Move, Connect, Interact: Introducing a Design Space for Cross-Traffic Interaction

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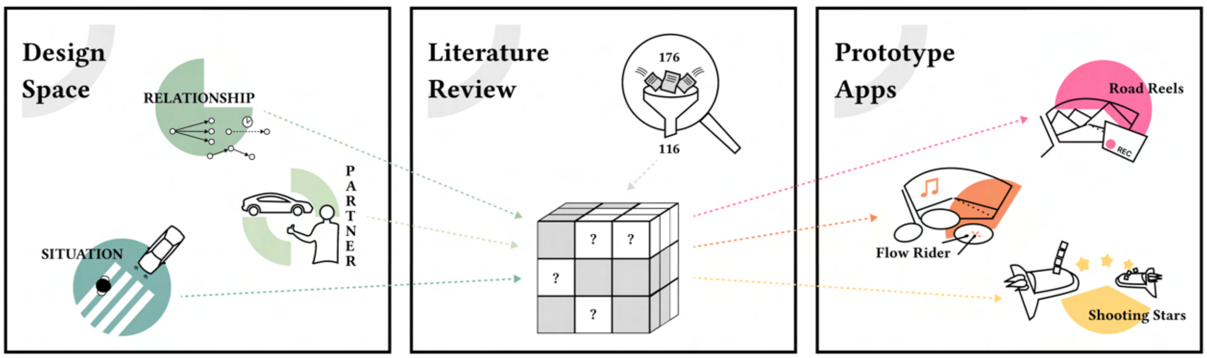

Fig. 1. With our design space on Cross-Traffic Interaction (CTI), we offer the possibility to systematically explore interaction prospects that arise through diverse traffic entities and increased connectivity. Through a systematic literature review, we identify research trends and show that large spaces remain unexplored. Further, we exemplify how our design space is applied by designing, prototyping, and evaluating three CTI applications.

Rising diversity through novel forms of mobility and increasing connectivity through intelligent systems and wireless connection is leading to a complex traffic environment. However, traditional automotive interface research often focuses on the interaction between vehicle and driver, passenger, or pedestrian, not capturing the interconnected relationships among various traffic participants. Therefore, we developed a design space for Cross-Traffic Interaction (CTI) based on a focus group with six HCI experts, encompassing the dimensions: (1) interaction partners, (2) their traffic situations, and (3) their interaction relationship. Through a systematic literature review, we classified 116 publications, showing less-studied interaction possibilities. Illustrating the practical application of our design space, we developed three interactive prototypical applications: *Shooting Stars*, *Flow Rider*, and *Road Reels*. A study (N=12) shows that the applications were received well and could improve traffic experience. Overall, our design space serves as a foundational tool for understanding and exploring the

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challenges and diverse opportunities within CTI, bridging the gap between traditional automotive interface research and the complex realities of modern traffic environments.

CCS Concepts: • **Human-centered computing → HCI design and evaluation methods**.

Additional Key Words and Phrases: Cross-Traffic Interaction, traffic, design space, automotive

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1 Introduction

Traffic is becoming a complex mix of different participants and mobility concepts. For example, the increase in automation leads to mixed traffic, adding complexity in how all these participants—like automated vehicles, human-driven vehicles, and pedestrians—safely and efficiently interact on the roads [106]. Emerging micromobility adds new types of road users [162], and specialized vehicles, such as autonomous shuttle buses, may share the road with unique sizes, speeds, and organizational needs (e.g., [173]). To effectively coordinate the diverse and growing number of traffic participants, it is essential to implement advanced technologies that facilitate enhanced communication among them. Recent advancements in communication technology have led to the development of vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) systems, which are pivotal in managing these interactions. Connected and automated vehicles (AVs) can communicate with each other (i.e., vehicle-to-vehicle interaction (V2V)), with other smart traffic devices (i.e., vehicle-to-anything (V2X) [14], e.g., infrastructure [44]), passengers [110], other road users (e.g., pedestrians [48]), and even non-road users (e.g., for remote control [157]). Also, smart traffic devices can communicate with each other and other road users [104].

Increased connectivity not only enables complex traffic management but also provides opportunities for individuals. With the rise of connected and automated vehicles, passengers can experience enhanced safety and convenience. For instance, real-time traffic data shared between vehicles can reduce congestion and shorten travel times. Additionally, connectivity opens up new possibilities for personalized travel experiences, such as dynamic route optimization based on user preferences or current road conditions. For individuals in AVs, for example, connectivity increases productivity by allowing people to work remotely or to participate in a social experience with passengers of other vehicles, other road users or the environment. The concept of "cross-car" multiplayer games has been identified as an opportunity, enabling occupants in nearby cars to engage in interactive gameplay, thus enhancing social interactions and entertainment options during travel [96]. Moreover, connectivity plays a crucial role in transforming transportation systems. The interconnectedness supports a wide range of mobility services, such as on-demand transportation options and advanced vehicle-sharing systems. These services can dynamically adjust to individual needs based on current traffic conditions, user location, and availability of vehicles, making them more responsive [123].

There is ongoing research into the Human-Computer Interaction (HCI) challenges introduced by increased connectivity and associated technologies. Key issues include challenges in interactions between drivers or passengers and AVs, sparking various research questions within communities like Automotive User Interfaces [1]. Another key area of investigation involves how AVs should communicate their behavioral intentions to other road users, such as pedestrians or cyclists, through external human-machine interfaces (eHMI) to ensure their actions are clearly understood [35, 48]. Within these topics, researchers have explored numerous design spaces, such as those for eHMI [41] and both uni- and multi-modal in-vehicle interactions [84].

However, while current research provides valuable insights into specific interactions between a single vehicle and individual human road users—such as drivers, passengers, or pedestrians, automotive HCI research often fails to address the broader capabilities that enhanced connectivity could enable. This oversight means that potential enhancements in current solutions facilitated by advanced connectivity are not fully explored. Moreover, this focused approach limits the scalability of solutions across increasingly diverse and interconnected traffic environments. Without considering the complex interconnections in modern traffic, solutions may fail to adapt to the evolving needs of modern traffic. For these solutions to be scalable, they must be capable of effectively managing interactions among multiple vehicles, various types of road users, and the broader traffic infrastructure. To truly leverage the potential of advanced connectivity, interaction research must evolve from existing specialized research fields to encompass a broader range of traffic dynamics.

As a first step, we thus introduce the term Cross-Traffic Interaction (CTI) to describe the interaction among diverse traffic entities, including, but not limited to, vehicles, drivers, passengers, pedestrians, smart (mobility) devices, and infrastructure facilitated by enhanced connectivity. CTI thus includes traditional automotive HCI, which mostly focuses on one-to-one interaction but also extends beyond, enclosing the complex, interconnected relationships of interaction in the upcoming traffic.

We further propose a design space to enable a systematic classification and exploration of CTI. It organizes CTI into three primary dimensions, where each dimension is defined by specific parameters: (1) *Interaction Partner* identifies who is involved in an interaction, including a range of road users and connected entities such as vehicle drivers, passengers, pedestrians, cyclists, and even non-road users. (2) *Situation* captures the context in which interactions occur, influenced by traffic density, road characteristics, and environmental conditions. Situations can vary significantly, affecting how interactions unfold. (3) *Interaction Relationship* details the nature of the interactions themselves, whether they are direct or mediated, and includes factors like position dependency or time synchronicity.

We explain how our design space serves as a *classification* and *ideation* tool for CTI research. We then demonstrate these approaches through practical examples: Initially, we used the design space as a *classification* tool by conducting a systematic literature review, categorizing 116 automotive HCI publications within the design space. Results show the expected focus of direct interactions between two interaction partners (mostly including one vehicle and a driver or pedestrian). Although there are some interaction concepts that go beyond this (e.g., [12, 42]), large parts of the design space remain unexplored, highlighting potential areas for further research. To explore the classification, we additionally implemented an interactive website. Demonstrating the usage of the design space as an *ideation* tool, we conceptualized and implemented three applications in the exemplary research field of in-vehicle gaming and evaluated them in a Virtual Reality (VR) simulator study (N=12). By focusing on one specific research field, we empirically show the potential of the design space to achieve existing research objectives within that field.

Contribution statement: (1) With our design space on CTI, we offer the possibility to systematically explore interaction prospects that result from emerging traffic entities and increased connectivity. (2) Through a systematic literature review, we identify trends and show that large spaces remain unexplored. (3) Further, we exemplify how our design space is applied by designing, prototyping, and evaluating three cross-traffic applications (see Figure 1).

2 Background and Related Work

Our work mainly builds on current mobility trends and their influence on CTI and existing design spaces in Human-Computer Interaction (HCI).

2.1 Technical Advancements, Mobility Trends, and Their Impact on Cross-Traffic Interaction

Technological progress leads to the emergence of diverse mobility trends.

Ever-increasing capabilities and automation of vehicles leads to a shift from a driving-centric design of in-vehicle interactions towards an activity-centric one [154], enabling diverse non-driving related activities (NDRAs) like watching movies or playing games [131]. In addition, the enhanced sensing technologies within vehicles enable context awareness (e.g., about the passengers' states [153], the current location, and the environment). This enables more engaging travel experiences and enhanced connectivity between passengers, vehicles, and surroundings such as innovative in-car gaming experiences [96, 159], music experience (e.g., through scene-adaptivity [89]), approaches that facilitate the usage of AVs as a social setting (e.g., for a future mobile office enhancing productivity [85, 148]), or concepts enabling cross-vehicle cooperative driving [58]. It also enables interaction between traffic entities and non-road users, which allows, for instance, remote control of vehicles [157]. Further, advanced wireless communication technologies ([26, 125]) allow V2A interactions. This even leads to considerations of implementations for crowd intelligence [24], enabling communication beyond single vehicles and across different situations.

