Cross-Car, Multiplayer Games for Semi-Autonomous Driving

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ABSTRACT
We investigate and characterize a design space for in-car games based on a survey of previous work, and identify an opportunity for "cross-car" multiplayer games played among occupants in nearby cars. This is supported by innovations in automotive technology like autonomous driving, full-window heads-up displays, and ad hoc communication between vehicles. In a custom virtual reality driving simulator, we created three games to illustrate design dimensions: Killerball, a competitive free-for-all game; Billiards, a player versus player, massively multiplayer online game with player assists; and Decoration, an idle-style game with multiplayer resource management. A 12-participant evaluation with a semi-structured interview revealed a positive response to input controls and HUDs, and suggests game genres have a similar effect on time for an emergency driving takeover task. We used insights from our process and evaluation to formulate design considerations for future cross-car games.

CCS Concepts
•Applied computing → Computer games; •Software and its engineering → Interactive games;

Author Keywords
in-car gaming; automotive user interfaces; design space

INTRODUCTION
Automotive companies have already unveiled systems that can autonomously drive a car in traffic jams [3] and on the highway [58], and fully autonomous cars are in development. To enable this, many modern cars are outfitted with advanced obstacle detection systems, using cameras or LIDAR (light detection and ranging) sensors, and vehicle-to-vehicle (V2V) communication to inform other vehicles of upcoming hazards on the road. At the same time, user interfaces for drivers are starting to incorporate heads-up-displays (HUDs) [19] and mid-air, gesture-based control [37]. As autonomous driving systems become safer and more reliable, they will enable all occupants to engage in activities unrelated to driving, such as playing video games [43].

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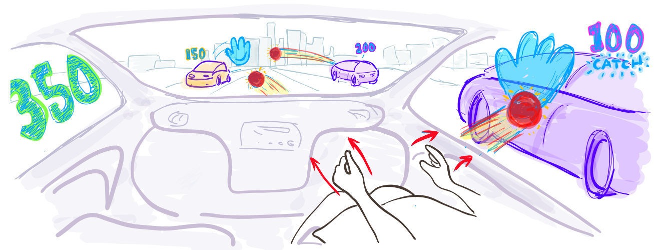

Figure 1. Envisioned cross-car games for semi-autonomous driving using a heads-up-display. Such games integrate the position of nearby cars into game play, and occupants of different cars can play together.

To better understand in-car games in general, we investigate and characterize a 13-dimension design space based on a literature review of existing games played in cars, and features of current and futuristic cars. To our knowledge, this is the first comprehensive review of in-car games. We find past work has focused on mobile device interfaces and games revolving around GPS landmark data, with little exploration of multiplayer interactions between nearby cars, or the use of large HUDs as an in-game information display.

We envision a new category of cross-car games for Level 3 and higher semi-autonomous vehicles [47] that use the position of nearby cars through HUDs, obstacle detection, and V2V communication (Figure 1). We use this concept to design three representative games: *Killerball*, a competitive free-for-all game; *Billiards*, a player versus player (PvP), massively multiplayer online game (MMOG) with player assists; and *Decoration*, an idle-style game with multiplayer resource management. In the same way that entertainment has filled idle time during commutes [1], we expect drivers could play games like these during periods of autonomous driving (anything from tens of seconds, to tens of minutes).

We aimed for a player experience tailored to the road environment, while also exploring different levels of multiplayer engagement and game genres. Each of our games have only one global instance of the game running. Players can join or drop out at any time, such as when a car turns off the road, without hampering gameplay. We believe this is an important design consideration for multiplayer, cross-car games. Also, although our focus is not making autonomous driving safer, understanding how games can be interrupted for emergency driver takeover remains important (*e.g.,* [16, 50, 63]). For this reason, we include a takeover task to test the impact of the different types of games.

Past work has suggested using HUDs for in-car games, but without prototypes or player evaluations [15, 48, 49, 54, 55, 61]. We developed a virtual reality (VR) driving simulator to render the car cabin, outside environment, and roadway with artificially controlled cars and intelligent computer-controlled players. It is designed as a framework to enable rapid prototyping of in-car games that leverage future technologies like vehicle-to-vehicle communication, full window HUDs, head tracking, and different input methods.

We evaluated our in-car games with 12 participants. They played the games (with occasional take-over tasks), completed the Player Experience Inventory (PXI) questionnaire [62] to measure player experience, and answered questions in a semi-structured interview. Overall, the games were rated highly in immersion, there was a positive response to the incorporation of HUDs in the games, and the different game styles did not significantly impact the takeover task completion time. All games were popular for different reasons.

We used a research through design approach [67], which has four criteria: *process*, *invention*, *relevance*, and *extensibility*. For *process*, we used our design space to explore new areas for in-car games given the novel technologies of modern or futuristic cars. In terms of *invention*, our novel games use a combination of HUDs and V2V communication to enable an exploration into cross-car gameplay. The *relevance* of these games is that they are more social alternatives to console and mobile phone games played in cars. They also allow drivers to keep their eyes on the road while playing. To ensure our work is *extensible*, we provide a thorough review of the state of the art for in-car games, document our game design process and final designs, and provide design directions for future in-car games.

Our contributions are: (1) an investigation and characterization of a design space for games played in cars; and (2) the design and evaluation of cross-car, multiplayer games for cars with full-window heads-up displays.

RELATED WORK

We conducted a literature review to better understand existing in-car games and to inform the characterization of a design space for in-car games. We used permutations of the search terms "car/vehicle/driving game/entertainment/gamification", "in-car experiences", "driving infotainment", and "pervasive games" in Google Scholar and the ACM Digital Library. We excluded close variants or extensions of works from within the same research group. Works that described or implemented a game or interactive entertainment experience for occupants of cars were included. Our focus was on cars, rather than vehicles more broadly, because cars form the majority of vehicles owned by individuals and are likely to be first targets for new gaming technologies by the automotive industry.

