the automotive sector has transformed traditional mechanical dashboards into software-driven, configurable, and highly integrated digital ecosystems. Contemporary, modern vehicles incorporate instrument clusters, central infotainment displays, steering-wheel controls, head-up displays, and advanced driver assistance systems within unified interaction environments [1,2].

While this evolution has expanded functionality and personalization, it has also introduced new ergonomic and cognitive challenges. Increased information density, multimodal interaction, and layered menu structures can elevate visual–manual distraction and cognitive workload. As a result, usability, readability, and interaction efficiency have become critical design concerns, directly linked to safety, driver trust, and overall user experience (UX) [3].

Within this context, ergonomics has progressively converged with Human-Centered Design (HCD), promoting iterative processes in which user needs, perceptual limitations, and behavioral characteristics guide both system development and validation [4]. Rather than evaluating HMIs solely in terms of technical performance, HCD emphasizes the integration of objective performance measures and subjective user perceptions across the entire interaction lifecycle [5]. Consequently, structured evaluation frameworks are increasingly required to ensure that digital automotive interfaces remain usable, safe, and accessible across diverse driver populations.

1.1. Background

Over the past decade, automotive HMI evaluation has been addressed through multiple experimental paradigms, including on-road studies, controlled real-vehicle testing, driving simulator experiments, and virtual reality (VR)-based environments. Each approach presents specific methodological advantages and constraints in terms of ecological validity, experimental control, safety, and scalability.

Real-world and on-road studies provide high ecological validity, capturing driver behavior in naturalistic traffic conditions. Research conducted in actual driving environments has examined the influence of in-vehicle interface characteristics on visual detection performance, manual interaction, and workload [6]. Naturalistic and real-road investigations have also been employed to analyze glance behavior, distraction patterns, and workload variations during interaction with embedded HMIs [7]. These approaches allow researchers to observe authentic behavioral adaptations and compensatory strategies under genuine traffic conditions. However, they often involve limited experimental control, safety constraints, and reduced repeatability of critical or hazardous scenarios.

To balance realism and control, driving simulators have become a widely adopted methodological solution. Simulator-based experiments enable systematic manipulation of interface parameters, such as control size, layout, and positioning, while ensuring driver safety and standardized environmental conditions [7,8]. High-fidelity simulators support detailed behavioral logging, including glance metrics, response times, and workload indicators, facilitating reproducible experimental designs. Furthermore, simulators allow the investigation of secondary tasks under controlled traffic dynamics, minimizing confounding variables inherent in real-road testing.

More recently, virtual environments have emerged as complementary platforms for UX evaluation of in-vehicle systems [9]. VR-based studies enable immersive contextual simulations while preserving a high degree of experimental flexibility. Compared to physical vehicle testing, VR platforms allow rapid interface prototyping, iterative design adjustments, and evaluation of early-stage concepts without the constraints of hardware implementation. Evidence suggests that well-designed virtual contexts can approximate subjective UX responses observed in field conditions, while offering enhanced repeatability and scalability.

In addition, interface-focused experimental research has examined dashboard readability, visual search behavior, and display configurations within simulated driving contexts [10]. These studies highlight the importance of structured experimental designs combining eye-tracking metrics, performance indicators, and validated UX questionnaires.

Despite these advances, the literature reveals substantial methodological variability. Differences in task definitions, measurement instruments, environmental setups, and data analysis procedures often limit cross-study comparability. While individual studies provide valuable insights, there remains a lack of standardized, replicable UX assessment protocols capable of being systematically transferred across projects and development cycles, particularly within industrial contexts.

1.2. Human-Centered Simulation in Automotive Product Development Process

Beyond methodological considerations, simulation environments are becoming strategically important in contemporary automotive development. Increasing system complexity, shortened innovation cycles, and the growing integration of software-driven interfaces demand evaluation tools that support rapid iteration and scalable validation [11].

Simulation-based platforms offer several. First, they allow controlled manipulation of environmental variables such as traffic density, speed variations, unexpected braking events, and other critical or borderline safety scenarios that would be unsafe or ethically problematic to reproduce in real traffic. Second, simulators enable precise logging of behavioral and interaction metrics, supporting detailed quantitative analysis. Third, they facilitate rapid prototyping and interface modification without the constraints of physical vehicle reconfiguration [12].

Importantly, simulation environments also allow the evaluation of early-stage or low-fidelity interface concepts before full physical implementation. This capability is particularly relevant for digital instrument clusters and software-defined HMIs, where design iterations can occur rapidly. From an industrial perspective, the early identification of usability issues reduces downstream redesign costs and enhances system reliability.

Nevertheless, while simulation provides flexibility and scalability, ecological validity remains a critical concern. For this reason, the development of structured evaluation protocols grounded in real-user interaction data is essential to ensure that simulated assessments maintain meaningful correspondence with real-world behavior. Establishing validated methodological baselines in physical contexts can therefore strengthen the credibility and transferability of subsequent digital evaluations [13].

1.3. Research Gap and Study Objectives

Although numerous studies have already investigated automotive HMIs using simulators, VR systems, or on-road experiments, evaluation practices remain fragmented [14]. There is limited methodological continuity between real-vehicle testing and digital simulation environments, and few structured protocols are explicitly designed for iterative transfer across physical and virtual contexts.

In industrial settings, UX assessments are often conducted using project-specific procedures, which may vary across vehicle platforms and development phases. Such heterogeneity can hinder longitudinal comparability, reduce decision-making transparency, and limit the integration of human factors considerations into strategic development processes [15].

The present study addresses this gap by developing and applying a structured human-centered UX assessment protocol for automotive HMIs. The protocol was first implemented in a real vehicle under static, non-driving conditions to establish a controlled yet ecologically grounded methodological baseline. The evaluation focused on key interface components, including the instrument cluster, central display, steering-wheel controls, and ergonomic adjustment commands, and integrated objective performance metrics with subjective usability and user experience measures.

Beyond the empirical findings, the study aims to contribute methodologically by proposing a replicable and transferable evaluation framework designed to support future implementation within a digitally simulated environment currently under development in collaboration with an industrial partner. By positioning real-vehicle testing as a foundational step toward scalable digital simulation, the proposed approach aligns with Human-Centered Design principles and supports iterative, data-driven refinement of automotive HMIs across both physical and virtual evaluation contexts.