Besides this, there is a trend towards micro-mobility and the use of small, lightweight transport modes like e-scooters and e-bikes for short-distance travel [2] highlighting further HCI challenges. Current research investigates challenges of interacting while using the transportation mode (e.g., examining the interaction of bicyclists with non-road users via their smartphones [134]) and interaction with other road users (e.g., studying the interaction of e-scooter riders with other road users via signaling hands [102]). Additionally, the emergence of Urban Air Mobility (UAM) adds a new layer to these interaction dynamics by introducing novel user interfaces and interaction scenarios in three-dimensional traffic environments [38, 113, 114].

These mobility trends are driving the need for CTI research as they open up diverse interaction prospects between people and mobility concepts that need to be considered but are often overlooked in existing specific research areas.

2.2 Design Spaces in automotive Human-Computer Interaction

The field of HCI utilizes design spaces [22, 74] and taxonomies [62] to understand the impacts of technologies on interaction [41], methodically categorize interaction concepts [62], and investigate potential design solutions [22]. Card et al. [22] illustrated the creation of a design space using morphological analysis, a technique for systematically exploring combinations of components, as originally proposed by Zwicky [181].

Design spaces within the automotive HCI research focus on exploring in-vehicle interaction [5, 70, 84, 91, 172]. Jansen et al. [84] examined in-vehicle interaction regarding the dimensions *human-actuated input and output modalities* and *locations throughout the vehicle interior*, building on an earlier design space by Kern and Schmidt [91], which did not consider automation yet. The design space shows the manifold possibilities in the interaction between vehicles and drivers/passengers while simultaneously classifying the modalities on the basis of human senses. Haeuslschmid et al. [70] explored the design space around augmented reality (AR) windshield displays with the dimensions *user*, *context*, *visualization*, *interaction*, and *technology*, which was later extended by Wiegand et al. [172] to also suit for mid-air 3D AR applications, showing the potential of novel display technologies for in-vehicle interaction.

Approaches for gaming in this context often rely on VR/AR and V2V connectivity to enable multiplayer games among passengers within the same vehicle as well as those in different vehicles. For example, Lakier et al. [96] developed a design space specifically focused on cross-vehicle multiplayer games for passengers in co-located vehicles. They presented the dimensions *is game*, *multiplayer*, *competition style*, *co-located cars*, *environment*, *presentation*, *input*, *driver plays*, *route influence*, *genre*, *intended traffic environment*, *required play time*, and *presence of teams*.

Design Spaces also exist in the area of vehicle-pedestrian interaction. Colley and Rukzio [41] considers dimensions for the interaction based on its concept (*locus*, *message type*, and *modality*) and its situation (*communication relationship*, *communication partner*, *number of lanes*, *acoustic noise level*, *traffic autonomy*, and *weather*). Holländer et al. [78] have proposed a taxonomy for VRUs.

While these existing design spaces provide valuable insights into their specific research fields, allowing for a detailed overview of possible design solutions, they cannot capture the interplay among diverse traffic entities and situations that characterize today's evolving traffic with ever-increasing connectivity. For example, existing design spaces for HVI do not include potentials and challenges of V2V communication. Yet, to address these, a broader perspective on HVI is required that considers not just the interaction between a user and a single vehicle but also the interaction with a network of many vehicles. These limitations necessitate a more broadly considered view of interaction within interconnected traffic, which should be facilitated by CTI research.

3 Focus Group

To better understand CTI and to identify important factors that play a role in this context, we conducted a focus group with experts (N=6) in HCI of Ulm University. The insights gained from this focus group informed the development of our proposed design space.

3.1 Participants

The participants of the focus group were, on average, *M=26.17* (*SD=1.72*; ranging from 24 to 29) years old. One identified as female and five as male. At the time of the focus group, five participants were working as research associates or Ph.D. students in the field of HCI. One participant was a master's student with two publications at AutomotiveUI.

3.2 Procedure

At the beginning, the participants signed a consent form. The session was divided into an introduction, idea collection, and discussion, and the audio was recorded throughout. The introduction consisted of an overview of the agenda, the focus group leaders, and arising (connectivity) technologies in traffic (i.e., automation, V2V, V2X, and Mixed Reality (MR)). For the idea collection, we used the 6-3-5 method, which is a group-structured brainstorming technique [16]. First, a problem is defined per person on a worksheet, which is then passed from person to person in the following rounds, providing ideas from which the next person can draw inspiration. We have used the method so that participants had to think of application concepts that could arise from the connectivity of various traffic entities. Those applications were written down and passed to the next person in the group. In the following two iterations, the participants had the task of extending the application concepts. In the last two iterations, participants should think of specific interaction concepts between traffic participants in the context of the described application. Afterward, the specific interaction concepts were transferred to post-its, and the participants had to group them and discuss possible design space dimensions and parameters. Finally, there was an open discussion. Overall, the duration of the focus group was 120 minutes.

3.3 Results

We conducted a thematic analysis of the discussion and written results. Therefore, two of the authors separately listened to the recordings and reviewed the sheets and post-its. Afterward, they grouped them into themes. In a subsequent discussion, the two authors discussed the themes and merged them into the final set.

Interaction Partners. The participants discussed possible interaction partners and concluded that *people*, *objects*, and the *environment* play the most crucial factor in the context of CTI. One participant assumed that "interaction is [...] in most cases with an object or the environment and in the rarest cases with a person directly" [P1].

Positional Dependency. The *proximity* between two interaction entities was named as a factor serving as a prerequisite for interaction. Proximity was defined as two people having visual contact. However, participants also considered shared routes, shared route areas, and shared events as possible factors. Events were considered to be (1) traffic-related, e.g., collisions or construction sites, or (2) context-related, e.g., weather conditions or seasonal influences. They suggested that interaction could benefit from interaction partners sharing one or multiple of these factors.

Relationship of Interaction Partners. Participants recognized the *relationship* between two people as another important factor for the establishment of CTI. They suggested that the relationship between interaction partners is a crucial factor for interaction design, especially when the interaction condition of proximity is not met. However, they also identified that interactivity does not necessarily require identifying a partner. An example was sharing music with other people nearby without them knowing who the music was coming from.

Situation. A dependency on automation was further mentioned, with a focus on (1) the level of automation of the ego-vehicle and (2) the level of traffic automation (e.g., mixed vs. fully autonomous). Concerning the ego-vehicle, it was stated that the vehicle state, such as speed and driving behavior, can impact CTI.

Special Features of CTI. Participants highlighted the dynamic development of traffic situations. One participant stated: "That's what makes the whole scenario so interesting, that I have changing people, vehicles, and objects in the vicinity" [P6]. One participant argued that the dynamic and speed of the environment change depending on the means of transportation, e.g., pedestrians move slower within a less dynamically changing environment compared to a vehicle, which has a direct impact on the interaction possibilities [P4].

3.4 Discussion

The results of the focus group show that CTI requires the definition of *Interaction Partners* as each comes with entity features, such as speed and traffic dynamics. Further, as the focus group indicated that objects and the environment can be essential parts of an interaction, we decided to not only include human interaction partners but also smart objects. Furthermore, we recognized environmental factors as an important factor in CTI, which is consistent with related design spaces, most of which also include environmental factors (e.g., [41, 96]). The focus group highlighted the importance of parameters describing the interaction relationship between interaction partners. This included whether interaction partners share the same position, similar relative positional factors (e.g., shared route), or if interaction partners know each other. Therefore, we chose to incorporate *Interaction Relationship*, along with the relevant factors, as one part of our design space.

4 Design Space

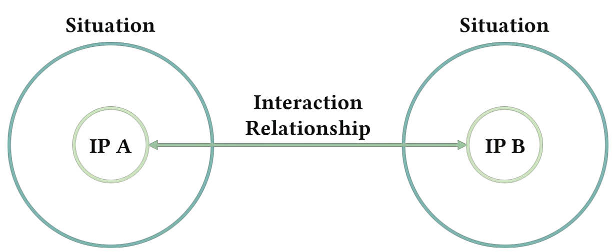


Fig. 2. Illustration of how our design space parts Interaction Partner (abbreviated as IP), Situation, and Interaction Relationship are interrelated using the example of two interaction partners in different situations.

To systematically categorize and explore the emerging interaction opportunities among traffic entities in CTI, we developed a design space based on related work and the results of the focus group. The design space is divided into three parts: (1) *Interaction Partner*, (2) *Situation*, and (3) *Interaction Relationship*. An interaction consists of any number of interaction partners that form an interaction relationship and the situations surrounding them. The interplay of our three design space dimensions is visualized in Figure 2, showing an example of two interaction partners in different situations. In the following, the dimensions of the respective parts are stated, and the parameters for each dimension are defined. We created Zwicky Boxes [181], a visual tool used in brainstorming and problem-solving, consisting of a grid or matrix structure to facilitate morphological analysis.

4.1 Dimensions and Parameters - Interaction Partner

Interaction Partner	Interaction partner	*vehicle driver*	*vehicle passenger*	*pedestrian*	*cyclist*	*motor-cyclist*	*official*	*non-road-user*	*smart vehicle*	*smart object*
	Role	*active*					*passive*			
	Input	*see [84]*								
	Output	*see [84]*								

Fig. 3. Dimensions and parameters of the design space part Interaction Partner.

Figure 3 shows an overview of the dimensions and corresponding parameters as Zwicky Box.