Existing work on in-car entertainment can be largely grouped into entertainment involving interaction with the environment, socializing with others on the road, more conventional entertainment experienced within a single car, gamified approaches to safe or eco-friendly driving, and entertainment that spans across multiple co-located cars. Our work focuses on cross-car, multiplayer games for cars with full window HUDs, and incorporates ideas from contemporary game genres such as idle games, rather than more conventional genres such as trivia.

Location-Based Interaction with the Environment – Many works have designed games involving interaction with landmarks or environmental conditions around the car. Sundström et al. [56] developed three gestural and prop-based in-car games to help children maintain a safe posture: balancing a virtual ball on the head enabled by a camera-based face tracking system; making various facial expressions at the camera, based on the car's acceleration; and using a jar prop to "catch" ghosts when the car goes into a dark area, such as underneath a bridge. Brunnberg, Juhlin, and Gustafsson [9] created a crime storytelling game for individual car passengers. Using a GPS receiver, geographical objects acted as triggers for key points in the story. Multiple interconnected stories were programmed in case one type of geographical object did not appear for a prolonged period of time. Players could point a prop in different directions and hear sounds affecting the story.

Capturing and annotating the car's surroundings for discovery and socialization purposes have also been a focus in recent work. Häkkilä, Colley, and Rantakari [23] suggested using mixed reality, in-car window HUDs to allow users to draw location-dependent annotations on top of their surroundings. They implemented a prototype using a smartphone's GPS and a laptop screen held up over the car's side window. Matsumura and Kirk [34] developed a video application for tablets allowing passengers to see something they missed and save photos from the video. A smartphone application could be used to review the photos after the drive. With their Vehicular Lifelogging project [36], McVeigh-Schultz et al. envisioned a system in which the experiences of any driver of the car could be logged. They created an in-car prototype integrating GPS coordinates and car information based on rain sensors (to detect windshield fluid), a sensor for detecting seated passengers, and other sensor data. This information was displayed on the car's built-in infotainment system, and a tablet-based reviewing application was developed for out-of-car use.

In Real Oriented Virtuality [66], Yamada et al. created an in-car virtual reality game for passengers by substituting real-world objects with virtual ones. For example, it might lower a drawbridge when the traffic light turns green. Players could interact with the virtual environment using a conventional game controller.

Car-to-Car Socialization – Schroeter, Rakotonirainy, and Foth [48] imagined that cars could enable social expression of drivers by tagging other nearby cars. For example, this could gamify safe driving, by enabling drivers to attach text in the form of "bumper stickers" to other cars to rate driving safety. However, no prototype system was implemented.

Research in car-to-car socialization has also been used to gamify driving routes. Chan [10] envisioned using smartphones as input devices for a game called "Playing in Traffic", which encouraged many drivers to drive together on non-routine routes. Players were rewarded both by driving on new routes and by driving in large groups.

Within-Car Games – With CarVR [24], Hock et al. prototyped a virtual reality in-helicopter balloon-shooting game for individual car passengers. The game was implemented using the Samsung GearVR headset and a conventional game controller. The helicopter in VR space would match the car's accelerations. This resulted in participants feeling less motion sick when the car was driving.

Multiplayer games for within-car play have also been explored. Several works [7, 65] designed games in which passengers could play trivia-style games on their phone or tablet. To enable multiplayer play, the driver could optionally choose to interact with the game by pressing in-car controls such as steering wheel buttons.

Gamification of Safe and Eco-Friendly Driving – Several works [13, 14, 29, 45, 51, 53] focused on gamifying safe and eco-friendly driving for the car driver. There are many common traits among these works, such as using the car's OBD (on-board diagnostics) to send data to a smartphone app, having the driver try to accelerate and decelerate smoothly to match target visuals, providing audio notifications, and including online leaderboards. Three notable exceptions are: a prototype game by Nykänen et al. [42] that uses only sound to give feedback to the driver by changing the instrumentation of a musical track; the "Mileys" game [25], in which the passenger tells the driver to drive smoothly; and a game by Fitz-Walter et al. [17] that requires the player to manually input odometer readings and perform driving manoeuvres to advance in a virtual "road trip". Several additional works suggest using the car's HUD to render virtual objects to collect or avoid as part of the gamification [15, 54].

Recent work has also focused on maintaining situational awareness in autonomous cars. For example, in the AutoGym [31] game, players ride an in-car exercise bike prop to match the idle time of the car, and in AutoJam [30], players tap on the steering wheel in accordance with the car's acceleration. In Pokémon DRIVE [49], the driver responds via an in-car control to artificial "AR hazards" presented on the windshield HUD, to earn rewards and maintain awareness.

Cross-Car Games – The Road Rager game [8] is arguably the most closely related to our work because it also presents a game for in-car, cross-car play. The game was designed for young passengers and it used interaction techniques suited to different traffic patterns (*e.g.,* passing cars, oncoming cars). A PDA's digital compass and GPS were used to determine orientations and distances of playing cars. This information was sent over an ad hoc network established between the PDAs in different cars. The system experienced technical problems during a small user study, so limited feedback could be obtained from participants. While Road Rager focused on the implementation of games in conventional cars, our work is the first to focus on the design of games that support multiple simultaneous players in more than two co-located cars and use full-window HUDs.

DESIGN SPACE FOR IN-CAR GAMES

Based on our literature review, as well as visionary work from the automotive industry (*e.g.,* full-window HUDs [19], V2V communication [32]), we investigated and characterized a design space for in-car games with 13 categorical dimensions. We use the term "dimensions" in the same sense as the "questions" of MacLean et al. in their Design Space Analysis method [33]. Our dimensions are categorical, each with a set of options from which a designer may choose. Table 1 summarizes past work along the most salient dimensions, with all dimensions described below. The groupings along the left side of the table are for convenience, and correspond to the groups of works in the literature review.

To characterize the design space, we examined the things that past works found important to the design of games for in-car play, and grouped them into dimensions and options. This grounds our three game prototypes in the large pool of existing work, and we hope that it will serve as a useful tool for designers of in-car games. After describing all the design dimensions, we use them to suggest promising future directions for the design of in-car games.