2. Materials and Methods

The methodological approach adopted in this study follows a three-phase human-centered framework designed to establish a validated baseline in real-vehicle conditions and subsequently enable structured transfer to a digital simulation environment. Figure 1 illustrates the overall physical-to-digital methodological framework adopted in this study, highlighting the transition from real-vehicle validation to protocol formalization and future integration into simulated evaluation environments.

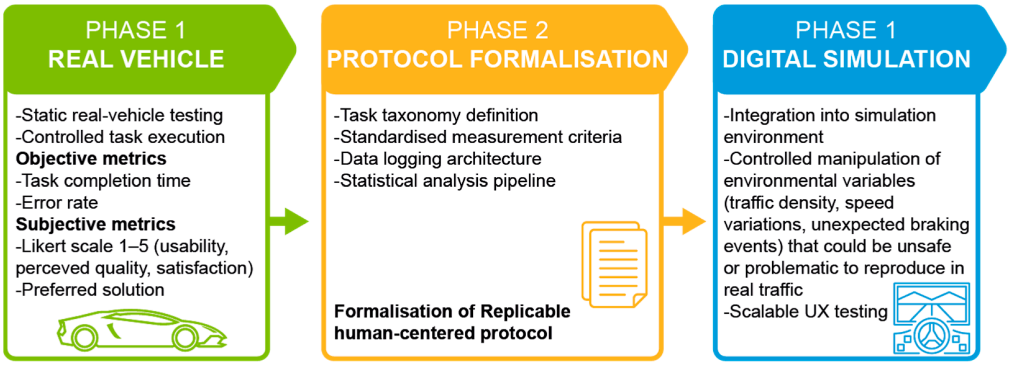

Figure 1. Overview of the Physical-to-Digital UX Evaluation Framework.

Although the overall framework includes the future implementation of the protocol within a simulated environment, the empirical validation reported in this paper is limited to the real-vehicle phase. The simulation component is presented as a methodological extension derived from the findings, procedures, and lessons learned during the physical evaluation.

The overall process consists of:

(1) empirical observation and data collection in a controlled real-vehicle setting;
(2) formalization and standardization of a structured UX assessment protocol grounded in behavioral and subjective metrics;
(3) methodological transfer and adaptation of the validated protocol to a digitally simulated evaluation environment currently under development in collaboration with an industrial partner.

The present paper primarily focuses on the first two phases of this framework. In Phase 1, a comprehensive usability evaluation was designed and implemented in a real vehicle under static conditions. Emphasis was placed on the definition of representative interaction tasks, the selection of objective and subjective performance metrics, the configuration of data acquisition procedures, and the development of a structured data analysis pipeline. In Phase 2, the insights derived from the empirical study, including observed usability issues, behavioral patterns, and statistical outcomes, were synthesized into a structured and replicable UX assessment protocol. This formalization process defined task taxonomies, measurement criteria, logging architecture, and statistical workflows, transforming the real-vehicle study into a reusable industrial evaluation framework. The findings and methodological lessons learned from the physical testing phase directly informed Phase 3, in which the validated protocol is being progressively adapted for integration into a digital simulation environment. The empirical results guided the identification of key parameters and technologies to be incorporated into the simulated platform ensuring methodological continuity between physical and digital evaluation contexts.

Through this physical-to-digital transition, the study establishes a coherent human-centered evaluation pipeline in which real-world validation supports the definition of scalable, simulation-based UX assessment processes.

The first phase of the study consisted of a structured human-centered usability evaluation conducted in a real vehicle under controlled, static conditions. This initial empirical investigation was designed to capture both behavioral performance and subjective user experience, providing an ecologically grounded baseline for subsequent methodological formalization. A consistent testing protocol was defined to ensure standardization across participants, tasks, and data collection procedures, integrating objective performance measures with subjective user evaluations. The following sections describe the participants involved in this initial real-vehicle study, the experimental setup, the task design, and the overall test procedure.

2.1. Participants

The study involved a total of 90 participants (N = 90), all of whom were internal employees of the company. Participant recruitment was carried out in collaboration with the company's Human Resources department, with the explicit goal of obtaining a sample that was balanced in terms of gender and age distribution. This approach was intended to reduce demographic bias and to ensure a representative internal user sample for the evaluation of the in-vehicle interfaces. No specific expertise in vehicle development or HMI design was required, allowing the sample to reflect a broad range of user familiarity levels with in-vehicle systems.

Participation was voluntary, and all participants were informed about the purpose and procedure of the study prior to testing. Data were collected and processed in anonymized form, and the study was conducted in accordance with internal ethical guidelines for user research activities. Detailed analyses of demographic variables and their effects on performance and subjective ratings are presented in Section 3.

2.2. Setup and Instrumentation

The clinic test was conducted in a real production vehicle under static conditions, with the vehicle parked and the engine switched off. No driving tasks were involved during the test, allowing participants to focus exclusively on interaction with the in-vehicle interfaces without additional cognitive or visual load related to vehicle control.

The evaluation focused on multiple Human–Machine Interface components, including the instrument cluster, the central display, steering-wheel controls, and dedicated commands for the ergonomic positioning of the driver. These ergonomic functions included seat adjustment, steering-wheel positioning, and rear-view mirror configuration, as they represent essential interactions performed during initial vehicle setup and directly influence user comfort and interface accessibility.

For methodological clarity, the evaluated cockpit HMIs were grouped into four categories: (i) information-display interfaces, represented by the instrument cluster; (ii) infotainment and interaction interfaces, represented by the central display; (iii) physical driving-related controls, including steering-wheel commands; and (iv) ergonomic adjustment interfaces, including seat, mirror, steering-wheel, and window controls. These HMI categories require partially different UX evaluation strategies. In the present study, all categories were evaluated through objective performance measures (task completion times and error occurrences), subjective user ratings, and qualitative observations. More generally, display-based interfaces may additionally benefit from visual-attention and workload-related measures, such as eye-tracking metrics and cognitive workload indicators, while ergonomic adjustment interfaces may be complemented by comfort, accessibility, and posture-related observations.

Objective interaction data were collected through a combination of direct observation and video recording (Figure 2). An action camera equipped with a suction-cup mount was fixed to the driver-side door window and positioned behind the participant's shoulder to approximate a point-of-view perspective of the interaction. This setup enabled detailed post-test analysis of user behavior, supporting accurate extraction of task completion times, error occurrences, and interaction sequences. The video recordings complemented the real-time observations conducted by the examiner, allowing verification and refinement of performance metrics during post-processing.