Interaction Partner. We posit that all road users and connected traffic objects (e.g., smart roads) can be interaction partners in CTI, and, due to constantly evolving mobility concepts and vehicles, the parameter cannot be captured holistically. Thus, we focus on those primarily represented within current works. Included in the design space are vehicle drivers, passengers, pedestrians, cyclists, motorcyclists, officials (e.g., police officers), smart vehicles, and smart objects (e.g., connected infrastructure) [41, 64, 78]. Further, we include non-road-users, as we argue that CTI can also occur between road users and non-road-users. Traffic participants of other (motorized/non-motorized) personal conveyances (e.g., skateboard, e-scooter) (see [78]) are excluded for the sake of clarity. Also, for VRUs, subcategories could be specified (see [78]) based on age (e.g., child) and impairment (e.g., mobility).

Role of Interaction Partner. Interaction partners can be active or passive [96]. An interaction partner is actively involved in an interaction if they provide explicit input or receive feedback. Contrary, an interaction partner is passive if they only provide implicit input (i.e., an input which "does not rely on the user having conducted the input to intentionally achieve it" [151, p.2]) and do not receive any feedback. Colley et al. [29] differ in the context of eHMI between uni- and bidirectional interaction. In our design space, bidirectionality is covered by mutually active participation in the interaction.

Input and Output. Jansen et al. [84] presented a design space for in-vehicle interaction with a focus on modalities stemming from the human senses. Due to the size, we reference the design space without explicitly including the input and output parameters in our design space. The possibilities for AVs and other conveyances differ. Thus, some modalities are not useful (e.g., smells for bicyclists). However, theoretically, they are transferable to all interaction partners.

4.2 Dimensions and Parameters - Situation

Situation	Number of lanes	*single*	*two-lane*	*three-lane*	*four-lane*	*five-plus-lane*
	Lane setting	*one-way*		*two-way*		
	Traffic density	*free flow*	*medium flow*	*jammed flow*		
	Traffic autonomy	*totally manual*	*mixed*	*totally autonomous*		

Fig. 4. Dimensions and parameters of the design space part Situation.

The dimensions under Situation refer to one interaction partner. Thus, interaction partners can share a situation (e.g., passengers of the same vehicle) or find themselves in different situations. These dimensions are traffic-related and hardly controllable by the designer but have a direct effect on the interaction requirements and possibilities. Hogan [76] highlights the challenge of defining interaction situations, stating that situations are, per definition, unique and that there is little consensus on how to define them. Several works that developed design spaces in subareas of CTI also point out the complexity of situation definition and are thus focusing on the main factors influencing the considered research area. Fuest et al. [64], for example, proposed a taxonomy that is tailored to the communication between one AV and one VRU. Colley and Rukzio [41] have combined dimensions included in Füst et al.'s [64] taxonomy and factors that influence crossing decisions [136]. Thus, it seems undesirable to incorporate all possible dimensions as it would be difficult to use. Nevertheless, it is important to note that other factors such as road conditions (e.g., merging lanes, intersections, traffic control, tunnels, or bus stops), road characteristics (e.g., curvature and slope), regulations (e.g., speed limits) or environmental conditions (e.g., weather, daytime, animals close to the road) also play a role in the interaction design. Based on multiple discussions, we have focused on the following aspects. The corresponding Zwicky Box is shown in Figure 4.

Number of lanes. Based on Colley and Rukzio [41], we differentiate between *single*, *two-lane*, *three-lane*, *four-lane*, and *five-plus-lane* roads.

Lane setting. Not included in the design space of Colley and Rukzio [41] but required for the road context and an important factor for CTI is the lane setting, which can be one- or two-way. Here, two-way refers to a road with oncoming lanes, while one-way refers to traffic flowing in one direction only.

Traffic density. The traffic density can be divided into free, medium, and jammed flow [146, 161]. Here, the traffic occupant's average speed is used to categorize the traffic.

Traffic autonomy. Traffic autonomy defines the autonomy of the entire traffic. According to Colley and Rukzio [41], we distinguish between totally manual, mixed, and totally autonomous traffic. The automation of the ego-vehicle also plays a role for the interacting partner within a vehicle, which is shown in the design space by the distinction between driver and passenger.

4.3 Dimensions and Parameters - Interaction Relationship

<table>
<tr><td rowspan="5">Interaction Relationship</td><td>Entity relationship</td><td colspan="3">close</td><td colspan="3">acquaintance</td><td colspan="3">stranger</td><td colspan="3">not applicable</td></tr>
<tr><td>Interaction mapping</td><td colspan="3">one-to-one</td><td colspan="3">one-to-many</td><td colspan="3">many-to-one</td><td colspan="3">many-to-many</td></tr>
<tr><td>Interaction flow</td><td colspan="6">direct</td><td colspan="6">indirect</td></tr>
<tr><td>Position dependency</td><td colspan="4">no</td><td colspan="4">absolute</td><td colspan="4">relative</td></tr>
<tr><td>Time synchronicity</td><td colspan="6">synchronous</td><td colspan="6">asynchronous</td></tr>
</table>

Fig. 5. Dimensions and parameters of the design space part Interaction Relationship.

The Zwicky Box with all parameters and dimensions included in this part can be found in Figure 3.

Interaction partner relationship. In CTI, encounters can take place between strangers but also with close people and acquaintances. How the interaction must be designed so that all interaction partners feel comfortable depends on the interaction partners' relationship. We distinguish between the levels *close person*, *acquaintance*, and *stranger* referring to Sorokowska et al. [152], which have also been used by Rixen et al. [138].

Interaction flow. Facilitated through the connectivity of interaction partners, interaction can occur directly or indirectly, mediated through another interaction partner. Such an indirect interaction partner can be any interaction partner listed in our design space.

Interaction mapping. For this dimension, we refer to the levels one-to-one, one-to-many, many-to-one, and many-to-many [86, 100], which are also applied in eHMI research (see Colley and Rukzio [41]).

Time synchronicity and position dependency. Ellis et al. [56] defined a time-space taxonomy for Computer-Mediated Communication (CMC), which divides interaction into four categories based on whether the interaction is synchronous (also real-time), or asynchronous (i.e., non-real-time) and whether interaction partners share a place or are distributed over different locations. Lakier et al. [96] considered interactions between occupants in nearby vehicles and thus are sharing a place. We refer to this as *absolute position dependency* and *time synchronicity*, meaning that interaction partners need to be physically at a specific location at a specific time to interact with each other. Interactions that can occur without sharing a specific location are defined as *no position dependency*. We further propose *relative position dependency*, which has not been considered yet. This allows the definition of interactions in which interaction partners share the same positional features or parameters without actually being at a shared position, e.g., both are waiting at a red traffic light, heading towards a common destination, or having the same point of interest in their line of sight.

5 Usage of the Design Space

We describe two approaches to use our design space to derive *research trends*, identify unexplored *interaction possibilities*, and design novel *concepts and applications*. The approaches, namely *classification* and *ideation*, are explained in the following.

5.1 Classification

Classification plays a crucial role in the systematic use of the design space, focusing on understanding and organizing current research and work. It starts by categorizing existing concepts into the design space. By the organized overview that arises from this, one can identify trends and determine how comprehensively CTI has been addressed. Further, it enables the identification of areas that lack sufficient solutions or where the potential for innovation is high. The insights gained from this classification process foster the development of targeted research questions, guiding subsequent explorations and investigations within CTI research.

5.2 Ideation

The ideation phase is integral to developing new interaction concepts and solutions. The process begins with the identification of open cells within the design space. Each open cell represents a combination of parameters that have not yet been explored or utilized. By systematically targeting these cells, users can propose new concepts or adaptations that have not been previously considered.

The ideation approach can also be used to evaluate and expand existing applications. In this case, the application is analyzed for its scalability and adaptability to different traffic situations.

Questions might include whether the application accommodates diverse types of traffic participants or if there are potential interaction relationships that have not yet been considered. This targeted exploration helps identify areas for improvement and potential expansion of the application.

Once new concepts or expansions are identified, it is essential to assess whether they can effectively enhance key metrics that are critical to the research field. Since our design space does not prioritize specific research areas, we cannot determine in advance which open cells will yield beneficial concepts. Therefore, each new idea or expansion must be carefully evaluated to ensure it contributes positively to the field by improving important metrics such as efficiency, safety, or user experience.

Alternatively, the ideation phase can be approached as a form of free brainstorming. Here, researchers or practitioners are not confined to specific research areas or existing problems. Instead, they explore the design space freely, allowing for the generation of ideas that are unbounded by current constraints or applications. This open-ended approach facilitates the discovery of completely novel concepts. To facilitate this, we implemented a function on our interactive website that outputs randomized cells of our design space, thus serving as a brainstorming tool.

6 Classification - Identification of Current Research Trends

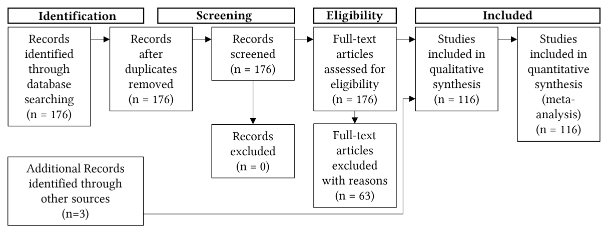


Fig. 6. PRISMA Flow Diagram [119] illustrating the publication selection process.

To address the challenge of understanding the current research in CTI, we use the design space as a *classification* tool. Through this approach, we systematically organize existing work, enabling us to (1) identify well-researched areas and clarify current trends, and (2) reveal research gaps. Thus, this classification provides a clearer understanding of the CTI field and guides future research focus towards unexplored CTI opportunities.