Is Game – Although our primary focus is games, our survey and design space includes other forms of related in-car entertainment, such as socialization systems. This dimension captures whether the system can be considered a game [2].

Multiplayer – Some entertainment and games rely on the presence of multiple, simultaneous, co-located car occupants or players. The style of play and player experience can vary dramatically based on whether players within the same car or players across multiple cars play with each other. Our definition of multiplayer may be more restrictive than some, because we do not treat online leaderboards as multiplayer.

Competition Style – Multiplayer games may be competitive, cooperative, or some combination of the two. Competitive games could derive from games traditionally played in cars such as "I spy" or "license plate games" (*e.g.,* finding cars with license plates from different parts of the country). Collaborative games could be inspired by truck convoys, which have been used for fundraising purposes [52].

Co-located Cars – As with pervasive games [39], players in co-located cars can be involved actively, in which case they are playing the game, or passively, in which case they act as an in-game object, but do not explicitly provide input. In either case, the road environment has the added challenge that cars frequently move out of a player's sight, so game mechanics have to consider this aspect.

Environment – Implicit information is provided to games based on the environment of the players. The information may come from the player's own car (*e.g.,* car velocity), GPS location data (*e.g.,* nearby landmarks), or directly-sensed environmental conditions (*e.g.,* brightness outside, weather, road

		Is Game	Multiplayer		Competition Style		Co-Located Cars		Environment			Presentation							Input							Driver Plays		Route Influence		Genre
Example Works			Within car	Between cars	Competitive	Cooperative	Active	Passive	Car	Location	Conditions	Phone/PDA	Tablet	HUD	In-car display	Sound	AR	VR	Phone/PDA	Tablet	Game Controller	Prop	Camera	Motion Tracking	In-car controls	Always	Sometimes	Destination	Path	
Location-based interaction with the environment	[66]	■									■					■		■			■									Shooter
	[56]	■							■		■				■	■						■	■							Action
	[23]			■			■			■				■			■		?	?	?	?	?	?	?					N/A
	[34]									■		■	■						■	■			■							N/A
	[9]	■								■		■				■			■			■								Location-based
	[36]								■	■	■		■		■					■							■			N/A
Car to car socialization	[10]	■		■		■	■			■		■							■							■			■	Location-based
	[48]			■			■									■	■		?	?	?	?	?	?	?	?	?			N/A
Within-car entertainment	[7]	■	■			■							■		■	■				■					■		■			Various
	[24]	■							■							■		■			■			■						Shooter
	[31]	■							■				■		■	■						■				■				Strategy
	[30]	■							■						■	■									■		■			Rhythm
	[65]	■	■			■				?	?	■							■								■			Trivia
Gamification of safe/eco driving	[15]	■						■			■			■			■						■			■			■	Action
	[25]	■							■	■		■				■	■		■											Strategy
	[14]	■							■						■											■				Action
	[45]	■							■			■			■	■			■							■				Strategy
	[29]	■			■				■			■				■			■							■				Strategy
	[42]	■							■							■										■				Action
	[51]	■			■				■	■		■			■	■			■						■	■				Strategy
	[53]	■							■			■				■			■							■				Action
	[49]	■							■					■			■								■	■				Action
	[13]	■							■						■	■										■				Strategy
	[17]	■							■	?	?	■							■											Adventure
Cross-car entertainment	[8]	■		■		■	■					■				■			■			■								Action
	Us	■		■	■	■	■					■		■		■	■		■					■			■			Various

Table 1. Main design dimensions (columns) mapped to systems in past work (rows). A black cell means the work applied the option. "?" means the work did not indicate whether the option was applied.

conditions). It can be used to gamify certain styles of driving, or for the achievement of location-based in-game goals.

Presentation – The game state may be presented on a smartphone or tablet, but also on an in-car display, via sound, or in AR or VR. A previous design space for location-based games [28] categorized games as mixed-reality or augmented reality. Our presentation dimension is more broad, and includes most of the ways occupants could observe the game state. As the automotive industry adds increasing amounts of technology inside vehicles, we expect to see more presentation methods such as HUDs and HMDs [19, 35].

Input – Unlike *environment*, we use *input* to refer to the explicit input that players provide. Players may interact with the game via the touch screen on their smartphone or tablet, a game controller, a motion tracking system, or an in-car control such as a touch screen infotainment system or radio channel dial. If a car were fully autonomous, traditional driving controls such as the steering wheel and pedals could be used for input. Alternatively, as new automated driving features become incorporated into cars, there will be potential for more input devices (*e.g.,* exercise bicycles [31]) to be added to the car in place of traditional controls.

Driver Plays – This dimension is associated with the level of attention that the driver must pay to gameplay. If the driver *always* plays, it means their presence is critical to the continuation of the game (*e.g.,* an adventure game would have to pause if the driver stops playing). If the driver *sometimes* plays, it means the driver can remove themselves from gameplay even as the game continues (*e.g.,* the takeover task in our games removes drivers temporarily from the global instance of the games, drivers can choose when to engage with trivia games played among passengers [7, 65]). In conjunction with the *Required Play Time* dimension below, *Driver Plays* indicates the level of autonomy that would be required for the players' car, to ensure safe gameplay. For example, if the driver *always* plays and the required play time is more than several minutes, this would suggest that the players' car should be fully autonomous to ensure that gameplay does not lead to car accidents. If the driver *never* plays, then any level of car autonomy should be suitable, because the driver could focus on driving as the passengers play.

Route Influence – Games may choose to incorporate the actual driving experience into gameplay, gamifying driving choices. A game could influence players' choice of route [10], or as with pervasive games not explicitly designed for cars, the players' choice of destination [59].