Figure 2. (**a**) Point-of-view perspective of the user during the test, captured by the action camera positioned behind the participant's shoulder. (**b**) Overview of the test environment.

2.3. Testing Procedure & Tasks

The usability evaluation was organized according to a structured testing workflow designed to ensure consistency across participants and comparability of the collected data. The protocol combined a predefined sequence of test phases with a task-scenario structure reflecting a realistic user journey within the vehicle environment. Figures 3 and 4 summaries the organization of the interaction tasks and the overall testing procedure adopted during the study.

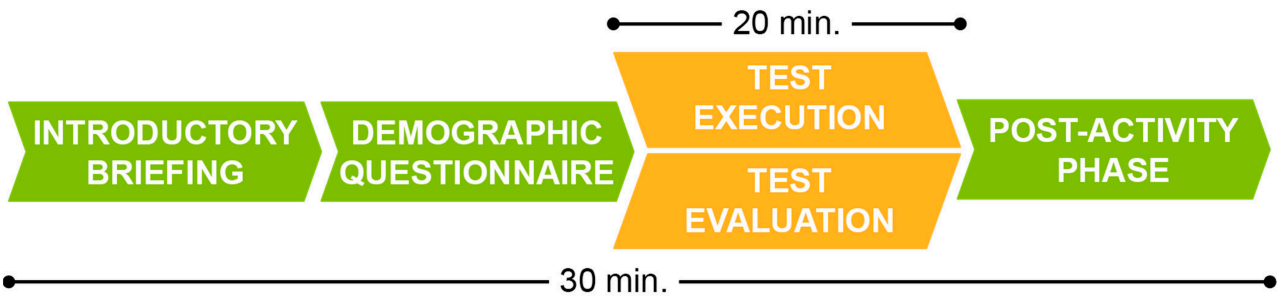

Figure 3. Workflow of the usability testing procedure.

The test structure consisted of five sequential phases: introductory briefing, demographic questionnaire, test execution, test evaluation, and post-activity feedback. At the beginning of each session, participants were welcomed and briefed by the examiner. The purpose of the study was explained, explicitly clarifying that the evaluation focused on the usability of the vehicle controls and interfaces rather than on participants' individual abilities or performance. Participants were also informed about the collection and processing of anonymized data and asked to provide informed consent regarding privacy and participation in the study.

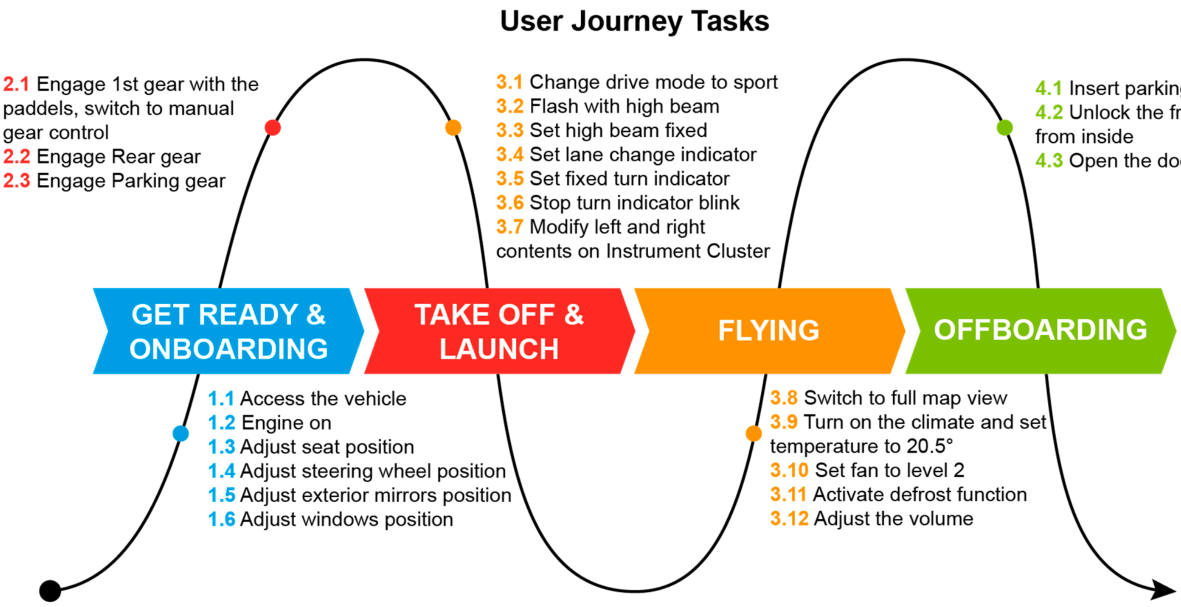

Figure 4. User journey structure and organization of interaction tasks.

Before starting the usability tasks, participants completed a demographic questionnaire collecting information related to age, gender, nationality, and familiarity with similar vehicle technologies. These variables were later used to support variance analyses and interpretation of user performance and subjective evaluations.

The interaction tasks were structured around a predefined user journey labelled "feel like a pilot", supporting a holistic and experience-oriented assessment of the in-vehicle HMI. Tasks were grouped into four macro-areas corresponding to key phases of vehicle interaction: Get Ready & Onboarding, Take Off & Launch, Flying, and Offboarding. This organization was intended to reproduce a realistic progression of user activities, from initial vehicle access and ergonomic configuration to driving-related interactions and vehicle exit.

Task selection followed three principal criteria: frequency of use, interaction relevance, and safety implications. Frequently used functions were prioritized to ensure ecological validity, while interactions involving key HMI components—such as the instrument cluster, central display, and steering-wheel controls—were selected to capture representative interface behaviors. Additional attention was given to functions potentially affecting driver attention and situational awareness, including lighting, indicators, climate settings, and drive-mode selection.

During the test execution phase, tasks were administered sequentially according to the predefined macro-areas. The examiner verbally introduced each task and observed participant interaction in real time, recording task completion times, error occurrences, behavioral observations, and spontaneous user comments. Objective data collection was supported through video recordings acquired from a point-of-view perspective using an action camera positioned behind the participant's shoulder.

At the end of each macro-area, participants completed subjective evaluations addressing perceived usability, perceived quality, and satisfaction using five-point Likert-scale items. This phase-based assessment structure enabled collection of contextualized user perceptions immediately after the interaction experience. The effective duration of the task execution phase was approximately 20 min, while the complete testing session lasted around 30 min including briefing, questionnaires, and post-task evaluations.

