DEPARTMENT OF TRANSPORTATION

Assessment of Pedestrian Safety and Driver Behavior Near an Automated Vehicle

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16. Abstract (Limit: 250 words)

As more automated vehicles enter shared roadways, an essential aspect of automated vehicle (AV) safety is understanding the interactions between these vehicles and other road users. Anecdotal incidents about aggressive following and overtaking behaviors at crosswalks near the Med City Mover (MCM), a low-speed automated shuttle (LSAV) pilot demonstration in Rochester, MN, suggested the need for a scientific study of the behaviors of drivers of manual vehicles near the LSAV. In this report, the research team conducted a series of laboratory and field studies aimed at better understanding the safety relationship between LSAVs and the humans with whom they share the road. Overall, the studies found an increased risk of overtaking and multiple threat passing near the MCM, which may increase the risk of pedestrian-involved crashes, sideswipe crashes, and rear-end crashes. Study findings suggested that poor human-machine interfaces, exceptionally slow vehicle speeds, and resultant large queues behind the MCM contribute to these risks. Improved communication interfaces, speeds more consistent with the surrounding traffic, and smaller queue size will be important factors that AV developers and future pilot demonstrations must consider to better promote pedestrian safety near AVs.

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Assessment of Pedestrian Safety and Driver Behavior Near an Automated Vehicle

Final Report

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List of Abbreviations

ADT: Average Daily Traffic

AV: Automated Vehicle

eHMI: External Human-Machine Interfaces

LSAV: Low Speed Automated Vehicle

MCM: Med City Mover

MnDOT: Minnesota Department of Transportation

OT: Overtaking

Executive Summary

There are clear safety opportunities with low-speed automated shuttles (LSAVs) to reduce the rate of injury and fatal crashes on our roadways. In a demonstration of the capabilities of LSAVs, the Minnesota Department of Transportation (MnDOT) sponsored a demonstration of a LSAV in downtown Rochester, MN, aptly named the Med City Mover. The Med City Mover (MCM), manufactured by EasyMile and operated by First Transit, operated in a pedestrian-heavy area of downtown Rochester from August 2022 to August 2023. Anecdotal incidents about aggressive following and overtaking behaviors of other drivers at crosswalks near the MCM suggested the need for a scientific study of the behaviors of drivers of manual vehicles near the LSAV. Given the novelty of the introduction of LSAVs into mixed-fleet environments, it is critical to understand the ways in which their presence, speeds, and communication strategies may change other road users' behaviors as well as their interactions with one another in ways that may be unintended and counter to safe and successful deployments of LSAVs.

Interviews with LSAV manufacturers and operators were conducted to better understand the common experiences in interacting with other road users and the roles that operators play in the critical role of the "human-in-the-loop" in an automated system. Operators reported day-to-day multimodal safety challenges, such as experiencing aggressive overtaking of the shuttle near pedestrians, a need to predict other road users' behaviors and to communicate with other road users through hand-gestures to smooth interactions with them. Both manufacturers and operators suggested that increasing the vehicle speed and enhancing public awareness were two potential solutions for addressing these challenges.

A field study was conducted to observe the behavior of drivers near the MCM and other manually driven vehicles to determine the relative risks present. The research team collected data along and near the MCM route twice a week from May 26, 2022, to August 30, 2023. Driver behavior data was observed at seven signalized and unsignalized intersections and from a passenger's perspective aboard the MCM or human-driven researcher vehicle along the MCM route/loop. Results found a significantly higher yielding rate of the MCM compared to manually driven vehicles at signalized and unsignalized crosswalks. However, drivers were significantly more likely to commit a multiple threat pass around the MCM in both a right turn at a signalized intersection and traveling straight at an unsignalized intersection. Overtaking was significantly more likely to occur around the MCM compared to the human-driven researcher vehicle around all segments of the MCM route. The MCM was more likely to have a queue of vehicles form behind it and this increase in queue risk was found to partially mediate the risk of being overtaken by other vehicles. Overall, the findings did not suggest a direct risk between the MCM and pedestrians, but increased overtaking behaviors around the MCM, particularly at crosswalks when pedestrians were present, suggested an indirect risk to pedestrians near the MCM.

The exceptionally slow speeds (e.g., 11 mph approximate top speed) that the MCM traveled at and the methods in which it presented flashing hazards when it yielded to pedestrians were identified for further study to determine their influences on drivers' decisions to overtake the shuttle. A series of three simulation studies, ranging from low to high fidelity, were conducted to examine how the MCM's appearance, speed, and external human-machine interface (eHMI) influenced drivers' decisions to overtake.

A low fidelity study with N = 85 participants at the Minnesota State Fair found that the speed of the lead vehicle was directly correlated to the overtaking tendency of participants, with the 10 mph speeds experiencing high overtaking rates. Conversely, the appearance of the lead vehicle, i.e., MCM or passenger van, was not found to be correlated with overtaking. Follow-up surveys found participants often misinterpreted the flashing hazards eHMI to be associated with loading/unloading, which may influence their decision to wait or overtake the shuttle. A follow-up low-fidelity crowd source study of N = 242 participants presented with animations of various eHMIs: flashing hazards, standard brake lights with turn signal, and an LED display in the rear window with text and icons communicating pedestrian crossing. Participants had a higher misinterpretation of the shuttle's behavior when presented with the hazard condition and indicated a lower rate of waiting behind the shuttle compared to the single light and both LED screen messaging conditions.

The high-fidelity simulation study of N = 46 participants found that participants presented with the text/icon were almost twice as likely to stop and wait for the MCM compared to participants presented with the double flashing/hazards. Similarly, participants presented with the Text/Icon were almost 40% less likely to commit a multiple threat pass around the MCM compared to participants presented with the double flashing/hazards. Finally, participants, on average, waited farther back from the MCM compared to participants presented with the double flashing/hazards.

Key findings across the various studies conducted as part of the project are summarized below:

- The MCM was found to yield to pedestrians at a significantly higher percentage than drivers of manually driven vehicles
- The MCM experienced increased queueing of vehicles behind the shuttle compared to other vehicles along the route
- The MCM experienced a higher risk of being overtaken by other vehicles when yielding to a pedestrian at both signalized and unsignalized crosswalks compared to other vehicles along the route
- Queuing behind the MCM was found to serve as a partial mediator for the effect of the MCM on other drivers' overtaking it while turning right at the signalized intersection in Rochester
- Lead vehicle speed was directly correlated to overtaking tendency via a video simulation study with lower speeds resulting in higher overtaking tendencies
- Participants had a higher misinterpretation of the shuttle's behavior and lower rate of waiting behind the shuttle when presented with the hazard signaling condition, currently employed on the MCM when in manual takeover
- A proposed text/icon signaling methodology resulted in the highest rate of participants stopping and remaining stopped behind the MCM when yielding to a pedestrian via a driving simulation study

RECOMMENDATIONS

The research presented highlights three key areas in which nearby driver performance, particularly regarding shuttle overtaking, around an LSAV such as the MCM can potentially be improved.

The first critical recommendation is to increase the LSAV's overall speed to better match that of the local traffic on low-speed roadways to reduce the risks of vehicle queuing behind it and overtaking, particularly at intersections.

The second, and most actionable recommendation, is to improve the eHMI of the LSAV. It is important to limit the use of hazards to standard conditions, such as emergencies and loading and unloading, and restrict their use during turning or yielding to pedestrians. An on-board LED screen, using a combination of text and icons, is recommended to communicate more detailed information regarding the shuttle's behavior, which may result in further improved understanding of the shuttle's actions and reduced overtaking behavior. Further research can investigate whether different types of messaging formats (words/icons/audio) or content (informational/command) are more effective for safe interactions between an LSAV and other vehicles in the context of stopping for pedestrians or other situations (waiting behind a stopped vehicle, not turning right on red, etc.).

A third recommendation is to minimize mixed traffic when the primary type of automated vehicles are LSAVs and there are significant traffic volumes, speed differentials, and a moderate to high road construction likelihood on the planned route.

Chapter 1: Research Planning and Literature Review Update

The present study is novel in that it targets driver behavior in the proximity of an automated shuttle with an emphasis on vehicle-pedestrian conflicts and risks. For this study, the automated shuttle of key interest is the Med City Mover (MCM), an EasyMile Shuttle operated by First Transit, in Rochester, MN. The MCM is a low-speed automated vehicle passenger shuttle capable of seating up to 6 passengers and standing room for the onboard operator. The MCM is presented below in Figure 1.1.

Figure 1.1 The Med City Mover (MCM) on the route in Rochester, MN, USA

Prior to site selection and study methodology determination, the team conducted an in-depth review of existing literature regarding automated vehicles (AVs) and specifically shuttles. The authors provide a summary of this existing literature including associated topics, such as multiple threat passing and overtaking. Also included as part of general research planning is a summary of interviews conducted with both the operators of the MCM shuttle and multiple AV manufacturers. AV manufacturers interviewed included Navya, May Mobility, and EasyMile. Following the summary of interviews with both AV manufacturers and operators is a description of the overall study methodology, a description of the site selection process, and a finalized list of sites that will be used to monitor driver behavior both along the MCM route and nearby.

1.1 Preliminary Literature Review

The Med City Mover (MCM) is a Minnesota Department of Transportation (MnDOT)-led demonstration project testing two low-speed, automated shuttles in Rochester, MN, to test and help MnDOT and local agencies plan for automated transportation in Minnesota. In the future, with the increasing ubiquity of various levels of automation in vehicles, there will be a shared levels-of-automation transportation network, with fully manual, partially automated, and fully automated vehicles sharing the same Minnesota roads. While planners and engineers have long studied how humans drive around other humans, what is not as well-known is human driving behavior around automated vehicles. While automated vehicles are intended to be safer and potentially more efficient than manually driven vehicles, there may be some initial or long-term disruption to driving norms as automated vehicles are introduced to share the road with drivers of manually driven vehicles. For example, prior research has observed that drivers may follow too close or engage in unsafe speeds around automated vehicles, and drivers have a higher risk of rear-end crashes with automated vehicles (Petrović et al., 2020). Furthermore, the risk to pedestrians as a secondary consequence of altered driver behavior around automated vehicles is less understood. Prior demonstrations of low-speed automated vehicle technologies in places such as Fort Bragg, Texas, (ARIBO pilot) observed that additional warnings and alerts would be useful to improve pedestrian safety, such as auditory signaling that the vehicle is stopping for a pedestrian (Coyner et al., 2020).

LSAVs are fully automated vehicles (SAE Level 4 / 5), which are restricted to protected and simpler road environments, operate at low speeds (around 10–15 mph), provide shared service, and share the right-of-way with other road users, either at specific locations or through the entire route (Cregger et al., 2018). Presumably, the key safety benefits of LSAVs are that they operate at lower speeds than most vehicles, which reduces the risks of pedestrian and vehicle fatalities (Coyner et al., 2020) and are not prone to attentional lapses that contribute to human error while driving. Thus, our research focuses on crash frequency likelihood, with a lesser emphasis on crash severity likelihood. However, simulation modeling has indicated that overly cautious automated vehicles can disrupt traffic efficiency and safety (Seth & Cummings, 2019).

1.1.1 General Crash Statistics and Risk Factors

1.1.1.1 General Crash Risk

For general intersection crash risk factors in urban settings, higher population density is associated with higher crash frequency (Wang et al., 2006). Greater volume and intensity or density of vehicles in the intersection is associated with more crashes (Dong et al., 2014; Tay, 2015; Wang et al., 2006), which can be exacerbated by a higher number of small and large trucks (Dong et al., 2014). A higher number of lanes on approach is associated with a higher number of crashes (Wang et al., 2006), notably four-lane roads (Tay, 2015). Evidence is mixed for right-turn-only lanes but left-turn protection reduces crash risk unless there is left-turn protection for more than one approach, because increasing the number of phases increases the risk of crash occurrence. Approaches with the highest speed limit tend to have more crashes at the intersection (Wang, et al., 2006). Wet surfaces (Tay, 2015) along with low intersection lighting and intersection angle (e.g., skewed angle intersections) increase crash rate, the latter presumably because of greater exposure of vehicles to the intersection (Dong et al., 2014; Tay, 2015). Finally, the longer average green time and higher green ratio for left turns and through phases will reduce the odds for crashes, and longer queue lengths on through lanes are associated with higher crash risks (Yuan & Abdel-Aty, 2018).

1.1.1.2 Bus Crash Risk

Analysis of similarly contributing factors for frequency and severity of crashes with buses, a similar form of manual transport to that of LSAVs that provide shuttle service, primarily focuses on driver characteristics, which is outside the scope of this study. However, some considerations on bus crash severity have observed a higher risk of both light injury and severe crashes at low illumination conditions, for two-way and multilane roads relative to one-way roads, for curved roads relative to straight sections, at intersections relative to non-intersections, and at roads with higher (5+ mph) or lower (less than 20 mph) speed limits relative to roads with speed limits between 35-50 mph (Kaplan & Prato, 2012).

1.1.1.3 Pedestrian Crash Risk

It is known that the risk of death to pedestrians involved in a crash is relatively low (5%) for vehicles traveling at 20 mph, whereas it is higher (45%) for vehicles traveling at 30 mph, indicating that crash severity risk for pedestrians is greater on high-speed limit roadways (U.K. Department of Transportation, 1987). For unsignalized intersection crossings, drivers are less likely to yield to pedestrians for roads with greater traffic volume (Craig et al., 2019), more likely to commit multiple threat passes with pedestrians present with roads with more lanes (Craig et al., 2019; Morris et al., 2020), presence of transit stops (Craig et al., 2019) and greater traffic speeds (Morris et al., 2020), and there is a greater risk of pedestrian crashes for roads with greater pedestrian traffic volume, greater pedestrian exposure, higher lane count, and a lack of a raised median (Zeeger et al., 2005). For signalized intersection crossings, pedestrian crossing volume (Pulugurtha & Sambhara, 2011; Schneider et al., 2010) and vehicle volume (Lee & Abdel-Aty, 2005; Schneider et al., 2010) are both positively correlated with pedestrian crashes. Furthermore, a significant presence of individuals under the age of 18 living in the area is associated with higher pedestrian crash rates (Schneider et al., 2010). Higher number of public transit stops and number of approaches (4-legged vs 3-legged) at the intersection is associated with greater pedestrian crash rates (Pulugurtha & Sambhara, 2011). The presence of commercial properties, non-residential driveways, and right-turn-only lanes may be associated with higher pedestrian crash rates (Schneider et al., 2010), although another study does not support this (Pulugurtha & Sambhara, 2011).

Research studies aimed at measuring pedestrian risk taking have found that male pedestrians are more prone to risky crossing and choose wait times at signals that are 27% shorter than those chosen by female pedestrians (Ravishankar & Nair, 2018; Tiwari et al., 2007). This behavior may put them at greater risk of being struck by a motor vehicle at a crosswalk. Generally, pedestrians are more likely to cross at random road segments than at marked crosswalks, e.g., zebra crossings, (Ravishankar & Nair, 2018), which may make their movements harder to predict for drivers and place them away from intersection-focused lighting at night.

1.1.2 Behavior Near Manually Driven Shuttles

1.1.2.1 Driver Behavior

For driving behind and around other vehicles and manual shuttles, presumably drivers follow a common model to manage the subtasks of lateral (steering) and longitudinal (speed) control, based on perception of where the vehicle is relative to the center of the roadway, whether any roadway curvatures are approaching, and the time headway to the lead car (modulated by a desired time headway). If the desired time headway is not met (one common estimation is 2 seconds time headway), the driver may make the decision to change lanes and overtake the lead vehicle (Salvuuci, 2006). Besides general time headway, size also influences following behavior, as drivers in one simulation study followed smaller cars slightly closer (10% closer) relative to larger vehicles such as buses, trucks, and tractors (Yoo & Green, 1999). When considering overtaking school buses, driver speeds and acceleration rates tend to be higher when traffic volumes are high and the vehicle is close to the bus, suggesting some degree of opportunism under high demand conditions (Chen et al., 2021).

1.1.3 Pedestrian Behavior

While the percentage of crashes around buses and other forms of passenger shuttles are low, bus managers and those responsible for safety around public transportation observe significant concerns for pedestrian safety around passenger unloading areas and pedestrian crossings near bus stops (Cafiso et al., 2013). This safety concern is mirrored by field data that observed poorer yielding to pedestrians near public bus stops at unsignalized marked crosswalks (Craig et al., 2019). This highlights a potential safety issue for automated passenger shuttles and pedestrian safety near some unloading sites.

Predicting crossing behavior of pedestrians can be more difficult than predicting driver behavior since pedestrians are less constrained by the built environment than vehicles (de Lavalette et al., 2009). There are several factors that influence pedestrian decision making and rule compliance including lane number and width, infrastructure, traffic signals, pedestrian task, and local culture (de Lavalette et al., 2009). A study of pedestrian risk taking near uncontrolled midblock and unsignalized intersections found pedestrians were more likely to run across the road when accepting gaps of buses compared to other vehicle gaps (Ravishankar & Nair, 2018), which may make the crossing pedestrians harder to detect by other oncoming traffic. This finding complements another study of crash report narratives that found indirect involvement of buses with crashes (e.g., pedestrians running across the street to catch the bus) to be more common than direct involvement in crashes (Brenac & Clabaux, 2005). Overall, these studies suggest that pedestrians may change their crossing behavior near buses or bus stops, which may increase their risks.

1.1.4 Automated Vehicles and Nearby Driver Behavior

The determination of risk factors for crashes involving automated vehicles is not possible due to the lack of widespread deployment and aggregation of available data. For example, a review of California DMV autonomous vehicle collision report system (California DMV, 2022) indicates that there have been 465 autonomous vehicle collision reports from 2014 to mid-May 2022, but this data has not yet been fully aggregated for analysis (an earlier analysis on a subset of this data was conducted by Petrovic et al., 2020). Here we discuss some preliminary research and case studies.

1.1.4.1 Aggressive Behavior Toward AVs

Some crashes with pedestrians have been due to the pedestrian's reported frustration with the automated vehicle (Mitchell, 2018), in which some individuals on foot attacked an automated vehicle. If aggressive acts occur at a greater rate toward automated vehicles compared to human-driven vehicles, including pedestrians attacking automated vehicles, this could represent a problematic dynamic between AVs and humans in general no matter their mode of transportation. The factors that lead to aggression and attacks like this are not fully understood but may be due to several factors as proposed by Li and colleagues (2022). People are reportedly more willing to behave more aggressively toward automated vehicles (Liu et al., 2020a) and demonstrate lower trust and less acceptable risk profiles toward automated vehicles compared to human-driven vehicles even given similar safety performance (Liu et al., 2020b). Given this, Li and colleagues (2022) test whether aberrant driving behavior by automated or autonomous vehicles provoke greater anger than similar behaviors by humans and whether this anger is associated with their general attitude toward automated vehicles and if this anger is negatively associated with their willingness to attribute "mind perception," a sense of rational agency and internal emotional experience, to the autonomous program. After being presented with similar driving anger scale scenarios (Deffenbacher et al., 1994) for humans or automated vehicles, participants reported more anger when the automated vehicle was involved in the aberrant driving scenarios, and this was associated more with mind perception rather than attitude toward AVs. Participants reported less anger with greater agency attributed to AV, but there was a U-shaped relationship between experience attribution (does the AV "feel"?) and anger, with low and high experience attributions being associated with more anger from participants (Li et al., 2022). The authors attribute the high experience attribution and anger phenomenon to an uncanny valley effect (Mori et al., 2012).

1.1.4.2 Other Crashes

Outside of aggression by humans, crashes involving higher level (e.g., Level 4) autonomous vehicles tend to be low impact. A case study of this is a crash between an autonomous shuttle developed by Navya and operated by Keolis and a truck tractor at Las Vegas in 2017 (NTSB, 2019). The truck was backing up into an alley and hit the shuttle. The National Transportation Safety Board (NTSB) attributed the cause of the crash to the expectation by the driver of the truck that the shuttle would stop at an adequate distance to allow the truck to finish backing into the alley, with a contributing factor being the inability of the attendant in the shuttle to be able to manually take control of the shuttle at the time (NTSB, 2019). This implies that a contributing factor of crashes may simply be drivers not successfully anticipating automated vehicle behavior. Petrovic and colleagues (2020) did a preliminary analysis on earlier collision reports received by the California DMV on crashes between 2015 and 2017 and observed that automated vehicle crashes, when compared to human driven vehicles, rarely involved broadside crashes or pedestrian crashes, but had a greater proportion of rear-end crashes, while other crash types had a similar percentage of crash reports for both automated and "conventional" vehicles.

There were no significant differences for driving maneuvers made prior to crash, but for driving errors made, drivers were more likely to be (1) driving at unsafe speeds or (2) following too closely when involved in crashes with automated vehicles, while drivers tended to commit more right-of-way violations with crashes involving conventional vehicles (Petrovic et al., 2020).

1.1.5 Automated Vehicles, Public Perception, and Behavior

1.1.5.1 Survey Issues

Several survey studies have been conducted on perception of automated vehicles. Here we review some of those studies, but it is worth noting some issues or concerns with studies of this type considering low speed automated shuttles (Machek & Peirce, 2021):

1. It is difficult for people to predict their future attitudes, especially for very new technologies.
2. The defined Operational Design Domain (ODD) for automated shuttle demonstrations may not be representative of how these shuttles will be used in the future, as they are usually on carefully selected routes.
3. The presence of the onboard supervisor may affect the passenger experience and may not translate to other supervisors or a case where there is no supervisor.
4. Those who ride the shuttle may already be attracted to novel designs and new technologies, suggesting that there is a self-selection bias for those who answer surveys of this type.
5. There is no true baseline for most of these studies, as either the route is entirely new, or people who are comparing the shuttle to another public transportation system are basing their comparison off the idiosyncrasies of a specific system (Macheck & Peirce, 2021).

Given these concerns, surveys should be given to both shuttle riders and non-riders and questions should assess the representativeness of respondents. Questionnaires should avoid confounding variables (for example, prototype automated vehicles with attendants can be more comfortable, operate at lower speeds, or cost less per fare than normal shuttles, and this may affect the perception of the technology itself), and questions about willingness to use automated shuttles should be very specific about the proposed service, otherwise respondents will mentally fill in the gaps.

1.1.6 AV Perception Survey Results

Some early surveys (i.e., 2014) of public opinion on self-driving vehicles across the U.S., the U.K., and Australia found generally positive expectations of the potential benefits of automated vehicles but high concern about personally riding in the vehicles (Schoettle & Sivak, 2014). When considering a more cross-national analysis, individuals from countries with higher GDPs tend to be less supportive of automated vehicles (e.g., intention to use), while the strongest individual factors common across 116 countries influencing automated vehicle acceptance include ease of finding parking spaces (more difficult parking means more acceptance of automated vehicles) and frequency of public transportation use (Nordhoff et al., 2018).

When considering European attitudes toward autonomous and manually driven buses, attitudes were relatively poor when respondents did not have any experience with or clear prior information about the system, but there was relatively higher preference for automated systems in cities where such automated shuttles were deployed (Alessandrini et al., 2016). For Danish respondents considering vehicle sharing with automated vehicles, individuals were distinguished as either skeptics, indifferentists, or enthusiastic in roughly equal distributions, with skeptics likely to be older, car reliant, and live in more rural areas (Nielsen & Haustein, 2018).

American respondents in Philadelphia found that two-thirds of their respondents were likely to ride an automated bus when an attendant was present, but this dropped to 13% willing to ride without an attendant (Dong et al., 2017). Most demonstration programs rolling out autonomous vehicles in the form of a shuttle program have found (over a survey of more than 25 such programs) that these were successful at getting the public to provide positive feedback and improved attitudes toward automated technologies, but an on-board attendant was still preferred to be present after exposure to the technology, and complaints were expressed about slow automated shuttle speeds and sudden braking (Nesheli et al., 2021).

1.1.6.1 Shared Roads

Participants who rode a driverless shuttle with a “hidden” safety attendant were relatively less worried about their safety when riding the shuttle but were still concerned about the safety of other road users near the shuttle, including pedestrians, indicating concern that pedestrians could not meet the eyes of a human driver, which helps communication, and that pedestrians may not understand the shuttle’s behavior when they tried to cross (Nordhoff et al., 2020). When it came to sharing the road with these vehicles, size appeared to play a factor, with 65% of American respondents feeling unsafe sharing the road with an automated freight truck, while a smaller percentage (17%) felt unsafe sharing the road with an automated passenger vehicle (Smith & Anderson, 2017).

A growing research interest in pedestrian behavior around automated vehicles has led to recent research in the area (Dey et al., 2019; Dommès et al., 2021; Kaye et al., 2022; Velasco et al., 2019; Rad et al., 2020). Characteristics that influence the willingness of individuals to step in front of an automated shuttle include larger distance or gap size between the automated shuttle and the pedestrian (Dey et al., 2019; Velasco et al., 2019; Rad et al., 2020), speed of the automated vehicle (Dey et al., 2019), age of pedestrian (Kaye et al., 2022; Rad et al., 2020), and presence of a zebra crossing (Velasco et al., 2019). Interestingly, trust ratings and ratings of perceived behavioral control (ease or difficulty to perform an action) are also associated with intention to cross in front of an automated vehicle (Velasco et al., 2019). The theory of planned behavior (TPB) has been shown to successfully account for pedestrian willingness to cross in front of an automated vehicle, which traces behavior from intentions, perceived behavioral control, attitudes, and subjective norms (Kaye et al., 2022), suggesting that the focus of policy should consider perceived behavioral control, attitudes, and known social norms around automated vehicles.

Dommès and colleagues (2021) also considered crossing behaviors of pedestrians in a virtual environment and found both older and younger pedestrians were hesitant to cross in front of the automated vehicle when the vehicle was close and braked suddenly. However, there was a willingness to cross the street when the automated vehicle stopped in the near lane and a “manually driven” vehicle approached in the far lane, creating the potential for a multiple threat crash, and those older pedestrians were surprisingly more likely to commit to this risky decision, presumably because older pedestrians were more likely to neglect the far lane (Dommès et al., 2014).

1.1.6.2 Older Drivers and AVs

Given the inherent benefit of automated shuttles for older drivers and that many of the aforementioned studies note that older drivers are more skeptical of automated vehicles, collecting feedback from older drivers is valuable for design and planning. Older drivers (65+ years) reported perceptions of improved usefulness of automated vehicles after exposures to a simulation of an automated vehicle and an actual automated shuttle (Classen et al., 2020; Classen et al., 2021a). Furthermore, a sample of older drivers' intentions to eventually use automated vehicles was primarily driven by their self-reported difficulty with driving, their acceptance of technology, and concerns with automated vehicles in general (Classen et al., 2021b).

1.1.7 External Human-Machine Interfaces (eHMIs)

The use of light bars and other methods to communicate with other users of the road have been studied in the human factors and automated vehicles literature as external human-machine interfaces (eHMIs), and the use of these external human-machine interfaces has been generally found to be more effective and they were perceived as safer and more trustworthy than vehicles that did not have these interfaces (Faas et al., 2020; Rouchitas & Alm, 2019), although no design standards have been specified given the current state of the literature (Dey et al., 2020; Rouchitsas & Alm, 2019). In one survey of these systems, pedestrians were by far the most targeted road user type of eHMIs (91%), followed by cyclists (23%), and then manually operated vehicles (14%) (Dey et al., 2020). Figure 1.2 demonstrates some commonly used design types for eHMIs, adapted from Dey and colleagues (2020).

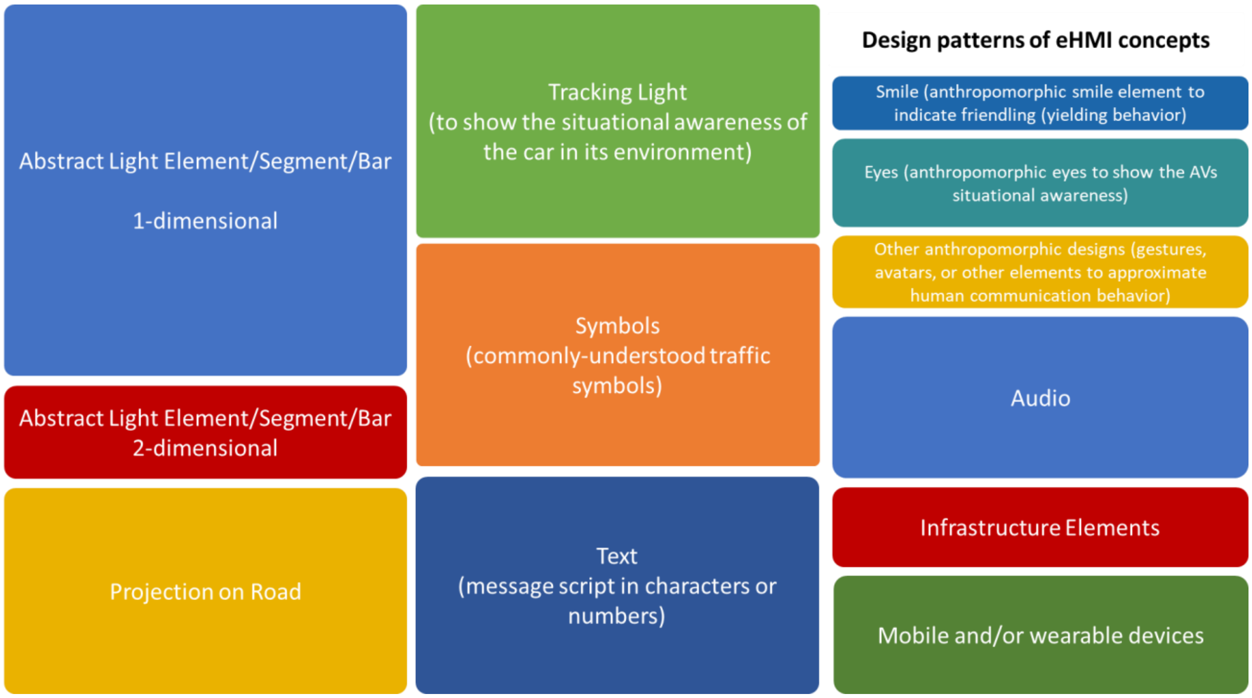


Figure 1.2 Observed design types for eHMIs by type and sized according to relative number of instances found for each, adapted from Dey et al., (2020).