Genre – Some games involve fast-paced action, while others require players to complete a puzzle. The genre of a game "is rooted not in game mechanics, but in game aesthetics; that is, play-experiences that share a phenomenological and pragmatic quality, regardless of their technical implementation" [2]. In theory, in-car games can be any genre, but there are practical limitations, such as the car's position in traffic and the fixed relationship among other passengers in the cabin, which may limit the forms of some genres. To make a genre inherently suitable for in-car play, these practical limitations should be considered as design opportunities.

The following three dimensions have not been included in Table 1. *Required Play Time* and *Intended Traffic Environment* are each only explicitly mentioned by one prior work ([7] and [8], respectively). *Presence of Teams* is not yet explored in the games described by prior work.

Intended Traffic Environment – The traffic environment influences which cars are involved and game mechanics, both from the aspects of road type (*e.g.,* local streets, highways, parking, alleys, dead end turnarounds, driveways, intersections, roundabouts, overpasses) and traffic conditions (*e.g.,* cars passing one another, oncoming traffic, traffic jams).

Required Play Time – The time required to play a game is a useful metric for categorizing games, especially since opportunities to play long, continuous games in cars are limited.

Presence of Teams – In the same way that conventional sports often involve teams, games played in cars could incorporate team mechanics. However, cars travel at different speeds towards different destinations. Unlike sports teams, teams for in-car games would have to be based on drivers sharing the same route, or be continually reformed by grouping co-located cars. There is also an added challenge of identifying teammates to players because players are inside their cars.

Directions for Design Practice

By identifying "gaps" in which few works have explored given design space dimensions, we highlight several key directions ripe for exploration. One of these directions, cross-car games, is the focus of this work. Past work also includes research outside of the domain of cars, which we use as inspiration for types of games to be played in-car.

Designing Games for Different Traffic Environments – The traffic environment is a unique aspect to games played by pedestrians and passengers of vehicles. Aside from a limited exploration of different speeds of encounters between cars in Brunnberg's *Road Rager* work [8], no research to date has focused on games that leverage the diversity of different traffic situations such as driving in parking lots and driving beside oncoming traffic. For example, a game could require players to launch items at cars passing by on overpasses; different game events could happen based on whether driving in a dense city traffic jam or in flowing, regularly spaced highway traffic.

Team-Based In-Car Games – To our knowledge, no games for cars involve a fixed number of competing (or cooperating) teams. Adapting games like Ingress [40] (a team-based pervasive game) for in-car play could be an interesting way to explore this area. In-car games involving teams could pit oncoming cars against each other, or group co-located cars into teams on a long highway trip to fight against virtual monsters on the road.

Games that Influence the Driving Route – Similarly, no work in the context of in-car entertainment has focused on designing games that influence the driving destination. While existing work includes games encouraging drivers to take alternate routes (*e.g.,* [10]), it would be interesting to explore games that also influence the destination. For example, shopping trips could be gamified with possible alternative destinations to minimize fuel use or distance travelled, or games could be used for tourism purposes as done outside of the car context [59].

Alternatively, designers could imagine that people will ride in (eco-friendly) cars with the explicit intent to play games, with no predetermined destination in mind. The game *Can You See Me Now?* by Benford et al. [5] had runners physically traverse a city to catch moving virtual (online) players. A similar game could be expanded to drivers or passengers of cars.

Competitive In-Car Games – Most existing competitive games played in cars revolve around beating high scores by driving safely or in an eco-friendly manner [51, 29]. Whether within the car, or between cars, how can we make engaging competitive games beyond using leaderboards? A game could incorporate teams that compete against each other, or free-for-all competition between all co-located cars on the road.

Cross-Car Games – Existing work on in-car entertainment involving co-located cars focuses on socialization [48, 10]. Games could also incorporate the capabilities of modern cars such as HUDs and cameras, to explore game genres, mechanics, and experiences involving collaboration and competition between drivers and passengers of co-located cars. The three games described next are a step towards understanding the possibilities for cross-car games.

PROTOTYPE GAMES

Three games were designed to explore a novel and exciting subset of the design space, namely, cross-car games that use large HUDs for presentation of game elements. We focus on cross-car games because of their timely potential value as design artifacts to the game research, game design, and automotive communities, given recent advances in V2V communication and HUD technologies.

The games use the design space *dimensions* as follows: they are *cross-car*; in other words, *multiplayer between cars* with *active* involvement of *co-located cars*, but no *presence of* *teams*. We explore both *competitive* games (Killerball) and *co-operative* games (Billiards, Decoration). To focus on cross-car interaction, we explicitly exclude *environment* information, and the games do not have any driving *route influence*. The games' *intended traffic environment* is local streets/highways. The games' *presentation* is a combination of *HUD*, *phone/PDA*, and *sound*, and *input* is received by *motion tracking* a *phone/PDA*. The *driver plays* when the car is driving autonomously (*i.e., sometimes*), with a *required play time* of tens of seconds.

Goals and Assumptions

Our goal was to design games with assumptions to ensure we incorporated realistic future car technology. All assumptions were made during initial ideation of what cross-car games might be, before actual games could be designed. Below are the assumptions we made; we see them as a minimal set for creating cross-car games. More assumptions (*e.g.,* different car seating arrangements [27]) could be made to design more sophisticated cross-car experiences.