3. Data Analysis

The data analysis was structured to support both descriptive and inferential investigation of user performance and subjective experience during the usability test. The analysis process consisted of four main stages: demographic overview, definition of performance and perceptual metrics, data preparation and processing, and statistical analysis.

3.1. Demographic Overview

A preliminary analysis was conducted to characterize the participant sample and support the interpretation of subsequent results. The final dataset included 87 valid participants, following the exclusion of incomplete records. The sample was balanced by gender, comprising 47 male and 40 female participants. Age was distributed across three predefined clusters: 24–30 years (n = 23), 31–45 years (n = 34), and 46–65 years (n = 30).

Most participants were of Italian nationality (94%), with a smaller proportion of German participants (6%). Familiarity with in-vehicle digital systems was self-reported and showed a broad distribution, ranging from not familiar at all (5.23%) and not very familiar (25.53%) to familiar (44.68%) and very familiar (24.47%). These demographic variables were retained for use as independent factors in the statistical analyses and for contextual interpretation of performance and subjective ratings.

3.2. Performance and Subjective Metrics

Two categories of metrics were analyzed. Objective performance metrics included task completion time, measured in seconds, and the number of errors committed during task execution. Errors were defined as incorrect command activation, task failure, or the need for examiner intervention.

Subjective metrics consisted of perceived usability, perceived quality, and satisfaction. Ratings were collected using non-standardized Likert scales ranging from 1 (low) to 5 (high). Subjective evaluations were recorded at the end of each task macro-area, allowing phase-specific assessment of user perception.

3.3. Data Preparation and Processing

Raw data collected during the test sessions were consolidated into a structured dataset using spreadsheet software. The dataset was organized in a tabular format suitable for statistical analysis, with separate fields for participant demographics, task identifiers, performance measures, and subjective ratings. The dataset was then imported into RStudio (Version 2024.12.1+563; Posit Software, PBC, Boston, MA, USA) for analysis.

All analyses were conducted using R, and the analytical workflow was documented through an R Markdown file to ensure transparency, traceability, and reproducibility. This approach enabled automated generation of statistical outputs, summary tables, and visualizations directly from the processed dataset.

3.4. Statistical Analysis

Inferential statistical analyses were conducted to examine whether observed differences in performance and subjective evaluations could be attributed to participant characteristics rather than random variation. Gender and age group were treated as independent variables, while task completion time and subjective ratings were treated as dependent variables.

For each task, one-way analyses of variance (ANOVA) were performed to compare mean task completion times across gender and age groups [16]. ANOVA was selected because it allows the comparison of mean values between two or more independent groups while controlling for within-group variability. This approach is particularly suitable for usability studies involving heterogeneous user samples and multiple categorical factors.

Statistical significance was assessed using a conventional alpha level of 0.05 [17]. A result was considered statistically significant when the associated p-value was below this threshold, indicating a low probability that the observed differences occurred by chance alone. p-values close to the threshold were also noted as potentially meaningful and interpreted with caution in relation to task context and variability.

When ANOVA results indicated statistically significant or near-significant effects, targeted post-hoc comparisons were conducted using independent-samples t-tests with Welch correction. These t-tests were employed to identify the direction and magnitude of differences between specific groups (e.g., male vs. female participants), while accounting for unequal variances and sample sizes. This two-step approach allowed broad screening of effects through ANOVA, followed by more focused analysis of meaningful group differences.

The same analytical framework was applied to subjective metrics aggregated by task macro-area. Separate ANOVAs were conducted for perceived usability, perceived quality, and satisfaction, with gender and age group as independent variables. All statistical analyses were performed using R, and detailed results are reported in the Results section. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

4. Result and Discussion

4.1. Physical Validation of the UX Assessment Protocol

Objective performance was assessed through task completion times and error occurrences across all tasks. Overall, participants were able to complete the majority of tasks efficiently, with low error rates, indicating a generally good level of usability across the evaluated interfaces.

Tasks requiring longer completion times and higher error rates were primarily associated with navigation within the interface, particularly those involving menu exploration and content switching. In contrast, tasks related to direct physical controls or frequently used driving functions were typically completed more quickly and with fewer errors.

From a human-factors perspective, this pattern can be explained by the different cognitive demands associated with the evaluated interaction types. Direct physical controls generally rely on well-established mental models and provide immediate tactile and spatial feedback, reducing the need for visual search and decision-making processes. Conversely, tasks involving menu navigation and content switching require users to locate, interpret, and select digital interface elements, increasing visual attention demands and interaction complexity. As a result, these tasks are more likely to generate longer completion times and a greater variability in user performance.

A summary of the ANOVA results for all tasks is reported in Table 1, which presents p-values for the effects of gender and age group on task completion time. Statistically significant results ($p < 0.05$) indicate that observed differences between groups are unlikely to be due to random variation alone and may reflect systematic usability differences across user characteristics.

The analysis of demographic factors was performed to assess whether the proposed protocol was capable of identifying potential usability differences across heterogeneous user groups. Evaluating the influence of age and gender is particularly relevant within Human-Centred Design approaches, as it helps determine whether specific interface elements may present accessibility, discoverability, or interaction challenges for particular user populations.

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Table 1. Summary of ANOVA results for task completion time across gender and age groups.

Task	Description	*p*-Value (Gender)	*p*-Value (Age)
1.1	Access the vehicle	0.4514	0.3873
1.2	Engine on	0.4425	0.0653
1.3	Adjust seat position	0.2026	0.0275
1.4	Adjust steering wheel position	0.0552	0.7025
1.5	Adjust external mirrors position	0.0064	0.9428
1.6	Adjust windows position	0.9409	0.7551
2.1	Engage 1st gear with paddles	0.2394	0.5615
2.2	Engage Rear gear	0.0038	0.2104
2.3	Engage Parking gear	0.1089	0.4058
3.1	Change drive mode to sport	0.1782	0.9082
3.2	Flash with high beam	0.1049	0.4336
3.3	Set high beam fixed	0.0338	0.5040
3.4	Set lane change indicator (3 blink)	0.3030	0.6431
3.5	Set fixed turn indicator	0.1803	0.3623
3.6	Stop turn indicator blink	0.4438	0.2431
3.7	Modify contents on Instrument cluster	0.0759	0.1488
3.8	Switch to full map view	0.9467	0.1732
3.9	Turn on climate and set 20.5 °C	0.2980	0.3977
3.10	Set fan to level 2	0.7969	0.4359
3.11	Activate defrost function	0.8132	0.5087
3.12	Adjust the volume	0.8377	0.0706
4.1	Insert parking brake	0.2367	0.0441
4.2	Unlock front trunk from inside	0.0708	0.6179
4.3	Open the door and exit	0.3050	0.2847