We retrieved relevant literature in a structured way. We queried the proceedings of the past three years (from January 2020 to June 2023) from ACM Conference on Human Factors in Computing Systems (CHI), ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI), and ACM International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI), which are significant gatherings for the automotive HCI community. Due to the traffic reference of the AutomotiveUI, we screened all proceedings here. For the other two conferences, we performed a keyword search (within the title and abstract) using OR operators across the terms *vehicle*, *car*, *pedestrian*, *cyclist*, *road user*, *driver*, *passenger*, *motorcyclist*, and *traffic*. We claim that CTI can take place between all traffic participants. However, we focus on publications where a human entity is involved in the overall interaction concept due to our focus on HCI and CMC. The inclusion criteria were: (1) The publication focuses on interaction where at least one human interaction partner is involved. (2) The publication is related to the CTI context. Further, we defined exclusion criteria: The publication is not a full paper proceeding, or its main contribution is a taxonomy, design space, literature review, or workshop.

To analyze the selected articles, we used Sysrev, which enabled us to screen the publications collaboratively. Two authors were involved in the screening and coding process. The first author reviewed each publication, and the second one reviewed 50 publications. Reviewing conflicts were discussed and resolved directly. After the screening, we included three additional papers from the area of in-vehicle gaming as this was identified as a trending research topic but could not be captured by our screening [21, 96, 159]. In total, 116 publications were included in the quantitative synthesis. Figure 6 shows the complete PRISMA [119] flow diagram, illustrating our paper selection process. To classify the considered interactions of the publications in the design space, our label set consisted of the research area and each design space dimension, where two main interaction partners, including the respective situation and (if applicable) indirect interaction partners could be labeled. Papers that included more than one interaction concept were divided into multiple entries.

Observations of interaction concepts based on our design space can vary in depth depending on the user's perspective. For a developer, a technical consideration of signal processing might be considered. However, our primary interest is understanding interaction concepts from an end-user-centric perspective. We thus labeled the concepts based on how they manifest in the (end) users' perception.

6.1 Results

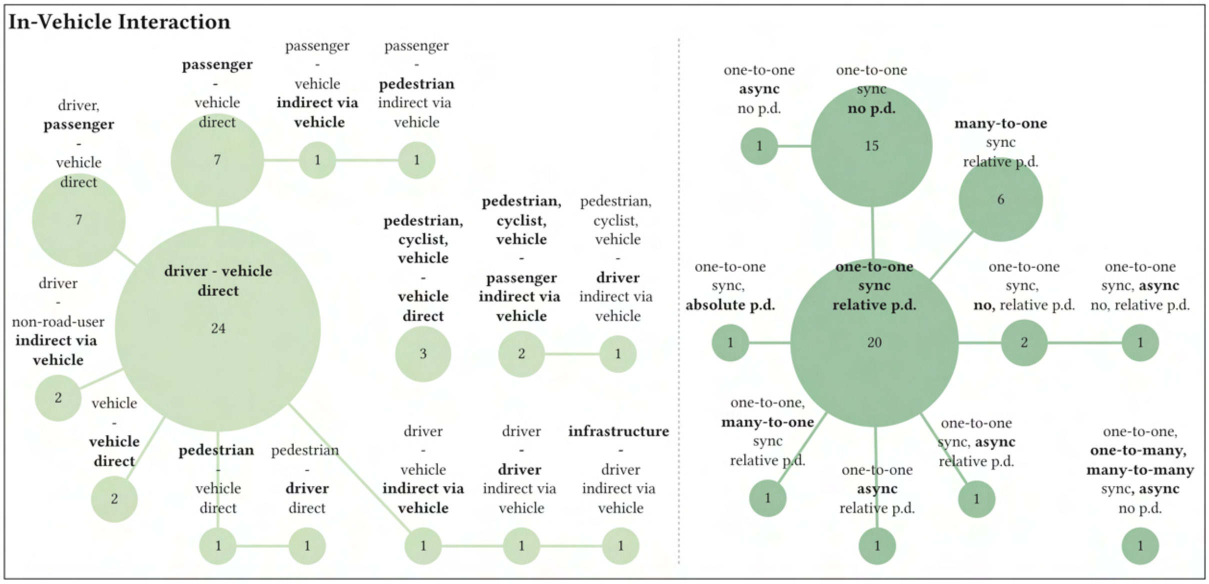


Fig. 7. Coding results for interaction partners (on the left) and the interaction relationship parameters (on the right) for in-vehicle interaction. The digit indicates the number of papers that consider the respective parameters. Parameter combinations that differ from the accumulating combinations are connected by strokes. The deviating parameters are highlighted in bold.

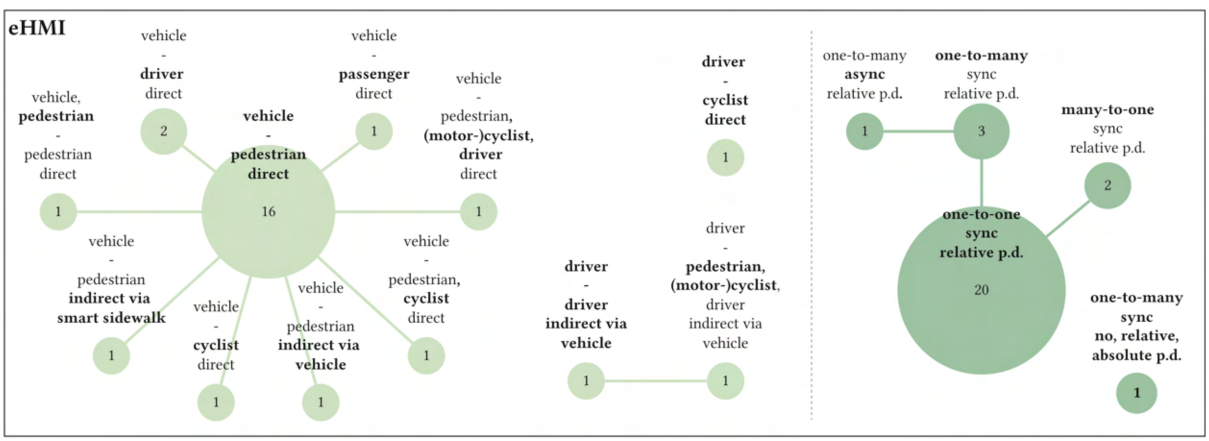


Fig. 8. Coding results for interaction partners (light green; on the left) and the interaction relationship parameters (darker green; on the right) for in-vehicle interaction. The digit indicates the number of papers that consider the respective parameters. Parameter combinations that differ from the accumulating combinations are connected by strokes. The deviating parameters are highlighted in bold.

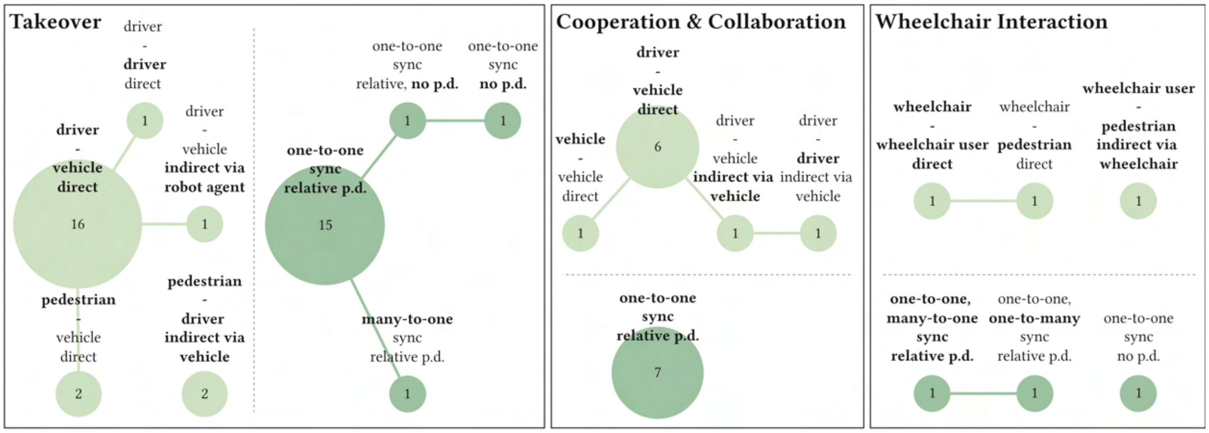


Fig. 9. Coding results for interaction partners (light green; left or top) and the interaction relationship parameters (darker green; right or bottom) for takeover, cooperation & collaboration, and wheelchair interaction. The digit indicates the number of papers that consider the respective parameters. Parameter combinations that differ from the accumulating combinations are connected by strokes. The deviating parameters are highlighted in bold.

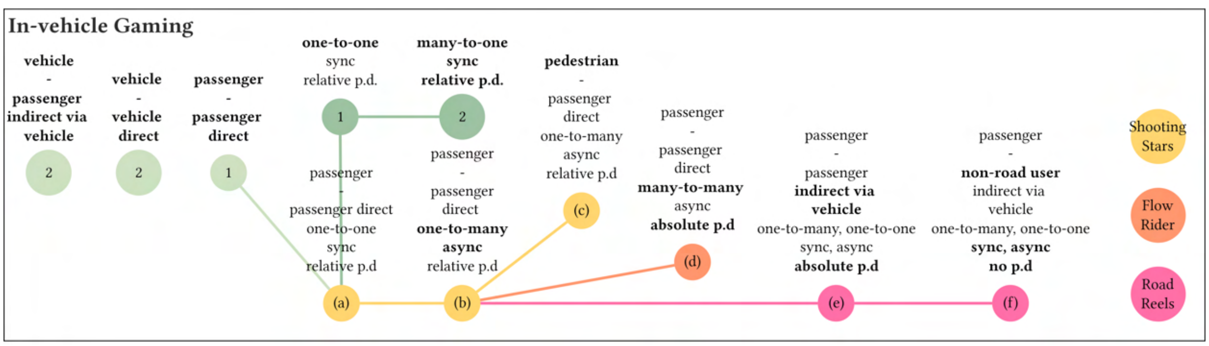


Fig. 10. Coding results for interaction partners (light green; on the left) and the interaction relationship parameters (darker green, in the middle) for in-vehicle gaming. The digit indicates the number of papers that consider the respective parameters. Parameter combinations that are preceded by a base combination (indicated by strokes) show which parameters differ in bold type. Additionally, the parameter combinations of the interaction concepts in our prototypical applications are visualized.