- Cars will be capable of continuous periods of tens of seconds to several minutes of autonomous driving during which drivers and passengers could play games (*e.g.,* in stop-and-go traffic, on the highway). Mainstream cars are acquiring autonomous driving features such as traffic jam autonomous driving [3] and highway autonomous driving [20, 58]. Many such features require drivers to maintain attention on the road, but we expect this requirement to be relaxed as the features become safer.
- Cars will have full-window HUDs. Several car companies have experimented with augmenting car windows with overlaid displays (*e.g.,* GM's "Windows of Opportunity" [19], Toyota's "Window to the World" [11], Nissan's "Invisible-to-Visible" [41]). Furthermore, focus groups have identified gaming as a possible application for windshield displays [22]. We assume the HUDs are 2D, rather than stereoscopic 3D, because only 2D would be practical with current display technologies when multiple passengers are viewing.
- Cars will be V2V-enabled, so game state can be shared between cars. Even without V2V communication, some state can already be shared with ad hoc wireless networks [9], however V2V is already starting to be integrated in some high-end cars (*e.g.,* Cadillac [32], Toyota [60]). As with any connected technology, there is always a security risk when sharing information, so V2V system designers will take precautions to minimize these risks.
- Cars will keep track of the approximate geometry, or bounding volume, of each nearby car involved in the game. With the use of V2V communication, the bounding volume information would be used for in-game collision detection. This could be achieved because future cars will likely build information networks about relative car positions and proximities [26]. If car manufacturers were to include a 3D model of the car in addition to bounding volume data, this could be used to augment gameplay (*e.g.,* a mirror reflection of a car in a game).
- Cars will be able to track the position of smartphones and passengers' heads within the car cabin (*e.g.,* using technologies like the Kinect or Leap Motion). In-car motion tracking has already been explored in the literature, and can be performed with high accuracy [6, 46].

Games

We wanted to explore games beyond those using only mobile device screens and touch input. With cross-car games, people would be aware of other people in their surroundings, and perhaps could cooperate with friends and family in their own car. Playing games with others who are physically present can lead to an increase in positive emotions and sense of belonging [12]. Further, cross-car games enable players to keep an eye on the road, potentially keeping drivers aware of the environment and improving driver takeover ability when compared with looking down at a screen. Naturally, some people would be interested in being social while on the road, while others would prefer to have the time to themselves. Our games cater to the former group. While existing work has focused on maintaining driver situational awareness (*e.g.,* [49]), our work focuses on game design.

We aimed to provide three distinct player experiences that are indicative of separate genres: (1) free-for all games, a multiplayer genre in which each player competes with all other players in the game (this game style can be considered zero-sum, because victory can only come at the defeat of another player); (2) MMOGs that feature a PvP core mechanic but allow for collaborative actions such as player assists; and (3) idle games, in which simple clicking actions are repeated frequently to earn in-game currency. We chose these three genres because they are popular and their forms are appreciably different from each other – we do not claim these are exhaustive or complete.

The driving environment is ephemeral, with cars frequently turning and changing speed. This guided us towards designing each game to have only one global instance, as is common with pervasive games [38]. In all games, scores and player names were rendered in front of their respective car. Over the course of development, the games went through a weekly process of being played by one or more test players until the major problems were resolved.

Killerball

Killerball's (Figure 2a) gameplay techniques were inspired by Baudisch et al.'s Imaginary Reality Gaming [4] and Tang, Winoto, and Wang's ball passing game [57], and adapted from the camp version of the competitive dodgeball game, played without teams. There are several balls, which players must throw at other players (1) by performing a throwing gesture with the VR controller. If a player catches the ball, points are deducted from the thrower (2). If a player is hit, points are deducted from them. Players gain bonus points when they successfully hit a car in an oncoming road lane. Balls can be spawned by turning the controller upward. In the background, all players gain points at a fixed rate over time so that scores remain positive. Balls can be thrown at players coming from any traffic direction. Periodically, the game is paused for all

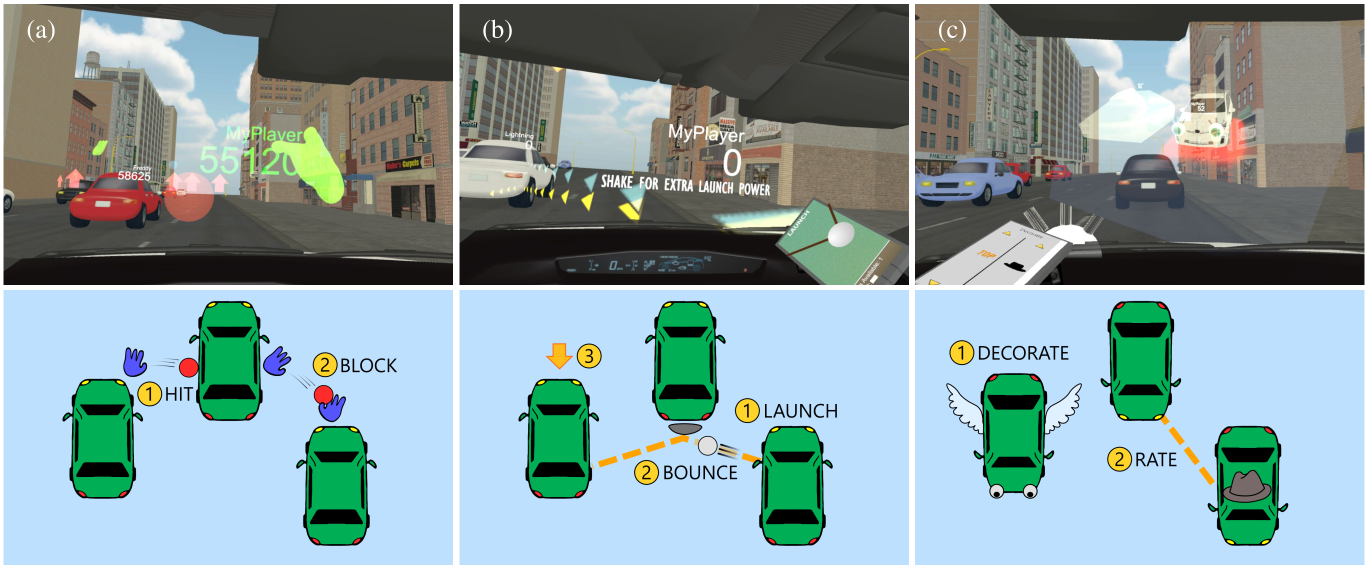

Figure 2. The three games: (a) Killerball; (b) Billiards; and (c) Decoration. VR scenes in gameplay at top, illustration of rules at bottom. The accompanying video also demonstrates these games and the VR prototyping setup.

players and a leaderboard of nearby players is shown on the windshield HUD for the duration of the intermission.