In terms of general research on effectiveness of eHMIs, text on AVs ("stopping," "stopped") are rated as more important by pedestrian participants as an information source, followed by symbols (hand, person walking) and then animated eyes (Wang et al., 2021). Text eHMIs also require no learning relative to animated or pictorial eHMIs and are rated as least ambiguous (de Clerq et al., 2019). This is also the case for text eHMIs compared to color light bars (green, red, etc.), although a combined green font "Walk" message is most likely to get participants to walk in front of the automated vehicle (Bazilinskeyy et al., 2019). However, pictorial designs are preferred in other studies (Othersen et al., 2018; Stadler et al., 2019). Light-strip based designs appear to perform worse in terms of comprehension time and required learning time relative to text-based, arrow-based, and picture-based eHMI designs for communicating to pedestrians, and the more appropriate location for these messages is on the grill or windshield instead of the roof (Guo et al., 2022). Similarly, a study of a light bar on a highly automated vehicle communicating intentions (e.g., yielding) found that pedestrians begin to gain better understanding of the communication patterns after about 12 exposures and reach the largest percent of understanding among pedestrians (i.e., only 62.5%) after 16 exposures and found pedestrians are overwhelmed by the presence of multiple HAVs with light bars in their vicinity (Rossi-Alvarez et al., 2021). The superiority of well-designed picture-based communication signals relative to light patterns has been replicated elsewhere (Zang et al., 2022).

Participants appear to prefer direct commands or advice from the automated vehicle (e.g., walk, go ahead), as opposed to communications of vehicle status (e.g., stopped) (Ackermann et al., 2019). Egocentric messages (written from pedestrian's perspective) from eHMIs (walk, go ahead, walking silhouette, stop sign) are more effective and less ambiguous than allocentric messages (written from another perspective) (e.g., after you, braking now, car giving way icon) (Eisma et al., 2021). Pedestrians do not particularly want information about an automated vehicle's "perception" of what is happening but benefit from knowing the status of the vehicle and what it intends to do (Faas et al., 2020), particularly vehicle intent (Forke et al., 2021). Systems that provide early anticipatory messages (e.g., will stop) promote earlier crossings by participants, but a significant minority of participants tend to rely on or over-trust the eHMI (irrespective of message timing), leading to disregarding vehicle motion cues when the automation fails (Kaleefathullah et al., 2020). Interestingly, the use of commonly known or familiar signals for yielding such as flashing headlights as an eHMI are better understood and considered during crossing decisions by pedestrians during low approaching speeds as opposed to more novel signaling systems (light band) that require more learning time (Lee et al., 2022).

1.1.8 Conclusions

The literature review helped to capture several important findings, issues, and potential solutions for the advancement of low-speed autonomous vehicles. In summary, the key findings of this review are:

- There are clear safety opportunities with low-speed automated shuttles.
- Environmental and infrastructure factors can increase crash risks.
- Deployments of LSAVs may need to focus on intersection and queuing factors to understand risks and risk mitigation solutions.
- Pedestrians may be at greater risk near public transportation hubs due to changes in driver behavior and changes in their own behavior in these environments.
- The interaction between AVs and other road users may be strained due to aggression, misattribution, low trust, and poor communication.
- eHMI are in the early stages of design and public understanding. Leveraging text or signaling that is already in use in manual interactions between road users (e.g., headlights flashing) may be superior to the creation of novel lighting configurations, which suffer from shallow learning curves.

Chapter 2: Interviews

2.1 Semi-Structured Interviews

2.1.1 Objectives

Based on the knowledge of literature, a semi-structured interview was developed to explore any safety considerations toward the current AV technologies from automated vehicle manufacturers. This present qualitative research focused on gaining an in-depth understanding of how these manufacturers and operators approach safety with a multi-model lens during their design, development, and operation of the level 4 automated vehicles, such as the MCM. The main goal was to explore the real-world experiences and challenges when the MCM interacts with other motor vehicles and non-motorists (e.g., bikes, pedestrians) on the road, and vice versa.

2.1.2 Study Design and Interview Team

In this study, the research team conducted five one-to-one interviews with representatives from three engaging AV manufacturers (i.e., EasyMile, May Mobility, and Navya) and one transportation service company (i.e., First Transit), through asking them open-ended questions in a virtual Zoom meeting setting. The composition of the research team for this task typically involved two to three researchers, including at least one lead interviewer with a Ph.D. in behavioral science and a facilitator who provides technical support and assists with taking field notes during the interview.

2.1.3 Study Sample

A total of six representatives, including four males and two females, participated in the AV manufacturer (n = 4) and operator (n = 2) interviews, respectively. For the vendor interviews, most respondents had a project management role in the company or service in the business development division, and therefore, they may have had limited technical knowledge of the AVs. In particular, the two representatives from Vendor #1 indicated an engineering background, one of whom also demonstrated direct working experience with the MCM in Minnesota. Table 3.1 provides detailed information on the job titles for each vendor representative.

The operator interviews involve two participants, both males. Operator #1 is a chief operator who also serves as a project manager for various autonomous vehicle projects across the country. His primary responsibilities consist of overseeing day-to-day maintenance and overall project logistics, operator hiring and training, and filling in as an operator as needed. Operator #2 is a deployment specialist who helps manage the AV operation and has been serving as an operator since 2018. The operating location of the AVs was different for Operator #1 (i.e., primarily in the state of Minnesota) and Operator #2 (i.e., in the state of Virginia).

2.1.4 Data Collection

Data collection period ranged from May 2nd to June 13th, 2022. Response data were collected through audio recordings and meeting transcripts upon the interviewees' consent. The interview session started with each participant completing several general introduction questions on their role and job descriptions in the company, followed by questions on their opinions and experiences pertinent to various safety aspects of the MCM and its relation to all other roadway users. Each interview session took approximately 1 hour for the company representative to complete. Due to the limited sample size, repeat interviews were performed with one MCM operator over 2 hours, split into two sessions. All questions were pre-approved by the MnDOT research technical committee and engaging companies, which can be found in Appendices A and B for the manufacturer and operator, respectively.

After the study, participants' quotations were reviewed, re-coded, and classified into multiple pre-identified topic areas. The following provides a qualitative synthesis of the key findings and takeaway messages from the semi-structured interviews for the AV manufacturers and the operator:

2.1.4.1 Automated Vehicle Manufacturer/Vendor Interviews

INTRODUCTION QUESTIONS

1. Why is your company interested in advancing CAV technology and what specific value(s) are you trying to provide?

All three vendors indicated bridging the gap in the first/last mile of transportation as a core value that drives their company to advance CAV technologies, particularly emphasizing the increase in mobility among those disadvantaged populations in communities. Two vendors highlighted the rapid growth of electric vehicles in the automobile industry and how the concept of sustainable power was intertwined with autonomous vehicle advancements. One vendor also suggested other potential benefits of advancing the levels of vehicle autonomy in the long term, such as alleviating driver shortages and preventing traffic incidents. More details can be found in Table 2.1 below.

Table 2.1 Summary table of the interviewees' information, role, and company's values in advancing CAV technologies

	Representative(s) Information	Company's Values and Interests in Advancing CAV Technologies
Vendor #1	<u># of Representative(s):</u> 2 representatives, both males <u>Role/Title:</u> 1) Managing Director of the company. 2) Program Manager with technical/engineering background and experience working with MnDOT.	Recognition of the massive gap in the "first and last mile" regarding transportation Higher priority level placed with AV due to considerations of avoiding crashes and injuries Autonomous transportation is of specific interest due to the scalability, especially regarding driver shortages Promote electric vehicles powered by sustainable resources

Vendor #2	<u># of Representative(s):</u> 1 representative, female <u>Role/Title:</u> Role of business development and project management	Primary focus is on first mile and last mile transportation, providing solutions to end-audience for communities and events Provide mobility to areas/groups where current mobility is either non-existent or not enough, e.g., airports, college campuses, and work campuses. One example user case is using the shuttles in the field among senior people at the Detroit medical center. Continuing interests in autonomous and/or electric vehicles
Vendor #3	<u># of Representative(s):</u> 1 representative, female <u>Role/Title:</u> Director of Business Development during the past 2 years	Primary goal is the aid in moving people with autonomous technology through systems that are already in place Another focus is on micro transit areas where there is a large population that need help with the first and last mile transit Big focus on multi-modal connections

SAFETY QUESTIONS

1. How do you prioritize your safety focus? Is the first focus to avoid a crash? What kinds of crashes are you focused on avoiding?

Overall, all vendor representatives highlighted safety as their "number one priority," yet their standpoints were slightly different when describing how "safety" could be supported in several ways.

- Vendor #1 representative (i.e., with technical experiences) suggested that their primary safety focus was to avoid all crashes, especially those involving pedestrians. They also commented that *"...cars trailing behind and causing an emergency brake could create a [rear-end] collision*". A second prioritized safety focus area was the route decision, also viewed as "*a key aspect to minimize any safety risks*".
- Vendor #2 representative (i.e., project manager) addressed "safety" from three focus areas--designing and developing a safer vehicle, conducting safe testing at each site, and providing safety training to operators before deployment. Specifically, vehicle safety engineering encompasses "*constructing vehicles [hardware] from the ground up*", as well as "*setting priority zones around the vehicle*" through complicated software systems.
- Vendor #3 representative (i.e., role in business development) suggested the company's main priorities were in the order of safety, rider experience, and autonomy. Selected quotations included *"…focus on commercializing AVs in a way that is community-minded…*", *"… [more education on] being a generally good road citizen…*", and *"No particular crash is of primary concern*".

It is essential to note the differences in participants' roles and technical backgrounds, potentially leading to variability of the priority placements in other focus areas besides safety.

2. What do you think are the greatest challenges for approaching safety between AVs and drivers of manually driven vehicles?

Most reported challenges by vendors focused on public understanding and behaviors of other manually driven vehicles around the shuttle. Selected quotations are

- "*Education of the general public is the primary challenge*" – Vendor #1
- "*The biggest obstacle is the difficulty in predicting when other drivers act abnormal or outside of the law, especially if a hard brake reaction is required*" – Vendor #2
- *"… [Challenges of] not only understanding what the public expects of vehicles but also what to expect from other drivers may do*". – Vendor #3

Another challenge raised by vendors related to the differences between the behavior of autonomous vehicles and drivers of manually driven vehicles

- There is a "*general disconnect between how the shuttle acts and how people would generally react*" – Vendor #1
- First, there are "*general differences between how AVs drive and individuals will drive*", such as low-speed and hard brake tendencies. – Vendor #3

Since the vehicle was not programmed to deviate from the prescribed lane or overtake any cars or bikes from behind, it may also be challenging for other road users to accurately interpret the intention of the shuttle under specific driving scenarios. When encountering an intersection, the shuttle does not make a right on red either, which could sometimes create a much longer queuing time than generally expected by following vehicles or pedestrians. Furthermore, "people not knowing how their decisions will affect how the shuttle will react (Vendor #1)" could also contribute to this disconnection.

3. Is there a dedicated traffic safety analysis conducted by the engineering team? If so, could you outline some traffic safety aspects analyzed?

All three vendors indicated the availability of a dedicated traffic safety analysis conducted by their engineering team before the AV deployment. Representatives from Vendor #1 suggested that "*a majority of traffic safety analysis is focused [on] route selection*" and provided examples of factors for determining if a route is optimized for automation. These factors include but are not limited to the quality of satellite connection, road conditions (e.g., slope, upkeep), nearby structures within each road segment, and intersection configurations if an intersection is on the route (e.g., signal phase time, speed), etc.

In addition, the representative from Vendor #2 outlined the responsibilities of the research and development team regarding traffic safety analysis, including:

1. Initial traffic and speed assessments for the deployment areas,
2. Review the route from the safety and practical standpoints, including traffic and pedestrian patterns and road state,
3. A thorough road mapping, and
4. In-depth analyses of the vehicle "bubbles'' and any algorithm development for the system.

Similarly, as suggested by Vendor #3, the engineering team also conducted in-person inspections of the deployment areas after scouting a new route. The purpose was to search for anything that may interfere with the autonomy system, review traffic, ego maneuvers, or other factors.

4. What role does technology play in safety? Similarly, what role do the aboard operators play in safety? Do you foresee either of these relationships changing in the future? If so, how?

From the vendors' perspective, the onboard operators currently serve as a "public ambassador" role, providing knowledge to passengers regarding what the shuttle may be doing and answering their questions. They are also the primary person concerning safety and are recommended to take manual control of the shuttle as needed. Moreover, the operators may also be responsible for logging any experiences or risky events during their day-to-day operations.

In the long term, this role is anticipated to transition slowly and smoothly away from the "operator" role to a more "remote" role (e.g., off-site "communicator" or "concierge"), until eventually eliminated. While vendors share a common faith in AVs' fully "driverless" state in the future, they also foresee the transition as a slow and gradual process. Representatives from Vendor #1 suggested two requirements for achieving this goal step-by-step, through advancing technologies in:

1. *"[Increasing] safety and reliability of other systems that the shuttle system will interact with*"
2. "*Decreas[ing] in the number of interventions required via the onboard operator*".

5. What qualifications are required for operators to have? What additional training is provided?

To the vendor's knowledge, there was not yet a standard for the autonomous vehicle operators (AVOs) qualifications. Some general requirements include the minimum age of 21 and those with valid driver's licenses. No formal engineering degree is required, though it is desirable if the operator is "tech-forward". The training program (duration varies) could potentially be delivered through in-classroom courses, mock training modules, and real-world driving/operation pieces of training. The operator should learn about how to interact with customers and demonstrate an understanding of the general technologies present in the vehicle. Some essential knowledge includes how the autonomy system makes decisions, what to look out for through mock scenarios (i.e., situation awareness), and how to monitor and troubleshoot system issues. The operation training portion could include "shadowing" and "shadowed" driving practices. Because the AV operation was conducted through a controller, one representative commented, "*that having video game experience usually leads to quicker training*". Those who lack constant focus regarding safety interventions or have difficulties using the controller in physical operation will be in denial of becoming an operator.

MULTIMODAL SAFETY QUESTIONS

1. Is the safety approach you take multi-modal in regard to safety of operations for various populations including passengers, roadway users in cars, bicyclists, and pedestrians? How do you evaluate your safety performance, specifically from a multi-modal lens?

All the vendors responded "Yes" when asked if the safety approach they took was multimodal concerning the safety of operations for various populations, including passengers, roadway users in cars, bicyclists, and pedestrians. Like previous responses, the vendors generally commented that the multimodal safety approach was viewed as part of the route selection (e.g., test algorithm with different user cases, including areas with bike facilities).

2. How do you approach safety with other vulnerable road users, specifically bikes, peds, and scooters?

Technologically, the shuttle was built with two "safety bubbles" –the "first bubble" has a longer radius with the algorithm taking into account the shuttle's speed, distance to objects, and other factors. Another "emergency bubble" was used to trigger emergency stopping scenarios when an object was detected within the bubble at a small radius around the shuttle. However, the algorithm system in place has limited ability to differentiate between objects within the safety bubble, whether a car or a pedestrian. Above all, the primary strategy to avoid collisions is to allow the "Vehicle [i.e., Shuttle] to adapt its speed," along with careful considerations of deployment locations, routes, and local regulations.

3. What do you think are the greatest challenges for approaching safety between AVs and pedestrians?

The discussion regarding the challenges between AVs and pedestrians were like those noted regarding drivers of other manual vehicles:

- "*The biggest difficulty will be predicting pedestrian behavior* ". – Vendor #1
- Advancing "*classification of agents*" technologies for "*differentiating between bikes, wheelchairs, and pedestrians [more accurately and reliably] is an expensive, difficult, and time-consuming process, but could be beneficial for predicting movements*". -Vendor #3

As suggested by Vendor #2, the current focus is more heavily reliant on raising the "awareness" among pedestrians and enhancing communications between the shuttle and pedestrians or other drivers. Strategies have been recommended to promote safer roadway infrastructure (e.g., lighted signs, clearly marked pedestrian crossings) and reduce pedestrian distractions (e.g., on the phone).

Another two practical issues brought out by the vendors regarding the interaction between AVs and pedestrians focus on pedestrian "comfort" and "intention of waiting vs. crossing." An example during the early deployment of MCM in Minnesota was described, of which vendors received feedback from local pedestrians indicating that "*they were not comfortable for the shuttle to stop exactly at the white line*." As a result, the current stopping distance has been moved back to 4 ft. away from the white line to help improve the pedestrian experience (Vendor #1). Importantly, one major technical challenge is "…*it can be difficult to differentiate between waiting and crossing pedestrians based on the pedestrians' location in the crosswalk* (Vendor #3)". Such an issue of correctly interpreting pedestrians' waiting versus crossing intentions and making timely decisions may apply not only to autonomous vehicles but also to drivers of other manually driven vehicles.

4. What has been your approach to date to reduce the risks of multiple threat passes involving your vehicles, drivers of manually driven vehicles, and crossing pedestrians?

To address this question, most of the vendors emphasized that multiple threat passes would be an issue with any vehicle and not just specific to the autonomous vehicles. Vendor #2 was unaware of how much effort had been put into this issue and Vendor #3 reported that less focus had been placed on this scenario as it was not a case that they experienced a lot. Notable points were raised in the discussion:

- It is perceived that "*speed could be a heavy factor regarding this issue*" and *"[this issue] might not be as much of a concern for vehicles traveling at a higher speed."* - Vendor #3
- There are recommendations for "*[providing] sufficient road signage along the route and at intersections may help to minimize this from occurring*" and "…*operators taking over control if they feel the vehicle is not traveling at an appropriate speed*." Vendor #3
- *"The technology is programmed based on assumptions that people (pedestrians and drivers) will act as intended/required by law*" and "…*that they cannot control other drivers/pedestrians when they are not in accordance with expectations/the law*." – Vendor #1

Notably, a tuned strategy recommended by Vendor #3 to reduce the risk of multiple threat crashes is to have the AVs slowly initiate the right-turning maneuvers (i.e., creeping forward and "claiming the intersection"), and yielding to pedestrians like a regular vehicle will act while making right turns at an intersection.

5. What design changes or technological advancements do you think are necessary to address these challenges?

First and foremost, a combination of technological advancements in hardware and algorithms appeared to be a primary source of improvement to address the present challenges, such as sensors with a more extended detection range, algorithm training and object-specific logic, thermal cameras, etc. Advancing technologies is also important in developing better communication systems between the shuttles and infrastructure or even other vehicles. Again, efforts need to be taken to improve the clarity of signage, particularly pedestrian crossings in the overall roadway system (Vendor #2).

Vendor #3 did not perceive they have as many recognition issues regarding their multimodal safety approach. Even if presented with these challenges, adding technologies such as thermal cameras to the next generation's products can be beneficial for differentiating cyclists and pedestrians from static objects and aid in recognizing the steam and exhaust [from people] challenges that can confuse the current LiDAR.

6. Any other ideas you have for changing the design, markings, feedback of the shuttle to make everyone else safer?

Several safety strategies have been in place to help make everyone else safer on the road. First, the shuttle was manufactured to follow specific physical recommendations, including taping cation messages along with the shuttle's window. The design aimed to improve the transparency of the shuttle's functions conveyed to drivers and other vulnerable road users, which typically consists of texts denoting the vehicle is autonomous and may make sudden stops. Vendor #1 also reported having experience working with a special pedestrian population, such as designing for blind people or people with wheelchairs. Regarding passenger accessibility, it is also essential to ensure full ADA compliance for the shuttle to accommodate as many passengers as possible (Vendor #2). Specifically, Vendor #3 commented that one primary autonomous vehicle focus of the company had been shifted to ridesharing and improving shared rider experiences through the deployment of average-sized vehicles. While the current vehicle deployments have been set to operate at 25 mph at most sites, the goal is to reach an operating speed at or very near to the speed limit for every road route (Vendor #3).

DISCUSSION ON AUTOMATED VEHICLE MANUFACTURER INTERVIEWS

The results from automated vehicle manufacturer interviews helped identify the essential components of various safety approaches the vendors took during their design, development, and operation of AVs, particularly regarding diverse populations, including passengers, roadway users in cars, bicyclists, and pedestrians. To summarize, the key takeaway messages of the interviews were discussed below:

Values and interests

- Addressing the "First and Last Mile" issue of transportation represented a primary and shared value/interest of AV manufacturers to make continuous efforts to advance AV technologies.
- Some perspectives on the company's current stage of the safety technology development, benchmarking, and technology limitations may be varied depending on the representative's role; however, their perceptions of safety were complementary to each other in general.
- Other focus areas include improving rider experience and transferring the autonomous focus to the vehicle sharing focus.

Multimodal safety approach and challenges

- “Disconnections between the expected and actual behaviors [interpreted toward or by the AVs]” represented the most significant challenge faced by vendors in their safety approach toward the interactions between AVs and other vehicles or pedestrians.
- Promoting public awareness and community education has been consistently emphasized by all AV manufacturers.
- Other factors that could have contributed to these disconnections may include specific automated vehicle design (e.g., low speed, vehicle size, markings, or labels of autonomy), roadway environment (e.g., insufficient signage or pedestrian cross markings), lack of effective communications, and others.

Potential knowledge gaps

- While a traffic safety analysis was in place before the deployment of AVs, the primary focus of this analysis is typically on route selection. For some vendors, the knowledge gap persists regarding public expectations of the automated vehicle and real-world driver or pedestrian behaviors around the AVs.
- Recommending incorporating human factors research/analysis into the cycle of design, development, training, and operation to help identify these behavioral issues (e.g., multiple threat passes), associated risk factors, and develop intervention strategies.
- The present research project may also help inform vendors of similarities or differences in public perceptions toward AVs among local and non-local road users. For example, extra confusion may be expected among those new to the area or unaware of the shuttle's autonomous nature.

2.1.4.2 Automated Vehicle Operator Interviews

GENERAL JOB-RELATED QUESTIONS AND TRAINING

1. Can you walk me through what your job looks like [as an operator]?

Operator #1 and Operator #2 described a similar routine involving tasks performed before, during, and after the vehicle's day-to-day operations:

- *Pre-trip inspection:* Upon arrival at work, an operator is responsible for completing a pre-trip checklist, including general vehicle inspections (e.g., new scratches, tire pressure) and various system checks (e.g., GPS, localization, communication).
- *Test on routes:* As suggested by Operator #1, their shuttle typically started with a separately programmed test route by "*autonomously driving from the garage, via the parking lot, to a set-up location (i.e., "test kitchen").*" Prior to picking up passengers, the operator also needs to verify the vehicle's proper functionality through a "deadheading" operation via thorough navigation of any obstacles along the route and identify any connection issues (e.g., cellular, radar, etc.). Similar tests were also reported by Operator #2.
- *On-board operations:* The operator's duties also include "*advertising to passengers (Operator #2)*" and *"[documenting] on the overall laps completed, passenger counts and any noteworthy occurrences such as emergency brakes (Operator #1).*"
- *Post-trip report:* Finally, the final task was to fill out an end-of-day report (including emergency logs) and plug the shuttle into the charging station.

2. What is the most challenging part of your job?

Operator #1 perceived the most challenging part of his job was troubleshooting issues, "*particularly those that required a level of maintenance that is difficult to complete remotely*" or "*require engineers to come on-site*". Another challenge regarding the hiring role of Operator #1 was to recruit operators with the necessary skills (after training) for a given project and retain them throughout the entire project duration, i.e., usually a short, fixed period.

Operator #2 raised that a major challenge of the job was to keep "*being aware of everything happening around the shuttle, whether it is in the same lane as the shuttle, or in other lanes*." Equally important was to "*look forward to any potential issues or obstacles, such as checking for cyclists when crossing a bike lane*."

3. Can you describe your training? Specifically, what training did you receive about how to interact with pedestrians? What qualifications do you think operators should have? What additional training should be provided, if any?

Each operator reported completing an internal training program provided by their transportation service company. Operator #1 provided the steps of their three-week training program:

- Finish a course training with relevant learning materials on safety, operations, standard paperwork, compliance videos, etc.
- Complete vehicle-specific and site-specific training in the context of the general project.

- Practice manual operation of the vehicles, followed by skill tests on drivers' abilities, including parallel parking, correct braking or acceleration, and other driving performance metrics.
- Perform autonomous operation of the vehicle and receive route training in the field, along with another instructor or senior operator on board to supervise.
- Complete a final safety test and a series of other tests relevant to the project, vehicle function, manual and autonomous driving, etc.

Similarly, Operator #2 described training on knowledge and shadowing operation as the two main components of the program, which lasted for two weeks. In addition, they could also receive extra training from the corresponding automated vehicle manufacturer to become an instructor. Notably, Operator #2 highlighted that a specific portion of the training was regarding how to interact with annoyed or upset drivers of other vehicles, including scenarios where other drivers overtake the AV when the AV yields to pedestrians (Detailed strategies are discussed later in the multimodal safety section).

Due to his additional role in hiring, Operator #1 was asked to provide opinions on the qualifications of an operator. The response includes general qualification requirements such as drivers over 21 years old and with a clean driving record. Based on the type of vehicles to operate, a commercial driver's license may be required. Operator #1 also indicated that desired qualities include being flexible to new and changing technology and demonstrating interpersonal skills in communicating with customers. When a remote-controlled unit was used for operating the vehicle, finger dexterity could be an additional requirement for selected project hiring, as well as familiarity with video game controllers.

4. What things that happen on the road are you keeping an eye out for while the shuttle is in operation?

Operator #1 reported there were not any scenarios where they felt the need to take over control of the vehicle consistently. They also mentioned construction and parked delivery trucks as the only scenarios where the operator's intervention may be needed. Operator #2 suggested that while there was *"90% focus on the front of the vehicle"*, it was important to keep an eye out for the two rear blind spots, particularly when the vehicle was changing lanes or pulling over. Another thing was to be aware of when drivers of other cars were behind the shuttle, using extra caution if they were tailgating or showing an intent to pass. Below quotations reflected the operators' levels of trust in the AVs:

- *"I trust them [i.e., the automated technology] more than I trust myself with these vehicles"* – Operator #1
- "*So, the thing about this safety that the vehicle is contributing to…we're almost guaranteed to never hit anything with the vehicle and its reaction is very quick. I believe it's about 30 times faster than our reaction time.*" –Operator #2

5. What things most frequently require you to manually take over operation from the shuttle? Can you describe an example that happened recently? Or engage the emergency brake? How do you diagnose the problem? What do you do to resolve or fix the problem?

Similar to Operator #1's response to the previous question, Operator #2 also reported the majority of disengagements occurred around double-parked cars/trucks (e.g., an Amazon delivery truck). Another common scenario was road construction, or maintenance sites, where people cut grass or blow debris off the sidewalk with a blower.

- "*…if we know that they're working on a sidewalk or something…we keep having to disengage around them every time, and we know they're going to be there all day.*" – Operator #2

When asked about their engagement with the emergency brake, both operators indicated this was rarely "manually triggered or pressed" over their more than five years of experience. Operator # 2 shared that the only time they initiated an emergency stop was when they were still in training and operating on a site in the southeast, where there was a lot of ongoing development around the route and new traffic patterns. The reason was to "[avoid conflict with] someone coming quickly onto a one-way road," "when the vehicle was initiating the turn to be on that road and was about to drive down the road backward". They reflected, "I probably could have used the soft stop if I was more experienced". However, "they always told new operators not to be hesitant if you think there is an emergency, and they'd rather air on this on the side of safety as a new operator".

The more commonly adopted maneuvers are “soft stops”, which can be triggered through a small touch screen on the shuttle (Operator #1) and enable manual “stops” at a comfortable pace (Operator #2). The more commonly adopted maneuvers are “soft stops”, which can be triggered through a small touch screen on the shuttle (Operator #1) and enable manual “stops” at a comfortable pace (Operator #2). “Ultimately we don't want to be driving in manual mode [as] it's much slower than autonomous [driving]…it’s 3 miles an hour compared to the 13 [mph].” – Operator #2

6. What role does technology play in safety? Similarly, what role do the onboard operators play in safety? Do you foresee either of these relationships changing in the future? If so, how?

Operator #1 perceived the role of the on-board operator “is just a backup of the vehicle” and was primarily needed “because of the way other drivers interact with the shuttle”. Selected quotations included:

- *“I would say, even in the technology's current state the onboard ambassador or the operator is **nearly obsolete**… [If the] vehicle is in a closed circuit, you wouldn't need an operator at all, especially if state law allowed it…”*
- *“But in a mixed traffic [situation] […] The operator is needed because of the way other drivers interact with the shuttle, this is a slow speed shuttle… **They pull in front of the shuttle and they cut it off**…When someone cuts off the shuttle and gets within the anti-collision zone or safety zone around the shuttle, then they cause it to do a slowdown or an emergency stop.”*

Operator #1 expected in the future, "we may not need an operator on the shuttle pending state laws". They provided three comments regarding future changes or removal of the operator’s role, including:

- *"...**increasing the speed of these shuttles**…we go about 12 mph on the route [with a speed limit of] 25 mph, and other drivers [sometimes] break the law and go 40 mph". "If the vehicle would perform, at 20 mph or 25 miles an hour at the speed limit, I think we would have less frustration* *and better interactions from other drivers and road users, and they would be less likely to cut us off."*

- "*More autonomous features in regular personal vehicles such as [the] latest backup cameras in adaptive cruise control*" could aid this process. *"I guess the integration of more autonomy and acceptance of that as well in other vehicles would probably be the last thing to get rid of the need for an operator on one of these shuttles."*
- *"Maybe in 5-10 years, but it depends, I guess, on how quickly* ***society adapts to autonomy*** *in their own personal life."*

Operator #2 commented that the operator primarily contributes to the situation that requires "*predictive conclusions*." In contrast, the removal of operators on board would affect safety given the significant role that the operator has in communicating with other drivers, "*directing traffic and pedestrians*," and "*losing the interactions with the onboard passenger*."