Most tasks did not show statistically significant differences across gender or age groups, suggesting consistent performance across the participant sample. However, significant effects were identified for a limited number of tasks. Age group significantly influenced performance for Adjust seat position (Task 1.3) and Insert parking brake (Task 4.1), with older participants generally requiring more time to complete these interactions. Gender-related differences were observed for Adjust exterior mirrors position (Task 1.5), Engage rear gear (Task 2.2), and Set high beam fixed (Task 3.3), where female participants exhibited longer average completion times.

To further investigate these effects, box plots in Figure 5 were used to visualise the distribution of completion times for significant tasks. These visualizations revealed higher variability and a greater number of outliers for the groups associated with longer completion times, suggesting increased interaction complexity or reduced intuitiveness for specific user segments.

Interestingly, the statistically significant tasks were not randomly distributed across the interaction spectrum. Most involved either ergonomic adjustment procedures (e.g., seat and mirror adjustment) or interactions requiring users to discover less frequently used controls and functions. Such activities typically involve exploratory behaviour and higher visual-search effort compared with routine driving-related interactions, potentially explaining the greater variability observed across demographic groups.

Although task completion time is reported as the primary objective metric in Table 1, error occurrences were also collected throughout the testing campaign and considered during the interpretation of the results. Overall, error rates remained low across most tasks, further confirming the generally high usability of the evaluated interfaces and supporting the performance trends observed through completion-time analysis.

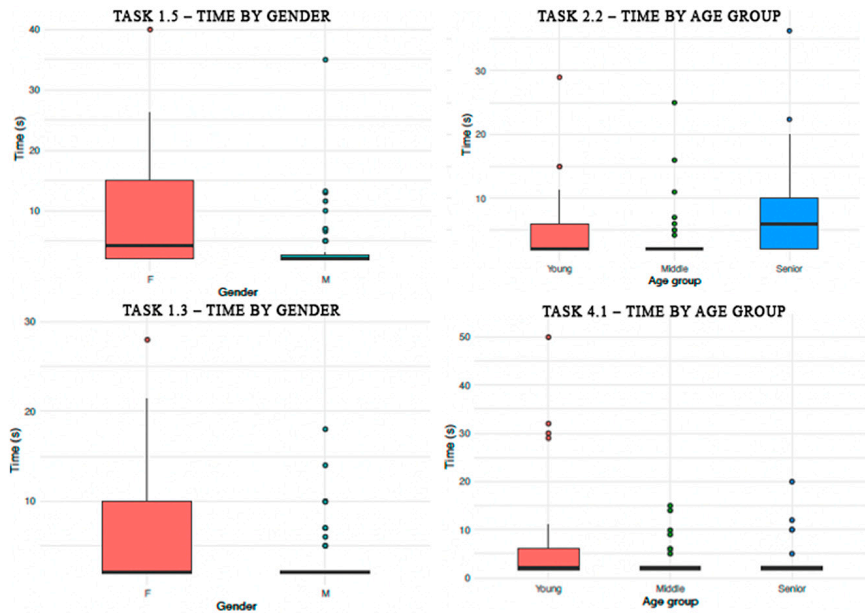

Figure 5. Distribution of task completion times for tasks showing statistically significant effects across gender and age groups.

Subjective evaluations of perceived usability, perceived quality, and satisfaction were generally high across all macro-areas, with ratings clustering toward the upper end of the scale. This pattern indicates positive overall user experience and confirms the effectiveness of the interface in supporting task execution.

The consistency observed between objective and subjective measures is particularly noteworthy. Although certain tasks generated longer completion times or increased variability among specific user groups, these difficulties did not substantially affect the overall perception of usability. This suggests that users were generally able to successfully recover from interaction challenges and maintain a positive evaluation of the system, highlighting the distinction between isolated usability issues and overall user experience.

Across macro-areas, perceived usability and satisfaction showed limited variability and consistently high scores, reflecting users' appreciation of the simplicity and clarity of the commands. Participants frequently commented on the ease of use and intuitive nature of the interactions.

Perceived quality ratings were also high overall but showed a more stable pattern across demographic groups, with less sensitivity to variance compared to performance metrics. Despite high quantitative scores, qualitative feedback revealed recurring comments related to the perceived simplicity of certain controls and materials, particularly when considered in relation to the vehicle's positioning and brand expectations.

Beyond the usability findings themselves, the results provide evidence of the feasibility and analytical capability of the proposed assessment protocol. The protocol successfully generated objective performance data, subjective evaluations, and qualitative observations across a heterogeneous sample of users. Furthermore, the statistical analyses were able to identify significant differences for selected tasks while confirming consistent performance across most interactions. These findings demonstrate that the protocol is sufficiently sensitive to detect usability-related variations without producing excessive variability or ambiguity in the collected data. The successful integration of objective and subjective measures further supports the methodological robustness of the proposed framework and its suitability for repeated industrial application.

4.2. Scientific Contribution of the Physical-to-Digital Approach

The scientific rationale of the proposed approach lies in the use of real-vehicle testing as an empirical grounding phase for the development of a transferable human-centred UX assessment protocol. In this study, the physical evaluation was not conceived merely as a stand-alone usability test, but as a methodological baseline for identifying representative interaction tasks, measurable UX indicators, behavioural patterns, and critical usability constraints under ecologically grounded conditions.

This physical grounding is particularly relevant for automotive HMIs, where user experience emerges from the interaction between visual information, manual operations, tactile and acoustic feedback, cockpit ergonomics, perceived quality, and cognitive workload. Previous studies have highlighted the importance of integrating ergonomic and workload-related dimensions within automotive interface evaluation processes, especially in increasingly digital and software-defined vehicle environments [18,19]. Similarly, physiological and behavioural monitoring approaches have demonstrated the value of combining objective and subjective indicators to better understand interaction complexity and user stress during human-centred evaluations [20].