Due to the lack of depth cues from the HUDs, the feature to manually spawn balls was added midway through development. This allowed test players who were weak at catching an opportunity to throw balls, while still leaving a challenge for more experienced players. We also considered having balls automatically snap to the player's hand position, but decided against this because the manual spawning afforded test players a greater sense of control. The intermission feature was also added during development because we found it useful to give players a chance to rest and gain a sense of progress.

Billiards

Billiards (Figure 2b) is a PvP-style MMOG with player assists (*i.e.,* cooperation). It includes a launching and bouncing mechanism inspired by Peggle [44], a puzzle video game. Cars are clustered into groups of up to five during each round of the game. Game rounds last approximately 25 seconds. This results in a minimal time commitment and reduces game disruption should a playing car drive out of range midway through a round. Within the group, one player will be assigned as the "launcher", while other players are "bouncers". The launcher has 20 seconds to launch a virtual billiard (1) at an indicated vehicle (3) to gain points. Launching is performed using a slingshot UI on a virtual smartphone (rendered on top of the VR controller). Launching the billiard so it bounces off the road or other vehicles before arriving at the target doubles the number of points awarded. By shaking the smartphone as players approach an oncoming car, they obtain a temporary bonus that doubles their maximum launch velocity. "Bouncers" can choose to assist launching players by pressing on the smartphone screen and pointing the phone in the direction to bounce. This spawns a virtual shield to deflect an incoming billiard towards the target vehicle (2), assisting the launcher and awarding the bouncer bonus points for a successful bounce. If the bouncer is the target vehicle, this player can bounce in any direction for bonus points. The target vehicle is indicated by a grey dotted line projected on the HUDs and in a birds-eye-view of nearby cars on the smartphone screen.

The Billiards game underwent many iterations during development. It was originally conceived of as a free-for-all game in which players could choose to be launchers or bouncers and there were multiple balls in play simultaneously. The goal was to bounce the balls off as many cars as possible. Test players found the presence of multiple balls to be overwhelming, and with no particular target set as a goal, felt that bouncing was underwhelming. As a result, the timed, group-based mechanics were introduced. The shake bonus was added during development as an effort to incorporate oncoming cars into gameplay. Because the pillars of the car occluded the launch trajectories, we also added indicator arrows directly on the HUDs to indicate the general direction of the target car.

Decoration

Inspired by idle games, in Decoration (Figure 2c), players can decorate their vehicles (1) with acquired props, such as eyes, hats, and wings. Props are equipped one-by-one, and a player's car can have multiple props equipped at any given time. Our prototype has eight unlockable decorations. As with Billiards, Decoration includes a virtual smartphone. A virtual mirror can be used to inspect the equipped decorations, and is oriented by rotating the smartphone. To unlock more decorations, the game incorporates cooperative resource management. Players must decorate their cars in appealing ways to be "liked" by other players (2), who can increase their level using an in-game rating system. Player levels drop slowly over time if they do not rate other players, incentivizing the rating mechanic.

The first iteration of Decoration did not drop player levels over time. This incentive was added during development because test players would frequently become engrossed in decoration to the extent that they would forget to rate other cars. The in-game rating system was initially designed to work in two steps: first, choose the rate command, and second, choose "like" or "dislike". Test players found this process overwhelming because they needed to repeatedly look up (at the player to rate) and down (at the smartphone). During development, we converted this system into a single "like" button that could be pressed without looking at the smartphone.

PROTOTYPING SYSTEM

We created our car game prototyping system using Unity 2018.1 and the SteamVR VR toolkit, designed for use with the HTC Vive VR headset and controllers.

When simulating a game, cars automatically drive along a straight road. The start positions, directions (forward or oncoming), and player statuses of all cars are configured using a text file. Cars have a configurable random chance of changing lanes and speeds, and have controllable speeds and spread parameters to simulate different traffic patterns (*e.g.* traffic jam, highway). The buildings and scenery in the environment can be toggled to simulate different environments (*e.g.* countryside, city centre).

The virtual cars are equipped with HUDs on all windows. The HUDs can render both *screen-fixed* and *world-fixed* objects [18], the latter of which render a 2D head-coupled perspective projection of "HUD-flagged" virtual objects in the scene. We include a configuration parameter to present these HUD-flagged objects in 3D, as if they were real, for debugging and experimentation purposes.

Our games use the HTC Vive for all input. However, the system is modular and could, for instance, use a Kinect for position tracking and a smartphone for touch detection. Our Vive tracking code provides hand controller position, rotation, and velocity. We use a Vive tracker mounted on a physical steering wheel to detect its orientation in our takeover task. The system is also able to render a virtual phone screen in place of the controller in VR space, that can receive input via taps and swipe gestures on the Vive trackpad.

Our prototyping system enables a single human player to play as the driver of the car. All other players are AI-controlled. Our system also supports multiple players in the same car, in which case co-passengers other than the driver are AI-controlled as well. The AI players use simple rules (*e.g.,* throw balls at reasonable angles at other cars with a certain level of inaccuracy) to mimic realistic human gameplay. AI-controlled players also enable us to ensure consistent game experiences across participants in our study.

The prototyping system allows for several forms of feedback and notifications to players, including sound, vibration of the Vive controller, popups on the virtual smartphone screen, screen-fixed popups on one or more of the window HUDs, animated indicators on the window HUDs, world-fixed popup graphics (projected on the HUDs), and particle effects.

EVALUATION

The goal of this study was to understand which types of games are better suited to cross-car play and HUD display. A secondary aspect was examining if game type impacts takeover times, a relevant measure in previous takeover studies. Our study was predominantly qualitative, based on a semi-structured interview about gameplay.

Participants – We recruited 12 participants (9 male, 3 female), aged 21 to 32 years (mean=25.8, SD=3.8) to play each of the games. All but one participant could drive a car, and all participants held the VR controller in their right hand. Remuneration was $10.