7. What areas do you see that need to be improved for the shuttle?

Some notable points were raised by the operators regarding the shuttle's safety performance:

- "*I don't think there's anything else needed. The vehicle, in my opinion, is completely safe…this company that we're working with […] they have never hit anything since 2014.*" – Operator #1
- "The safety aspects of the vehicle [are] definitely proven…I'd be very surprised if the vehicle ever ran into somebody. Usually, the scenario that happens with the vehicle, if it was to happen, would be somebody running into us." – Operator #2

Additional recommendations for areas to be improved included providing extra levels of localization (e.g., sonar, radar, etc.), redundant systems to improve the overall monitoring, and other more complex technologies to be developed (Operator #1). In addition, "If there's too much rain around the vehicle, it may see it as obstacles and it won't be able to drive autonomously" (Operator #2).

MULTIMODAL SAFETY QUESTIONS

Interacting with drivers of other vehicles

Operator #1 broke down the frustrations they tend to have with other drivers that were:

- *"25% the speed of the vehicle;"*
- *"25% that it is a driverless vehicle because you know people are maybe a little unsure about it, or they don't like the technology."*
- *"I would say 50% of it is just other people's driving habits, whether they're not paying attention, or they're in a hurry."*

  "We often have an instance where we'll be driving down […]. It's a two-lane road where cars will pull up from behind us, get into the left-hand lane, and then pull right in front of us in the right-hand lane, and cut us off and turn to stay to try to get ahead of us, which is interesting because we don't make that turn, anyway."

"I'm sure you've seen this in your personal experience on the road. [These drivers] feel sensitive urgency to get ahead of a slide moving their vehicle at the risk of potentially hitting a pedestrian in the crosswalk." "[Such a scenario] occurs multiple times a day, anywhere from 5 to 20 times a day...less frequent was when there may be a serious risk." – All adapted from Operator #1 quotations

Interacting with bicyclists

Operator #2 detailed the importance of knowing everything that is happening around them and the difficulty of the task because "*the majority of the time, you want to be looking forward to see if there's any potential incident that could happen in front of you*." They provided an example of this:

> *"When a vehicle is approaching a station, sometimes it'll have to travel over a bike lane. That can be difficult to remember exactly where the vehicle crosses the bike lane and then look behind you to ensure there are no higher-speed cyclists or bikes with motors or electric scooters. The vehicle is not going to slam on its brakes for somebody behind it, and typically, when we're pulling over, we're going fairly slowly. So, it's the operator's job to do that predictive analysis and say this cyclist will hit me if I go over his bike path because he's going pretty quickly."*

Interacting with pedestrians

Interacting with pedestrians was discussed by Operator #2 as something that can create uncertainty in their decision making. They describe the problem in this way:

> *"The majority of the time you're using a soft stop because pedestrians at a mid-block crosswalk… [by the state law] if somebody is standing by a crosswalk waiting to cross, then you have to yield to them so that's something that the system cannot detect. When a pedestrian is waiting, is it just there on the side of the road, or is it waiting to cross? We [have to] leave that determination up to the operator. The vehicle was programmed to reduce its speed slightly when it's about to cross the mid-block crosswalk, giving the operator a chance to press the soft stop button. Because most of the time, there's nobody there, and the vehicle will continue to go through."*

Strategies for addressing multimodal safety issues

Notably, In the AV deployments in Virginia, the operators used several strategies to help interact with other road users, including:

- Post stickers on the back of the vehicle indicating the vehicle's operation and stopping likelihood, e.g., text messages of "CAUTION AUTOMATED VEHICLE MAPPING IN PROGRESS PLEASE KEEP CLEAR" and "SLOW VEHICLE".
- Promoting public notice or AV awareness through installing signage along the route, e.g., text messages of "CAUTION LOW SPEED AUTONOMOUS VEHICLE" and pedestrian placard
- Providing Autonomous vehicle road markings, e.g., pictures and labels
- Perform a slow "creeping" turn when pedestrians are present at a signalized turn location, to limit opportunities to overtake by other drivers.

- Trained to give hand gestures to others as a form of communication, e.g., anecdotally, this seemed to reduce the aggressiveness and anger when other drivers overtook the AV.

DISCUSSION ON AUTOMATED VEHICLE OPERATOR INTERVIEWS

In summary, the key findings of the automated vehicle operator interviews were:

- Both operators had a similar routine, similar training experiences, and high level of trust in AVs.
- Compared to some manufacturers, the operators appeared to have a better knowledge of the multimodal safety challenges around the AVs in their day-to-day operation experiences. However, they generally accepted that it's their role to predict other road users' behaviors, interact with them, and make decisions at the current stage of technology development.
- Similar to the manufacturers, the operators also suggested increasing the vehicle speed and enhancing public awareness were two potential solutions for addressing these challenges.
- The operator revealed an "overtaking" issue, which has also helped guide the study design for other ongoing research regarding pedestrian safety in the current project.

The effectiveness of the "hand-gesture" strategy in reducing the frequency of aggressive behaviors around the AVs might warrant additional investigations. However, the general differences in public AV awareness/acceptance and pedestrian safety culture in the two states (Minnesota and Virginia) may also affect how other road users respond to this strategy or AVs in general.

Chapter 3: Field Study

3.1 Field Study Methodology

The overall study aimed to assess the impact of LSAVs, in this case the Med City Mover (MCM), on both driver behavior and pedestrian safety through a multi-faceted approach. The field data collection study fits within the overall study methodology which included a series of driving simulation components and eHMI recommendations, see Figure 3.1.

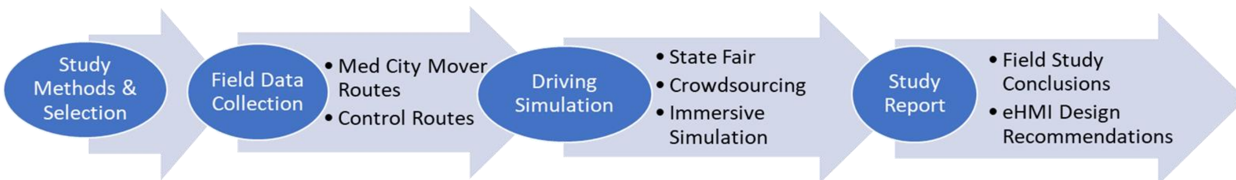


Figure 3.1 Overall study methodology and progression

Driver behavior and driver-pedestrian interactions within the downtown Rochester area was observed and recorded through a series of staged and natural crossings at signalized and unsignalized sites. Selected sites were analyzed so that driver behavior in the proximity of the MCM could be compared to driver behavior on the route of the MCM and to nearby similar areas off the MCM route. Key areas of focus for this data collection and analysis were driver overtaking rates of other vehicles, particularly the MCM, and other dangerous scenarios that put the MCM and any nearby pedestrians at risk.

The results of the field study were used to inform the subsequent driving simulation studies to help understand the key contributing factors that influence driver risk taking near the MCM and any potential design changes to the MCM's operations or eHMI which may reduce these risks.

3.1.1 Site Selection

In total, four intersection types were identified for analysis which included signalized and unsignalized sites along the MCM route, as well as signalized and unsignalized sites near the MCM route. Data collected at these sites allowed the research team to draw conclusions about the relative risks of risky driving behaviors near the MCM compared to other manually driven vehicles, both with and without the presence of pedestrians, on and off the route.

It was important for the on-route and off-route sites to be as similar as possible to reduce potential confounding variables influencing driver behavior such as posted speed limits, number of lanes, average daily traffic, and pedestrian volumes. Signalized and unsignalized sites along the MCM route were selected from the limited intersections available and feasible. The off-route sites were as similar as possible to the selected on-route site in terms of the previously listed potential confounding variables. Selected sites are described below and depicted in Figure 3.2.

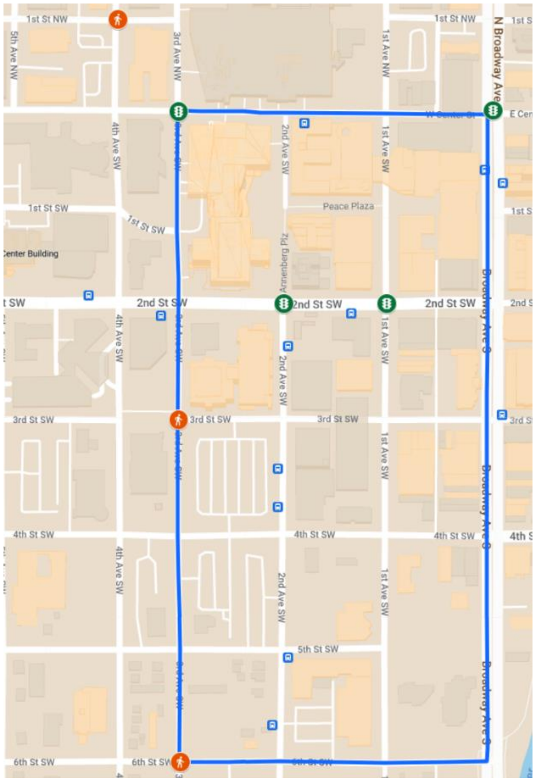


Figure 3.2 Selected signalized (green traffic light) and unsignalized sites (orange pedestrian) along the Med City Mover Route (blue line) and off the route

3.1.1.1 Signalized Sites

The MCM made four right turns along its route, three of which were signalized intersections. Two signalized intersections, *3rd Ave SW & W Center St* and *W Center St & Broadway Ave S*, on the MCM route were selected for data collection due to their relatively high pedestrian volumes and overtaking opportunity, see Table 3.1. Two comparable nearby signalized intersections, *2nd St SW & 1st Ave SW* and *2nd St SW & 1st Ave SW,* were selected as the off-route locations given they were expected to experience comparable turning behaviors, because the two sites have a shoulder that could be used as an unofficial turn lane, and drivers at these sites were expected to frequently encounter buses on the right shoulder, which would have required yielding to crossing pedestrians. The 1st Ave location was the primary data collection site and the 2nd Ave location was used as an alternative site when the 1st Ave location was closed during the "Thursdays Downtown" festival which occurred during the study period.

Table 3.1 Signalized study sites, locations, and route alignment

Intersection	On MCM Route?	Major Road		Minor Road	
		Location	Layout	Location	Layout
3rd Ave SW & W Center St	Yes	3rd Ave SW	3L + 1T/BL*	W Center St	2L + 1T
W Center St & Broadway Ave S	Yes	W Center St	2L + 1T	Broadway Ave S	4L + 1T
2nd St SW & 1st Ave SW	No	2nd St SW	4L	1st Ave SW	2L
2nd St SW & 2nd Ave SW	No	2nd St SW	4L	2nd Ave SW	2L

Note. L = Lanes, T = Turn Lane Only, * = One Way, and / denotes shared lane type for a single lane.

3.1.1.2 Unsignalized Sites

MCM route contained two thru-STOP unsignalized, marked crosswalks; however, due to construction on 6th Ave, the team was only able to collect driver behavior at one site, *3rd Ave SW & 3rd St SW.* An unsignalized intersection was selected, *6th St SW & 3rd Ave SW*, in which the MCM turns from 6th St SW onto 3rd Ave SW. A comparison off-route unsignalized crosswalk at *4th Ave NW & 1st St NW* was selected as the best available crosswalk with similar features to the *3rd Ave SW & 3rd St SW* site, i.e., one-way road, 25 mph, and similar vehicle and pedestrian traffic. See Table 3.2 for unsignalized sites.

Table 3.2 Unsignalized study site, locations, and route alignments

Intersection	On MCM Route?	Major Road		Minor Road	
		Location	Layout	Location	Layout
3rd Ave SW & 3rd St SW	Yes	3rd Ave SW	2L*	3rd St SW	2L*
6th St SW & 3rd Ave SW	Yes	6th St SW	2L + 1T	3rd Ave SW	2L*
4th Ave NW & 1st St NW	No	4th Ave NW	2L*	1st St SW	2L

Note. L = Lanes, T = Turn Lane Only, * = One Way, and / denotes shared lane type for a single lane.

3.1.1.3 Onboard Driver Observations

In addition to collecting observations of driver behavior from a pedestrian perspective, an additional data collection method observed driver behavior from a driver/passenger perspective. For these observations, a staff member recorded driver behavior of other vehicles while acting as a passenger in the vehicle of interest. This data supplemented the limited exposures to the MCM with the other data collection methods when only one shuttle was in operation and helped to increase observations of overtaking on straight road segments and other intersections along the MCM route.

Data collection sessions included observations while the MCM or a researcher vehicle drove the MCM route two times through, i.e., two loops. Driver behavior observations were segmented into four straight roadway segments and four right turn intersection segments. See Table 3.3 for loop segments.

Table 3.3 MCM Loop Segments for Onboard Observations

Segment Type	Segment Location
Straight	*W Center St*
Right Turn	*W Center St & Broadway Ave S*
Straight	*Broadway Ave S*
Right Turn	*6th St SW & Broadway Ave S*
Straight	*6th St SW*
Right Turn	*6th St SW & 3rd Ave SW*
Straight	*3rd Ave SW*
Right Turn	*3rd Ave SW & W Center St*

3.1.2 Data Collection Methodology

Data collection was conducted in a series of two-to-three-person team visits to Rochester, MN. The team would first arrive in the morning and collect data at each of the sites and along the route while driving the researcher vehicle and aboard the MCM. The team would then spend the night in Rochester to complete data collection on the second day at each site and along the route before returning to the Twin Cities at the end of day. These trips to Rochester for data collection were scheduled on a weekly basis which resulted in a total of 14 trips and 27 days of data collection.

Data collection occurred during the MCM hours of operation, between 9:00 AM and 3:00 PM. The coding team coordinated lunch breaks with MCM operators to limit data collection while the MCM was not in operation. The order of data collection across sites was varied to account for time-of-day influences. For example, sites visited in the morning on the first data collection day were visited in the afternoon on the second day. Additionally, the coding team varied the times of day for MCM on-board data collection to sample all hours of operation. Similarly, on-board data collection in the researcher vehicle tended to occur in the morning of the first data collection day, usually between 9:30am and 11:00am, and in the afternoon of the second day, usually between 12:30pm and 3:00pm.

The research team collected all data through a mixed approach of paper notation, through the first five weeks, and digital notation through Qualtrics surveys, through the remaining weeks. Data collected via paper was converted to digital copies on a per crossing/cycle/road basis. The paper-to-electronic data transcribing process was bypassed in later data collection sessions by recording all observations on a tablet computer via a series of Qualtrics surveys.

The city of Rochester hosted the "Thursdays Downtown" festival from June 16th to August 18th, which closed 1st Ave to vehicle traffic and increased pedestrian volumes in the area. Data collection sessions were intentionally set to coincide with the festival to capture increased traffic volumes and vehicle-pedestrian conflicts. The off-route signalized site, *2nd St SW & 1st Ave SW,* could not be measured during these events and the alternative, *2nd St SW & 2nd Ave SW,* location was measured instead.

In addition to the regular events in the downtown Rochester area that altered driver behavior, construction proved to be a limiting factor to data collection and likely influenced driver behavior. During the data collection period, various construction projects were located both along and near the MCM route. The research team continued to collect driver behavior data whenever possible given the constraints due to construction. A summary of the construction throughout the data collection along or near the MCM route is presented in Table 3.4.

Table 3.4 Summary of construction observed throughout the field data collection period

Location	Dates	Impact	Notes/Summary
3rd Ave SW	5/26 - ongoing	Reduced to one lane from 6th St SW to 3rd St SW	Moved halfway through further south of 3rd Ave and 3rd St
6th St SW	~6/1 - ongoing	Initially fully closed to traffic except MCM, later opened to two lanes	
Broadway Ave S	5/26 - ~6/24	Shoulder lane closed from W Center St to 5th St SW	Later moved to eastern side of Broadway Ave
Broadway Ave S	8/14 - ongoing	Shoulder lane closed from W Center St to 2nd St SW	

3.1.2.1 Signalized Intersections

Data collection at signalized sites was conducted using a series of staged and natural pedestrian crossings. The coding protocol specified crossing during the walk cycle to observe right-turning driver behavior, particularly in the presence of pedestrians. Coding teams of two were sent to these sites for data collection, in which one coder recorded driver behavior and the other coder acted as a pedestrian through staged crossings during the walk cycle when natural pedestrians were not present. These staged crossings ensured that there was an opportunity for driver yielding and overtaking to occur. Staged pedestrians followed the safe crossing protocol (see **Appendix C**) and placed themselves several paces from the crosswalk entrance and approached when a right turning vehicle began to initiate their turn. If natural pedestrians were present, the staged pedestrian waited away from the crosswalk so that the natural pedestrian-vehicle interactions could be coded.

Data was collected at each site until 20 walk cycles of the signal could be observed. It was anticipated that three instances involving the MCM could be recorded during the 20 cycles; however, this was based on the expectation that two MCMs would be in operation at once which was ultimately found to be a rare instance and only one MCM was typically in operation during the study.

Data collection at these signalized intersections primarily focused on yielding or stopping for pedestrians and overtaking behavior of right turning drivers. Additional factors that the coding team recorded include the vehicle type (MCM or regular vehicle), number of vehicles in a queue behind a yielding vehicle, the rate at which the queuing vehicles overtake the yielding vehicle, presence of a pedestrian during an overtaking event, and other external factors that may affect yielding and overtaking such as significant traffic backups. Unsafe events by drivers, e.g., turning too quickly or too close to a pedestrian, or by pedestrians, e.g., violating the walk signal, were recorded by the coding team in a general category to capture these infrequent events that did not merit individual data entry classifications. Finally, instances in which the MCM had to be rebooted at the intersection were coded when observed. Figure 3.3 shows the coding sheet used to record all observations at signalized sites. This data collection method was then shifted to an electronic data collection method using iPads and Qualtrics survey software (see **Appendix C**).

Location: Major: ________________ Minor: ___________________
Describe condition: ____________________ Coder ____________
Date: __________ Start Time:__________ Stop Time:______________

Legend:
* - Unsafe driving

Walk Cycle	Turning (No Ped Present)	Far Crosswalk		MCM Queue	Overtake - MCM			OV Queue	Overtake - OV			Left Turn No Yield	Backup Queue	MCM Reboot
		Yield	Not Yield		Turn (No Ped)	Turn (Ped)	Straight		Turn (No Ped)	Turn (Ped)	Straight			

Figure 3.3 Abbreviated view of the signalized site data collection sheet

3.1.2.2 Unsignalized Intersections

Teams of two coders collected driver behavior at the unsignalized intersections through a series of staged crossings, in which one coder acted as a pedestrian (*staged pedestrian*) to cross the crosswalk and the other coder recorded driver behavior. The staged pedestrian followed safe crossing protocol (see **Appendix C**) to ensure their safety. The staged pedestrian would approach the intersection as vehicles were just beyond the “dilemma zone” (i.e., about 141 feet from the crosswalk on flat roads for 30 MPH) to allow adequate time for vehicles to see and respond to pedestrians. Researchers would then place a foot in the street while looking in the direction of the oncoming vehicle, signaling that they were intending to cross the street. Once the oncoming vehicle had yielded or slowed significantly, the researcher would wave in acknowledgement to the driver, ensure all other lanes of traffic were yielding, and completely cross the crosswalk. If no drivers yielded to the pedestrian, they would cross once a safe gap in traffic allowed them to proceed across. A second researcher observing the crossing would code all relevant driver behavior. After 10 staged crossings, the researchers exchanged roles to limit individual exposure. In cases where natural pedestrians were present, the staged pedestrian stepped back to allow the natural driver-pedestrian interaction to be coded. In total, a combination of 20 staged and natural crossings were completed at each site during a data collection session.

Data collection at unsignalized crosswalks focused primarily on driver stopping and overtaking behavior, labeled as multiple threat (MT) passes and attempts, in the presence of a pedestrian at the crosswalk with and without the presence of the MCM. Other dangerous scenarios were also recorded, such as hard braking or billiard braking, i.e., hard braking behind a yielding vehicle, occurrences. The coding sheet used to record all observations at unsignalized sites is shown below in Figure 3.4.

Location: ____

Describe condition: ______________________ Coder #1__________ Coder #2__________

Date: ________________ Start Time:____________ Stop Time:____________

	Staged Crossings	Not Yield	Distance Cars Yielded from Crosswalk		MT Pass	MT Attempt	Hard Brake	Billiard Brake	Queue	Hang Back or Force Yield	MCM
			Less Than 10 ft	Greater Than 10 ft							
Coder 1	1										
	2										
	3										
	4										
	5										
	6										
	7										
	8										
	9										

Figure 3.4 Abbreviated unsignalized site data collection sheet

3.1.2.3 Onboard Data

Onboard data was collected from both the MCM and researcher vehicles that drove along the MCM route. Onboard driver behavior observations from the MCM were collected in tandem with the observations collected at selected sites. A team member collected these observations once per data collection session, in which the team member would ride the MCM shuttle for two full cycles of the route. If a member of the public wished to ride the shuttle during a data collection session and no other seats were available, the team member would depart to allow passengers to ride the shuttle. The team would return and ride the shuttle later in the data collection session to ensure two full loops of driver behavior are observed and recorded per data collection session.

In addition to observing and collecting driver behavior near the MCM along the route, driver behavior was observed from the perspective of a standard human-driven vehicle. For these observations a team member drove their own vehicle along the MCM route, and another team member recorded nearby driver behavior identical to that recorded while riding the shuttle. The driving team member was instructed to drive similar to the MCM regarding lane choice, stopping behavior, and only turning right when the signal is green; however, the researcher vehicle was driven up to the posted speed limit when traffic conditions allowed.

Data collection focused on driver queuing and overtaking behavior of other drivers around the researcher vehicle, highlighting when it occurred in the presence of a pedestrian or while turning. Additional factors that the coding team recorded include the frequency and number of vehicles in a queue behind the yielding vehicle that was being ridden, multiple threat attempts and occurrences, and any other potentially notable occurrences like emergency braking or restarting of the MCM. The resulting driver behavior around a standard vehicle was then compared to driver behavior observed around the MCM. See Figure 3.5 for the on-board data collection sheet.

Subject Vehicle: MCM ____ or Research Vehicle: ____ Describe condition: ____ Coder ____________
Date: _________________ Start Time:______________ Stop Time:______________

		Yielding		Corner					Straight					Misc			
						Overtake			Multiple Threat (Ped)		Lane Change						
	Location:	Yield	Not Yield	Turn No Ped	Queue	Turn (No Ped)	Turn (Ped)	Straight (Turn)	MT Pass	MT Attempt	Cut off Behind	Cut off Far	Straight	Take over (Manual Lane Change)	Emergency Stop (Hard Brake)	MCM Reboot	Left Turn Cut Off
Loop #1	C																
	CB																
	B																
	B6																
	6																
	63																
	3																
	3C																

Figure 3.5 Abbreviated onboard data collection sheet

3.2 Results

3.2.1 Data Collection Overview

Driver behavior data was collected at six intersections (three unsignalized sites and three signalized sites) and from a passenger's perspective aboard the MCM or human driven research vehicle along the MCM route/loop. The HumanFIRST Laboratory research team collected driver behavior data from the eight sites/loops between May 26th and August 30th, see Figure 3.6. By design, data was collected two days per week, with all eight sites/loops being observed each day. Data was usually collected Thursday and Friday, although some weeks data was collected on Wednesday and Thursday. Data was collected between 8am and 3pm. Data was not collected during the rain for safety reasons.

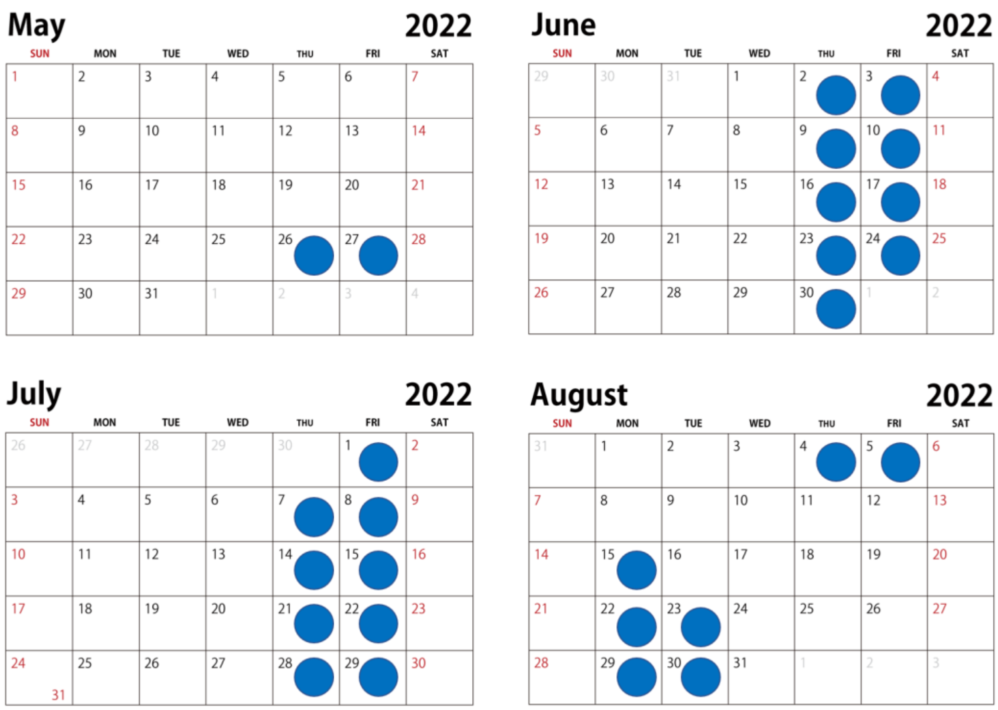


Figure 3.6 All (27) days of field data collection marked in blue

During a data collection session at signalized crossings, coders observed 20 walk cycles per site. For unsignalized crossings, coders attempted a total of 20 crossings during which incoming traffic should yield, 10 times per coder, with any observed natural pedestrian crossing replacing a planned staged crossing. Coders also rode both the MCM and a researcher-driven vehicle around the MCM's designated loop twice, collecting data on other drivers' behavior around the driven vehicle.

3.2.2 Data Collection Session Details

Frequencies of data collection sessions are detailed in the tables below. The data collection sessions were segmented into **cycles** for signalized intersections (see Table 3.5), **crossings** for unsignalized intersections (see Table 3.6), and **loops** for in-vehicle MCM route data collection (see Table 3.7). The total number of these data collection segments during the study period are detailed in these tables by site, on route status, and the inclusion of the MCM in each observation.

Table 3.5 Signalized data collection occurrences and overview

Site	Location	Total Cycles	MCM Observations
Center & Broadway	On Route	537	36
Center & 3rd	On Route	493	35
	Total	1030	71
2nd & 2nd	Off Route	204	N/A
2nd & 1st	Off Route	305	N/A
	Total	**509**	**N/A**
	Grand Total	**1539**	**71**

Note: MCM observations were limited due to the speed of the shuttle and the number of shuttles in operation throughout the data collection period.

Table 3.6 Unsignalized data collection occurrences and overview

Site	Location	Total Crossings	MCM Observations
3rd & 6th	On Route	506	29
3rd & 3rd	On Route	496	24
	Total	949	53
1st & 4th	Off Route	543	N/A
	Total	**543**	**N/A**
	Grand Total	**1545**	**53**

Note: MCM observations were limited due to the speed of the shuttle and the number of shuttles in operation throughout the data collection period.

Table 3.7 Onboard data collection occurrences and overview

Site	Vehicle Type	Total Route Loops
On Board MCM	MCM	50
	Total	50
Research Vehicle	Car	42
Research Vehicle	SUV	6
	Total	**48**

Note: Some (3) loops of collected MCM data consisted of partial loop data due to other passengers riding the shuttle, causing the team to pause data collection

3.2.3 Analytical Approach

The primary objective examines the safety benefits and risks of the MCM on surrounding road users. This was determined by examining the extent to which the MCM outperformed regular vehicles in stopping for pedestrians. In addition, this research further evaluated the overtaking behaviors of other drivers around the MCM compared to drivers of regular vehicles when crossing or turning right at an intersection on/along the MCM operation route. From a community safety perspective, a secondary objective focused on determining whether the MCM operation had an overall influence on the regular vehicles' behaviors even when the MCM itself is not present, by examining onsite and off-site MCM-route performance by human-driven vehicles.

Based on the earlier operator interviews and preliminary analysis of the field tests, a much larger number of overtaking event occurrences were reported around the MCM, compared to a regular vehicle. To further analyze the underlying mechanism of such an observed elevated risk, we hypothesized that the queue has a mediation effect on the relationship between the MCM's presence in the intersection traffic and overtaking behaviors by other drivers around it. That is, due to its low speed and inability to turn right on red at signalized intersections where the maneuver is permitted, the MCM may potentially create more queuing vehicles behind or alongside it when crossing or turning right at an intersection. Subsequently, such a queue, unlike the unstopped (or unobstructed) traffic flow, would be more likely to give rise to a longer waiting time and more aggressive maneuvers among other drivers around the MCM, including an increased risk of unsafe overtaking behaviors that can be potentially harmful to pedestrians. Figure 3.7 illustrates a simple theoretical framework of the relationship between the MCM's presence in the intersection traffic and overtaking behaviors by other drivers, retreating the queue as a mediator.

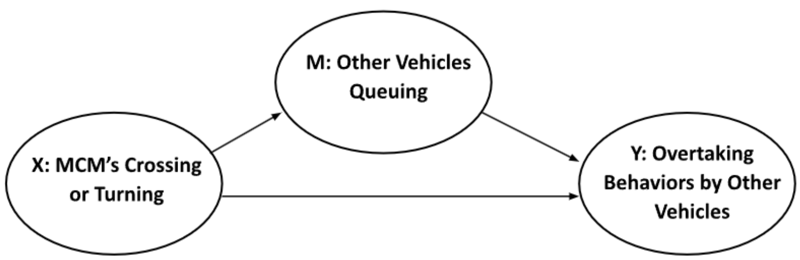


Figure 3.7 Theoretical framework of the relationship between the MCM's presence in the intersection traffic and overtaking behaviors by other vehicles, treating the queue as a mediator

To examine whether the queue is a partial or full mediation effect, we tested the following four possible relationships (Baron & Kenney, 1986) where X presents the exposure of interest, Y presents the study outcome, and M presents the potential partial or full mediator:

1. Test the total effect of X on Y
2. Test the relationship between X and M
3. Test the relationship between M and Y, controlling for X
4. Determine whether M is partial or full mediator, through incorporating M into a model and assessing whether there is an appreciable reduction (e.g., > 10% rule) in magnitude of the parameter estimate comparing the adjusted estimate (i.e., direct effect) to the crude (i.e., total effect).