For this section, we focus on the design space dimensions that can be designed, i.e., interaction partners and their interaction relationship. Nevertheless, we see that interaction concepts are strongly influenced by situations, which is why it is essential to take them into account in their design and evaluation. Therefore, we have classified all publications into each design space part. The complete tables can be found in Appendix A.

Due to the size of the design space and the complexity of visualizing each of the parameter combinations across all dimensions (and not separated into the design space parts), we additionally implemented an interactive website. It visualizes all combinations and allows the proceedings to be filtered by all dimension parameters. This allows the investigation of current research trends independent of specific research fields.

We examined the interaction concepts for each identified research area. We searched for patterns in the parameter combinations (i.e., the covered design space cell) of considered interaction partners and interaction relationships.

Looking at in-vehicle interaction (see Figure 7), there is a trend towards the interaction with passengers alongside drivers and many-to-one interaction between other road users and the driver/passenger as indirect interaction via the vehicle. One interaction concept that includes infrastructure could be identified [12]. In addition, most concepts are relative or not position-dependent. Only one requires an absolute position [12]. Asynchronous interaction was also considered [19, 65, 137, 149].

When looking at eHMI (see Figure 8), our design space shows an accumulation of concepts considering a direct, synchronous, relatively position-dependent, one-to-one interaction between vehicles and pedestrians. Some publications step away from this by examining concepts where one or multiple parameters differ from the accumulating parameter combination. For example, some consider the interaction between a vehicle and road users other than pedestrians, such as cyclists, motorcyclists, or other drivers (e.g., [9, 117, 120]). Similarly, one can recognize a trend towards one-to-many interaction, i.e., scalable concepts that facilitate interaction with more than one road user (e.g., [51]).

The interaction between the driver and the vehicle is the focus of takeovers, cooperation, and collaboration (see Figure 9). The two research areas are further characterized by relative position dependence, e.g., when the vehicle reaches its operational driving domain (ODD). However, interactions related to takeovers were also considered with no position relation, e.g., as driver-initiated takeovers [80, 121]. Additionally, indirect cooperation between several drivers facilitated by the vehicle [58] and the effect of an additional indirect robot agent on the takeover performance [168] were researched.

Our literature review found one paper regarding wheelchair interaction [179] (see Figure 9) with several interaction concepts united, i.e., direct one-to-one interaction between the wheelchair and the wheelchair user, as well as many-to-one interaction between pedestrians and the wheelchair. Further, indirect interaction via the wheelchair between wheelchair users and pedestrians was considered.

Works related to other research areas each accumulate at one cell in the design space, which is why we refrained from visualizing them. Here, the focus has been on synchronous one-to-one interaction with relative position dependency. This includes publications in the area of adaptive driving [143], teleoperation interfaces [157], accessibility [109], vehicle-pedestrian interaction (not covered through eHMI) [79, 107], driver-passenger interaction [15], or motion sickness [133].

Deviating from this by considering no position dependency are interaction concepts from the area of cycling smartphone interaction [177], driver monitoring [17, 92, 93]. One-to-many or many-to-one concepts are considered in the areas of enhancement of situation awareness for visually impaired people [99], pedestrian-vehicle interaction [79, 169], e-scooter rider-road user interaction [102], and human-human-robot interaction [52].

Entertainment [18] and contestable camera cars [7] stand out due to asynchronous interaction concepts.

7 Ideation - Prototyping Applications

In the following, we demonstrate how the *Ideation* approach is applied by designing three applications. In doing so, we show the applicability of our design space and its feasibility to advance existing research fields.

For the demonstration, we have chosen the research field of in-vehicle gaming as an example. This decision is based on findings from the *classification*, which identified this area as relatively new and unexplored. Based on the classification (see Figure 10), we can see that existing concepts are limited to direct interaction between passengers of different vehicles and indirect interaction between passengers and vehicles via other vehicles (i.e., V2V). Those interactions are characterized by synchronous one-to-one/many-to-one interactions with

Fig. 11. Screenshots of the applications showing each of the CTI concepts.

relative position dependency. Thus, the concepts do not consider diverse entity relationships, absolute/no position dependency, or asynchronous interaction.

Recognizing these gaps, we aimed to explore new possibilities by designing three applications. One is based on similar existing concepts [21, 96, 159], while the other two were conceived through brainstorming sessions involving three authors. Our goal was to develop applications that address these gaps effectively, focusing on absolute position dependency, asynchronous interaction, and diverse entity relationships while ensuring that the applications are appreciably different from each other. It's important to note that these applications and their interaction concepts are not complete explorations of the field.

The following section will show in detail how the applications were brainstormed and developed with the design space as an *ideation* tool.

7.1 Shooting Stars

Shooting Stars is an in-vehicle VR game where players engage in tower-building and tower-destroying battles on a virtual spaceway. Players can construct towers on their spaceships and shoot towers of other players. The gameplay incorporates co-located interactions, where players interact with passengers of other cars based on proximity. This concept is influenced by the Road Rager game [21] and the ideas presented by Lakier et al. [96]. These interactions occur during encounters such as passing or overtaking other players and meeting at traffic-light accumulations. Additionally, the incorporation of real-world and virtual objects in the game play is inspired by the endless runner style game proposed by Togwell et al. [159].

Additionally, we extended the game concept by integrating asynchronous interaction and including additional road users. Below, we detail the interaction concepts and explain their potential for the game's interaction design.

- Direct shooting of towers: Either a passenger plays against passive vehicles acting act as in-game objects or against passengers of another vehicle who are actively involved in the game (see Figure 10 (a) and Figure 11 (a)). In both cases, the interaction is direct, one-to-one, synchronous, and relatively dependent on the positions of the interaction partners as the game depends on, e.g., distance of the vehicles.
- Indirect shooting by setting shooters on the road: The interaction can be classified as above; however, it is asynchronous (see Figure 10 (b) and Figure 11 (b)). Additionally, other interaction partners are actively involved in the game. Therefore, e.g., pedestrians can set shooters on the road (see Figure 10 (c) and Figure 11 (c)). This allows passengers to not only play with passengers in their current surroundings but also with acquaintances and close people who, e.g., drive the same route at different times of the day.

7.2 Flow Rider

The existing gap of absolute position-dependent interaction concepts led us to the development of *Flow Rider*. It is an in-vehicle VR game that allows users to virtually place melodies on the road, with other users able to hear and dynamically contribute to the evolving musical composition. This idea was chosen with music as the medium to explore absolute position-dependent interaction because we found it exciting to link compositions directly to the source of inspiration and make it tangible for other players. In the following, we explain the interaction concepts.

- Listen to and record music: Passengers place sounds on the road that others can asynchronously hear and contribute to. The interaction concept is absolutely position-dependent, as passengers need to be at the specific position at which a sound was recorded. Since many people can hear one person's song and one song can originate from many people, the interaction is defined as many-to-many (see Figure 10 (d) and Figure 11 (d)).

7.3 Road Reels

With the next application, we aimed to explore the gaps of indirect interaction and interaction with non-road users. Here, we drew inspiration from social media applications that allow users to share experiences with users who cannot physically participate (in our case: non-road users). We also recognized the potential for social media applications to benefit from indirect interaction facilitated through vehicles equipped with numerous sensors and AR/VR capabilities. Thus, we developed *Road Reels*, a concept that leverages AV cameras to capture 3D footage of the surroundings, enabling users to create and share immersive travel experiences. Through VR integration, (1) other users driving the same route can experience the trip under different environmental conditions, and (2) friends and family can co-experience the trip immersively.

- Experience and record environments and environmental conditions: Passengers can record and share their experience. As the vehicle is needed to record and upload the environment, the interaction is indirect via the vehicle. Further, as passengers (such as in *Flow Rider*) need to be at the specific position at which an experience was recorded, the interaction concept is absolutely position-dependent (see Figure 10 (e) and Figure 11 (e)).
- Share and live stream experience: Passengers can share or live stream their experience with non-road users, enabling synchronous and asynchronous interaction. As non-road users do not have to be at a specific location to experience it, the interaction is not position-dependent (see Figure 10 (f) and Figure 11 (f)).

To demonstrate the practical benefits of applications developed through our *ideation* approach with CTI, we implemented these concepts as interactive prototypes using Unity. This implementation enabled participants to interact with non-playable characters (NPCs), scripted to behave like other players, thereby creating a realistic and interactive environment.

Our evaluation specifically focused on user experience, social experience, and usability, as these are the key metrics in in-vehicle gaming. We assessed how well the prototypes performed under these metrics, aiming to provide a comprehensive understanding of their impact.

To collect this data, we conducted a within-subject VR driving simulation study with 12 participants (7 females and 5 males). We recruited the participants through mailing lists of our university. On average, they had an age of M=25.25 (SD=2.42) years. Eight had experience with AR/VR, while 4 did not. When asked about participation in multiplayer games during their free time, 7 participants responded with “Yes” and 5 responded with “No.” Participants reported playing between 1 and 10 hours of multiplayer games per week, with the average being M=5.00 (SD=3.79) hours. Most participants (11 out of 12) reported active use of social media, with 9 using it daily and 2 using it weekly.