Consequently, a robust UX assessment methodology should not rely exclusively on simulated scenarios or isolated usability indicators, but should first be informed by empirical evidence collected in real interaction contexts. The real-vehicle study therefore enabled the identification of meaningful task categories, interaction-critical behaviours, and measurable UX dimensions sensitive to interface complexity and user perception.

At the same time, simulation environments are becoming increasingly important within contemporary automotive development processes due to their flexibility, scalability, and ability to support controlled experimentation. Simulator- and VR-based studies have demonstrated the advantages of digital environments for investigating driver behaviour, interaction strategies, workload, and interface usability under reproducible conditions [8,9]. However, recent systematic investigations have also highlighted substantial methodological heterogeneity in automotive UX evaluation practices, particularly regarding task definition, instrumentation, metrics, and protocol standardisation [21]. This variability often limits cross-study comparability and reduces the transferability of experimental findings across projects and development phases.

The novelty of the proposed methodology lies in the formalisation of empirical real-vehicle evidence into a structured physical-to-digital evaluation framework. Rather than treating real and virtual testing as separate or alternative methodologies, the proposed protocol establishes methodological continuity between the two environments. Core assessment components, including task taxonomy, task completion time, error occurrence, interaction sequence, perceived usability, perceived quality, satisfaction, and qualitative behavioural observations, are preserved as environment-invariant elements supporting comparability between physical and simulated evaluations.

Within this framework, the transition toward simulation extends the analytical capabilities of the protocol without replacing its original human-centred structure. While the real-vehicle evaluation provides ecological grounding, the simulated environment enables higher experimental control, repeatability, safe manipulation of high-demand scenarios, rapid prototyping of alternative HMI configurations, and integration of advanced sensing technologies. Automated interaction logging, eye tracking, physiological monitoring, workload assessment, and simulator telemetry can therefore be integrated into the evaluation pipeline to support more detailed behavioural and cognitive analyses [8,20].

Compared with existing approaches focusing separately on field studies, simulator experiments, or VR evaluations, the contribution of this work is therefore primarily methodological. The proposed framework defines a repeatable and transferable UX assessment pipeline capable of maintaining consistency across both physical and digital evaluation contexts. This approach contributes to the state of the art in three principal ways: (1) by providing a structured and reusable UX assessment protocol grounded in real-vehicle interaction data; (2) by defining transferable metrics and procedures supporting methodological continuity between real and simulated testing environments; and (3) by enabling progressive integration of simulation-based evaluation within human-centred automotive development processes, allowing early-stage HMI concepts to be assessed before physical implementation while maintaining a validated connection with real-world user behaviour.

4.3. Protocol Formalisation and UX Assessment

The results obtained from the physical user testing phase were used not only to evaluate the usability of the selected in-vehicle HMIs, but also to formalize a structured human-centered UX assessment protocol. The protocol elements proposed for future evaluations were directly derived from the observations obtained during the physical testing phase. For example, the increased completion times observed for digitally mediated interactions highlighted the importance of detailed interaction logging and behavioural analysis, while the variability detected across specific user groups reinforced the need for standardized and repeatable assessment procedures. Similarly, the combination of objective performance metrics and subjective user feedback demonstrated the value of adopting a multidimensional UX evaluation approach. Consequently, the proposed protocol was designed to preserve the most informative measures identified during the real-vehicle evaluation while extending the range of data that can be collected within simulated environments. The results obtained from the physical user testing phase were used not only to evaluate the usability of the selected in-vehicle HMIs, but also to assess the feasibility, analytical robustness, and transferability of the proposed UX assessment protocol. The successful execution of the study across a large and demographically heterogeneous participant sample demonstrated the practical applicability of the protocol within an industrial context, while the collected data provided evidence of its capability to generate meaningful usability and user experience insights. In line with the physical-to-digital framework presented in Figure 1, the empirical evidence collected in the real vehicle was transformed into a reusable methodological structure based on three main components: interaction tasks, measurable UX indicators, and standardized data collection procedures.

From a performance perspective, the real-vehicle evaluation highlighted that most tasks were completed efficiently and with low error rates, confirming the overall usability of the assessed interfaces. However, tasks involving digital navigation, menu exploration, and content switching required longer completion times and generated more errors than direct-control interactions. These findings indicate that the protocol must be able to distinguish between different interaction modalities and identify usability constraints associated with increasing interface complexity.

From a perceptual perspective, subjective evaluations showed consistently high ratings for perceived usability and satisfaction, while perceived quality revealed more nuanced feedback. In particular, qualitative comments suggested that some controls were perceived as less premium than expected in relation to the vehicle's positioning. This result confirms the importance of including not only efficiency-oriented metrics, but also experiential indicators capable of capturing perceived quality, satisfaction, and symbolic aspects of interaction.

From a methodological perspective, the integration of objective measures, subjective ratings, and qualitative observations proved essential for obtaining a comprehensive understanding of UX. Task completion time and error rate provided measurable evidence of interaction efficiency and effectiveness, while subjective evaluations and user comments helped interpret the experiential meaning of the interaction. This combination allowed the physical study to move beyond a single usability test and become the basis for a repeatable industrial assessment protocol. The protocol demonstrated its ability to support standardized data collection, objective statistical analysis, and structured interpretation of user experience outcomes, thereby providing preliminary evidence of its scientific rigor and practical applicability.

Beyond its empirical findings, the real-vehicle evaluation also serves as a validated methodological baseline for the future development of digital and simulation-based HMI assessment environments. While virtual and simulated platforms offer important advantages in terms of flexibility, scalability, and early-stage prototyping, their effectiveness depends on preserving methodological continuity and human-centered validity across physical and digital contexts.

The performance indicators, subjective measures, and analytical procedures defined during the physical evaluation therefore provide reference criteria for the development of simulation-based UX assessment protocols. In particular, core dimensions such as interaction timing, error tracking, structured subjective feedback, and qualitative behavioral observations should be preserved to ensure comparability between real and simulated testing environments.

While both evaluation phases share the same human-centred methodological foundation, they pursue complementary objectives. The primary purpose of the physical evaluation is to establish an empirical baseline under realistic interaction conditions, validate the assessment procedures, and identify the most informative UX indicators. In contrast, the simulation-based evaluation is intended to support early-stage concept assessment, comparison of alternative design solutions, controlled experimentation under different operating conditions, and iterative refinement before final physical validation. Consequently, although the core UX dimensions remain consistent across phases, the available measurement tools, experimental flexibility, and analysis opportunities can be significantly expanded within the simulated environment.