3.2.4 Signalized Intersections Results

The following result section consists of five parts:

1. An overall description of the *data collected*
2. *Yielding performance for regular human-driven vehicles only*
3. *Yielding performance for the MCM and regular human-driven vehicles*
4. *Overtaking behaviors of other surrounding vehicles*
5. *Summary of results at signalized intersections*

For estimating the yielding or stopping rate, the total number of turning vehicles with the presence of pedestrians (i.e., which indicates the potential conflict) was included as an offset variable in the models, through summing up the number of turning vehicles that yielded to pedestrians and those that did not yield to pedestrians.

3.2.4.1 Data Collected

Data collection was performed over a total of *N* = 1,582 intersection traffic signal cycles at signalized intersections. Among them, 297 signal cycles (19.4% out of 1,582) contained no turning vehicles (e.g., a regular human-driven vehicle turned on red), and therefore were not able to provide meaningful information on the outcomes of yielding performance or overtaking behaviors. The remaining 1,285 signal cycles were included in the final analyses. In particular, 73 signal cycles (5.7% out of 1,285) captured the MCM turning right in the traffic flow and 1,212 signal cycles captured regular human-driven vehicles only (i.e., in absence of an observed MCM). The composition of the regular-vehicle cycles included 831 (64.7% out of 1,212) collected on/along the MCM operation route and 381 collected at the control sites (i.e., off-route).

3.2.4.2 Yielding performance for Regular Human-Driven Vehicles Only

As shown in Table 3.8, the rate of turning vehicles in the absence of pedestrians was almost identical for regular human-driven vehicle-only cycles at on-route versus off-route intersections, which was approximately one vehicle per lighting cycle. Similarly, there was no statistically significant difference between the percentage of vehicles yielding to pedestrians among regular vehicles, regardless of the route type, (Mean difference = 1.1%, 95% CI = [-0.9%, 1.1%], $p = 0.897$).

Table 3.8 Comparisons of the yielding performance for regular vehicles only at the on-route intersections versus off-route intersections (i.e., reference)

	# of cycles[a]	Rate (i.e., counts per cycle) (SD)	Rate Ratio[b] [95% CI]	Mean Yielding Percentage (SD)	Mean Difference[b] [95% CI]
Turning vehicles (No Ped)					
Off-route intersections	381	0.94 (1.0)	1.0 --	n/a	n/a
On-route intersections	831	0.95 (1.1)	1.0 [0.7, 1.4]	n/a	n/a
Vehicles yielding to pedestrians (With Ped)					
Off-route intersections	159	n/a	n/a	83.2% (35.0%)	0.0 --
On-route intersections	493	n/a	n/a	83.5% (32.4%)	1.1% [-0.9%, 1.1%]

a. For the measure of turning vehicles (no ped), the number of signal cycles included all observed cycles at on- and off-route intersections; for the measure of average percent of vehicles yielding to pedestrians, only signal cycles that could have the potential conflicts with pedestrians were included.
b. All models accounted for the effects of rush hour, weather condition, and individual differences of intersections.

3.2.4.3 Yielding Performance Between the MCM and The Regular Human-Driven Vehicles

Table 3.9 compares the yielding performance between the MCM and the regular human-driven vehicles, at the on-route intersections. As was shown, the rate of the MCM turning in the absence of pedestrians per traffic signal cycle was less frequent than the regular vehicle; however, the result was not statistically significant, Rate Ratio = 0.78, 95% CI = [0.5, 1.3], p = 0.345. Only two events (i.e., out of 39 cycles) of the MCM not yielding to pedestrians were observed, compared to 82 cases (i.e., out of 493 cycles) for the regular vehicles. Compared to regular vehicles, the safety benefits of the MCM were evidenced by a statistically significantly greater yielding percentage to pedestrians at intersections (Mean difference = 12.1%, 95 CI% = [2.7%, 21.6%], p = 0.012).

Table 3.9 Comparisons of the yielding performance between the MCM and the regular human-driven vehicles, at the on-route intersections

	# of cycles[a]	Rate (i.e., counts per cycle) (SD)	Rate Ratio[b] [95% CI][b]	Mean Yielding Percentage (SD)	Mean Difference[b] [95% CI]
Turning vehicles (No Ped)					
MCM	73	0.73 (1.0)	0.78 [0.5, 1.3]	n/a	n/a
Regular vehicle	831	0.95 (1.1)	1.0 --	n/a	n/a
Vehicles yielding to pedestrians (With Ped)					
MCM	39	n/a	n/a	94.9% (22.3%)	12.1% [2.7%, 21.6%]
Regular vehicle	493	n/a	n/a	83.5% (32.4%)	0.0 --

a. For the measure of turning vehicles (no ped), the number of lighting cycles included all observed cycles at on- and off-route intersections; for the measure of average percent of vehicles yielding to pedestrians, only lighting cycles that could have the potential conflicts with pedestrians were included.
b. All models accounted for the effects of rush hour, weather condition, and individual differences of intersections.

3.2.4.4 Overtaking Behaviors of Other Surrounding Vehicles

Queuing vehicles were counted under the circumstances of a right-turning vehicle yielding to a pedestrian in the secondary crosswalk and halting the movement of other right turning vehicles behind it (see Figure 3.8). Overtaking behaviors were captured by the research team at the signalized intersections which included one or multiple vehicles passing another vehicle in a right turn. The overtaking was recorded as a binary outcome under three different overtaking circumstances: when there was no pedestrian present in the crosswalk (see Figure 3.9), when there was a pedestrian present in the crosswalk, and when the overtaking driver moved out of the right turn queue and continued straight through the intersection after overtaking.

Figure 3.8 A queue forming behind a vehicle at a turn

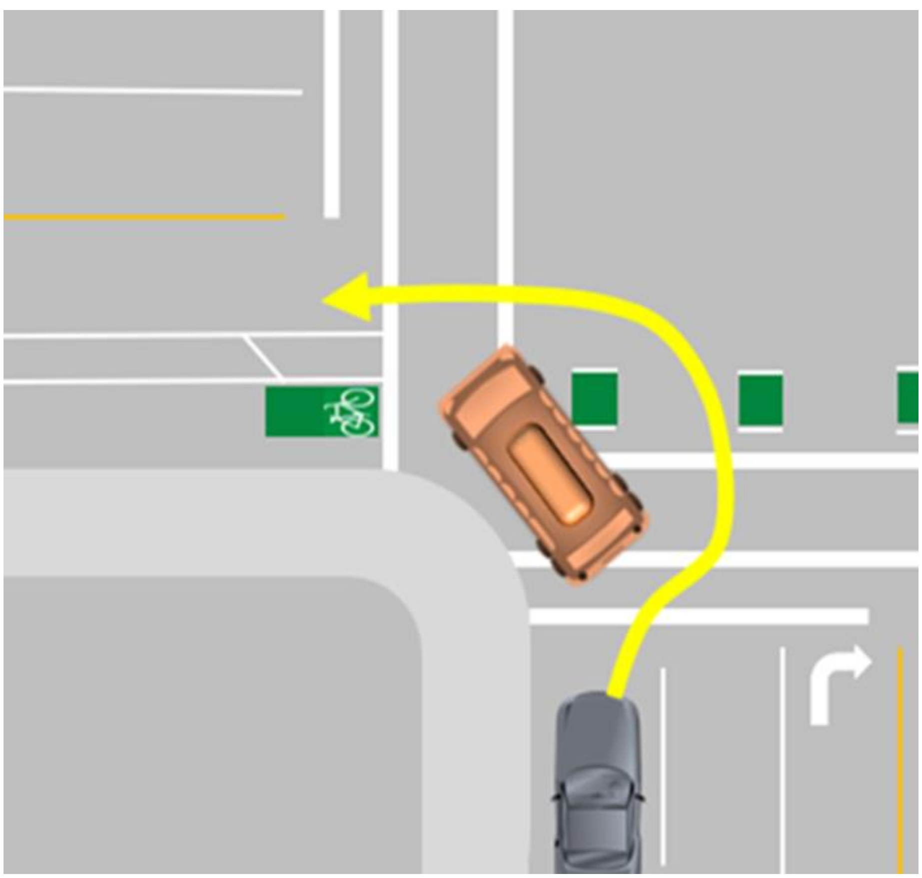


Figure 3.9 Diagram of overtaking at a turn with no pedestrian present

The MCM was observed to incur a greater number of queuing vehicles behind it when it yielded to a pedestrian (i.e., 260 queued vehicles in 73 cycles) compared to regular vehicles (i.e., 84 queued vehicles in 831 cycles), see Table 3.10. Further, there was a greater proportion of queuing vehicles per cycle who overtook the MCM than the proportion of queuing vehicles per cycle that overtook a regular vehicle.

Table 3.10 Descriptive statistics of the overtaking behaviors, around the MCM and regular vehicles

	Total # of the queue	Total # of OT Turning (no ped)	Total # of OT Turning (with Ped)	Total # of OT Straight
The MCM (*N* = 73 cycles)	260	3	4	9
Regular vehicle (*N* = 831 cycles)	84	11	5	10

The analysis and interpretations of the mediation analysis examining the relationship of queuing on overtaking risks can be shown in the following example for the OT turning (no ped). The results of the following analyses for each model are presented below in Table 3.11.

Model 1: OT = MCM + covariates; interpretation: The risk of the MCM's being overtaken by another vehicle from behind while turning right with no pedestrians was 48.9 times that of the regular vehicle. Risk ratio = 48.9 95% CI = [13.1, 183.5].

Model 2: Queue = MCM + covariates; Interpretation: Compared to the regular vehicle, the MCM's turning right with no pedestrians was 2.7 times more likely to lead to a greater number of queuing vehicles behind it (or being interpreted as the rate of queuing vehicles per lighting cycle), Rate Ratio = 3.7, 95% CI = [3.4, 3.9].

Model 3: OT = Queue + covariates; Interpretation: Compared to the regular vehicle, the risk of the MCM's being overtaken by another vehicle from behind while turning right with no pedestrians was 1.6 times higher, associated with one unit increase in the number of queueing vehicles behind it. Risk Ratio = 2.6, 95% CI = [1.7, 3.8].

Model 4: OT = Queue + MCM + covariates; After adjusting for the queue in the model, the adjusted risk ratio was 30.8. Compared to the total effect of 48.9, there was a 37% reduction on the effect measure, further indicating the queue potentially served as a partial mediator for the MCM on the risk of the OT Turning (No Ped) behavior.

Table 3.11 Multivariate analysis results and the presence of mediation effect of the queue

	OT Turning (No Ped)	OT Turning (With Ped)	OT Straight
Model 1	48.9 [13.1, 183.5]****	17.0 [3.6, 80.8]***	9.3 [3.3, 25.9]****
Model 2	3.7 [3.4, 3.9]****	Same to the left	Same to the left
Model 3	2.6 [1.7, 3.8]****	2.7 [1.6, 4.5]***	2.1 [1.4, 3.0]****
Adjusted Model	30.8 [7.6, 124.2]****	7.8 [1.3, 45.3]*	5.6 [1.8, 17.9]**
Presence of the Mediation Effect	*YES: 37% reduction in the effect measure;*	*YES: 54.1% reduction*	*YES: 39.8% reduction*

**** represents $p < 0.0001$, *** represents $p < 0.001$, ** represents $p < 0.01$, * represents $p < 0.05$

3.2.4.5 Summary of Results at Signalized Intersections

The yielding performance of the regular human-driven vehicles did not appear to be modified at intersections on the MCM route. Very minimal differences were found for the yielding performance of the regular human-driven vehicles at intersections on- or off- the MCM route. As expected, the MCM was associated with a significantly higher percentage of yielding to pedestrians at signalized intersections compared to manually driven vehicles. The queue appeared to serve as a partial mediator for the effect of the MCM (versus regular vehicle as the subject vehicle) on other drivers' overtaking it while turning right at the signalized intersection in Rochester. Compared to the regular vehicle, the MCM was associated with a nearly 30-fold increased risk of being overtaken while turning right at a signalized intersection, for all study outcomes.

3.2.5 Unsignalized Intersections Results

The following result section consists of three parts:

1. An overall description of the *data collected*
2. *Yielding performance for regular human-driven vehicles only*
3. *Yielding performance for the MCM and regular human-driven vehicles*

3.2.5.1 Description of Data Collected for Unsignalized Intersections

Data collection was performed over a total of N = 1,535 crossings at unsignalized intersections. Among them, 55 crossings involved the MCM (3.5% out of 1,535 total crossings, 5.6% of 979 on-route crossings). The composition of the regular-vehicle crossings included 924 (94.4% out of 979) collected on/along the MCM operation route and 556 collected at the control sites (i.e., off-route).

3.2.5.2 Driving Performance for Regular Human-Driven Vehicles Only

Table 3.12 compares the performance outcome measures for regular human-driven vehicles, comparing off-route and on-route intersections. The measures reported present the rates and the ratio of the rates along with the confidence interval [95% CI] of the difference of the rates per crossing. The results were significantly different for the on-route and off-route sites for all outcome measures (yielding count, queuing count, multiple threat passing, and multiple threat passing attempts (all *p*s < .001). Presumably, the greater vehicle volumes and proximity to the interstate of the off-route site influenced this higher rate of risky driver behaviors towards the staged and natural pedestrians crossing at the unsignalized off-route site. However, this implies that there do not appear to be major negative consequences for regular vehicle behavior due to driving on the same route as the MCM (on-route sites).

Table 3.12 Comparisons of the driving performance for regular vehicles only at the on-route intersections versus off-route intersections

	# of crossings	Count	Rate (i.e., counts per crossing)	Rate Ratio (on-route to off route)	Estimated Mean Difference in Rate[a] [95% CI]
Not Yielding Vehicles					
Off-route	556	810	**1.454**		
On-route	924	683	**.739**	**.51**	**-.706 [-.858, -.554]**
Queues					
Off-route	556	212	**.381**		
On-route	924	259	**.280**	**.74**	**-.098 [-.180, -.016]**
Multiple Threat Pass					
Off-route	556	20	**.036**		
On-route	924	5	**.005**	**.14**	**-.031 [-.044, -.017]**
Multiple Threat Attempt					
Off-route	556	34	**.061**		
On-route	924	14	**.015**	**.25**	**-.045 [-.068, -.023]**

a. All models accounted for the effects of rush hour and weather conditions. Estimated differences are provided by statistical models controlling for other variables.

3.2.5.3 Driving Performance Between the MCM and Regular Human-Driven Vehicles

Table 3.13 compares the performance outcome measures on crossings for regular human-driven vehicles and crossings involving the MCM, considering only on-route unsignalized intersections. The measures reported present the rates and the ratio of the rates along with the confidence interval (95% CI) of the difference of the rates per crossing. The results were significantly different (i.e., all ps < .001) for regular vehicles and the MCM for all outcome measures (yielding count, queuing count, multiple threat passing, and multiple threat passing attempts). Regular vehicles tended to yield less to pedestrians at the intersections (rate of .739 failure to yields per crossing) compared to crossings involving the MCM (rate of .164 failure to yields per crossing). However, for all other outcome measures, the relative rate per crossing was significantly greater for the MCM-involved crossings, with greater rates for the MCM for queuing when yielding, multiple threat passes, and multiple threat pass attempts.

Table 3.13 Comparisons of driving performance between the MCM and the regular human-driven vehicles (i.e., reference), at the on-route intersections

	# of crossings	Count	Rate (i.e., counts per crossing)	Rate Ratio (MCM to Regular Vehicle)	Estimated Mean Difference in Rate[a] [95% CI]
Not Yielding Vehicles					
MCM-involved	55	9	**.164**		
Regular vehicle	924	683	**.739**	**.22**	**-.591 [-.886, -.296]**
Queue					
MCM-involved	55	67	**1.218**		
Regular vehicle	924	259	**.280**	**4.4**	**.933 [.719, 1.147]**
Multiple Threat Pass					
MCM-involved	55	10	.182		
Regular vehicle	924	5	.005	36.4	**.176 [.137, .214]**
Multiple Threat Attempt					
MCM-involved	55	7	.127		
Regular vehicle	924	14	.015	8.5	**.113 [.058, .168]**

a. All models accounted for the effects of rush hour and weather conditions. Estimated differences are provided by statistical models controlling for other variables.

3.2.5.4 Summary of Results at Unsignalized Intersections

The yielding performance and other outcome measures of interest (e.g., multiple threat passing) of the regular human-driven vehicles appear to be modified at the site off the MCM route, suggesting no blatantly adverse effects of being present on the MCM route in general.

For driver behavior on the MCM Route, the MCM was associated with a significantly higher rate of yielding to pedestrians at unsignalized intersections. However, for risky secondary events associated with yielding (i.e., queuing, multiple threat passing and multiple threat pass attempts), the MCM was associated with nearly 4 times the risk of a queue forming while yielding, 8 times the risk of a multiple threat pass attempt, and 36 times the risk of a multiple threat pass occurring. The latter is a particularly risky scenario for pedestrians who are at risk of being struck by the passing vehicle at full speed, as observed in Figure 3.10.

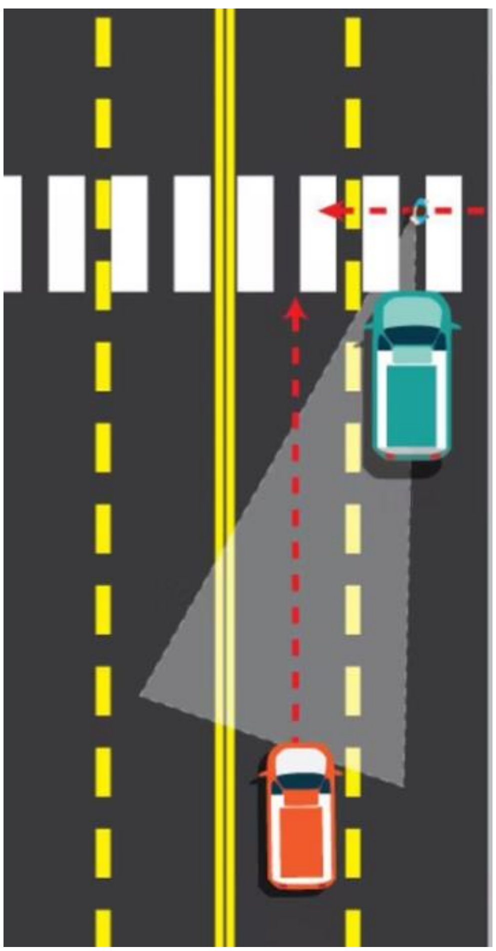


Figure 3.10 Example of multiple threat passing scenario at an unsignalized crosswalk. Image modified from Slate.com

3.2.6 Onboard Data Results

The following result section consists of three parts:

1. *An overall description of the data collected*
2. *An analysis of the onboard data at straight segments on the route*
3. *An analysis of the onboard data at the corner/turn sections on the route*

3.2.6.1 Description of Onboard Data

Data collection was performed over a total of 94 total loops, 46 loops around the route riding the MCM, and 48 loops in the researcher vehicle for 32 days. This resulted in 200 corner section data points and 200 straight segment data points for the research vehicle, and 190 corner section data points and 191 straight segment data points for the MCM.

3.2.6.2 Driving Performance of Surrounding Vehicles for Straight Segments

Multiple threat passing and attempts, and queuing were assessed while the two vehicles yielded to a pedestrian on the straight segments to consider effects of straight segment driving on pedestrian safety. Further, the count of vehicles moving from behind the vehicle were considered (see the bottom left vehicle on Figure 3.11), because this represents a crash risk where the driver may result in a rear end collision with the MCM or the researcher vehicle while making their lane change and risks disrupting traffic. Finally, the count of vehicles cutting in front of the MCM or the researcher vehicle was also considered (see top right vehicle on Figure 3.11), because this also has a minor sideswipe risk. This maneuver also risks the MCM engaging in a hard stop to avoid a collision, which disrupts traffic and further risks a rear-end collision with any vehicles following closely behind the MCM.

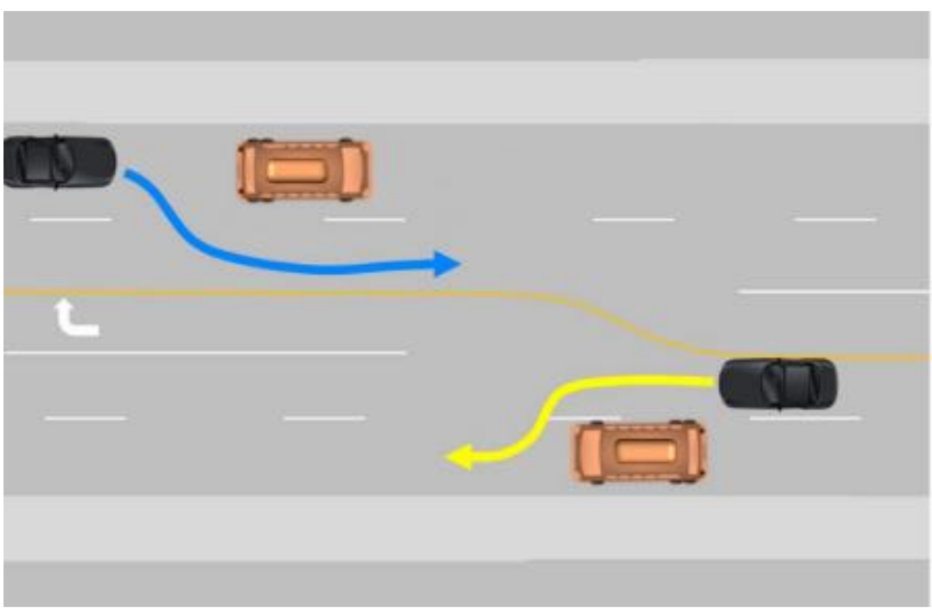


Figure 3.11 Examples of lane change behaviors around the MCM or researcher vehicle captured on loop straight segments

The analysis on straight segments, controlling for weather and individual segment variation, indicates that there was no observed difference for the MCM and the researcher vehicle when it came to multiple threat passes, multiple threat pass attempts, or queuing behavior when the vehicle in question yielded to a pedestrian on the straight segment. This may be due to the lack of opportunity to observe more frequent yielding behavior, given that there were only 23 yielding events to a pedestrian on straight segments for the MCM and 19 yielding events to a pedestrian for the researcher vehicle.

The analysis did observe significant differences between rate of cut-offs and lane changes from behind on the straight segments for the MCM compared to the researcher vehicle, with all $p < .001$. See Table 3.14.

Table 3.14 Comparisons of *straight segment* driving performance near the MCM and near the researcher driven vehicle on the MCM route

	# of straight segments	Count	Rate (i.e., counts per straight segment)	Rate Ratio (MCM to Researcher Vehicle)	Estimated Mean Difference in Rate[a] 95% CI
Multiple Threat Pass					
MCM	191	5	.026		
Researcher vehicle	200	0	.000[b]	5.2[b]	-.027 [-.060, .007]
Multiple Threat Attempt					
MCM-involved	191	4	.021		
Regular vehicle	200	2	.010	2.1	-.010 [-.035, .014]
Lane Change Cut-Off					
MCM-involved	191	182	**.953**		
Regular vehicle	200	14	**.070**	**13.6**	**-.891 [-1.117, -.666]**
Lane Change from Behind					
MCM-involved	191	279	**1.461**		
Regular vehicle	200	9	**.045**	**32.5**	**-1.438 [-1.683, -1.192]**
Queue					
MCM-involved	191	4	.021		
Regular vehicle	200	8	.040	.53	.022 [-.031, .076]

a. All models accounted for the effects of weather conditions and individual variance due to each straight segment. Estimated differences are provided by statistical models controlling for other variables.
b. Proxy value given zero cases of MT Pass for RV, in order to calculate the rate ratio. This value was calculated by taking a single hypothetical case over the # of straight segments (1/200), which was .005.

3.2.6.3 Driving Performance of Surrounding Vehicles for Corner Sections

The analysis on corner sections, controlling for weather and individual segment variation, indicates that there were observed differences for the MCM and the researcher vehicle when it came to overtaking turns when there was no pedestrian present ($p = .002$), overtaking turns when there was a pedestrian present ($p = .031$), and the rate of a queue forming when the vehicle yielded ($p < .001$). See Table 3.15.

Table 3.15 Comparisons of *corner section* driving performance near the MCM and near the researcher driven vehicle on the MCM route

	# of corner sections	Count	Rate (counts per corner section)	Rate Ratio (MCM to Researcher Vehicle)	Estimated Mean Difference in Rate[a] [95% CI]
Overtake Turn (No Ped Present)					
MCM	190	15	**.079**		
Researcher vehicle	200	0	**.000[b]**	**15.8[b]**	**-.080 [-.129, -.030]**
Overtake Turn (Ped Present)					
MCM	190	10	**.053**		
Researcher vehicle	200	0	**.000[b]**	**10.6[b]**	**-.052 [-.099, -.005]**
Queue					
MCM	190	131	**.689**		
Researcher vehicle	200	48	**.240**	**2.9**	**-.453 [-.622, -.284]**

a. All models accounted for the effects of weather conditions and individual variance due to each straight segment. Estimated differences are provided by statistical models controlling for other variables.
b. Proxy value given zero cases of MT Pass for RV, in order to calculate an estimated rate ratio. This value was calculated by taking a single hypothetical case over the # of straight segments (1/200), which was .005.

3.2.6.4 Summary of Results for Onboard Data Collection

For the straight segments, there was a higher rate of risky lane change behaviors for both changing lanes from behind the MCM and cutting off the MCM when compared to the research vehicle, representing a higher risk for sideswipe crashes and rear-end crashes (should the MCM engage in a sudden stop in response to being cut-off), as well as additional traffic disruption.

For the corner segments, the analysis supported what was observed for the signalized intersection data analysis. Compared to the researcher vehicle, there is a higher rate of overtaking with and without a pedestrian present when the MCM is involved, and a higher rate of queues forming behind the MCM when the MCM yields to a pedestrian.

3.3 Discussion

The analysis presented here primarily considers the risk posed to pedestrians with the MCM sharing the road with other human-driven vehicles, with a secondary consideration of the risk to other drivers and traffic disruption. The general takeaway is that the **direct risk** between the MCM itself and pedestrians is minimal, as the MCM yields at a significantly higher rate to pedestrians at both signalized and unsignalized intersections. However, the **indirect risk** to pedestrians due to changes in human driver activity around the MCM appears to be significantly greater. This is reflected in the higher rate of overtaking behaviors at signalized intersections and multiple threat behaviors at unsignalized intersections. A contributing factor to the higher risk of overtaking behaviors at signalized intersections is the greater rate of queuing behind the MCM, possibly due to its relatively lower traveling speed and inability to turn right on red traffic signals, although queuing does not completely explain the higher rates of overtaking. Finally, there are heighted crash and traffic disruption risks due to higher rates of lane change behaviors around the MCM, both from behind the MCM and cutting in front of the MCM.

Chapter 4: State Fair and Crowdsourcing Studies

4.1 State Fair Study

4.1.1 Introduction and Research Questions

Previous work as part of this project verified the elevated queueing and overtaking effect associated with the presence of the Med City Mover (MCM) via field data collection in Rochester. The present study aimed to explore potential causations for the elevated overtaking effect observed via a short study conducted at the University of Minnesota's Driven to Discover (D2D) booth at the Minnesota State Fair 2022. The research team has identified three potential aspects of the MCM's operations that may be associated with overtaking to be explored as part of this study: the shuttle's speed, the shuttle's appearance, and the shuttle's signaling system. Each of these aspects have been included in the following study with shuttle speed and appearance included as part of a simulated driving scenarios experiment and signaling systems included as part of the post-study questionnaire. The research team anticipated that speed and signaling may influence overtaking tendencies while shuttle appearance was less likely to have an effect.

4.1.2 Methods

4.1.2.1 Participants

A total of 85 participants (40 men, 44 women, and 1 nonbinary) were involved in the D2D study at the Minnesota State fair. The ages of participants ranged from 18 to 80 years of age with a mean age of 49.46 (SD = 18.75). Additional participant demographics were collected which included racial background, areas of driving, driving activity within Rochester, and public transportation usage. These results are presented below in Table 4.1.

Table 4.1 State fair study participant demographics

What is your highest level of education?	
Some high school	0
High school diploma or GED	11
Associate degree	8
Some college, no degree	14
Bachelor's degree	21
Graduate or professional degree	28
What is your ethnicity?	
Hispanic or Latino	5
Not Hispanic or Latino	80
What is your racial background?	
American Indian or Alaska Native	0
Asian	3
Black or African American	0
Hawaiian or Other Pacific Islander	0
White	77

Multiracial	4
In which area(s) do you drive the most often?	
Urban	23
Suburban	46
Rural	16
How often do you drive in the city of Rochester, MN?	
Daily	1
Weekly	1
Monthly	5
Yearly	17
Less than yearly	19
Never	42
How often do you use public transportation (e.g., buses or light rails)?	
0 - Never	20
1 - Hardly Ever	38
2 - Occasionally	20
3 - Quite Often	3
4 - Frequently	2
5 - Nearly All the Time	2

4.1.2.2 Experimental Design

The general research design followed a 3x2x2 design, with 3 signal types, 2 event types, and 2 pedestrian conditions. The 3 signal types were between subjects, with each participant experiencing one of three signal conditions (double flashing, single/no flashing, or text/icon). The event types were within-subjects, with each participant experiencing signalized intersection events and unsignalized crossing events. The pedestrian conditions were within-subjects, with each participant experiencing events with a pedestrian either present or absent. The study was reviewed by the University of Minnesota IRB (STUDY00016063) which determined it was "Not Human Subjects Research" as defined by DHHS and FDA regulations.

4.1.2.3 Participant Recruitment

The study took place at the Driven to Discover research building hosted by the University of Minnesota during the Minnesota State Fair. State fair attendees were allowed to freely enter the booth to participate in various research projects being conducted by the university. Interested attendees were invited by the research team to participate in the presented study, and if interested, were directed to another staff member to begin the study. Prior to participation, potential participants were informed of the estimated project duration, approximate content covered, and payment. Requirements to participate were being 18 years or older and an active Minnesota driver's license.