Apparatus – The previously specified prototyping system was used. The physical steering wheel was mounted on a desk, which acted as the dashboard surface. Participants wore an HTC Vive Pro headset and used an HTC Vive controller.

Task – The participants were instructed to play the three games, Billiards, Killerball, and Decoration, for up to five minutes each. Once, randomly during the play time of each game (between 3:00 and 4:20 minutes), participants were required to complete a takeover task. A practice round for the takeover task was given before participants played any games.

Our takeover task assesses a player's ability to regain spatial awareness when interrupted during a game. The task starts when a large white-on-red text takeover prompt appears on the currently observed HUD with an audible alarm. To complete the takeover task, the player must set the VR controller down and steer the physical steering wheel in the direction of the first lamp post they see (the steering wheel does not move the car). Lamp posts are evenly spaced on the sidewalk on alternating sides of the road. After completing this task, the game resumes.

We measure the *Takeover Time*, the time taken to perform the takeover, as a dependent variable. If the player fails to takeover within ten seconds, then the takeover is marked as "failed". Past work has assumed that a car's autonomous driving system is able to predict a takeover request five to seven seconds in advance [21]. Our takeover task's maximum allowable time of ten seconds was selected to be slightly longer than this amount reported in the literature. Artificially limiting the maximum takeover time could lead to too many takeover failures to measure an accurate takeover time.

Design and Procedure – The study was within-subjects, with GAME as a three-level independent variable. Before playing each game, participants were told they would be playing cross-car games with other players on the road, in a virtual reality car simulator. They were shown a video demonstrating the game rules and gameplay. Participants were *not* told that the other players were controlled by AI, because this can affect players' perceptions of gameplay [64]. Each participant played all three games for up to five minutes each, and game order followed a balanced Latin square. After each game, participants were asked to rate the game using the PXI questionnaire [62] for measuring player experience. After playing all three games, a semi-structured interview asked the participant to compare various aspects of the games, such as the incorporation of the HUDs, the input controls, and overall preferences.

Results

The PXI survey produces ten player experience dimensions useful for characterising games: *Meaning*, *Mastery*, *Curiosity*, *Immersion*, *Autonomy*, *Goals and Rules*, *Audiovisual Appeal*, *Challenge*, *Ease-of-Control*, and *Progress Feedback*. Each dimension is the average of several 7-point Likert-type questions (1 = strongly disagree, 7 = strongly agree). We used an ANOVA to test for effects of GAME on each of the scores. Due to the large variety of player types within the participants, only a significant effect of *Control* was found. Relevant descriptive statistics for other dimensions are provided for completeness. An affinity diagramming approach was used to categorize participant opinions collected during the semi-structured interview, and have been organized by topic below.

Overall Game Preferences – All the games were almost equally popular, with five players choosing Decoration as their favourite, four players choosing Billiards, and three choosing Killerball. Decoration was popular because of excitement when unlocking new decorations (2 participants), relaxing gameplay (3 participants), and simplicity of controls (2 participants). Compared to Decoration, these participants found that the other games had elevated time pressure and did not like the more competitive nature of these games. Billiards was popular because of the clear and easy to understand goals (2 participants), simplicity of launching controls (3 participants), and strategic aspects lacking in the other two games (2 participants). Killerball was popular because it was action-packed compared to the other games that involved more waiting.

The PXI dimension *Goals and Rules* (mean=5.2, SD=1.2) was rated positively, meaning that goals and rules were clear to players. *Autonomy* (mean=4.2, SD=1.6) was rated neutral to slightly positive, meaning that players felt they had some freedom to play the game as desired, and *Challenge* (mean=4.2, SD=1.3) was rated neutral to slightly positive, meaning that players felt that the difficulty somewhat matched their skill level. *Curiosity* (mean=4.5, SD=1.3) was rated slightly positive, meaning players had interest in the progression of the games. *Audiovisual Appeal* (mean=4.9, SD=1.4) was rated slightly positive.

Co-located Play – In reference to gameplay preferences, four players explicitly communicated their enjoyment of the co-located nature of the games. P7 liked the games because of their ability to form "impromptu relationship[s]" with other players on the road. P2 noted that our games are different from multiplayer mobile phone games because our games rely on multiple physically-present people playing together. This participant said they would not play a multiplayer game in a car if not for this co-located aspect to the gameplay.

Further, participants unanimously agreed that it would be acceptable to play the games with strangers. They cited reasons such as lack of direct communication with other players (2 participants), no sharing of private information with other players (3 participants), and similarity of the games to online games played with strangers (4 participants).

Compared with Traditional Video Games – Cross-car games were said to be more immersive (2 participants) and demanding for attention (3 participants) than traditional games (*e.g.,* console, phone, computer). P4 noted the additional physical effort required to play our in-car games compared to phone games, but thought this could be an effective way to integrate exercise into their routine. Four participants also noted that the car games felt like "time-killers" or "time-fillers", because they lacked the story and progression of a typical adventure game. Along these lines, PXI *Meaning* (mean=4.1, SD=1.4) was rated neutrally, meaning players were neutral in terms of feeling connectedness with the games. Seven participants stated that they play conventional video games as car passengers, but two other participants claimed they would be more likely to play games similar to our prototypes than conventional video games.

Heads-up Display – The use of multiple window HUDs was generally well received by participants, with five participants giving a positive response, five giving a neutral response, and two giving a negative response. PXI *Immersion* was high for all games (mean=5.3, SD=1.0), meaning that players were absorbed in the games, possibly in part as a result of the HUDs. The primary criticisms of the HUDs were the lack of depth cues (5 participants) and their abrupt edges (2 participants).

Two participants also mentioned the awkwardness of looking out of windows other than the windshield, P2 even felt in danger because they were taking their eyes off the road. We also noticed several participants attempting to turn around in awkward positions to see the side windows or rear window of the car. P11 mentioned feeling uncomfortable turning around because of the front-facing seats of traditional interior car layouts.