7.4 Measures

For the gaming applications *Shooting Stars* and *Flow Rider*, we assessed *Player Experience* by employing the Player Experience Inventory (PXI) [3]. For the social media application *Road Reels*, we measured *System Usability* with the System Usability Scale (SUS) [20]. For each application, we assessed *User Experience* using the short version of User Experience Questionnaire (UEQS) [150] and *Social Experience* with the corresponding subscale of the Gameful Experience Questionnaire (GAMEFULQUEST) [77]. We further asked participants to rate if they would use such an application on a 5-point Likert scale (1=*not at all*; 5=*definitely*).

Additionally, we conducted a semi-structured interview, which was guided by the following questions:

- Please describe the application and its main properties and features and give your opinion about them.
- What do you think of the social interactions in the application?
- With whom would you like to use such an application?
- How could scenarios/situations look like in which you would use it? (For Social Media separated into a) use at home and b) use in the car)
- Can you think of anything that could further improve the concept? Explain how and why.
- Could the app somehow change your driving or commuting behavior? Why?
- Do you see any potential for the abuse of such an application?

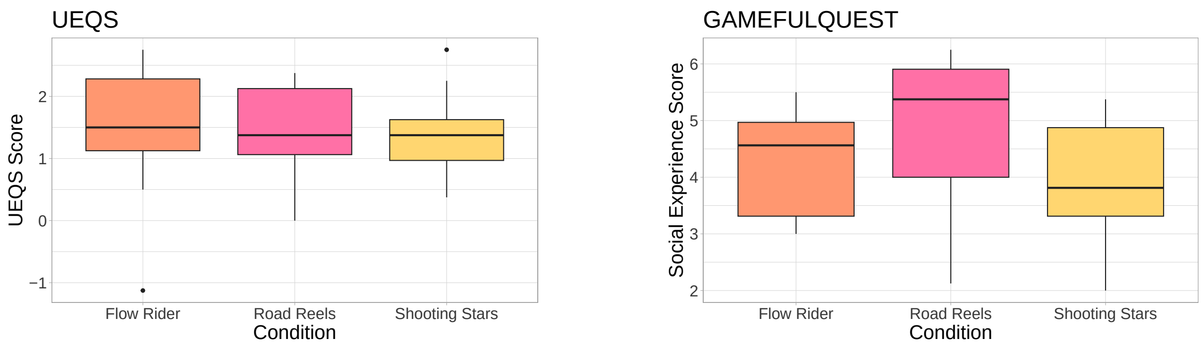
7.5 Procedure

Each participant was exposed to all three of the applications described in the previous section. Initially, participants were briefed on the study’s procedure, ensuring a clear understanding of the tasks and expectations. Following the introduction, they were required to sign an informed consent form and complete a demographic questionnaire. Afterward, they experienced the 3 conditions according to a balanced Latin square. They had the task of playing the game/experiencing the application, and interacting with other users. Each condition lasted five to seven minutes, with completion times being based on the AV reaching the end of a predetermined driving route. All user interactions took place during this period. Each condition was followed by a questionnaire employing the named subjective measurements and a semi-structured interview. The complete study duration was about 60 min. Participants were compensated with 10€.

7.6 Quantitative Results

Descriptive statistics can be found in the appendix (see Table 8).

System Usability. In terms of *System Usability*, the application *Road Reels* received a SUS Score of M=80 (SD=9.05), which can be considered as good [11].



UEQS

Social Experience subscale of GAMEFULQUEST

Fig. 12. UEQS (left) and Social Experience subscale of GAMEFULQUEST (right) for the applications *Flow Rider*, *Road Reels* and *Shooting Stars*

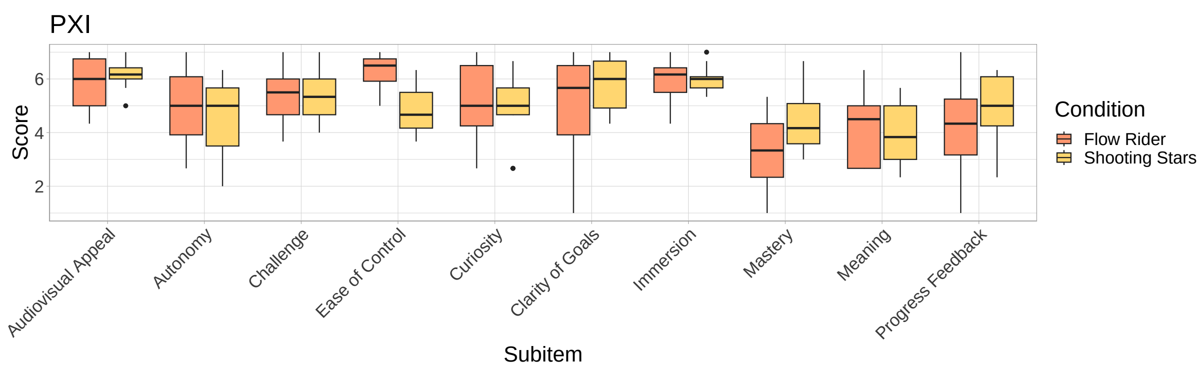


Fig. 13. Scores of the PXI subscales listed on the x-axis for *Flow Rider* and *Shooting Stars*

User Experience and Player Experience. *User Experience* was rated similarly for all applications (see Figure 12 (left)). For *Player Experience*, it is noticeable that *Mastery* of *Flow Rider* was rated as comparatively low (M=3.33, SD=1.22) (see Figure 13). Further *Ease of Control* was rated high for *Flow Rider* (M=6.31, SD=0.67).

Social Experience. Considering the *Social Experience*, *Road Reels* interestingly received higher ratings (M=4.81, SD=1.51) than *Flow Rider* (M=4.25, SD=0.94) and *Shooting Stars* (M=3.91, SD=1.07) (see Figure 12 (right)).

Usage. When asked to rate if they would use such an application, *Shooting Stars* was rated higher (M=3.75, SD=0.45) than *Flow Rider* (M=3.50, SD=1.31) and *Road Reels* (M=3.50, SD=1.17).

7.7 Qualitative Findings

We conducted a thematic analysis of the interviews. The interviews were transcribed using WhisperX [10]. Afterward, three authors read the transcripts, separately grouped the answers into themes, and developed codes inductively. In a subsequent discussion, the codes were discussed and merged into a final set of codes. Then, the lead author coded the interviews again deductively.

Application Design. The applications *Shooting Stars*, *Flow Rider*, and *Road Reels* were generally well-received, with 10 out of 12 participants finding each enjoyable. P3 appreciated the "very, very nice design". However, participants found it challenging to contribute to the music in *Flow Rider* [P1, P3, P4, P6, P8, P11], which is also reflected in the quantitative data. Further, some VR-related problems were stated regarding haptics [P8, P5] and the look and feel of the instruments [P2, P3, P10].

Importance of Synchronous Interaction and Identification in Direct Interaction for Social Experience. The role of synchronous interaction in the perception of social engagement was a recurring theme among participants. A majority expressed that social interaction was only felt when it occurred in real-time. Specifically, participants [P3, P4, P9] articulated that they did not perceive any form of social interaction when engaged in asynchronous activities. Regarding game mechanics, P4 mentioned that they would not utilize the asynchronous shooter function in *Shooting Stars* because the action was not immediately visible. Similarly, P5 noted that "there wasn't really any social interaction in that sense. I couldn't send emojis to other people somehow after I shot them down because they couldn't see it anyway because they were behind me".

The fact that in *Shooting Stars*, despite direct interaction, real players were not represented in VR led to a lack of social identification [P1, P2, P3, P7]. It instead felt "like an [non-player character game] [P7]. Also, P4 expressed a preference for recognizing users they know within *Shooting Starts*. This was also reflected in *Flow Rider* as P1 and P4 felt it would be helpful to know which sounds were coming from whom.

Instagramization of Vehicles. We found that the possibility of sharing and interacting with non-road users led to behavioral patterns typical for social media transferring to vehicle usage. Some participants stated, especially for *Road Reels*, that they would potentially adjust their driving behavior to be able to share likable content [P3, P5, P12]. Specifically, P12 stated that they "would pick the most beautiful route to drive, so maybe no longer the fastest, but rather the one where you see the most scenery. So that [they] can show off the most, so to speak".

8 Discussion

8.1 Effects of Cross-Traffic Interaction Concepts on In-Vehicle Gaming Goals

The findings of our study strongly emphasize the importance of synchronous interaction for social engagement. Similarly, asynchronous interaction with absolute position dependency strongly relates to situated interaction, which has been explored in contexts such as home interaction [108, 130]. Situated interaction, such as leaving messages at meaningful places, is an important form of social communication among home inhabitants. The physical location becomes an essential component of a message's meaning, and the physical presence of the message can provide situational awareness [108]. This suggests that the perception of asynchronous interaction as social can be enhanced if the situation, location, or time of receiving a message has significant meaning to the individual. This aspect must be considered in the design of applications if enhancing social experience is a key metric. We also recognize the value of asynchronous interaction as a complementary concept, especially in enabling sustained interaction in dynamically changing situations. For example, two friends in different vehicles might interact synchronously and dependently when meeting at a traffic light. However, as situations evolve, interaction strategies that allow for asynchronous or position-independent engagement are crucial for maintaining contact.

8.2 Versatility of Cross-Traffic Interaction Design Space

Our work provides the first structural approach to exploring CTI. When creating the design space, we mainly focused on the types of interaction partners and situations relevant to current research.