4.1.2.4 Go/No-go Assessment

After completion of a short demographic questionnaire, participants were directed to complete a short go/no-go assessment which is a modified version of the Continuous Performance Test (Riccio et al., 2001). The purpose of this assessment was to measure the participant's capacity for sustained attention and response control which may approximate overall impulsiveness during rapid decision making.

During this assessment participants were asked to watch a screen and respond, via hitting the spacebar, for all letters presented except for the letter X. Letters were rapidly presented for approximately one minute with responses collected for later assessment. This assessment was completed a total of four times, once before each of the simulated driving scenarios, to determine base impulsiveness and changes across the four simulated driving scenarios.

4.1.2.5 Simulated Driving Scenarios

Each participant completed four scenarios in which they watched a short video and were told to imagine themselves as the driver in each video. In each video the participant watched from the perspective of following a vehicle in the right lane on a multi-lane road. The vehicle in these scenarios was either the MCM, shown below in Figure 4.1, or a white van, shown below in Figure 4.2, and was traveling at either a low speed of 16 km/h (10 mph) or a higher speed of 40 km/h (25 mph). The 2x2 design with both shuttle appearance and speed resulted in four scenarios (16 km/h van, 16 km/h MCM, 40 km/h van, 40 km/h MCM) that each participant experienced in a randomized order.

Figure 4.1 The simulated Med City Mover (MCM) traveling down the right lane of a 4-lane urban street

Figure 4.2 The simulated passenger van traveling down the right lane of a 4-lane urban street

During the simulated driving scenario, the lead vehicle traveled the same distance in each scenario from the starting position, eventually stopping at mid-block crosswalk. The duration of videos varied with the low-speed vehicles traveling for approximately 1 minute and 30 seconds and the higher speed vehicles traveling for approximately 35 seconds before braking. When braking, the lead vehicle would emit either brake lights (passenger van) or flashing hazard lights (MCM), mirroring the rear signaling systems for both vehicles observed in the real world. Approximately 3 seconds after coming to a complete stop at the crosswalks, a prompt was shown on screen asking the participant whether they would wait behind the vehicle or pass around the vehicle by changing lanes.

4.1.2.6 Post-Study Questionnaire and Payment

Following the fourth simulated driving scenario, participants were instructed to complete a short post-study questionnaire. This questionnaire asked participants whether they could identify any vehicles from the simulated environments as autonomous vehicles and which level of automation they had. Additional questions asked about the MCM specifically and whether participants were familiar with the shuttle prior to participation. Finally, the survey included a scenario that asked participants to envision themselves behind the MCM at a signalized intersection with intentions to turn right. Participants were shown one of two different scenarios. In one scenario the MCM had both rear lights flashing, similar to the signaling system used in the field and the other scenario the shuttle had only the turn signal light flashing. Participants were asked what they interpreted the shuttle was doing and whether they would wait behind the shuttle or go around it. Upon completion of the study, participants were compensated for their time with a branded drawstring bag worth approximately $2.00 U.S.

4.1.3 Results and Discussion

4.1.3.1 Simulated Driving Scenario

NO PEDESTRIAN HAZARD SCENARIOS

Results from the simulated driving scenario of the most interest were the decisions to wait or pass the lead vehicle under each of the four conditions. Ultimately there were no observable differences between wait and pass tendencies across the two vehicle types for either of the speed conditions. Conversely, vehicle speed was predictive of the decision to pass, Wald $\chi 2 = 6.348$, $df = 1$, $p = .012$, 95% Wald CI [.118, .947], indicating that participants were more likely to select pass for the slower speed vehicles (regardless of appearance). Other factors such as age ($p = 0.074$) and gender ($p = 0.384$) were not predictive of such passing behavior. The wait or pass decisions across the four conditions are summarized below in Table 4.2.

Table 4.2 Simulated driving scenario pass/wait decisions

	Faster		Slower	
	Wait	**Pass**	**Wait**	**Pass**
MCM (*n* = 85)	43 (50.5%)	42 (49.4%)	32 (47.6%)	53 (62.4%)
White van (*n* = 85)	48 (56.5%)	37 (43.5%)	37 (43.5%)	48 (56.5%)

PRIMARY REASON FOR PASS/WAIT DECISION

Following the competition of the four simulated driving scenarios, participants were then asked what factors most affected their decision to wait or pass the lead vehicle. A summary of these responses is presented below in Table 4.3. Across all participants there were three primary factors that affected their decision to pass: speed (n = 44), the rear lights (n = 28), or other factors (n = 13). When analyzing whether any reasons for waiting or passing was predictive of behavior, it was determined that speed of the shuttle was a significant predictor of behavior, B = 1.233, OR = 3.432, p = .007, indicating that those who chose speed as a key influencer were more likely to pass the lead vehicle. Other factors such as age (p = 0.064) and gender (p = 0.267) were not predictive of such passing behavior.

Table 4.3 Self-reported primary reason for pass/wait decisions

Primary Reason for Pass/Wait	Count
Speed	44
Rear Lights	28
Other	13

4.1.4 Subjective Feedback

SHUTTLE FEEDBACK

As part of the post-study questionnaire, participants were informed that the orange lead vehicles, the MCM, from the simulated driving scenarios were autonomous vehicles that are being tested in the field today. Immediately after, they were asked whether they thought the shuttle was a good idea. The responses to this question are provided below in Table 4.4. Very few participants selected an option indicating that they do not think the shuttle is a good idea (n = 5, 6.0%), with a majority selecting either unsure (n = 30, 36.1%) or in favor of the shuttle (n = 48, 57.6%).

Table 4.4 Participant feedback whether the shuttle is a good idea (*n = 83*)

	Absolutely	*Probably*	*Unsure*	*Probably Not*	*Definitely Not*
Do you think the shuttle is a good idea?	*11*	*37*	*30*	*3*	*2*

SIGNAL INTERPRETATION

Immediately following the subjective feedback section, participants were asked to envision themselves behind the MCM at a signalized intersection with intentions to turn right while being presented with one of the previously discussed two signaling methods scenarios (hazard/both lights and turn signal/one light). Participants were then asked what they believed the shuttle was doing. Participants were allowed to select multiple options from the list: turning, emergency braking, parking, loading/unloading, yielding/stopping for a pedestrian, malfunctioning, and other as an open text entry. Responses for signal interpretation are presented below in Table 4.5. For the hazard signaling condition, a majority of participants selected yielding/stopping for a pedestrian (n = 50, 60.2%) or loading/unloading (n = 36, 43.4%), while fewer participants selected either of these options for the turn signal condition at 27 (32.5%) and 6 (7.2%) respectively. For the turn signal condition, the most common interpretation was that the shuttle was turning (n = 61, 73.5%) while only 2 (2.45) participants selected turning for the hazard signaling scenario.

Table 4.5 Participant self-reported signal interpretation responses

	Hazard (Both Lights)	Turn Signal (One Light)
Turning	2 (2.4%)	61 (73.5%)
Emergency braking	5 (6.0%)	1 (1.2%)
Parking	3 (3.6%)	4 (4.8%)
Loading/Unloading	36 (43.4%)	6 (7.2%)
Yielding/Stopping for a pedestrian	50 (60.2%)	27 (32.5%)
Malfunctioning	4 (4.8%)	1 (1.2%)
Other	1 (1.2%)	0

SIGNAL BASED BEHAVIOR

Finally, for these scenarios participants were also asked whether they would wait behind the shuttle, go around the shuttle, or other as an open text entry. The results from these questions are presented below in Table 4.6. There was an observable difference in participant responses across the two signaling systems with a larger majority of participants indicating they would wait behind the shuttle under the turn signal (92.7%) compared to the hazard signal (78.3%). Similarly, a higher percentage of responders indicated they would go around the shuttle for the hazard signal (19.3%) than the turn signal (7.2%).

Table 4.6 Participant self-reported expected behavior across signaling systems

	Hazard (Both Lights) [n = 83]	Turn Signal (One Light) [n = 83]
Wait behind the shuttle until it begins to move	65 (78.3%)	77 (92.7%)
Go around the shuttle	16 (19.3%)	6 (7.2%)
Other	2 (2.4%)	0

4.1.5 Conclusions

The purpose of this study was to serve as a preliminary exploratory study into what aspects of the MCM shuttle may be correlated with dangerous overtaking behavior when yielding to pedestrians. The three aspects analyzed in this study included the shuttle's appearance, the shuttle's speed, and the signaling system used when yielding. Through the simulated driving scenarios, it was determined that the speed of the shuttle directly correlated to the overtaking tendency of participants with lower speed lead vehicles having a higher overtaking rate. Conversely, the appearance of the shuttle was not found to be correlated with overtaking. Finally, there was an observed difference in signal interpretation between the signaling system of signage (hazard/both lights) and a more traditional turn signal. While the hazard signaling system was associated with a higher understanding of yielding to a pedestrian it was also associated with loading and unloading while not being associated with turning. This interpretation may contribute to a lower rate of waiting behind the shuttle behavior with more overtaking reported. This potential confusion regarding the signaling of the system is expected to be explored in further detail via a driving simulation study conducted in the HumanFIRST driving simulator.

4.2 Crowdsourcing Study

4.2.1 Introduction and Research Questions

Following the state fair study, the research team conducted a preliminary study regarding MC signal interpretation via a short survey on Prolific. The aims of the survey were to further verify trends of varied interpretation of the signaling system in use by the MCM while exploring potential alternate designs which included the previously discussed single light system in which only the turn signal would flash as well as two implementations of an on-board LED screen that would display a message to following drivers. The team anticipated poor understanding of the hazard lighting configuration associated with higher rates of shuttle overtaking.

4.2.2 Methods

A total of 242 participants were recruited via prolific.com who were active residents within the United States and indicated having a driver's license. The study was split across two recruitment periods in which 120 and 120 participants participated in the study. Due to each population having similar demographics as well as responses, the data across the two groups has been combined for the following analysis. A total of 111 (45.87%) participants were male with 125 (51.65%) female and 6 (2.45%) preferring not to report their gender. Participant's ages ranged between 19 and 75 (M = 36.86, SD = 12.30). Additionally, participants reported the primary area in which they drive which had 78 (32.23%) participants driving the most in urban areas, 132 (54.45%) in suburban areas, 24 (9.92%) in rural areas, and 8 (3.30%) preferring not to respond.

4.2.3 Results and Discussion

4.2.3.1 Signal Interpretation

After initial demographic questions, participants were shown a scenario in which they were asked to envision themselves behind the MCM at a signalized intersection with intentions to turn right, while the MCM they were following came to a stop and tuned on one of the four possible signaling systems: a single turn signal flashing (Figure 4.3), hazard lights flashing (Figure 4.4), a turn signal and an LED screen displaying “PED X-ING” (Figure 4.5) or a turn signal and an LED screen displaying “PEDESTRIAN CROSSING” (Figure 4.6). Participants were then asked what they thought the shuttle was currently doing based on the rear signaling of the shuttle. The responses are presented below in Table 4.7. A majority of participants indicated that they interpreted the shuttle as loading/unloading when presented with the hazard signaling system at 55.56%. When presented the turn signal system, a majority of participants interpreted the shuttle as primarily turning (60.66%). Participants were more split between turning and yielding/stopping for a pedestrian for both LED message signaling systems. 36.21% of participants who experienced the “PED X-ING” message and 45.00% of participants who experienced the “Pedestrian Crossing” reported the shuttle as turning with 41.38% and 35.00% reporting the shuttle as yielding/stopping for a pedestrian, respectively.

Figure 4.3 Single turn signal

Figure 4.4 Hazard lights flashing

Figure 4.5 Turn signal and an LED screen displaying crossing icon and text “PED X-ING”

Figure 4.6 Turn signal and an LED screen displaying crossing icon and text “PEDESTRIAN CROSSING”

Table 4.7 Crowdsourced signal interpretation responses

	Hazard (Both Lights) [n = 61]	Turn Signal (One Light) [n = 63]	PED X-ING Message [n = 58]	PEDESTRIAN CROSSING Message [n = 60]
Turning	7 (11.11%)	37 (60.66%)	21 (36.21%)	27 (45.00%)
Emergency braking	2 (3.17%)	2 (3.28%)	0	0
Parking	3 (4.76%)	0	1 (1.72%)	4 (6.67%)
Loading/Unloading	35 (55.56%)	9 (14.75%)	11 (18.97%)	6 (10.00%)
Yielding/Stopping for a pedestrian	13 (20.63%)	10 (16.39%)	24 (41.38%)	21 (35.00%)
Malfunctioning	3 (4.76%)	1 (1.64%)	1 (1.72%)	1 (1.67%)
Other	0	2 (3.28%)	0	1 (1.67%)

4.2.3.2 Signal Based Behavior

When asked whether they would wait behind the shuttle until it begins to move, pause for a few seconds before passing, or go around the shuttle, participants were primarily in agreement across all signaling systems, except for the hazard condition. Participants' reported expected behavior are presented below in Table 4.8. A majority of participants, ranging from 77.59% to 85.00%, indicated that they would wait behind the shuttle in the turn signal condition and both LED message board conditions. This rate of reported waiting until the shuttle began to move dropped to 58.73% for those who experienced the hazard condition with an elevated proportion of participants indicating that they would pause for a few seconds then go around the shuttle.

Table 4.8 Crowdsourced self-reported expected behavior across signaling systems

	Hazard (Both Lights) [*n* = 61]	Turn Signal (One Light) [*n* = 63]	PED X-ING Message [*n* = 58]	PEDESTRIAN CROSSING Message [*n* = 60]
Wait behind the shuttle until it begins to move	37 (58.73%)	50 (81.97%)	45 (77.59%)	51 (85.00%)
Pause a few seconds and then go around the shuttle	24 (38.10%)	9 (14.75%)	11 (18.97%)	7 (11.67%)
Go around the shuttle	1 (1.59%)	2 (3.28%)	2 (3.45%)	1 (1.67%)
Other	1 (1.59%)	0	0	1 (1.67%)

4.2.3.3 Signal Clarity

The final portion of the survey presented each participant with the hazard signaling scenario in a variety of different scenarios, told what action the shuttle was taking, and asked the participant to rate how clear the signaling system was at indicating various potential shuttle actions. These actions as well as the responses are presented below in Table 4.9. Participants generally reported that the hazard signaling system was the clearest to signal loading and unloading of passengers or that something had gone wrong, and the shuttle was in Emergency Manual Takeover mode. Conversely, the hazard signaling system was the least clear and most confusing when indicating that the shuttle was either turning right or yielding to a pedestrian before turning right.

Table 4.9 Crowdsourced self-reported hazard signal clarity for indicating different behaviors

	Very Unclear and Confusing	Somewhat Unclear	Neither Clear nor Unclear	Somewhat Clear	Very Clear and Understandable
Turn right (not yielding to a pedestrian)	162	44	2	20	14
Load and unload passengers	2	16	18	109	97
Convey something has gone wrong and the shuttle is in Emergency Manual Takeover	26	63	25	81	47
Yield to a pedestrian trying to cross the road midblock	36	71	27	82	26
Yield to a pedestrian before turning right	66	106	25	39	6

4.2.4 Analysis

The following analyses directly test differences between the four signal types for Signal Interpretation and Signal Behavior. We focus on these two categories (interpretation and behavior) because they have the most direct translation to safety concerns and potential redesign for later testing. The survey data was aggregated into counts, and post-hoc analyses follow each significant and marginally significant result.

Table 4.10 Prolific crowdsourced survey signal interpretation analysis

Dependent Variable	Probability Distribution and Log Link	AIC	Chi-Square (df)	Omnibus Significance
Turning	Poisson, Log	27.291	23.365 (3)	**<.001*** **
Emergency braking	Poisson, Log	13.227	5.545 (3)	.136
Parking	Poisson, Log	16.258	6.592 (3)	.086
Loading/Unloading	Poisson, Log	25.360	30.281 (3)	**<.001*** **
Yielding/Stopping for a pedestrian	Poisson, Log	26.486	7.840 (3)	**.049***
Malfunctioning	Poisson, Log	16.992	1.726 (3)	.613
Other	Poisson, Log	12.614	4.499 (3)	.212

The following post-hoc analyses consider the significant effects of the omnibus model on turning, yielding/stopping for a pedestrian, and loading/unloading observed in Table 4.10. The selections for the hazards signaling condition representing turning vehicles (*M* = 7) was significantly fewer than that of the single flashing condition representing turning vehicles (*M* = 37), *p* < .001, and significantly fewer than that of the pedestrian x-ing condition representing a turning vehicle (*M* = 21), *p* = .008, and significantly fewer than the pedestrian crossing condition representing a turning vehicle (*M* = 27), *p* = .001. There was also a significant difference between the pedestrian x-ing condition and the signal flashing condition (*p* = .036). There was no significant difference between the other conditions (all *p'*s > .10).

The selections for the hazard signaling condition representing a loading/unloading vehicle (*M* = 35) were significantly more than that of the single flashing condition representing loading/unloading vehicles (*M* = 9), *p* = .001, and significantly more than that of the pedestrian x-ing condition representing a loading/unloading vehicle (*M* = 11), *p* < .001, and that of a pedestrian crossing condition representing a loading/unloading vehicle (*M* = 6), *p* < .001. There was no significant difference between the other conditions (all *p'*s > .10).

The selections for the hazard signaling condition representing a vehicle yielding or stopping for a pedestrian (*M* = 13) was marginally less than that of the pedestrian x-ing condition indicating a vehicle yielding or stopping for a pedestrian (*M* = 24), *p* = .071. There was a significant difference between the single flashing condition (*M* = 10) and the pedestrian x-ing condition (*M* = 24), *p* = .016, and the between the single flashing condition and the pedestrian crossing condition (*M* = 21), *p* = .048. There was no significant difference between the hazard (double) signal condition and the single flashing condition (*p* = .532) or the hazard condition and the pedestrian crossing condition (*p* = .170). There was also no significant difference between the pedestrian crossing and pedestrian x-ing conditions (*p* = .655).

Table 4.11 Prolific crowdsourced survey signal behavior analysis

Dependent Variable	Probability Distribution and Log Link	AIC	Chi-Square (df)	Omnibus Significance
Wait	Poisson, Log	30.628	2.768 (3)	.429
Pause	Poisson, Log	25.135	12.449 (3)	**.006****
Go Around	Poisson, Log	17.227	.680 (3)	.878
Other	Poisson, Log	12.000	2.773 (3)	.428

The following post-hoc analyses consider the significant effects of the omnibus model on the decision to pause observed in Table 4.11. The selections for the hazards signaling condition eliciting the decision to pause and then go around (*M* = 24) was significantly greater than that decision for the single flashing condition (*M* = 9), *p* = .009, the pedestrian x-ing condition (*M* = 11), *p* = .028), or the pedestrian crossing condition (*M* = 7), *p* = .002. There are no significant differences between the other signaling conditions (all *p*s > .10).

4.2.5 Conclusions

The purpose of this crowdsourcing experiment was to further validate preliminary findings from the state fair study and explore potential alternate signaling systems for use in future driving simulation work. Findings from the state fair study were further validated, as participants in this study showed higher misinterpretation of the shuttle's behavior when presented with the hazard condition and indicated a lower rate of waiting behind the shuttle compared to the single light and both LED screen messaging conditions. Similarly, yielding to pedestrians and turning right were indicated as the least clear with hazard signal indication, despite those being common uses of the hazard signal when the shuttle was yielding to a pedestrian when attempting to turn right. These results highlight a key concern regarding the MCM signaling systems in place, which were further investigated in the final driving simulation study.

Chapter 5: Driving Simulation Study

5.1 Experimental Design

5.1.1 General Experimental Paradigm

5.1.1.1 Participants

The experiment recruited 46 participants with current driver's licenses in the state of Minnesota, generally between the ages of 18 and 45 (i.e., to reduce the chance of simulation sickness), although older participants were scheduled if available. These participants were screened so they had no conditions that would make them prone to simulation sickness.

5.1.1.2 Design

The design of the study was a 2 x 3 mixed factorial design, with two levels of drive order that is repeated or within subjects, and three levels of signal type, (Double Flashing, Single/No Signal, Text/Icon) which is between subjects. See Table 5.1. See Appendix E for images of the signaling types presented in the driving simulation study.

Table 5.1 Signaling conditions in procedural order with hypothetical participants.

PARTICIPANT ID	PRACTICE	DRIVE 1	DRIVE 2
Participant X	*Practice Scenario*	*Double Flashing*	*Double Flashing*
Participant Y	*Practice Scenario*	*Single/No Signal*	*Single/No Signal*
Participant Z	*Practice Scenario*	*Text/Icon*	*Text/Icon*

5.1.1.3 Signal Signage Designs

The primary purpose of this study was to determine whether different pedestrian yielding signaling systems resulted in a higher risk of overtaking. Various existing and proposed signaling systems (designed by the research team) have been implemented in this study. The following paragraphs and figures provide further detail of each experimental condition, design choice logic, and anticipated results.

One signaling system, referred to as the double signal system in the context of this study, had both rear brake lights flash at a steady rate while the vehicle was coming to a stop and while it was yielding to the pedestrian. This system was designed to mimic the manual takeover signaling system used by the MCM shuttle whenever the onboard supervisor takes control of the vehicle and is shown below in Figure 5.1. This manual takeover is often done when yielding to a pedestrian, thus the double signaling system is what has been implemented in the field for the MCM shuttle. The experimental condition using the double signaling system served as a direct comparison to what was seen during field work in which the research team observed an elevated risk of overtaking around the shuttle. The research team anticipated a similar elevated risk of multiple threat passing and overtaking to that observed during field data collection in Rochester during 2022.

Figure 5.1 Double signal or flashing hazard system at unsignalized intersection

An alternative signaling system design proposed by the research team and tested in the driving simulator was the turn/no signal signaling system. Similar to traditional turning signals on vehicles, this condition had the turn signal flash while turning at the signalized site in addition to the brake lights. When the shuttle was not turning, at the unsignalized sites, there was no flashing signal and only the brake lights were lit. The turn/no signal signaling system is shown below in Figure 5.2. The research team anticipated a lower risk of multiple threat passing when using this experimental signaling system due to an observed lower multiple threat passing rate around vehicles compared to the MCM.

Figure 5.2 Turn/No signal signaling system at signalized site

A signaling system tested as part of this study was a design that incorporated an LED-style message board signaling to other drivers that the shuttle is yielding to a pedestrian and is shown below in Figure 5.3. This signaling system took the turn signal signaling system and added a message board in the back window that reads "PED X-ING" with two pedestrian crossing symbols on each side, as shown below in Figure 8. This design is similar to the message board design implemented on the Bear Tracks automated shuttle in White Bear Lake which used a similar screen in the front and rear windows to provide messages to other drivers and pedestrians. The research team predicted that this signaling system would see the lowest risk of multiple threat passing around the shuttle as it incorporated the turn signal system with an additional message to driving indicating what the shuttle was doing and that there was a pedestrian crossing ahead, explicitly communicating the shuttle's intended actions and the reason for its current stopping.

Figure 5.3 Text/Icon signaling system at signalized site

In addition to the previously discussed experimental conditions, there were two conditions in which no pedestrian was present, defined as “no event” conditions, in which no yielding scenarios occurred at both the signalized and unsignalized intersections. There was one no event scenario for both the shuttle and the van lead vehicle types. These conditions served as control conditions to provide general overtaking rates of the lead vehicles when no pedestrian is present. In addition to serving as a control group, these conditions served as a distractor from the experimental conditions by presenting events where there was no pedestrian or yielding occurring.

5.1.2 Description of Simulation Model

5.1.2.1 Driving Simulator Environment

The simulated driving performance test was conducted in the HumanFIRST immersive, motion-based driving simulator manufactured (see Figure 5.4) by Realtime Technologies, Inc. The simulator consists of a 2013 Ford Fusion full vehicle cab with realistic operation of controls and instrumentation including force feedback on the steering and realistic power assist feel for the brakes. The simulator is powered by the latest generation PCs with the latest generation simulation creation software that provides high fidelity simulation for all sensory channels to generate a realistic presence within the simulated environment. The visual scene is projected through three new, high lumen, high-resolution projectors and a seamless, cylindrical screen which maximizes the 210-degree forward horizontal field of view. Complimentary right and left LCD mirrors are embedded into the standard mirror housing of the chassis for an OEM look. A custom-fitted glass cockpit includes a dashboard cluster panel that can replicate any configuration of vehicle gauges and display. Auditory feedback pertaining to the driving world is provided by a 3D surround sound system.

Figure 5.4 HumanFIRST immersive driving simulator

The Smart Eye Pro camera system (i.e., Smart Eye AB, Gothenburg, Sweden) was utilized for collecting video of the participant's face, head, and upper torso during each drive. The system consists of four in-vehicle digital infrared cameras (three on the dash and one below the center console touch screen, see Figure 5.5) that enabled multiple perspectives of the participant to be captured. An additional camera was positioned between the headrests in the vehicle that was facing forward during each drive. This camera was used to collect live recordings of each participant from a viewpoint within the vehicle for later assessment and coding. The live stream of the participant's face from the four cameras and the additional forward-facing camera were recorded for later analysis of observable movements, facial expressions, or positional indicators (see Figure 5.5).

Figure 5.5 Screenshot of four cameras capturing participant and forward view of simulation

5.1.2.2 Participant Recruitment

Participants were contacted from a list of previous HumanFIRST simulation study participants. These participants were screened so they had no conditions that would make them prone to simulation sickness. Eligible participants included licensed drivers with no cognitive or physical constraints that might limit their performance, have normal or corrected-to-normal vision (20/40 or better, normal color vision), normal hearing function, and normal cognitive function. Participants were excluded from the study if they have a history of hearing loss that inhibits everyday conversation, health problems that affect driving, inner ear or balance problems, history of motion (or sea) sickness, lingering effects of stroke, tumor, head trauma, or infection, and history of migraines or epileptic seizures. Those eligible for participation were then contacted via email to schedule a time to participate in the study.

5.1.2.3 Arrival

After participants provided informed consent, they began the experiment. Participants then answered a few brief questionnaires about their driving attitudes and demographics (APPENDIX D) on a laptop. Upon completion of the questionnaire, participants completed a practice drive, in which they were instructed to drive along a designated urban route, continuing straight until forced to turn due to signage in the sim environment. The practice drive vehicle maneuvers were similar to the maneuvers required in the experimental drives to familiarize participants with the maneuver and minimize any potential simulator performance or behavioral effects. Participants were surveyed for symptoms of simulation sickness to ensure they were able to safely continue in the study.

5.1.2.4 Practice Drive

During the practice drive, as shown below in Figure 5.6, participants experienced the MCM pulling out in front of them in three different situations. In the first case, the MCM drove through an intersection before pulling over to park. In the second case, the MCM simulated a breakdown by stopping in the right turn lane after signaling the intention to turn right with its blinker, then turning on its flashing hazard lights and staying stationary. This forced participants to overtake the MCM and drive around it. In the third case, the MCM simulated a breakdown that was fixed by stopping before crossing straight across an intersection, turning on its flashing hazards, waiting ten seconds, then turning its hazard lights off and continuing through the intersection and pulling over to park. Upon completion of the drive there was an on-screen message to stop the car and put it into park. Participants then got out of the vehicle and completed the wellness questionnaire followed by a short questionnaire which included some short self-report responses about the experience (APPENDIX D).

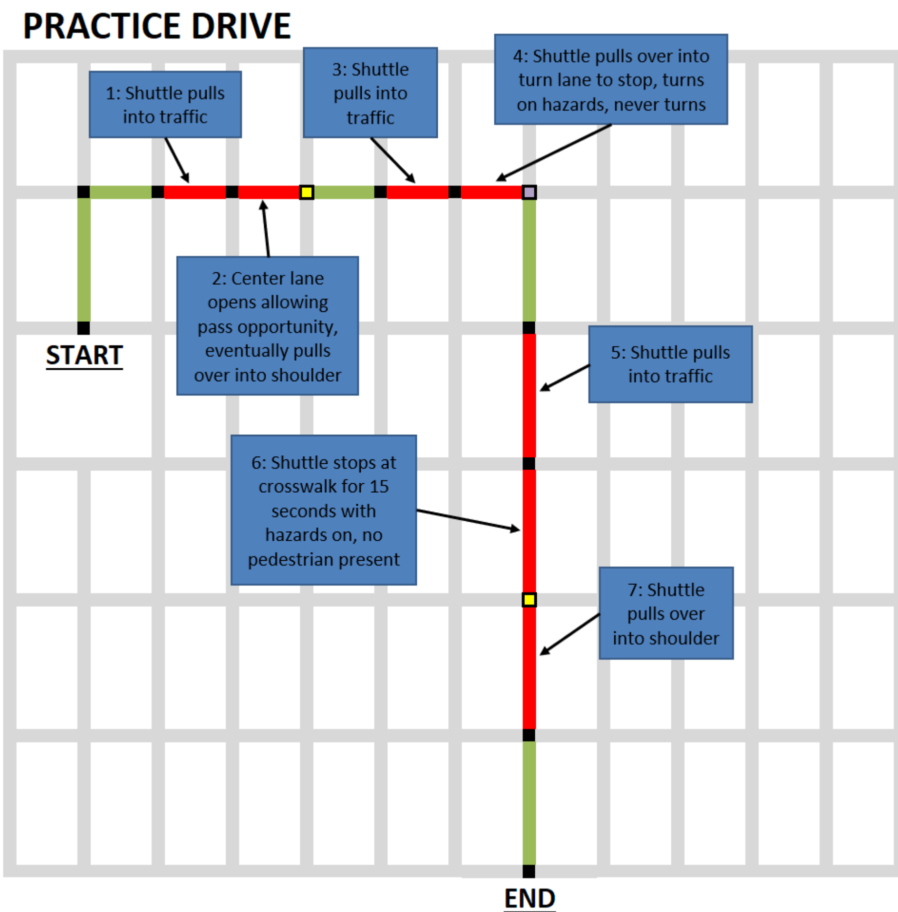


Figure 5.6 Practice drive route layout and labeled events

5.1.2.5 First Experimental Drive

After completing the questionnaires, participants then completed the first experimental drive, shown below in Figure 5.7. Participants were instructed to continue driving straight until being forced to turn. In this drive, participants encountered the MCM a total of four times. The MCM would either yield to a pedestrian or not, and either turn right or continue straight. All combinations of those behaviors were encountered by participants in this order, unsignalized intersection (straight) with no yielding, signalized intersection (turn) with yielding, unsignalized intersection (straight) with yielding, and finally, signalized intersection (turn) with yielding. While yielding to a pedestrian, the MCM would use one of the three (normal braking/signaling, hazard flashers, or custom text) signaling methods to indicate to the driver behind it that it was yielding. The method of signaling a participant received was consistent across all scenarios. As in the previous drive, upon completion of the drive there was an on-screen message to stop the car and put it in park, after which they got out of the vehicle and completed the wellness questionnaire followed by a short questionnaire which included some short self-report responses about the experience, particularly the RSME (APPENDIX D).