Moreover, the empirical insights gained regarding interaction complexity and experiential perception help identify which additional technologies and measurement tools may enhance the analytical sensitivity of future simulated assessments. Table 2 summarizes the main metrics adopted during the physical evaluation phase, indicating how each measure was collected, which tools were used, and why each metric is relevant within a human-centered UX assessment framework.

Table 2. Metrics adopted during the physical UX evaluation phase and their methodological relevance within the human-centered assessment framework.

Category	Metric	Measurement Method	Tools/Instruments	Relevance for UX Assessment
Objective Performance	Task completion time	Time required to complete each task	Action camera video analysis + examiner observation	Evaluates interaction efficiency and operational usability
Objective Performance	Error rate	Counting incorrect actions, failed tasks, or examiner intervention	Examiner observation + post-test video review	Identifies usability constraints and interaction complexity
Behavioural Observation	Interaction sequence	Observation of user interaction flow and navigation behaviour	Action camera recordings	Supports analysis of user strategies and interaction patterns
Behavioural Observation	Hesitations and spontaneous comments	Real-time annotation during task execution	Examiner notes	Reveals uncertainty, confusion, and perceived interaction difficulties

Table 2. *Cont.*

Category	Metric	Measurement Method	Tools/Instruments	Relevance for UX Assessment
Subjective UX	Perceived usability	Post-task Likert-scale evaluation	Custom questionnaire	Assesses ease of use and intuitiveness
Subjective UX	Perceived quality	Post-task Likert-scale evaluation	Custom questionnaire	Evaluates perceived premium quality, haptic feedback, and interface refinement
Subjective UX	Satisfaction	Post-task Likert-scale evaluation	Custom questionnaire	Measures emotional response and overall interaction appreciation

4.4. UX Assessment in Simulated Environments

Building upon the validated real-vehicle evaluation, the proposed UX assessment protocol is being progressively extended to support implementation within a digitally simulated environment. Since the simulation platform is currently under development, the present study does not report empirical simulator-based results. Instead, this section describes how the protocol components validated during the physical evaluation can be transferred to a digital environment while preserving methodological consistency, measurement comparability, and human-centred design principles. The transition toward simulation is conceived not as a replacement for physical testing, but as a methodological evolution of the human-centered framework established during the empirical validation phase.

It should be noted that the simulation-based implementation described in this work refers specifically to a modular static driving simulator currently under development in collaboration with the industrial partner. The platform is designed to reproduce both the digital interfaces and the physical cockpit environment through configurable hardware components and interchangeable 3D-printed mock-ups. Consequently, the protocol presented in this study has been conceived and adapted for this specific evaluation environment. Future work will investigate its applicability and potential adaptations to other simulation platforms characterized by different levels of fidelity, immersion, and interaction modalities.

The real-vehicle study enabled the definition of a structured assessment architecture consisting of four macro-phases: introductory briefing, pre-test preparation, controlled test execution and evaluation, and post-activity feedback. This structure ensured consistency across participants, standardization of interaction tasks, and integration of objective performance metrics with subjective user evaluations. The empirical findings obtained during the physical testing phase informed the identification of interaction-critical tasks and the definition of core measurement indicators, including task completion time, error occurrence, qualitative behavioral observations, and structured subjective ratings.

Figure 6 illustrates the proposed adaptation of the UX assessment workflow for digitally simulated HMI evaluation environments. Within the simulated environment, the same human-centered macro-structure is preserved to ensure methodological continuity between physical and digital evaluations. However, the digital context enables a substantial extension of the analytical capabilities of the protocol.

During the execution phase, interaction scenarios can be dynamically manipulated to include variations in traffic density, environmental conditions, time pressure, or critical driving events. Such manipulations allow usability and UX assessments to be performed under controlled high-demand conditions that would be difficult, unsafe, or impractical to reproduce during static real-vehicle testing. In addition, the simulated environment enables systematic comparison between alternative interface layouts and interaction concepts through rapid prototyping workflows.

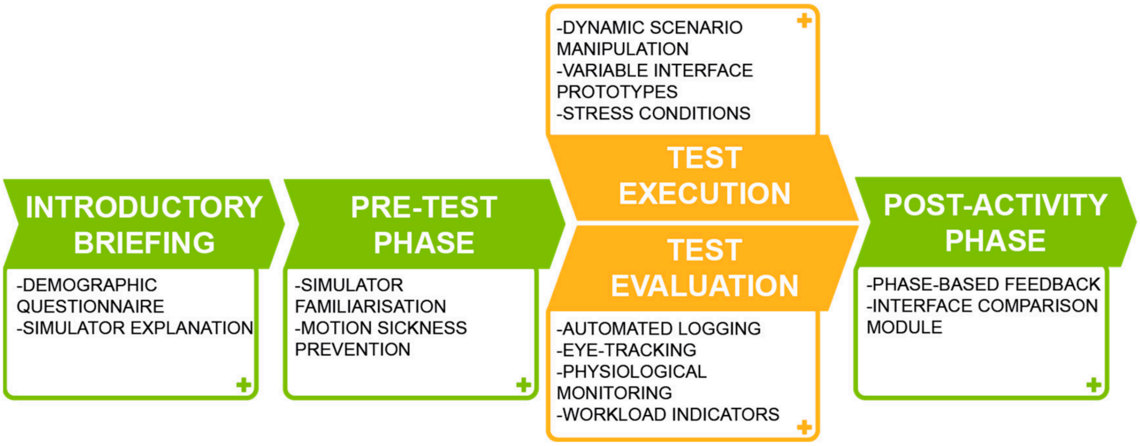

Figure 6. Proposed UX assessment protocol for digitally simulated HMI evaluation.

Similarly, the evaluation phase can be enhanced through the integration of advanced digital measurement technologies. Automated interaction logging, navigation-path reconstruction, eye-tracking systems, and physiological monitoring tools may provide higher-resolution behavioral and cognitive data while maintaining comparability with the validated physical baseline. Importantly, these additional data layers are not intended to replace the original protocol metrics, but rather to improve analytical sensitivity and support deeper understanding of user interaction mechanisms.

Furthermore, the simulated environment enables evaluation of early-stage or low-fidelity HMI concepts before physical implementation, supporting iterative refinement during the primary phases of development. This capability is particularly relevant in contemporary automotive design processes, where software-defined interfaces evolve rapidly and require scalable human-centered validation methodologies.