However, we do not consider the design space to be concluded, especially as traffic continues to evolve. With new forms of mobility like micromobility [144], urban air mobility [101], or drones [90] emerging, we encourage researchers and designers to think expansively about potential interaction partners. In this context, it is also essential to consider that interaction partners, traffic situations, and requirements for interaction relationships are not only becoming more versatile but also can change quickly. Transitions can happen fast, and situations may be short-lived, making the interactions around them very dynamic. Thus, when considering interaction in applications and interaction concepts, we motivate researchers and developers to capture the versatile and dynamic nature of evolving traffic when developing and evaluating concepts. Our design space allows for a generalized approach that can be applied to various research areas. Thus, our design space does not delve into content-specific factors. For example, in the context of gaming, if the interaction is competitive or cooperative (e.g., considered by Lakier et al. [96]) or considering takeovers, both the vehicle or the driver could be the initiator. Content-specific factors represent an adjacent area of inquiry that offers a different lens through which to examine CTIs.

8.3 The Critical Role of Purpose and Goal Orientation in Cross-Traffic Interaction Design Space Ideation

Our work shows that the dynamic nature of interactions in cross-traffic situations presents significant challenges and opportunities. Our approach provides a broad overview of the contextual dynamics in CTI and facilitates brainstorming and the development of new interaction concepts and solutions.

The design space deliberately avoids setting specific design goals. This strategy allows the design space to be applied to a broad range of research fields and objectives rather than being limited to a predefined set of purposes found in existing work. As a result, it remains flexible and adaptable to new technologies and changing societal needs.

However, our study's findings emphasize the importance of aligning the ideation process and the development of interaction concepts with clear, underlying goals. The solutions developed need to be evaluated to verify their effectiveness in achieving specific research objectives. This critical evaluation ensures that the solutions are not only novel but also practical and relevant and make a substantial contribution that is consistent with the defined research objectives.

We thus encourage researchers, designers, and practitioners to critically evaluate the relevance of each interaction concept or solution derived from the design space to ensure that each new idea or solution not just fills an empty cell but also advances the intended research goals.

8.4 Limitations and Future Work

While our paper offers a comprehensive view of CTI possibilities and offers a systematic approach to derive new research questions, applications, and interaction concepts, it is essential to recognize some limitations and point out possible future work.

While we chose the parameters we presented for interaction partners to cover the majority of current considerations, the design space allows for (and even encourages) extensions.

Our systematic literature review only covers publications since 2020 and a small set of other publications relevant to this work [21, 96, 159]. Nevertheless, trends are identifiable, and the generally high number of relevant publications shows the general importance of CTI in current research. The classification of the current research does not allow to distinguish between passengers of the same vehicle and different vehicles. However, including this aspect in the classification and its visualization would have meant introducing an additional complexity layer. After discussions among the authors, we decided against this because most of the relationships can be inferred from within the research area. Yet, one should keep this in mind when using it.

A moderate number of participants took part (N=12). However, our focus was on providing initial qualitative insights into how various CTI concepts influence the game experience rather than conducting statistical comparisons of applications. Still, considering that most of the participants were young, it is unclear how these findings can be applied to other age groups. Thus, the generalizability and transferability of our findings to broader populations are limited.

Further, participants were asked to imagine that they were wearing VR and AR glasses as they participated in the VR simulation study, which could confuse the distinction between the simulation and the study scenario in the *Shooting Stars* application. The same applies to the other applications for the distinction between simulated world and augmented content. We tried to minimize this effect by using various methods, such as detailed introductory texts or neon lighting effects for augmented content in the *Flow Rider* application. Further, all participants could explain the applications and their interaction concepts. Statements such as "[...] the task was sort of to balance [the tower] as the vehicle moves, and it moves according to the actual vehicle" [P7] support this. However, we cannot say with certainty that this had no influence on the results. In general, simulations of the applications with more degrees of freedom could be beneficial (e.g., [34] or [75]) in future work, further taking into account the implications a dynamically moving environment could have on interaction strategies.

9 Conclusion

We present a design space for CTI. Based on related design spaces and a focus group (N=6) with HCI experts, we identified the three parts: (1) *Interaction Partners*, (2) *Situations*, and (3) *Interaction Relationships*. The design space is directed towards researchers, designers, and practitioners to identify interaction challenges and opportunities emerging through the ever-increasing connectivity in traffic.

We outlined how our design space acts both as a *classification* and *ideation* tool for CTI research. As a classification tool, we systematically reviewed and categorized 116 automotive HCI publications, discovering a predominant focus on direct interactions between two partners, typically involving a vehicle and a driver or pedestrian. Despite some concepts that exceed traditional focus, we found that large parts of the design space are yet to be explored, which underscores the substantial potential for future research.

As an ideation tool, our design space facilitated the development of three applications in the research field of in-vehicle gaming. These applications were evaluated through a VR simulator study (N=12), showcasing the capabilities and challenges of our design space to effectively guide the achievement of established research objectives within a specific research field.

We have discussed the practical implications of our study results, the versatility of the design space, and the critical role of maintaining a clear focus on purpose and goal orientation when employing it as an ideation tool.

Open Science

The Excel spreadsheet containing the classifications of publications derived from our systematic literature review is made publicly available as open-source material. Additionally, the accompanying website will maintain open access. Upon reasonable request, we are also willing to share the implementation code for our applications.

Acknowledgments

We thank all focus group and study participants.

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A Classification

Interaction Partner		IP A				
		vehicle driver	*vehicle passenger*	*pedestrian*	*cyclist*	*motorcyclist*
IP B	*vehicle driver*	cooperation and collaboration: [58] eHMI: [9, 36] takeover: [33]	in-vehicle interaction: [32, 135]	driver-passenger interaction: [15]	eHMI: [6, 9] in-vehicle interaction: [32]	eHMI: [9]
	vehicle passenger		human-human-robot-interaction: [52] in-vehicle multiplayer gaming: [21]	in-vehicle interaction: [30, 149, 174]	in-vehicle interaction: [149, 174]	
	pedestrian			SA for PVIs: [99] eHMI: [98]		
	cyclist					
	motor-cyclist					
	official					
	non-road-user					
	smart vehicle					
	smart object					
	other					

Table 1. Overview of considered interaction partner A (IP A) and B (IP B) - Part 1

Interaction Partner		IP A				
		official	*non-road-user*	*smart vehicle*	*smart object*	*other*
IP B	vehicle driver		in-vehicle interaction: [19, 137]	adaptive driving: [128, 143] cooperation and collaboration: [27, 129, 132, 165, 166, 171] dHMI, eHMI: [117] driver monitoring: [17, 92, 93] driver-passenger interaction: [15] eHMI: [9, 118] entertainment: [18] in-vehicle interaction: [19, 23, 32, 40, 43, 46, 55, 65–68, 71–73, 83, 87, 88, 94, 95, 112, 115, 122, 135, 137, 142, 155, 158, 160, 163, 175, 176, 178, 180] takeover: [45, 53, 54, 63, 80, 82, 116, 121, 124, 126, 127, 139, 145, 147, 164, 168]	in-vehicle interaction: [12]	e-scooter rider-road-user interaction: [102] in-vehicle interaction: [19]
	vehicle passenger			accessibility: [109] eHMI: [37] in-vehicle interaction: [23, 31, 46, 59, 65, 68, 83, 103, 140, 149, 155, 158, 167, 174] in-vehicle multiplayer gaming: [96, 159] motion sickness: [133]	human-human-robot-interaction: [52]	in-vehicle interaction: [61]
	pedestrian			eHMI: [4, 9, 13, 25, 28, 29, 37, 39, 42, 47, 49–51, 57, 69, 97, 98, 105, 120, 141, 156] in-vehicle interaction: [30, 32, 149, 174] pedestrian-vehicle interaciton: [107] pedestrian-vehicle interaction: [79, 170] takeover: [45, 63]		e-scooter rider-road-user interaction: [102] wheelchair user-pedestrian interaction, wheelchair-user interaction: [179]

Table 2. Overview of considered interaction partner A (IP A) and B (IP B) - Part 2 (A)

B Descriptive Statistics of Study

Interaction Partner		IP A				
		official	*non-road-user*	*smart vehicle*	*smart object*	*other*
IP B	*cyclist*		cycling smart-phone inter-action: [177]	eHMI: [9, 81, 120] in-vehicle interaction: [32, 149, 174] vehicle-cyclist interaction: [111]		e-scooter rider-road-user inter-action: [102]
	motor-cyclist			eHMI: [9]		e-scooter rider-road-user inter-action: [102]
	official					
	non-road-user			contestable camera cars: [8] teleoperation interfaces: [157]		
	smart vehi-cle			cooperation and collaboration: [165] in-vehicle interaction: [31, 32, 40, 149, 174] in-vehicle multiplayer gaming: [96, 159]		e-scooter rider-road-user inter-action: [102]
	smart object					
	other					wheelchair user-pedestrian interaction, wheelchair-user interaction: [179]

Table 3. Overview of considered interaction partner A (IP A) and B (IP B) - Part 2 (B)