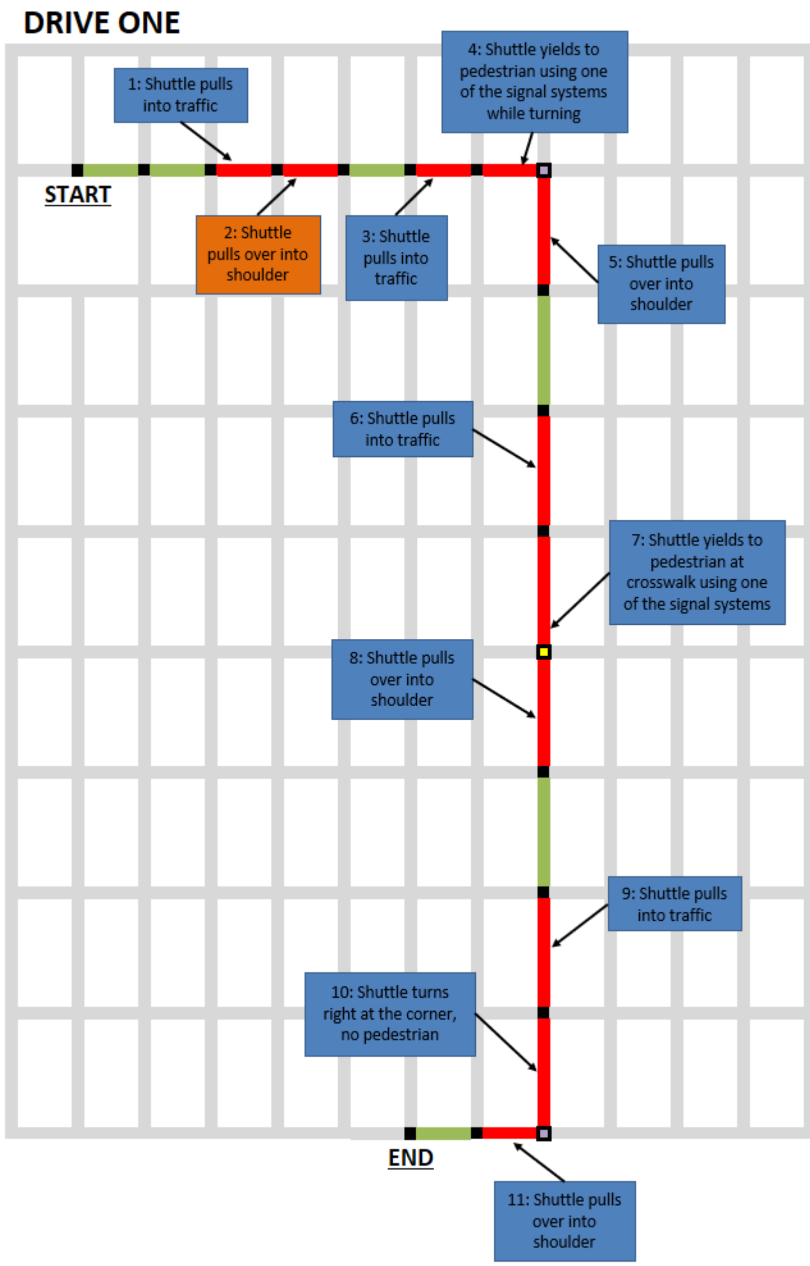


Figure 5.7 First experimental drive route layout and labeled events

5.1.2.6 Second Experimental Drive

Finally, participants completed the second experimental drive, see Figure 5.8. Similar to the second drive, participants encountered the MCM four times, with the MCM yielding to pedestrians while both driving straight (midblock crosswalk) and turning right (signalized intersection) and also stopping with no pedestrians present when turning right (signalized intersection) and going straight (midblock). The third encounter with the MCM in this drive was at a straight intersection where the MCM had a simulated breakdown. The mover stopped, put its hazard lights on, waited ten seconds, and then turned its hazard lights off and continued through the intersection. Upon completion of the drive, there was an on-screen message to stop the car and put it in park, after which the participant got out of the vehicle and completed the wellness questionnaire followed by a short questionnaire which included short self-report responses about the experience (APPENDIX D).

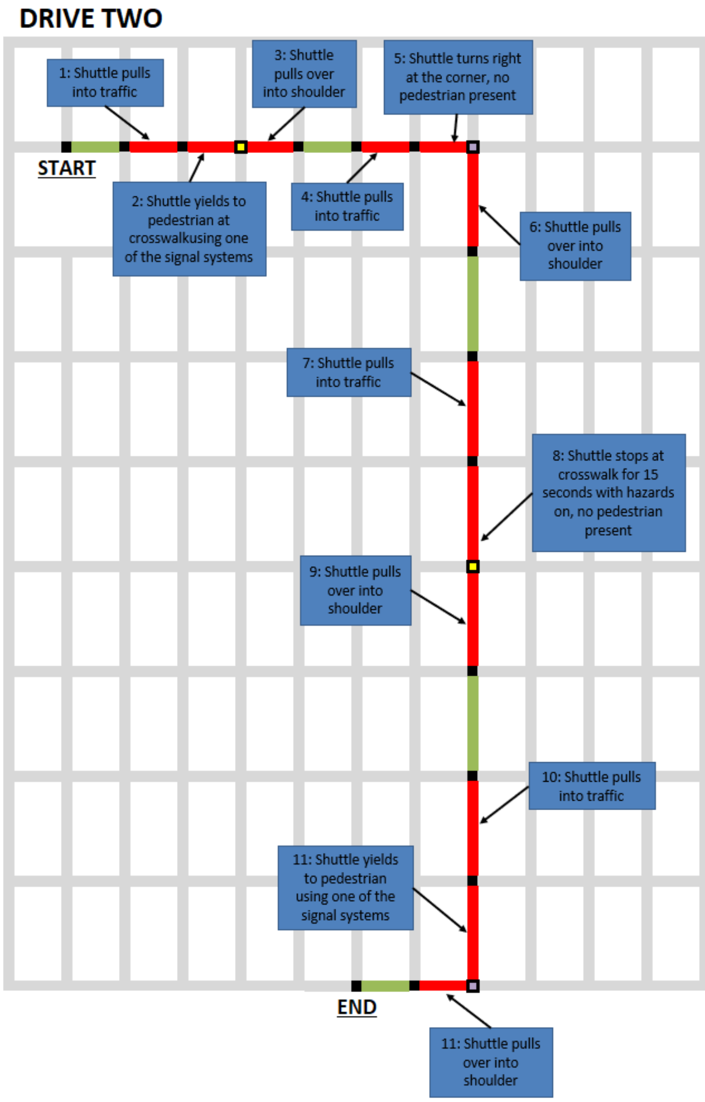


Figure 5.8 Second experimental drive route layout and labeled event

5.1.3 Detailed Variables

The following variables were collected via simulation software and observed monitoring of the participants behavior during the driving simulation scenarios. Event-based dependent variables at unsignalized and signalized intersections, such as full wait behind the MCM and multiple threat passing, are detailed in Table 5.2 and depicted in Figures 5.9 and 5.10. These variables were recorded through mixed-methods approach of video coding and driving simulation output. Self-report measures regarding signal interpretation and appropriate driving responses were collected and are listed in Table 5.3.

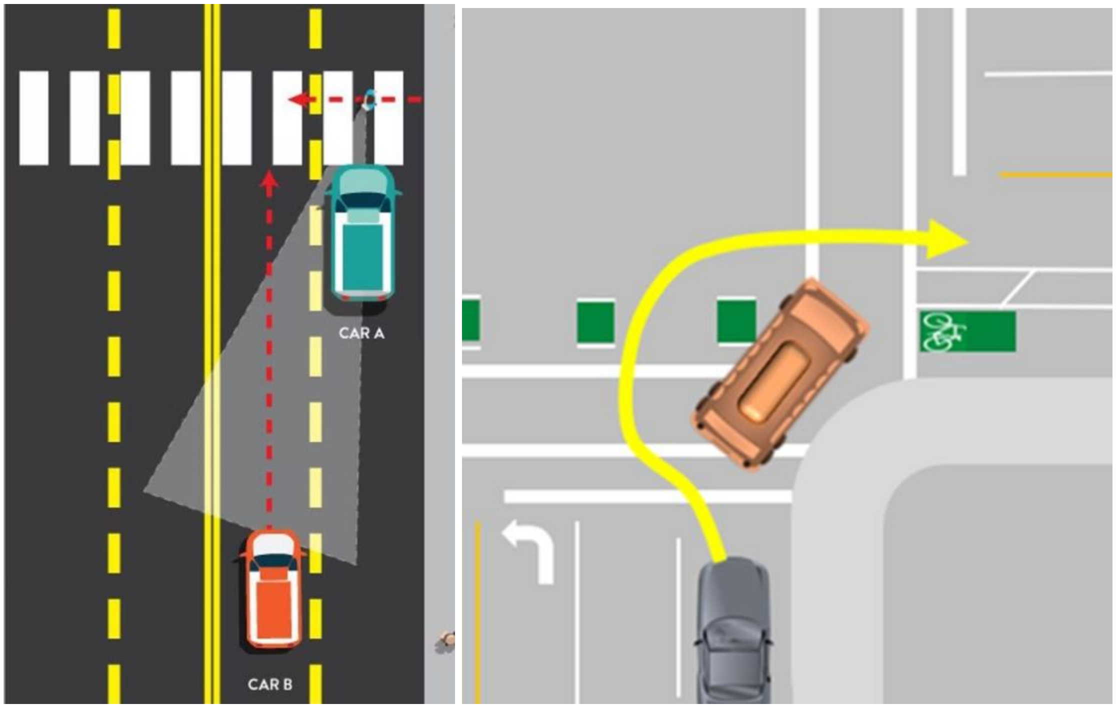


Figure 5.9 Examples of multiple threat passing at unsignalized (left) and signalized (right) intersections

Figure 5.10 Example of Full Wait Behind MCM at signalized intersection

Table 5.2 Event-based, categorical driving simulation variables at unsignalized and signalized events

Variable	Description
Full Wait Behind	Participant either waits or does not wait behind MCM until event ends
Pass MCM after 10 seconds malfunction	Participant passes the MCM after 10 seconds of waiting after MCM stops during malfunction event
Multiple threat pass	Participant passes lead vehicle and continues on during yielding event, between when the MCM has stopped and when the MCM begins moving again
Multiple threat attempt	Participant begins to pass lead vehicle during yielding event, but stops before crossing the crosswalk (all types)
Multiple threat attempt – Hard Brake	Participant begins to pass lead vehicle during yielding event, but hard brakes before crossing the crosswalk
Multiple threat attempt – Soft Brake	Participant begins to pass lead vehicle during yielding event, but soft brakes before crossing the crosswalk (all braking types)
Slow Creeping Multiple Threat Attempt	Participant begins to pass lead vehicle during yielding event, does not fully stop and continues to slowly creep forward until event has ended
Yielding minimum distance to MCM	Minimum distance between participant vehicle and MCM during yielding event
Yielding minimum distance to Pedestrian	Minimum distance between participant vehicle and pedestrian during yielding event
Crosswalk crossing speed	Speed while overtaking going through the crosswalk
Maximum Deceleration	Maximum braking force (deceleration)

Note. **Bolded** variable names were analyzed in statistical analyses in Results section.

Table 5.3 Self-report and subjective variables (See Appendix D)

Variable	Description
Safety and Technology Opinions	Self-reported Likert-scale ratings of opinions regarding current roadway safety and technology
Signifying Autonomy	Self-reported effectiveness of various visual features ability to signify vehicle autonomy
Signal interpretation	Self-reported interpretation of various signaling systems
Overtaking Decision	Self-reported decision to overtake in various scenarios

5.1.4 Analysis and Expected Results

The analysis primarily considered regressions on other variables that are binary (e.g., overtake yes/no). Special attention was paid to differences in driver behavior, particularly waiting behind or overtaking the lead vehicle, during exposure to a yielding signaling system (i.e., which signaling system has the lowest rate of overtaking or highest rates of waiting). The primary expected results were a higher rate of overtaking, shorter braking distances and greater crossing speeds when presented with the double flashing system, and a lower rate of these events with the text/icon system.

5.2 IRB

The study protocols titled "Assessing Automated Shuttle HMI with Other Drivers" were submitted to the University of Minnesota Institutional Review Board (IRB) on 1/10/2023. The study was reviewed by the University of Minnesota IRB (STUDY00018055) which determined it was "Exempt" as defined by DHHS and FDA regulations.

5.3 Results

5.3.1 Participants

A total of 46 participants (56.5% male, 41.3% female) were recruited to participate in the study with 2.5% preferring not to say. Participants' ages ranged between 19 and 77 (M = 41.04, SD = 16.81). Participants reported a range of highest education levels with a majority (42.5%) reporting a bachelor's degree. The majority (97.8%) of participants self-reported as white and not Hispanic. Participants' living areas were reported as a mix between urban and suburban (50.0% and 45.7% respectively) with only 4.3% living in rural areas. Similarly, participants reported driving in urban and suburban areas more frequently (89.1% collectively) with only 10.9% driving mostly in rural areas. Detailed results summarizing participant demographic information are shown below in Table 5.4.

Table 5.4 Participant demographics

What is your highest level of education?	
Some high school	1
High school diploma or GED	2
Associate degree	5
Some college, no degree	8
Bachelor's degree	20
Graduate or professional degree	10
What is your ethnicity?	
Hispanic or Latino	1
Not Hispanic or Latino	45
What is your racial background?	
American Indian or Alaska Native	2
Asian	6
Black or African American	1
Hawaiian or Other Pacific Islander	0
White	35
Multiracial	2
Do you consider yourself to live in an urban, suburban, or rural area?	
Urban	23
Suburban	21
Rural	2
In which area(s) do you drive the most often?	
Urban	23
Suburban	21
Rural	5
How often do you use public transportation (e.g., buses or light rails)?	
0 – Never	8
1 – Hardly Ever	20
2 – Occasionally	11
3 – Quite Often	2
4 – Frequently	3
5 – Nearly All the Time	2

5.3.2 Driving Behavior

5.3.2.1 No Pedestrian Hazard Scenarios

Across the three drives, there were three events in which the shuttle stopped at an intersection and displayed the hazard lights regardless of participant experimental group. At one such signalized event the shuttle remained stationary and never proceeded, while at the two unsignalized events the shuttle waited 10 seconds before beginning to move again. The purpose of these events was to determine if participants would pass the shuttle if it stopped unexpectedly and to prime the participants that the shuttle may stop in an unexplained manner, as the MCM occasionally did in Rochester. These passing events did not coincide with a pedestrian present, but for cohesion with other events, this passing behavior is labeled as a multiple threat pass for this analysis. All three events saw high rates of multiple threat attempts and passing, with the percentages of these behaviors ranging from 73.91% to 84.78% of the time. Few participants, 8.70% to 10.87% depending on the event in question, yielded the entire duration behind the shuttle when it stopped for 10 seconds. This behavior is summarized in Table 5.5.

Table 5.5 Shuttle malfunction driver behavior.

	Full Wait	Multiple Threat Attempt	Multiple Threat Attempt (Hard Brake)	Multiple Threat Attempt (Soft Brake)	Slow Creeping Multiple Threat Attempt	Multiple Threat Pass	Pass MCM After Waiting 10 Seconds
Signalized – Hazards Full Stop (n = 46)	5 (10.87%)	37 (80.43%)	1 (2.17%)	10 (21.74%)	14 (30.43%)	34 (73.91%)	2 (4.35%)
Unsignalized – Hazards 10 Second Wait 1 (n = 46)	4 (8.70%)	39 (84.78%)	1 (2.17%)	8 (17.39%)	6 (13.04%)	37 (80.43%)	1 (2.17%)
Unsignalized – Hazards 10 Second Wait 2 (n = 46)	4 (8.70%)	34 (73.91%)	0	8 (17.39%)	4 (8.70%)	34 (73.91%)	0

5.3.2.2 Signalized Intersection Events

Each participant experienced two events in which the MCM shuttle stopped for a pedestrian at a signalized intersection, showing only one of the three signaling conditions (double flash, single flashing, text/icon) depending on the participant's random experimental assignment. These exposures occurred once in the first experimental drive (see Figure 5.7) and once in the second experimental drive (see Figure 5.8) with the participant experiencing the same signaling condition in each drive. The resulting yielding and multiple threat attempt/pass behavior at these signalized events are shown below in Table 5.6 and Table 5.7.

Across all three conditions, there was an observable increase in full duration yielding (i.e., Full wait behind the MCM until the MCM begins moving again) with a decrease in both multiple threat attempts and multiple threat passing at the second signalized yielding event, indicating a potential order effect between the two exposures. During first exposures, the text/icon condition saw the highest rate of full duration yielding (56.25%) while also seeing the highest rate of multiple threat attempts (75%); however, while seeing the lowest rate of multiple threat passing (6.25%). During first exposures, the single signal condition saw slightly lower full duration yielding (46.66%) and multiple threat attempts (53.33%) and slightly higher multiple threat passing (13.33) rates. During first exposures, the double flashing or hazard condition saw the lowest full duration yielding (26.67%) and highest multiple threat passing (26.67%) rates. Across all three conditions there was an increase in full duration yielding and decrease in both multiple threat attempts and multiple threat passing during the second exposures.

Table 5.6 Signalized yielding behavior.

	First Exposure			Second Exposure		
	Full Wait	Multiple Threat Attempt	Multiple Threat Pass	Full Wait	Multiple Threat Attempt	Multiple Threat Pass
HAZARD (*n* = 15)	4 (26.67%)	11 (73.33%)	4 (26.67%)	8 (53.33%)	9 (60.00%)	1 (6.66%)
SINGLE (*n* = 15)	7 (46.66%)	8 (53.33%)	2 (13.33%)	8 (53.33%)	4 (26.67%)	1 (6.66%)
TEXT/ICON (*n* = 16)	9 (56.25%)	12 (75.00%)	1 (6.25%)	12 (75.00%)	1 (6.25%)	0

Table 5.7 Signalized multiple threat behavior.

	First Exposure				Second Exposure			
	Multiple Threat Attempt			Multiple Threat Pass After Ped	Multiple Threat Attempt			Multiple Threat Pass After Ped
	Hard Brake	Soft Brake	Slow Creeping		Hard Brake	Soft Brake	Slow Creeping	
HAZARD (*n* = 15)	0	7 (46.66%)	1 (6.66%)	4 (26.67%)	1 (6.66%)	7 (46.66%)	3 (20.00%)	2 (13.33%)
SINGLE (*n* = 15)	0	5 (33.33%)	2 (13.33%)	3 (20.00%)	1 (6.66%)	7 (46.66%)	3 (20.00%)	2 (13.33%)
TEXT/ICON (*n* = 16)	1 (6.25%)	10 (62.50%)	6 (37.50%)	1 (6.25%)	0	1 (6.25%)	0	1 (6.25%)

5.3.2.3 Unsignalized Crosswalk Events

Similar to the signalized intersection events, each participant experienced two unsignalized events in which the MCM shuttle stopped for a pedestrian and the MCM presented with one of the three signaling conditions (double flash, no flashing, text/icon). The resulting yielding and multiple threat attempt/pass behavior at these signalized events are shown below in Table 5.8 and Table 5.9.

Like the signalized events, there is an indication of an order effect, given an observable increase in full duration yielding with a decrease in both multiple threat attempts and multiple threat passing from the first to the second exposure. When analyzing the first exposures, the number of participants yielding for the full duration behind the shuttle was lower during the hazard condition (20.00%) compared to the single signal (46.66%) and text/icon (75.00%) conditions. A similar higher rate of multiple threat passing was observed for the hazard condition (46.66%) in comparison to the single signal (26.67%) and text/icon (18.75%) conditions. There was no discernable difference regarding multiple threat attempts across the three signal conditions for these unsignalized yielding events.

Table 5.8 Unsignalized yielding behavior.

	First Exposure			Second Exposure		
	Full Wait	Multiple Threat Attempt	Multiple Threat Pass	Full Wait	Multiple Threat Attempt	Multiple Threat Pass
HAZARD (*n* = 15)	3 (20.00%)	9 (60.00%)	7 (46.66%)	8 (53.33%)	7 (46.66%)	4 (26.67%)
SINGLE (*n* = 15)	7 (46.66%)	6 (40.00%)	4 (26.67%)	9 (60.00%)	5 (33.33%)	2 (13.33%)
TEXT/ICON (*n* = 16)	12 (75.00%)	6 (37.50%)	3 (18.75%)	12 (75.00%)	2 (12.50%)	2 (12.50%)

Table 5.9 Unsignalized multiple threat behavior.

	First Exposure				Second Exposure			
	Multiple Threat Attempt			Multiple Threat Pass After Ped	Multiple Threat Attempt			Multiple Threat Pass After Ped
	Hard Brake	Soft Brake	Slow Creeping		Hard Brake	Soft Brake	Slow Creeping	
HAZARD (*n* = 15)	1 (6.66%)	3 (20.00%)	2 (13.33%)	6 (40.00%)	0	5 (33.33%)	3 (20.00%)	4 (26.67%)
SINGLE (*n* = 15)	0	0	1 (6.66%)	2 (13.33%)	1 (6.66%)	1 (6.66%)	0	4 (26.67%)
TEXT/ICON (*n* = 16)	2 (12.50%)	3 (18.75%)	1 (6.25%)	2 (12.50%)	0	2 (12.50%)	0	2 (12.50%)

5.3.3 Subjective Feedback

5.3.3.1 Safety and Technology

Across the pre- and post-study surveys, participants were asked various questions regarding their views and opinions of safety and technology. Participants responded that they were moderately happy with the state of technology in vehicles today with a mean score of 3.39 out of 5 and responded that it was important that vehicle technology be changed to improve safety with a mean score of 4.39 out of 5. Similarly, participants reported that it was very important that roadway designs are changed to improve safety with a mean score of 4.7 out of 5. Regarding the current state of roadways, participants were neutral on the current state of Minnesota roadways, responding with a mean score of 3.01 out of 5. Finally, immediately following participation in the study, participants were asked whether they thought the automated shuttle was a good idea, in which a majority of participants responded in favor of the shuttle. The results from these safety and technology questions are presented below in Table 5.10.

Table 5.10 Participant opinions regarding roadway safety and technology.

How happy are you with the state of technology in today's vehicles?				
1 – Not happy at all	**2**	**3**	**4**	**5 – Absolutely happy**
0	5	20	19	2
How important is it for you that vehicle technologies be changed to improve safety?				
1 – Not Important at All	**2**	**3**	**4**	**5 – Very Important**
0	1	7	11	27
How important is it for you that roadway designs are changed to improve safety?				
1 – Not Important at All	**2**	**3**	**4**	**5 – Very Important**
0	0	2	10	34
How happy are you with the state of Minnesota roadways?				
1 – Not happy at all	**2**	**3**	**4**	**5 – Absolutely happy**
1	10	22	13	0
Do you think the shuttle is a good idea?				
Absolutely	**Probably**	**Unsure**	**Probably Not**	**Definitely Not**
13	18	10	3	2

5.3.3.2 Signifying Autonomy

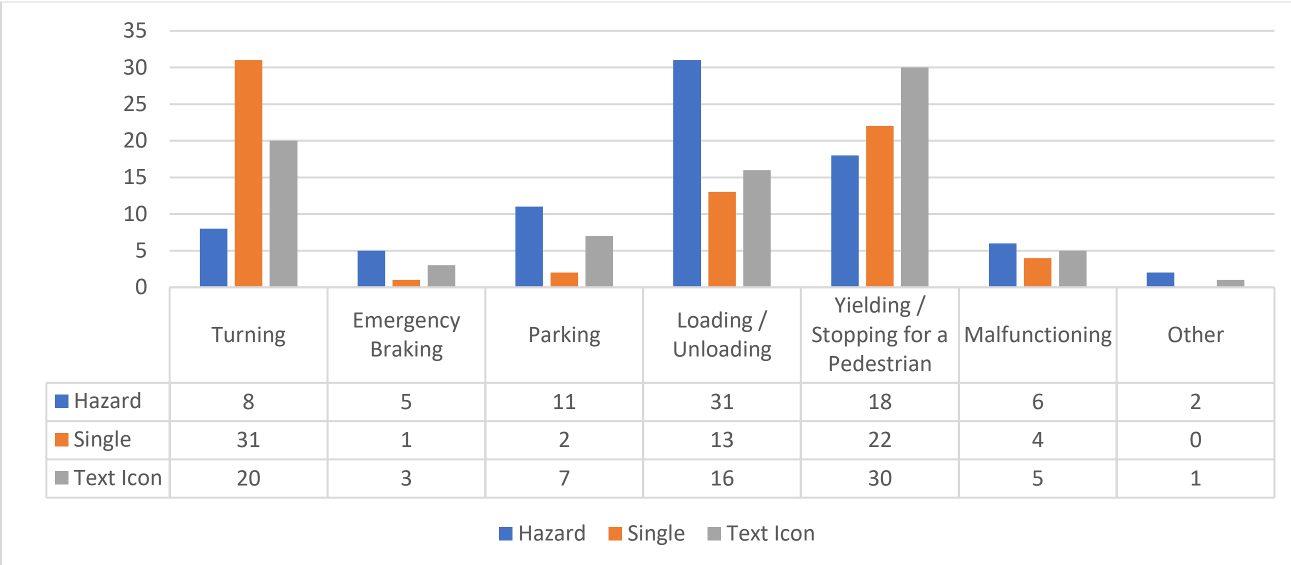
After completing the three driving scenarios, participants were asked to then rank the effectiveness of each method for signifying vehicle autonomy presented below in Table 5.11. Across all participants, each methodology, except for text only and icon only categories, were rated approximately the same ranging from an average rank score of 3.44 to 3.58, just under the scale midpoint of 4. Text only and icon only were ranked higher (5.49 and 5.02 respectively) indicating poorer effectiveness in signifying that a vehicle is autonomous on their own compared to the other methodologies included. It should be noted that this question did not allow for participants to rate multiple methods at the same effectiveness level.

Table 5.11 Shuttle autonomy signifiers survey responses.

	1	2	3	4	5	6	7	Average
Blue light bar	9	10	7	3	8	3	5	3.44
Text only	3	3	2	2	5	11	19	5.49
Icon only	3	1	5	6	6	16	8	5.02
Additional flashing lights	4	8	13	11	4	3	2	3.44
Improved flashing lights	8	8	6	8	7	4	4	3.58
LCD message	7	9	7	6	9	4	3	3.56
Vehicle wrap/color	11	6	5	9	6	4	4	3.47

5.3.3.3 Shuttle Interpretation

Each participant was presented with a series of three scenarios in a randomized order, as animated GIF image files, in which they were following a MCM approaching a signalized intersection. At the intersection the shuttle pulled into the right lane and turned on one of the three signaling conditions. The participant was then asked to indicate what they interpreted the shuttle was doing out of the 6 provided options listed below or indicate another unlisted behavior as Other. The responses to signal interpretation are provided below in Figure 5.11



	Turning	Emergency Braking	Parking	Loading / Unloading	Yielding / Stopping for a Pedestrian	Malfunctioning	Other
Hazard	8	5	11	31	18	6	2
Single	31	1	2	13	22	4	0
Text Icon	20	3	7	16	30	5	1

Figure 5.11 Signal interpretation survey responses

When assessing signal interpretations, there was a noticeable difference in the number of participants indicating that the shuttle was turning across the three conditions with the hazard condition having the fewest number of participants correctly identifying the behavior as yielding for a pedestrian. There was a corresponding increase in the number of participants who interpreted the hazard condition to indicate loading/unloading compared to the other conditions. Finally, the number of participants interpreting the single and hazard conditions as yielding or stopping for a pedestrian was comparable (i.e., 22 and 18, respectively), while there were more participants (i.e., 30) responding that the text/icon condition indicated yielding.