Table 3 summarizes the proposed metrics, measurement methods, and digital technologies intended for integration within the simulated UX assessment framework, highlighting their contribution to enhanced human-centered evaluation capabilities.

Table 3. Proposed metrics, digital technologies, and analytical capabilities integrated within the simulated UX assessment framework.

Category	Metric	Measurement Method	Tools/ Instruments	Relevance for UX Assessment
Objective Performance	Task completion time	Time required to complete each task	Action camera video analysis + Simulator logging system + Eye tracker	Evaluates interaction efficiency and operational usability
Objective Performance	Error rate	Counting incorrect actions, failed tasks, or examiner intervention	Action camera video analysis + Simulator logging system + Eye tracker	Identifies usability constraints and interaction complexity
Behavioural Observation	Interaction sequence and navigation paths	Observation of user interaction flow and navigation behaviour	Action camera recordings	Supports analysis of user strategies and interaction patterns

Table 3. *Cont.*

Category	Metric	Measurement Method	Tools/ Instruments	Relevance for UX Assessment
Vehicle Control Behaviour	Steering, pedal, and vehicle-input timing	Continuous acquisition of driver control inputs	Driving simulator telemetry	Enables reaction-time analysis and assessment of driver behaviour during tasks
Visual Attention	Gaze distribution and fixation duration	Eye-tracking analysis	Eye tracker	Evaluates visual workload, discoverability, and attentional demand
Cognitive Workload	Physiological response and stress level	ECG and biosignal acquisition	ECG sensors/wearable biosensors	Supports estimation of mental workload and stress during interaction
Physical Ergonomics	Driver posture and body movement	Seat-pressure and posture monitoring	Smart seat sensors/pressure sensors	Assesses ergonomic comfort and interaction posture
Subjective UX	Perceived usability	Standardised usability questionnaires	SUS (System Usability Scale)	Provides validated usability assessment [22]
Subjective UX	Cognitive workload perception	Standardised workload questionnaires	NASA-TLX	Evaluates perceived mental, physical, and temporal demand [23]
Subjective UX	User experience perception	UX questionnaires	UEQ/AttrakDiff	Captures hedonic and experiential aspects of interaction [24]
Experimental Flexibility	Critical and high-demand scenarios	Controlled environmental manipulation	Simulation environment	Enables safe evaluation under hazardous or difficult driving conditions (e.g., low visibility, wet roads, emergency events)
Early Design Validation	Evaluation of low-fidelity interface concepts	Rapid virtual prototyping	Configurable digital HMI prototypes	Supports iterative refinement during early development phases

From an industrial perspective, the proposed framework may contribute to a more efficient HMI development process by enabling earlier usability assessments, reducing dependence on late-stage physical prototypes, and supporting iterative design refinement within controlled digital environments [25]. Although the present study does not include a quantitative comparison against conventional development approaches, the structured transition from physical validation to simulation-based assessment establishes the methodological foundation required for future investigations of development efficiency, testing costs, and design-cycle optimisation.

Although simulation-based evaluations are commonly employed during early design stages to reduce development costs and accelerate iteration cycles [26], the framework presented in this study follows a different sequence because it originated from an existing industrial testing campaign conducted on a production-ready vehicle. Consequently, the real-vehicle evaluation served as the empirical foundation for identifying relevant UX metrics, validating assessment procedures, and defining the protocol before its transfer to a simulated environment. The proposed approach should therefore be interpreted as a methodology-development process rather than as a generic vehicle-development workflow.

5. Conclusions

This study proposes a human-centered UX assessment protocol for simulated evaluation environments grounded in experimental data collected through real-vehicle testing.

The research first developed and applied a structured usability evaluation conducted in a real vehicle under static conditions, establishing an empirical baseline for the assessment of in-vehicle Human–Machine Interfaces (HMIs).

The results demonstrated generally high levels of usability and user satisfaction across a wide range of interaction tasks, with limited performance differences across demographic groups. Objective performance measures highlighted specific challenges associated with navigation within digital interfaces, while subjective evaluations confirmed the overall clarity and ease of use of the system. These findings not only provide insights into the usability of the evaluated HMI but also contribute to the definition of measurable interaction indicators that can inform future evaluation frameworks.

Beyond the empirical outcomes, the primary contribution of this work lies in its methodological and applied value. The study formalized a structured and repeatable UX assessment protocol that integrates behavioral performance metrics with subjective user evaluations. This framework can support consistent data collection and evidence-based decision-making within industrial HMI development processes, while also providing a validated baseline for the design of simulation-based evaluation methodologies.

Several methodological limitations should be acknowledged. Subjective experience was assessed using custom rating items rather than standardized instruments such as the System Usability Scale (SUS) or NASA Task Load Index (NASA-TLX), which limits direct comparability with existing studies. In addition, objective performance measures relied primarily on video recordings and examiner observations, without the support of advanced sensor-based measurement systems.

An additional limitation concerns the simulation-based component of the framework. While the present study defines a structured methodology for transferring the protocol to a digital environment, empirical validation of the simulator implementation has not yet been completed and therefore remains part of future work.

Future work will also extend the proposed protocol through the integration of complementary measurement tools and the parallel development of a digital simulated evaluation environment currently being designed in close collaboration with the industrial partner. The simulated platform will reproduce both the vehicle context and the physical characteristics of HMI interfaces, enabling controlled experimentation and iterative usability testing across different design configurations.

Its primary objective is to support UX and usability evaluations of early-stage interface concepts, allowing potential interaction issues to be identified and addressed during the initial phases of development rather than after hardware implementation. Within this framework, advanced measurement technologies such as eye-tracking systems may provide detailed insights into visual attention and interface discoverability, while physiological sensors—including heart rate variability or electrocardiography—could support a more comprehensive assessment of cognitive workload and user stress.

By bridging empirical real-vehicle validation with scalable simulation-based evaluation, the proposed approach contributes to strengthening human-centered methodologies for automotive HMI development and supports more efficient and iterative design processes.

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Abbreviations

The following abbreviations are used in this manuscript:

HMI	Human–Machine Interface
ANOVA	Analysis of Variance
ECG	Electrocardiography
HRV	Heart Rate Variability
NASA-TLX	NASA Task Load Index
SUS	System Usability Scale
UEQ	User Experience Questionnaire
UX	User Experience
VR	Virtual Reality

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