Interaction Partner		Interaction Partner									
Interaction flow	Role	*vehicle driver*	*vehicle passenger*	*motorcyclist*	*cyclist*	*pedestrian*	*official*	*non-road-user*	*smart vehicle*	*smart object*	*other*
direct	*active*	**72:** [6, 9, 12, 15, 17–19, 23, 27, 32, 33, 36, 40, 43, 45, 53–55, 58, 63, 65–68, 71–73, 80, 82, 83, 87, 88, 92–96, 102, 112, 115–118, 121, 122, 124, 126–129, 132, 135, 137, 139, 142, 143, 145, 147, 155, 158–160, 163–166, 168, 171, 175, 176, 178, 180]	**21:** [15, 21, 23, 30, 31, 37, 52, 60, 61, 65, 68, 83, 103, 109, 133, 140, 149, 155, 158, 167, 174]	**2:** [9, 102]	**7:** [6, 9, 81, 102, 111, 120, 177]	**28:** [4, 9, 13, 25, 28, 29, 37, 39, 42, 47, 49–51, 57, 69, 79, 97–99, 102, 105, 107, 120, 135, 141, 156, 170, 179]		**5:** [8, 19, 137, 157, 177]	**105:** [4, 8, 9, 13, 15, 17–19, 23, 25, 27–32, 37, 39, 40, 42, 43, 45–47, 49–51, 53–55, 57, 60, 61, 63, 65–69, 71–73, 79–83, 87, 88, 92–98, 102, 103, 105, 107, 109, 112, 115–118, 120–122, 124, 126–129, 132, 133, 135, 137, 139–143, 145, 147, 149, 155–160, 163–168, 170, 171, 174–176, 178, 180]	**2:** [12, 52]	**3:** [19, 102, 179]
	passive	**1:** [46]	**1:**[46]		**3:**[32, 149, 174]	**6:** [30, 32, 45, 63, 149, 174]			**9:** [31, 32, 40, 96, 111, 149, 159, 165, 174]		
indirect	*active*								**18:** [9, 12, 19, 30–32, 36, 40, 42, 45, 58, 63, 96, 137, 149, 159, 165, 174]	**3:** [37, 168, 179]	
	passive										

Table 4. Overview of considered role of direct and indirect interaction partners

Interaction Relationship	Time synchronicity	*synchronous*			*asynchronous*		
	Position dependency	*absolute*	*relative*	*no*	*absolute*	*relative*	*no*
Interaction Mapping	*one-to-one*	**1**: [12]	**82**: [4, 6, 9, 13, 15, 17, 19, 21, 25, 27–31, 33, 37, 39, 40, 43, 45–47, 49, 50, 52–54, 57, 58, 60, 61, 63, 68, 69, 71, 79–82, 87, 94, 97, 99, 103, 105, 107, 109, 115–117, 120, 122, 124, 126–129, 132, 133, 135, 139–143, 145, 147, 149, 156, 157, 160, 164–166, 168, 170, 171, 175, 176, 178–180]	**23**: [19, 23, 55, 66–68, 72, 73, 80, 83, 88, 92, 93, 95, 112, 121, 137, 155, 158, 163, 167, 177, 179]		**4**: [8, 18, 19, 149]	**3**: [19, 65, 137]
	one-to-many	**1**: [9]	**6**: [9, 51, 52, 102, 118, 179]	**2**: [9, 137]		**1**: [36]	**1**: [137]
	many-to-one		**16**: [30–32, 40, 42, 45, 79, 96, 98, 99, 111, 149, 159, 170, 174, 179]				
	many-to-many			**1**: [137]			**1**: [137]

Table 5. Overview of the considered interaction relationship

Situation		Number of lanes					Lane setting		Traffic density			Traffic autonomy		
		single	*two-lane*	*three-lane*	*four-lane*	*five-plus-lane*	*one-way*	*two-way*	*free flow*	*medium flow*	*jammed flow*	*totally manual*	*mixed*	*totally autonomous*
takeover	[80, 82, 145, 147]			■			■							
	[54, 63, 139]		■					■						
	[53, 126]								■					
	[33]		■					■		■				
	[45]		■				■							
	[139]	■						■						
	[124]	■					■		■					
	[164]				■		■		■					
	[53]										■			
cooperation and collaboration	[129, 132, 171]	■						■						
	[165]			■			■							
	[58]			■				■						
	[166]			■			■		■					
	[166]		■				■		■					
	[27]								■					
eHMI	[13, 29, 42, 105]	■						■						
	[39]	■						■		■				
	[28]	■						■					■	
	[98]	■						■						■
	[25, 50]	■							■					
	[81]		■				■							
	[97]								■					
	[37, 57, 118]												■	
	[6]											■		

Table 6. Overview of considered situation parameter in the evaluation (A)

Situation		Number of lanes					Lane setting		Traffic density			Traffic autonomy		
		single	*two-lane*	*three-lane*	*four-lane*	*five-plus-lane*	*one-way*	*two-way*	*free flow*	*medium flow*	*jammed flow*	*totally manual*	*mixed*	*totally autonomous*
in-vehicle interaction	[122, 175, 180]	■						■						
	[160]		■							■				
	[71, 72]			■			■							
	[160]				■					■				
	[43]							■						
	[31]										■			
	[65]											■		
	[55]												■	
ecological driving	[40]		■				■							
e-scooter-rider-road-user interaction	[102]	■						■	■					
pedestrian-vehicle interaction	[79]												■	
vehicle-pedestrian interaction	[107]	■					■							
driver-passenger interaction	[15]		■				■							
dHMI	[117]	■						■					■	
driver monitoring	[93]		■				■		■					
	[93]		■				■			■				
vehicle-cyclist interaction	[111]	■					■							

Table 7. Overview of considered situation parameter in the evaluation (B)

	Variable	Levels	Min	q_1	$\widetilde{x}$	$\bar{x}$	q_3	Max	s	IQR
1	GAMEFULQUEST Social Experience	Flow Rider	3.00	3.31	4.56	4.25	4.97	5.50	0.94	1.66
2	GAMEFULQUEST Social Experience	Road Reels	2.12	4.00	5.38	4.81	5.91	6.25	1.51	1.91
3	GAMEFULQUEST Social Experience	Shooting Stars	2.00	3.31	3.81	3.91	4.88	5.38	1.07	1.56
4	PXI Audiovisual Appeal	Flow Rider	4.33	5.00	6.00	5.86	6.75	7.00	0.97	1.75
5	PXI Audiovisual Appeal	Road Reels								
6	PXI Audiovisual Appeal	Shooting Stars	5.00	6.00	6.17	6.19	6.42	7.00	0.56	0.42
7	PXI Autonomy	Flow Rider	2.67	3.92	5.00	5.03	6.08	7.00	1.37	2.17
8	PXI Autonomy	Road Reels								
9	PXI Autonomy	Shooting Stars	2.00	3.50	5.00	4.47	5.67	6.33	1.52	2.17
10	PXI Challenge	Flow Rider	3.67	4.67	5.50	5.39	6.00	7.00	1.04	1.33
11	PXI Challenge	Road Reels								
12	PXI Challenge	Shooting Stars	4.00	4.67	5.33	5.33	6.00	7.00	0.86	1.33
13	PXI Ease of Control	Flow Rider	5.00	5.92	6.50	6.31	6.75	7.00	0.67	0.83
14	PXI Ease of Control	Road Reels								
15	PXI Ease of Control	Shooting Stars	3.67	4.17	4.67	4.83	5.50	6.33	0.94	1.33
16	PXI Curiosity	Flow Rider	2.67	4.25	5.00	5.19	6.50	7.00	1.48	2.25
17	PXI Curiosity	Road Reels								
18	PXI Curiosity	Shooting Stars	2.67	4.67	5.00	4.89	5.67	6.67	1.19	1.00
19	PXI Clarity of Goals	Flow Rider	1.00	3.92	5.67	5.00	6.50	7.00	1.98	2.58
20	PXI Clarity of Goals	Road Reels								
21	PXI Clarity of Goals	Shooting Stars	4.33	4.92	6.00	5.83	6.67	7.00	1.00	1.75
22	PXI Immersion	Flow Rider	4.33	5.50	6.17	5.89	6.42	7.00	0.92	0.92
23	PXI Immersion	Road Reels								
24	PXI Immersion	Shooting Stars	5.33	5.67	6.00	6.00	6.08	7.00	0.47	0.42
25	PXI Mastery	Flow Rider	1.00	2.33	3.33	3.33	4.33	5.33	1.22	2.00
26	PXI Mastery	Road Reels								
27	PXI Mastery	Shooting Stars	3.00	3.58	4.17	4.44	5.08	6.67	1.10	1.50
28	PXI Meaning	Flow Rider	2.67	2.67	4.50	4.17	5.00	6.33	1.24	2.33
29	PXI Meaning	Road Reels								
30	PXI Meaning	Shooting Stars	2.33	3.00	3.83	3.94	5.00	5.67	1.17	2.00
31	PXI Progress Feedback	Flow Rider	1.00	3.17	4.33	4.19	5.25	7.00	1.84	2.08
32	PXI Progress Feedback	Road Reels								
33	PXI Progress Feedback	Shooting Stars	2.33	4.25	5.00	4.94	6.08	6.33	1.23	1.83
34	SUS Score	Flow Rider								
35	SUS Score	Road Reels	62.50	77.50	80.00	80.00	83.12	95.00	9.05	5.62
36	SUS Score	Shooting Stars								
37	UEQS	Flow Rider	-1.12	1.12	1.50	1.49	2.28	2.75	1.08	1.16
38	UEQS	Road Reels	0.00	1.06	1.38	1.42	2.12	2.38	0.70	1.06
39	UEQS	Shooting Stars	0.38	0.97	1.38	1.39	1.62	2.75	0.69	0.66
40	OWN ITEM Usage	Flow Rider	1.00	2.75	4.00	3.50	4.25	5.00	1.31	1.50
41	OWN ITEM Usage	Road Reels	1.00	3.00	4.00	3.50	4.00	5.00	1.17	1.00
42	OWN ITEM Usage	Shooting Stars	3.00	3.75	4.00	3.75	4.00	4.00	0.45	0.25

Table 8. Descriptive statistics for each of the assessed questionnaires and subscales.