5.3.3.4 Signal Behavior

Participants were asked what action they would take in the aforementioned survey scenarios, given that they would be intending to turn right at the presented intersection. The options were: Wait behind the shuttle until it begins to move, pause a few seconds and then go around the shuttle, go around the shuttle, and other. Participants reported being more likely to wait behind the shuttle for the single light and text/icon conditions (65.2% and 63% respectively), while participants in the hazard condition were more likely to pause a few seconds and then go around the shuttle (54.3%). Similarly, more participants indicated that they would go around the shuttle during the hazard condition (13%) compared to the single and text/icon conditions (6.5% and 4.3% respectively). Participants self-reported behavior in this scenario are provided below in Table 5.12

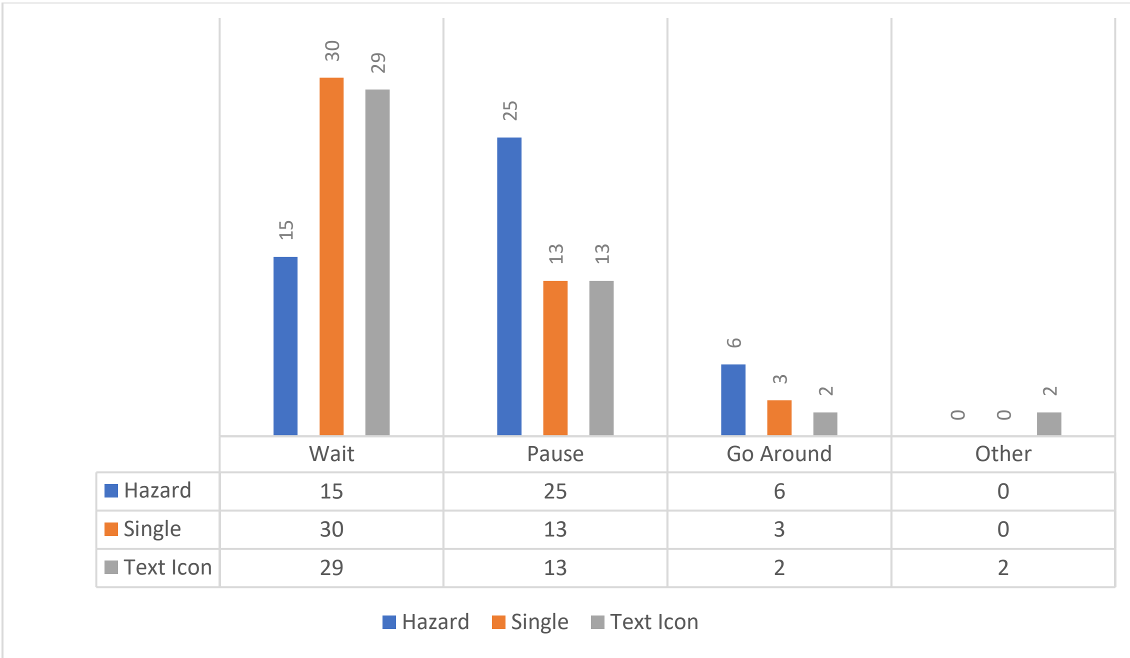


Figure 5.12 Signal behavior survey responses

5.4 Analysis

5.4.1 Simulation Statistical Analysis

The following analyses conducted to test driver performance in the driving simulation are characterized in the following ways:

1. Only considering comparisons between the MCM signal types.
2. Constrained to only pedestrian crossing events, not pedestrian-absent events.
3. Combined across signalized and unsignalized events to improve statistical power.

The reason for these conditions is that the key research questions focus on the MCM human-machine interface or signals, and these differences are presented in the pedestrian crossing events. However, there are only two specific events presented across drives for the unsignalized crossing, and two for the signalized crossing. This constrains the study's statistical power, due to limited sampling of the dependent variables in question. Therefore, to account for this issue, we combine the unsignalized and signalized events to provide four common, measurable events for each participant. See Table 5.12. The hazard signal condition is the reference condition in all tests. If the omnibus analysis is significant or marginally significant, we present the parameters and their breakdowns (e.g., Beta weights, Exp(B)).

Table 5.12 Driver performance analysis.

Dependent Variable	Probability Distribution and Log Link	AIC	Chi-Square (df)	Omnibus Significance	Parameter	B (SE)	Sig *p*-value	Exp(B)
Full Wait Behind (Y/N)	Binomial, Probit	19.59	8485 (2)	**.014***	Single	.385 (.232)	.097	1.47
					Text/Icon	.663 (.23)	**.004****	1.94
					Hazard	0	-	-
Multiple Threat Pass (Y/N)	Binomial, Probit	17.53	11.354 (2)	**.003****	Single	-.394 (.258)	.126	.67
					Text/Icon	-.961 (.300)	**.001****	.38
					Hazard	0	-	-
Yielding Minimum Distance to MCM	Gamma, Log	1084.05	11.361 (2)	**.003****	Single	.295 (.131)	**.024***	1.34
					Text/Icon	.437 (.128)	**.001****	1.55
					Hazard	0	-	-
Yielding Minimum Distance to Ped (m)	Gamma, Log	1217.66	1.126 (2)	.570 *(Not sig.)*				
Crosswalk Crossing Speed (m/s)	Gamma, Log	718.57	1.657 (2)	.437 *(Not sig.)*				
Max Deceleration	Normal, Identity	287.45	2.779 (2)	.249 *(Not sig.)*				

The analyses indicate that, when considering both signalized and unsignalized pedestrian crossing events where the simulated MCM stops for the pedestrian and uses one of three signaling systems, there is:

1. A significant main effect of signal system for participants to choose to wait or stop behind the shuttle for the full duration of the event.
2. A significant main effect of signal system for a multiple threat pass occurring during one of these events.
3. A significant main effect of signal system for minimum distance between the participant vehicle and the MCM.

For choosing to wait or stop behind the MCM for the full duration of the event (a binary yes/no variable), there was a significant difference between the text/icon condition relative to the hazard condition, in that participants in the text/icon condition were approximately 1.94 times more likely to stop and wait behind the MCM compared to the hazard signal condition. There were no differences between the single flashing condition and the other signal conditions.

For participants choosing to make a multiple threat pass during the stopping event (a binary yes/no variable), there was a significant difference between the text/icon condition relative to the hazard condition, in that participants in the text/icon condition were less likely (0.38 times) to make a multiple threat pass compared to the hazard signal condition. There were no differences between the single flashing condition and the other signal conditions. This version of the multiple threat pass variable is defined as the multiple threat pass in the variable definitions in Table 5.2, which corresponds with the definition of a multiple threat pass as a vehicle passing a stopped vehicle in the same direction of travel, without stopping and remaining stopped for the duration of the event (Morris, Craig, & Van Houten, 2020; pg. 152).

For the minimum distance in meters from the participant vehicle to the MCM during the yielding event, there was a significant difference between the text/icon condition relative to the hazard condition, in that participants in the text/icon condition were further away (1.55 times) in terms of average minimum distance to the MCM, compared to the hazard signal condition. There was also a significant difference between the single flashing condition and the hazard signal condition, with participants being further away on average (1.34 times) in the single flashing condition relative to the hazard signal condition.

5.4.2 Survey Statistical Analysis

The following analyses directly test differences between the three signal categories for signal interpretation (Figure 5.11) and Signal Behavior (Figure 5.12). The analysis for signal interpretation is presented in Table 5.13, and the analysis for signal behavior is presented in Table 5.14. Unlike the driver behavior analysis, which was primarily binomial data, the survey data was aggregated into counts, making post-hoc analyses more interpretable. The post-hoc analyses follow each significant result.

Table 5.13 Survey signal interpretation analysis

Dependent Variable	Probability Distribution and Log Link	AIC	Chi-Square (df)	Omnibus Significance
Turning	Poisson, Log	20.057	14.494 (2)	**.001****
Emergency braking	Poisson, Log	14.472	2.911 (2)	.233
Parking	Poisson, Log	16.672	6.884 (2)	**.032***
Loading/Unloading	Poisson, Log	20.314	8.831 (2)	**.012***
Yielding/Stopping for a pedestrian	Poisson, Log	20.919	3.147 (2)	.207
Malfunctioning	Poisson, Log	16.404	.403 (2)	.818
Other	Poisson, Log	10.614	2.773 (2)	. 250

The following post-hoc analyses consider the significant effects of the omnibus model on turning, parking, and loading/unloading observed in Table 5.13.

The selections for the hazards signaling condition representing turning vehicles (*M* = 8) was significantly fewer than that of the single flashing condition representing turning vehicles (*M* = 31), *p* < .001, and significantly fewer than that of the text/icon condition representing a turning vehicle (*M* = 20), *p* = .023. There was no significant difference between single flashing condition and text/icon condition (*p* = .123).

The selections for the hazard signaling condition representing a parking vehicle (*M* = 11) were significantly more than that counted for the single flashing condition representing a parking vehicle (*M* = 2), *p* = .013, and there were no significant differences observed between the text/icon condition (*M* = 7) and the other conditions (all *p*s > .09).

Finally, the selections for the hazard signaling condition representing a loading/unloading vehicle (*M* = 31) were significantly more than that of the single flashing condition representing loading/unloading vehicles (*M* = 13), *p* = .007, and significantly more than that of the text/icon condition representing a loading/unloading vehicle (*M* = 16), *p* = .029. There was no significant difference between single flashing condition and text/icon condition (*p* = .577).

Table 5.14 Survey signal behavior analysis

Dependent Variable	Probability Distribution and Log Link	AIC	Chi-Square (df)	Omnibus Significance
Wait	Poisson, Log	21.013	6.209 (2)	.045
Pause	Poisson, Log	19.895	5.333 (2)	.069
Go Around	Poisson, Log	15.263	2.281 (2)	.320
Other	Poisson, Log	8.614	4.394 (2)	.111

A significant effect was observed in the omnibus model for choosing to wait behind the shuttle.

The selections for the hazards signaling condition leading to the choice to wait (*M* = 15) was significantly fewer than that of the single flashing condition leading to the choice to wait (*M* = 30), *p* = .025, and significantly fewer than that of the text/icon condition leading to the choice to wait (*M* = 29), *p* = .035. There was no significant difference between single flashing condition and text/icon condition (*p* = .896).

A marginally significant effect was observed for pausing and then going around the vehicle, and the relatively low sample size for survey research suggests that the reason this is not significant is because of a power issue (*n* = 46), and that concrete findings for pausing were observed in the large-scale survey found elsewhere in the final report. Interestingly, the observed effect in the simulation survey for waiting was not observed in the large-scale survey, suggesting that direct experience with the simulated shuttle, one's previous behavior behind the simulated shuttle (e.g., the desire to maintain consistency between behavior and reported attitude) or the presence of in-person observers affected participants' report on their likelihood of waiting behind the shuttle.

5.5 Conclusions

The research questions focused on whether there were observable differences in driver performance between the three external human-machine interfaces (eHMIs), one being the double flashing "hazard" condition used in the MCM in Rochester, MN, USA, another being a more traditional single flashing condition imitating a turn signal in human-driven vehicles, and another being a text/icon LED condition indicating a pedestrian is present. The analysis on driver behavior indicates that, when considering both unsignalized and signalized stops together, there is significantly better driver performance in the text/icon condition in terms of fewer multiple threat passes and increased waiting behind the shuttle compared to the hazard signal condition, and that the single flashing condition tended to be in the middle of the other two conditions in terms of safety metrics. This pattern of performance in stopping and multiple threat passing may also have resulted in greater average minimum distance between the simulated MCM and the participant vehicle during pedestrian stops for the text/icon condition relative to the hazard signal condition, although there was also greater average distance between the two vehicles in the single flashing signal condition compared to the hazard condition. In terms of interpretability, there tended to be a perception that the hazard signal system represented a parking or loading/unloading vehicle compared to the other signal systems, and that the single flashing and text/icon condition were more likely to be perceived to represent a turning vehicle compared to the hazard signal condition. Participants reported being less likely to wait behind the hazard signaling conditions relative to the other two conditions, and a similar yet marginal effect was observed for pausing and going around. These patterns of self-reported perception in the survey support the observed pattern of driver performance results in the simulator.

Chapter 6: Discussion and Conclusions

6.1 Project Aims

This project aimed to assess driver behavior in proximity to the Med City Mover (MCM) LSAV operating within downtown Rochester, MN, particularly regarding when the shuttle was yielding to pedestrians at signalized and unsignalized crosswalks. Operators of the MCM reported experiencing elevated risk of other drivers overtaking the shuttle during general operations; noting there was a further increased risk of overtaking when the shuttle was yielding to a pedestrian creating the possibility of a multiple threat pass. As a result, the research team aimed to directly measure this noted overtaking behavior and whether it occurred at higher rates around the MCM relative to other vehicles and determine/test potential explanations and methods to reduce the risk of overtaking. These research objectives were broken down and presented as three key research aims:

1. Quantitatively verify elevated overtaking rates of the MCM shuttle observed by shuttle operators.
2. Determine potential causes leading to the elevated overtaking behavior if this higher rate was observed.
3. Design and test recommendations for improving driver behavior and reducing overtaking risk, if necessary.

To assess each of these research aims, the research team conducted a series of studies employing a combination of methods. These studies included: interviews with shuttle operators and manufacturers, field data observations of driver behavior, experimental methods at the state fair and crowdsourcing studies to assess driver perception of the shuttle, and a driving simulation study to assess driver performance and perception of proposed external human-machine interface (eHMI) designs, including turn signals and LED signs.

6.2 Operator and Manufacturer Interviews

The research team conducted a total of 6 interviews with both representatives of AV manufacturers (n = 4) and MCM operators (n = 2) via Zoom. The transcripts of these interviews were then reviewed for areas of interest with key interest focused on shuttle operation and interaction with other drivers or pedestrians. The primary purpose of these interviews with the AV manufacturers was to identify essential components of various safety approaches vendors took during their design, development, and AV operation. Through these interviews with manufacturers, it was discovered that each manufacturer's primary interest was in addressing "first and last mile" transportation for individuals; however, they noted that current radar-based technology was a key limitation they faced regarding regulations and environments in which the shuttle can be deployed. They often noted that because of the technological limitations there was a need to incorporate human factors research in consideration of how the shuttle operates and interacts with other drivers/pedestrians.

Interviews with the shuttle operators were primarily geared toward addressing this limitation and the need for further understanding of how the shuttle operates and interacts with the expectations of other drivers/pedestrians. Both interviewed MCM operators noted this gap between the shuttle's operations and other drivers' and pedestrians' expectations during use in the field, which they attempted to bridge via human-human interactions with the use of hand gestures to other drivers and pedestrians. Operators also further verified the issue of increased overtaking of the shuttle, which they attributed to both the overall speed of the shuttle relative to nearby traffic as well as incorrect expectations of the shuttle's actions by the public.

6.3 Field Data Observations

To validate observed overtaking of the shuttle noted by the operators, the research team conducted a field study in which team members observed driver behavior both in proximity of the MCM and independent of the MCM (i.e., around other human-driven vehicles). This behavior was collected via a series of staged crossings at both signalized and unsignalized crosswalks as well as by riding the MCM or driving a researcher vehicle along the MCM's route. Key measurements of interest from these observations included yielding rates, frequencies of queueing behind the yielding vehicles, and overtaking rates and multiple threat pass/attempt rates. Analysis of these results prioritized the risk posed to pedestrians with the MCM sharing the road with other human-driven vehicles with a secondary emphasis of risk to other drivers and general traffic disruption.

Through the analysis of these field observations, it was observed that there was a minimal direct risk between the MCM and pedestrians, as the MCM yields at a rate significantly higher than other drivers at both signalized and unsignalized crosswalks. While the MCM itself does not pose any additional **direct** risk to pedestrians, there is an increased **indirect** risk to pedestrians because of changes in risky human driver activity in proximity to the MCM shuttle. This indirect risk to pedestrians is indicated via the increased rate of overtaking and multiple threat behavior observed in proximity of the MCM relative to the rate observed near typical human-driven vehicles on the same route/location. The research team hypothesizes that this behavior may be due to the following reasons: The lower speed of the MCM relative to the general speed of traffic, the MCM's rule to not turn right on red at traffic signals, and/or due to a miscommunication of behavioral intentions between the MCM and other drivers (e.g., the MCM's "yielding to pedestrians" indications being misunderstood).

6.4 State Fair and Crowdsourcing Studies

Based on the interviews and the field data, the research team proposed that the shuttle's relative speed and signaling eHMI may influence overtaking tendencies when the shuttle is yielding to a pedestrian. However, these differing factors cannot be disentangled from the unique appearance and automated nature of the shuttle in the field. To directly ascertain the effect shuttle speed has on overtaking behavior, a study was conducted at the Minnesota State Fair in 2022, experimentally manipulating speed and appearance. The results indicated that the speed of the lead vehicle, both the shuttle and a generic van, was significantly related to the overtaking tendency of a participant. Participants were more likely to overtake the lead vehicle when the vehicle was traveling slower, indicating that the speed at which the MCM operates was highly likely to contribute to the increased rate of overtaking in the field.

A survey-based study conducted via Qualtrics, aimed to assess the contribution of eHMI designs or signal methodology on overtaking and other risky behaviors. Participants were presented a shuttle attempting to turn right at a signalized intersection with four different potential signaling eHMIs: turn signal, hazard, PED X-ING message, and PEDESTRIAN CROSSING message. Participants reported their most likely behavior in response to the eHMI and their best interpretation of the behavioral intent communicated by the eHMI. Results indicated the lowest rate of waiting behind the shuttle for the hazard signaling design, while also indicating that the hazard signaling was the least clear at indicating that the vehicle was intending to turn right at the intersection. These results strongly suggest that the employed signal design for yielding to a pedestrian for the MCM in Rochester, the hazard signaling eHMI, may lead to driver miscomprehension of the shuttle's intended behavior, leading to increased overtaking risk.

6.5 Simulation Study

To directly investigate the effect the signaling eHMI has on driver performance following the MCM, a simulation study was designed to analyze three signaling designs at both signalized and unsignalized intersections. Each participant experienced one of the three signaling conditions during the study at intersections with and without a pedestrian present. It was found that the hazard signaling condition had the worst or riskiest driver performance in terms of higher overtaking behavior and lower waiting duration behind the shuttle, while the text/icon LED signaling condition had the lowest rate of shuttle overtaking and highest waiting duration. This decreased rate of overtaking for the text/icon LED signaling condition was related to a greater observed minimum distance between the participant vehicle and the simulated MCM as well as the participant vehicle and the simulated pedestrian. These results indicated that signaling design affects driver performance, thus changing the design to one that directly communicates the LSAV's intentions (e.g., text/icon LED indicating stopping for a pedestrian) can potentially reduce the risk to the shuttle due to overtaking, as well as the indirect risk to the pedestrians.

6.6 Recommendations, Limitations, and Future Work

6.6.1 Recommendations

The research presented highlights two key areas in which nearby driver performance around an LSAV such as the MCM, particularly regarding shuttle overtaking, can potentially be improved.

Speed of vehicle — The first area, as shown via the experimental study conducted at the Minnesota State Fair, is through an increase in the MCM shuttle's overall speed at which it travels to better match that of the local traffic. It was shown that lower speeds, regardless of lead vehicle type, result in a tendency to want to pass the lead vehicle. While the research team recommends increasing the shuttle's speed to better match the natural flow of traffic as a potential method in reducing overtaking risk, it is acknowledged that speed of the vehicle is limited by the capabilities of the vehicle's design and employed technology. Given the increase in lane change and overtaking by drivers around the MCM relative to drivers around the human driven researcher vehicle, the greater amount of risky overtaking maneuvers by human drivers at crossings when the MCM was involved, and the simulation data indicating that low automated vehicle speeds are a primary factor in eliciting this risky behavior, it may be reasonable to separate mixed traffic involving low-speed automated vehicles from moderate-to-high volume traffic corridors, particularly with significant pedestrian traffic present or significant average speed differentials (e.g., speed limit > 15mph).

Signaling eHMIs — The second, and more actionable, area in which driver performance can potentially be improved is via modifications to signaling eHMI employed by the MCM shuttle. In the crowdsourcing study and the driving simulation study, the results indicated confusion regarding the currently employed hazard signaling system used when manually yielding to pedestrians. There appears to be miscommunication between the shuttle and drivers when presenting the hazard signals in the LSAV, which results in an increased tendency to pass the shuttle. By modifying the signaling system to a single turn signal, or no signal when yielding while going straight, there was a reduced rate of overtaking. There was a further reduction in overtaking choice when a message indicated that the shuttle was yielding to a pedestrian via an on-board LED screen. As a result, the research team recommends using a turn signal or no signal outside the standard brake lights, more consistent with how other vehicles signal in similar yielding situations. The further addition of a system that can communicate more detailed information regarding the shuttle's behavior, such as an LED screen and pedestrian crossing text/icon, could result in further improved understanding of the shuttle's actions and reduced overtaking behavior.

6.6.2 Limitations

There are study limitations to consider regarding the field data portion of this research, particularly regarding site selection and roadway modifications during the data collection period. Due to the MCM route in Rochester, there were only a few locations for yielding scenarios to occur in which pedestrians and the shuttle could legally conflict (e.g., marked crosswalk) with the MCM yielding the right of way. Thus, the research team was limited in site selection options for staged crossings. This limitation was compounded further via frequent and ongoing construction present within the downtown Rochester area at the time (spring/summer 2022). The construction often limited or redirected the flow of traffic and in some cases reduced the number of lanes, limiting the opportunity for overtaking behavior by other vehicles. While construction and site selection were limiting factors for data collection, the driver behavior observed remained consistent regarding overtaking rates throughout the data collection period.

Additional limitations to the field data observation portion of the research included coder variability. The visible characteristics of coders and staged pedestrians, such as racial differences or dark skin tones, could have also influenced driver behavior with lower yielding rates to these coders and pedestrians compared to white or light-skinned coders (Goddard et al., 2015; Coughenour et al., 2017). Similarly, gender differences across coders, staged, and natural pedestrians also could have influenced driver behavior with female pedestrians receiving higher yielding rates (Zafri et al., 2022). Finally, the demeanor of the staged pedestrian may also have varied across research team members, with some team members approaching the crosswalk with greater assertiveness than others, thus influencing driver decision making (Shaon et al., 2018).

Limitations in the state fair experimental study and the driving simulation study include a potential mismatch between the study samples and the driver populations of interest, because most recruited participants were local to the Twin Cities metropolitan area and therefore may not exhibit precisely the same attitudes, perceptions, and behaviors of those in Rochester or in other locations that have an LSAV or will have an LSAV in the future. The research team anticipates that the general pattern of results will generalize to most populations of interest, but this is an assumption. Furthermore, the methods in the state fair and driving simulation also use experimentally constrained, artificial, and simulated scenarios that may not reliably translate to the real world, especially in terms of the strength of the observed effects.

6.6.3 Future Work

Future research should consider the findings and limitations of this study to further optimize communication between the MCM and nearby drivers or pedestrians to reduce the risk of drivers overtaking the shuttle, which puts all parties at risk. Similar reassessment of shuttle communication to nearby drivers should be considered in other scenarios and shuttle behaviors, such as emergency stops or manual takeover of the shuttle by the onboard operator. The information collected during interviews with operators highlights how their decisions to manually take over and their communication methods with drivers of manually driven vehicles (e.g., waving or other hand gestures) are an important component of human-in-the-loop automation. Future studies should examine how integral on-board operators' social interactions and anticipatory responses are for safe and efficient behavior of LSAVs and human-driven vehicles and how feasible automated shuttle operations may be without them.

This work should include further examine eHMI signaling methods employed by the shuttle and practical implementation of further communicative features, such as an on-board LED screen capable of presenting various messages to following vehicles. The exact format and content on the screen, and the need for its use awaits further research (e.g., text vs. icon, information vs. directives, and low-speed context vs. higher-speed context). Future studies examining these signaling methods can take advantage of work done with eHMIs on automated vehicles designed to communicate to pedestrians and validate whether the results obtained in vehicle-pedestrian communication also translate to vehicle-driver communication, such as the superiority of text-based (Bazilinskeyy et al., 2019) or picture-based (Othersen et al., 2021) communication signals to light patterns, the preference for direct commands over communications of vehicle status (Ackermann et al., 2019), or egocentric messages ("go ahead") relative to allocentric messages ("braking now") (Eisma et al., 2021). Because drivers and pedestrians are adopting different modes of transportation, and research for driver-directed eHMIs is relatively sparse, it is not guaranteed that the same design advantages will hold true for drivers as they do for pedestrians.

The findings of this study highlighting the indirect risks to pedestrians due to the presence of LSAV should be expanded to other regions of the country and in other types of corridors to determine the extent to which risky overtaking behaviors are found beyond the deployment observed in this study. The location of the MCM in downtown Rochester provided an innovative examination of multi-modal interactions near a LSAV in a relatively pedestrian-heavy corridor. However, the traffic speeds in this area may be lower than other potential deployment sites and could underestimate some of the risks that pedestrians and other non-motorists, such as bicyclists, face as more LSAV deployments are launched. The methods employed in this study can be leveraged and expanded to further the understanding of the benefits and potential unintended consequences of LSAV deployments. Finally, the opportunities, constraints, and implications of recommendations for separating low-speed automated vehicles from moderate-to-high volume traffic corridors should be an area of future exploration and research study.

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Appendix A: Vendor Interview Questions

Topics:

- high level around what their focus is with safety and what they consider to be other road users (bikes, peds, scooters, etc.).
- understand how they are approaching safety and where they are looking to make advancements.
- Is the focus to first and foremost, not run into/crash into anything, regardless of other safety impacts that could occur?
- Are they evaluating their vehicle and technology performance with a multi-modal lens for all roadway users, not just the safety of those in their vehicles?

Introduction Questions

1. Why is your company interested in advancing CAV technology and what specific value(s) are you trying to provide?

Safety Questions

1. How do you prioritize your safety focus? Is the first focus to avoid a crash? What kinds of crashes are you focused on avoiding?
2. What do you think are the greatest challenges for approaching safety between AVs and drivers of manually driven vehicles?
3. Do you have an engineering team conducting traffic safety analysis? If so, what is their primary focus?
4. What role does technology play in safety? Similarly, what role do the aboard operators play in safety? Do you foresee either of these relationships changing in the future?
    1. If so, how?
5. What qualifications are required for operators to have? What additional training is provided?

Multimodal Safety

6. Who is your focus on for safety of operations? Passengers in your vehicles? Other roadways users in cars, on bicycles, walking or rolling?
    1. How do you evaluate safety performance?
    2. How do you evaluate safety performance from a multimodal lens?
7. How do you approach safety with other vulnerable road users, specifically bikes, peds, and scooters?
8. Do you conduct any engineering traffic safety analysis for all roadways users?
9. What do you think are the greatest challenges for approaching safety between AVs and pedestrians?
10. What has been your approach to date to reduce the risks of multiple threat passes involving your vehicles, drivers of manually driven vehicles, and crossing pedestrians?
11. What design changes or technology advancements do you think are necessary to address these challenges?
12. Any other ideas you have for changing the design, markings, feedback of the shuttle to make everyone else safer?

Appendix B: Operator Interview Questions

General Job-Related Questions and Training

1. Can you walk me through what your job looks like?
2. What is the most challenging part of your job?
3. Can you describe your training?
    1. Specifically, what training did you receive about how to interact with pedestrians?
    2. What qualifications do you think operators should have? What additional training should be provided, if any?
4. What things that happen on the road are you keeping an eye out for while the shuttle is in operation?
5. What things most frequently require you to manually take over operation from the shuttle?
        1. Can you describe an example that happened recently?
    2. Or engage emergency brake
    3. How do you diagnose the problem?
    4. What do you do to resolve or fix the problem?
6. What role does technology play in safety? Similarly, what role do the aboard operators play in safety? Do you foresee either of these relationships changing in the future?
    1. If so, how?
7. What areas do you see that need to be improved for the shuttle?

Other Driver Focused Questions

8. Can you talk about what it's like interacting with other drivers on the road?
9. How often do you find yourself directing traffic around the shuttle?
10. How fast do you think the shuttle should be traveling? Do you think the speed of the shuttle influences the behavior of other drivers and the flow of traffic?

Pedestrian Focused Questions

11. How has your approach to stopping for pedestrians changed over time?
12. What feedback, if any, have you received from pedestrians and passengers regarding interactions with pedestrians?
13. How has this interaction changed over time?
14. Can you describe the interaction with pedestrians and other drivers when you encounter both at once?
15. How frequently do you find the shuttle or yourself yielding to a pedestrian and how often does another driver overtake you while yielding?
16. What do you think would help make pedestrians safer during these interactions?
17. What do you think would help drivers be less risky around the shuttle, particularly regarding pedestrians?
18. Any other ideas you have for changing the design, markings, feedback of the shuttle to make you and everyone else safer?

Appendix C: Electronic Field Data Collection Tools

HumanFIRST Laboratory
SAFE CROSSING PROTOCOL

Safe Crossing Protocol

This protocol should be read aloud before each staff members serves as the staged pedestrian for each coding section (i.e., 10 staged crossings).

- Always stay alert and be aware of traffic from all sides and all lanes.
- Follow the Safety Crossing Instructions closely.
- Always ensure that the oncoming vehicle is clearly yielding or stops before proceeding.
- Make eye contact and signal to the driver that you intend to cross in front of them.
- Do not put yourself in an unsafe situation. If a vehicle is traveling too fast or too close, step back to a safe position.
- On multi-lane roads, always stop at the lane line, search and make sure the next lane is clear.
- Above all, do not attempt to cross if it cannot be done safely!