Input Control – Input controls for the Billiards and Decoration games were well received. Killerball controls were reported to be more challenging due to the lack of visual depth cues combined with uncertainty in the throwing trajectory (7 participants). Three participants found the opposite true, stating that the Killerball controls were easy to use. Participants found the launching controls in Billiards easy to use despite the lack of depth cues, thanks to the yellow line indicating the estimated ball trajectory.

There was a main effect of GAME on the PXI *Control* dimension ($F_{2,18} = 6.09$, $p < 0.01$, $\eta^2_G = 0.29$), with post hoc t tests with Holm correction determining that Decoration (5.4, SD = 0.7) was easier to control than Billiards (3.4, SD = 1.7; $p < 0.05$). Overall, PXI *Ease-of-Control* (mean=4.5, SD=1.5) was rated slightly positive, and *Mastery* (mean=4.2, SD=1.4) was rated neutral to slightly positive, meaning players felt somewhat skillful playing the games after the five minute play time.

Effect on Car Takeover Ability – The takeover task times and the perceived ability to takeover were comparable for all three games. There were four total takeover failures spread across four participants and all three games. These failed takeover trials were assigned the maximum allowed takeover time of 10 seconds. Treating the last practice round as a baseline activity, an ANOVA found no significant effect of GAME on

Takeover Time. The median takeover time was 4.9s (SD = 2.2) for the practice round *when no game was being played*, and 5.6s (SD = 2.1) while playing a game. This was reflected in the results of the interview. All participants stated that their ability to takeover was roughly the same for all the games. Four participants mentioned that the extra body motion in the Killerball and Billiards games could be distracting for the takeover. All but one participant said that the games were easy to resume after completing the takeover task.

DISCUSSION

Based on our results and experience designing the three games, we highlight key contributions to existing game design knowledge and aspects for game designers to consider when creating cross-car games.

Games using In-Car HUDs – The three games received high PXI *Immersion* ratings (over 5 on the 7-point scale), possibly suggesting that participants found the HUDs to be successful. However, because the car simulation is in VR, participants unfamiliar with VR may have been influenced by the novelty of the VR environment rather than the gameplay itself. Future validation with HUDs in a real car would further substantiate these results.

Exclusively using HUDs to display game state is challenging because of occlusion caused by the car's roof support pillars. Also because of occlusion, it is challenging for players to see objects in the immediate vicinity of the player's own vehicle. When designing cross-car games, it is advantageous to have an in-car representation of the events going on outside the car. For example, in our Billiards game, the target car is marked on the HUDs, and can be difficult to find if it is behind or beside a player's car. We alleviated this by providing a birds-eye-view on the player's phone that also indicates the target car. An alternative approach would be to creatively incorporate pillar occlusion as an element of gameplay, such as a "peek-a-boo" game.

To be comparable to current in-car display technologies, our simulation renders the HUDs as 2D, eliminating depth cues. This added perceptual challenge and created some frustration in Killerball, because resolving distances of incoming and thrown balls is a key part of the game. In contrast, Billiards rendered trajectory lines for in-flight balls, making distance judgement easier. We recommend using additional cues to compensate for lost depth perception, rather than making it a challenge for players. Consequently, input controls should visualize depth-sensitive effects before committing an action.

Evolving Cars and In-Car Games – During gameplay, several participants chose to bend awkwardly to see out the car's side and back windows, when more comfortable postures with the same viewpoint were possible. This is likely due to the novelty of playing immersive games in cars. Car layouts may change in the future to accommodate new activities [27], but current semi-autonomous cars retain a similar interior layout to conventional cars. For the near future, we recommend that designers of cross-car games provide in-game cues suggesting ways that players can move more comfortably, or allow a player's attention to be mostly focused towards the windshield.

Takeover – The lack of significant differences in takeover times between each of the games and the practice takeover task suggests that our games are comparable from a takeover safety standpoint. It is surprising that our games' takeover times were similar to that of the practice round during which no game was played. However, the takeover times of the practice rounds were longer than comparable existing takeover studies (*e.g.,* 2.1–3.1 seconds [21]). The additional takeover time in our system could be attributed to higher cognitive load of our takeover task (identifying an object in the environment) compared to the obstacle avoidance tasks of existing studies. It is also possible that when the participants tried to put the VR controller down as part of the takeover task, the small difference in height between the experimental setup's desk and the VR simulation's dashboard caused the player to slow down. Nonetheless, the median takeover time of 5.6 seconds with our games is still less than the 7 second takeover request times used in the literature [21]. We believe our results serve as conservative estimates of takeover times in practice. More participants would be needed to ascertain if there are sub-second time differences between game genres.

Limitations and Future Directions

We suggest several ways to expand our games and prototyping system. The PXI *Meaning* category received neutral average scores for the games, suggesting that certain players do not like "time-filler" games and hope for a more meaningful gaming experience. Exploring the adaptation of adventure-oriented games would cater to these player types. It would also provide additional knowledge of the impact of the increased emotional involvement in these games on takeover times.

Our prototyping system allows for only a single human player, and all others are AI-controlled. The system could be extended to support multiple real players in the same car, or in other virtual cars. This would be useful to design for social contexts with many passengers, and to understand the nature of cooperative and competitive behaviour between players.

Finally, our prototyping system does not offer an interface for players to choose which game to play. Such a feature could be designed and integrated into car entertainment systems. It would also be beneficial for gameplay to provide an "opt-in to car games" feature, in which non-playing cars could be incorporated into the games. For example, our Billiards game could be extended to allow bouncing off any "car games-enabled" car on the road.

CONCLUSION

We contributed an investigation and characterization of a design space for games played in cars, codifying existing work along dimensions such as *environment*, *presentation*, and *route influence*. Inspired by an underexplored area of the design space, we contributed to game design knowledge through the design of cross-car, multiplayer games using full-window HUDs. Evaluation of our prototype games showed that the HUDs were well received and immersive, despite some occlusion from car pillars. We look forward to seeing how the evolution of car technologies shapes the future of in-car gameplay.

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