Figure C1. Safe Crossing Protocols for unsignalized and signalized intersections

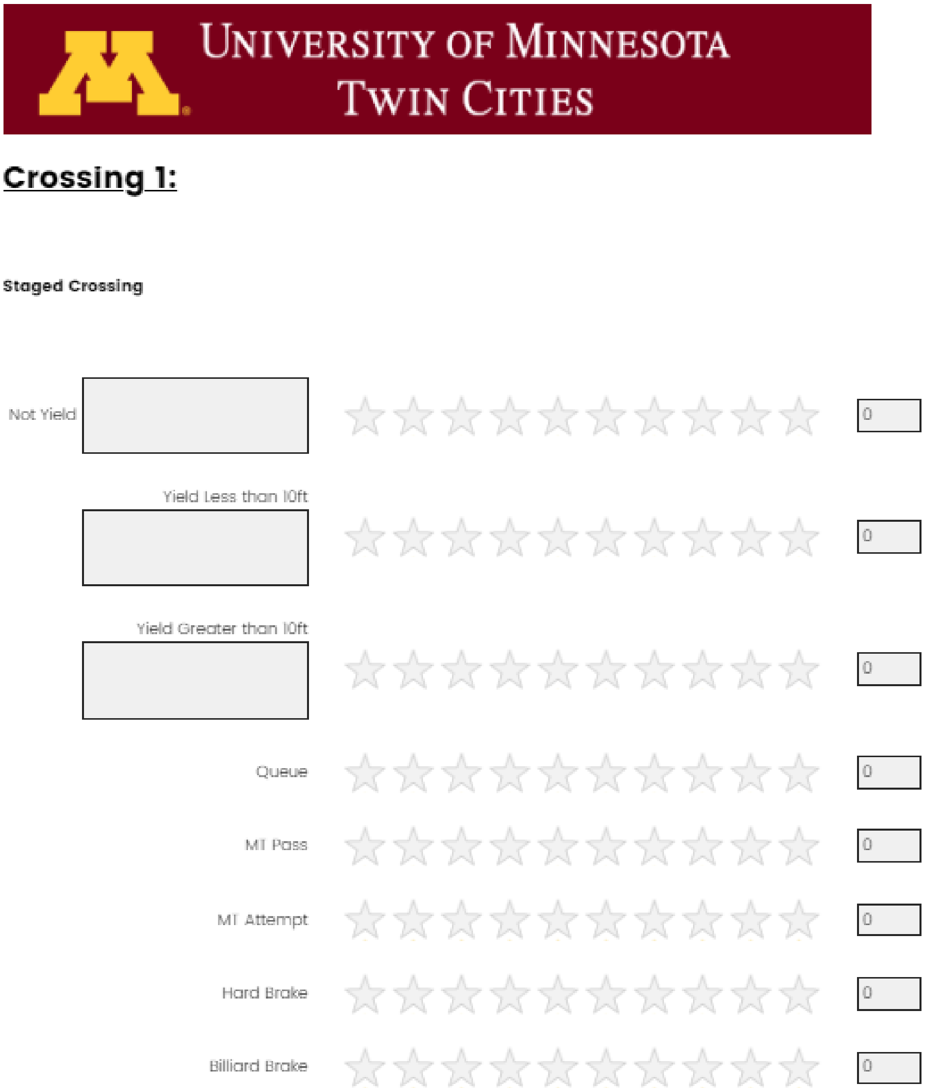


Figure C2. Qualtrics Unsignalized Data Collection Electronic Entry for Staged Crossings

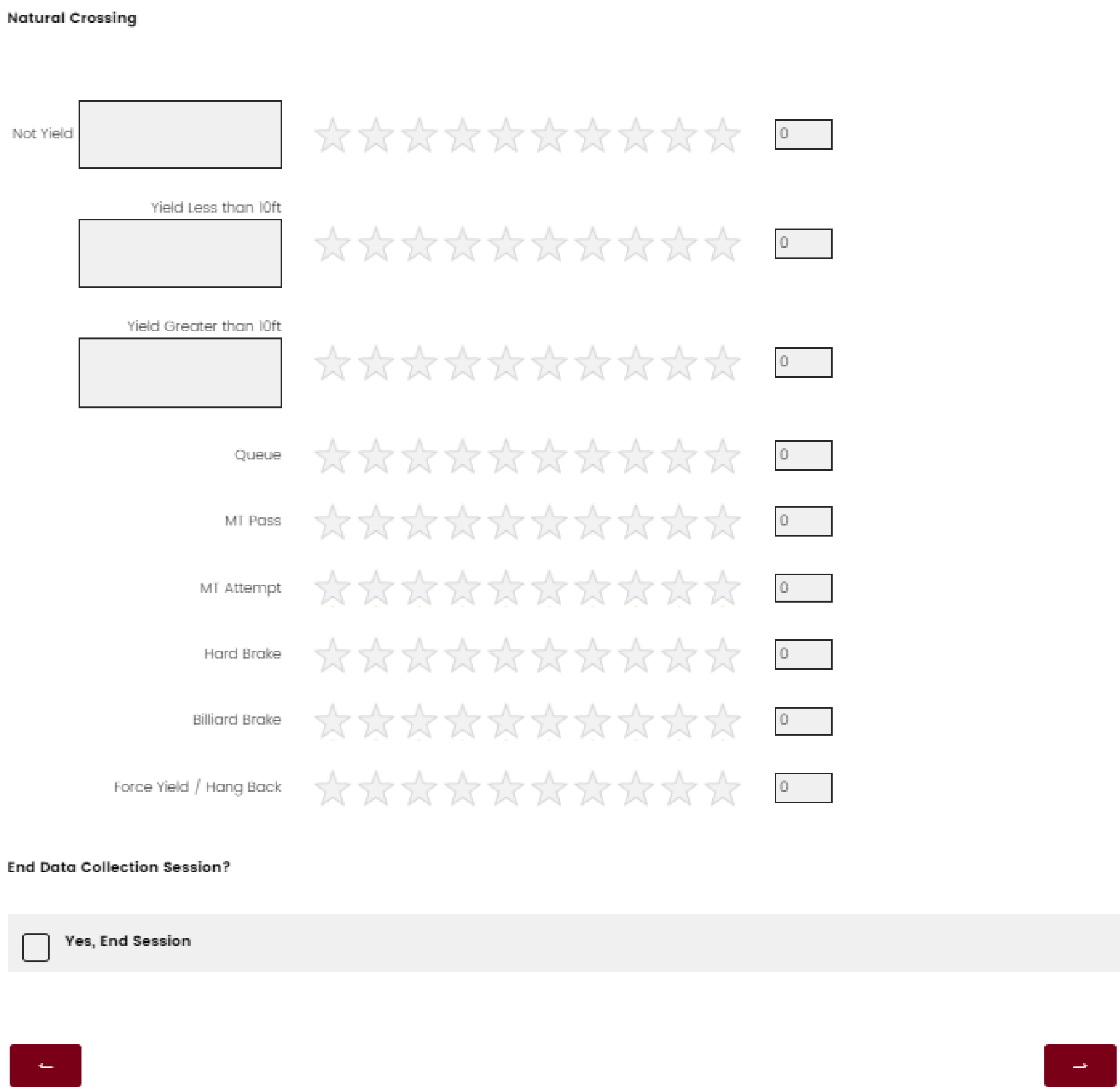
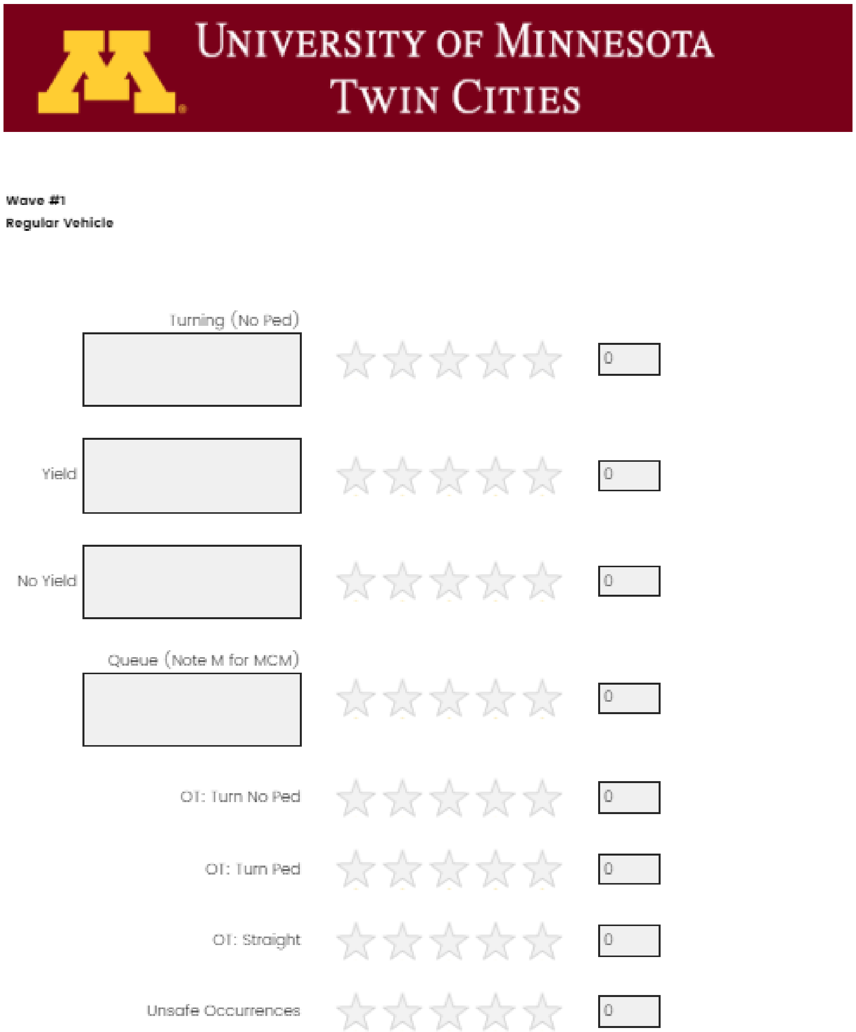


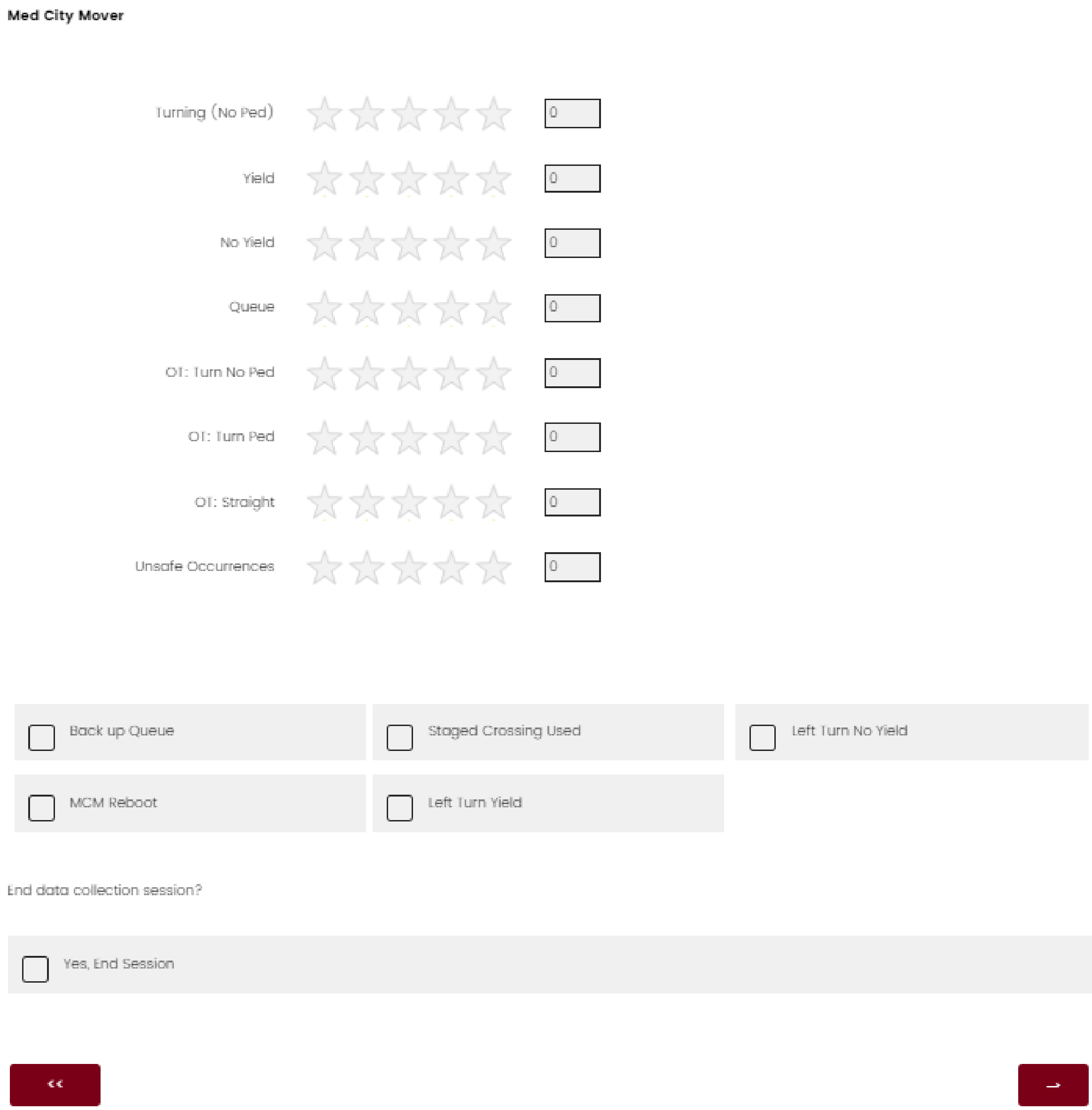
Figure C3. Qualtrics Unsignalized Data Collection Electronic Entry for Natural Crossings


University of Minnesota
Twin Cities

Wave #1
Regular Vehicle

Turning (No Ped) 0
Yield 0
No Yield 0
Queue (Note M for MCM) 0
OT: Turn No Ped 0
OT: Turn Ped 0
OT: Straight 0
Unsafe Occurrences 0

Figure C4. Qualtrics Signalized Data Collection Electronic Entry for Regular Vehicles



Med City Mover

Turning (No Ped)	☆☆☆☆☆	0
Yield	☆☆☆☆☆	0
No Yield	☆☆☆☆☆	0
Queue	☆☆☆☆☆	0
OT: Turn No Ped	☆☆☆☆☆	0
OT: Turn Ped	☆☆☆☆☆	0
OT: Straight	☆☆☆☆☆	0
Unsafe Occurrences	☆☆☆☆☆	0

☐ Back up Queue ☐ Staged Crossing Used ☐ Left Turn No Yield

☐ MCM Reboot ☐ Left Turn Yield

End data collection session?

☐ Yes, End Session

‹‹ →

Figure C5. Qualtrics Signalized Data Collection Electronic Entry for MCM

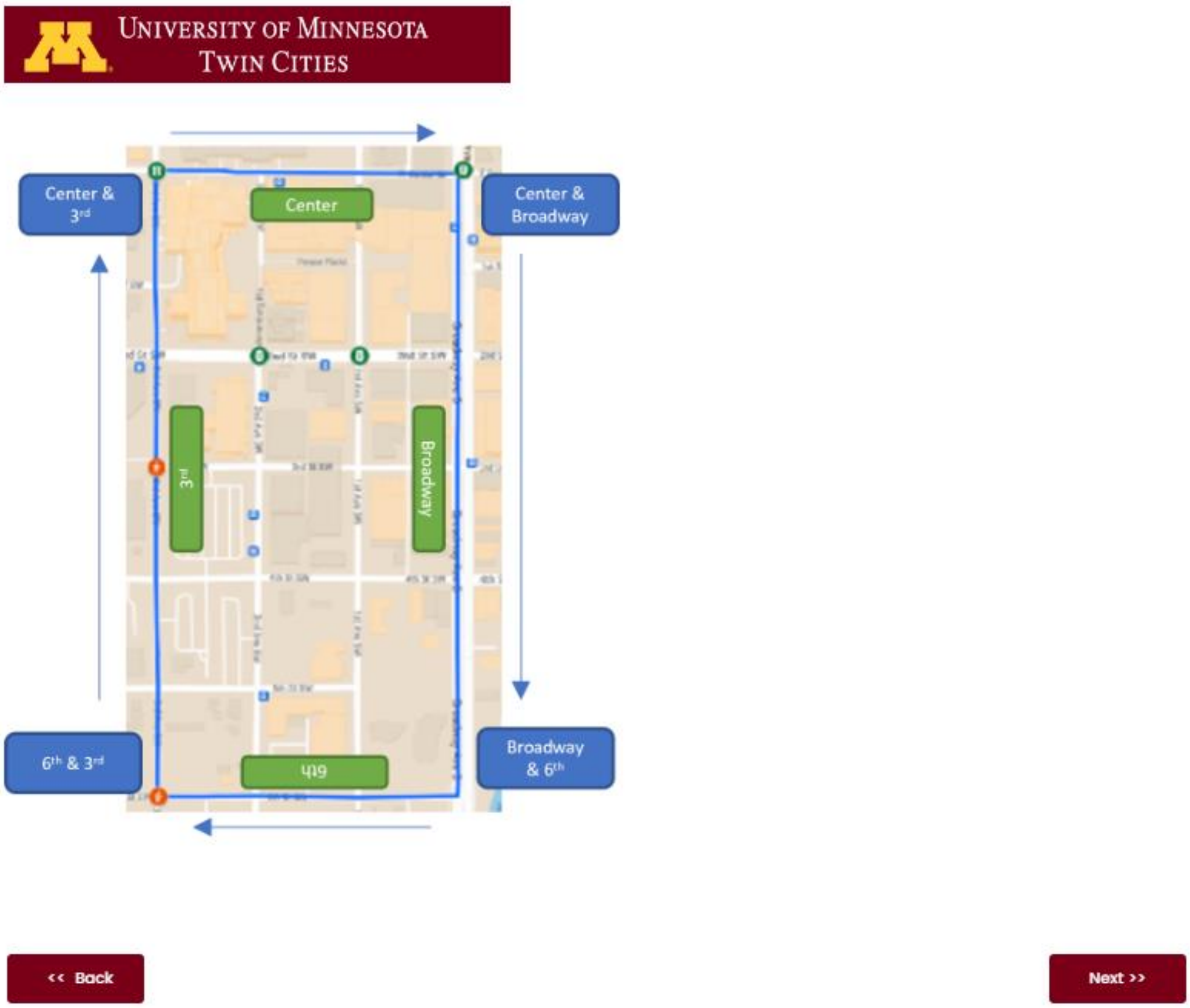


Figure C6. Qualtrics Onboard Data Collection Reference Map

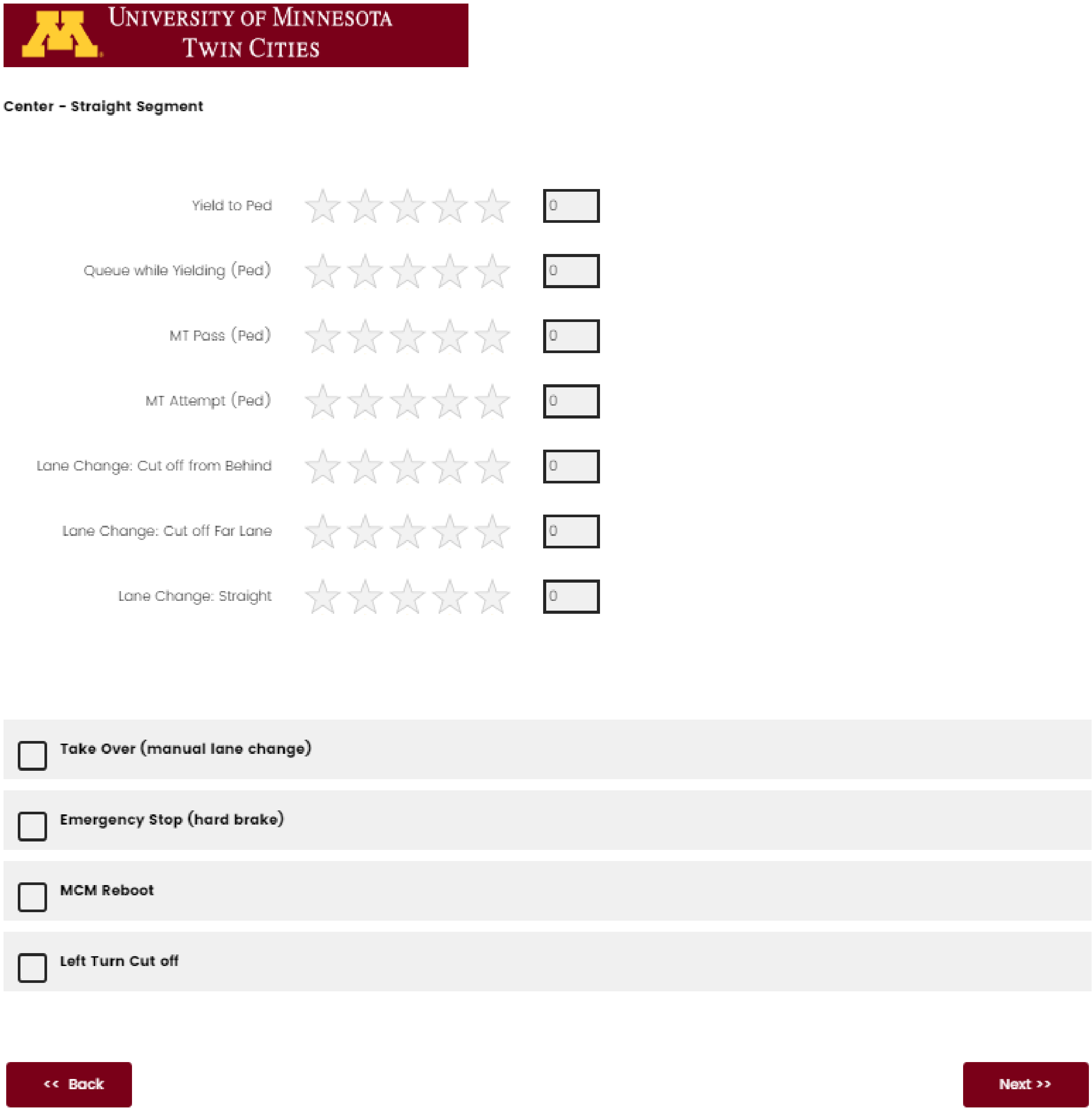
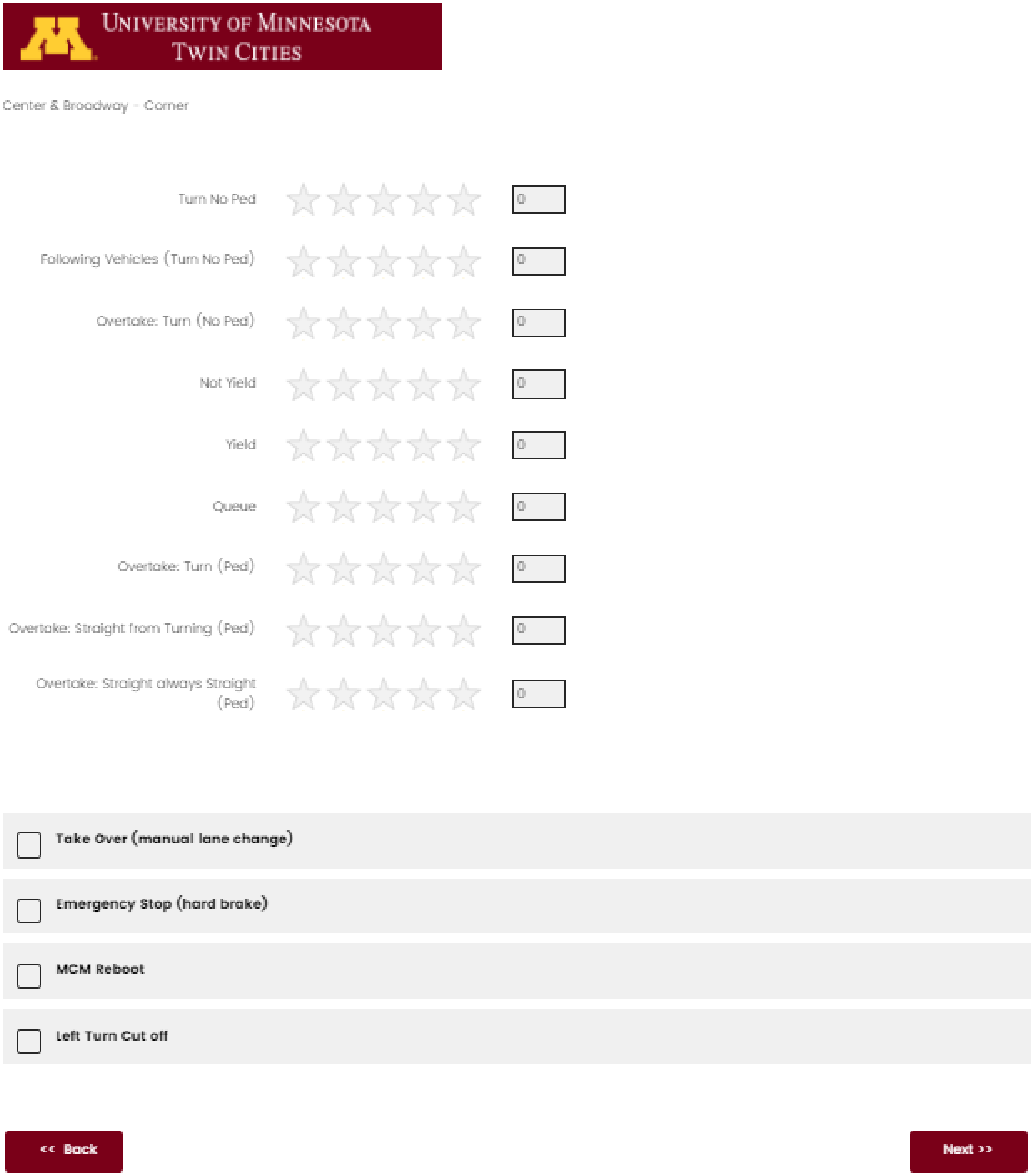


Figure C7. Qualtrics Onboard Data Collection for Center Ave Straight Segment



University of Minnesota
Twin Cities

Center & Broadway - Corner

Turn No Ped	0
Following Vehicles (Turn No Ped)	0
Overtake: Turn (No Ped)	0
Not Yield	0
Yield	0
Queue	0
Overtake: Turn (Ped)	0
Overtake: Straight from Turning (Ped)	0
Overtake: Straight always Straight (Ped)	0

- [ ] Take Over (manual lane change)
- [ ] Emergency Stop (hard brake)
- [ ] MCM Reboot
- [ ] Left Turn Cut off

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Figure C8. Qualtrics Onboard Data Collection for Center & Broadway Turning Segment

Appendix D: Driving Simulation Questionnaires

Pre-Study Demographic and Driver Behavior Questionnaires

General Questionnaire

Demographics

1. Please enter your age:
2. What is your gender?
    - Male
    - Female
    - Other

3. What is your highest level of education?
    - Some high school
    - High school diploma or GED
    - Associate degree
    - Some college, no degree
    - Bachelor's degree
    - Graduate or professional degree
    - Other

4. What is your ethnicity?
    - Hispanic or Latino
    - Not Hispanic or Latino

5. What is your racial background?
    - American Indian or Alaska Native
    - Asian
    - Black or African American
    - Hawaiian or Other Pacific Islander
    - White
    - Multiracial
    - Other

6. Please enter your zip code: ___________

7. Do you consider yourself to live in an urban, suburban, or rural area?
    - Urban
    - Suburban
    - Rural

8. In which area(s) do you drive the most often?
    - Urban
    - Suburban
    - Rural

Personal Involvement Questions

1. 1. How often do you use public transportation (e.g., buses or light rails)?

0 - Never	1 - Hardly Ever	2 - Occasionally	3 - Quite Often	4 - Frequently	5 - Nearly All the Time

2. How happy are you with the state of technologies in today's vehicles?

1 Not happy at all	2	3	4	5 Absolutely happy

3. How important is it for you that vehicle technologies be changed to improve safety??

1 Not important at all	2	3	4	5 Very important

4. How important is it for you that roadway designs are changed to improve safety?

1 Not important at all	2	3	4	5 Very important

5. How happy are you with the state of Minnesota roadways?

1 Not happy at all	2	3	4	5 Absolutely happy

Personal Involvement Questions

1. Ignore a yield sign and almost collide

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

2. Fail to notice pedestrians crossing

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

3. Underestimate the speed of an oncoming vehicle

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

4. Get into the wrong lane when approaching

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

5. Fail to check your mirrors before pulling

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

6. Fail to notice a pedestrian

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

7. In a line of cars nearly hit the car in front of you

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

8. Brake too hard on a slippery road

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

9. When turning right nearly hit a cyclist

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

10. Hit something when backing up

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

11. Attempt to pass a vehicle that you hadn't noticed was signaling

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

12. Intending to drive to destination A, realize you are en route to B

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

13. Attempt to swerve around another vehicle to pass

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

14. Forget where you parked your car

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

15. Realize you have no clear recollection of the road

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

16. Switch on one thing instead of another

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

17. Attempt to leave a parking space in the wrong gear

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

18. Drive especially close to or flash the car in front of you

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

19. Get involved in unofficial races

0	1	2	3	4	5
Never	Hardly	Occasionally	Quite Often	Frequently	Nearly All the Time

20. Deliberately disregard the speed limit

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

21. Feel angered by another driver's behavior

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

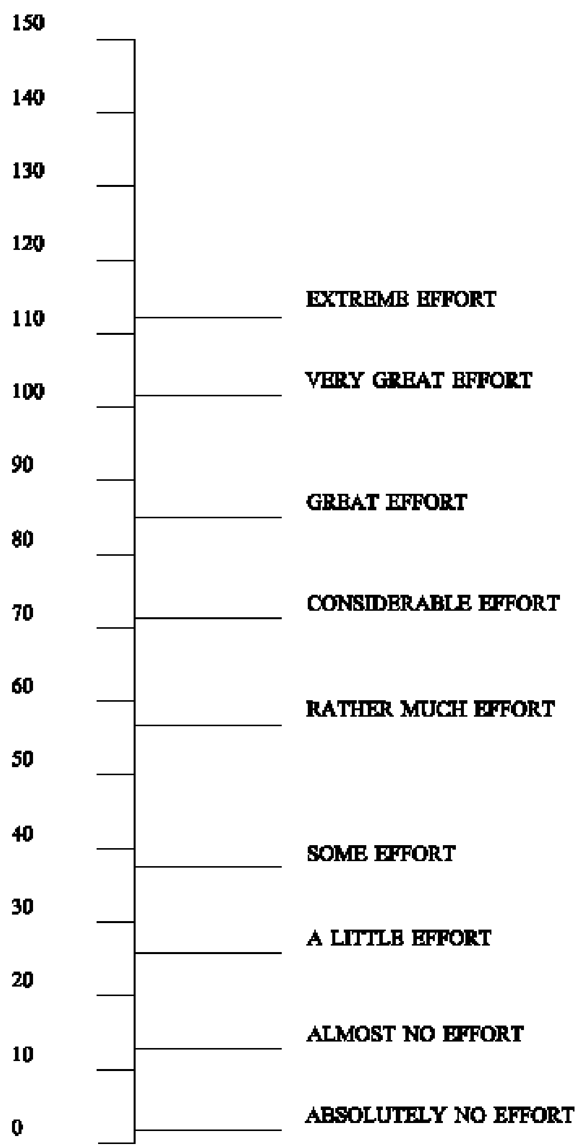
22. Drive over the legal blood-alcohol limit

0 Never	1 Hardly	2 Occasionally	3 Quite Often	4 Frequently	5 Nearly All the Time

Post-Study Self-Report Questionnaires

Rating Scale Mental Effort

Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task you've just finished



Post Study Self-Report Questionnaire:

1. Rank the effectiveness of each aspect in signifying an autonomous vehicle:
    - Blue bar
    - Text only
    - Icon only
    - Implemented flashing lights
    - Improved flashing lights
    - LCD message
    - Vehicle wrap/color

2. Is this the first time that you have ever seen (either in person or via video/picture) the unique, orange and purple shuttle?
    - Yes
    - No

[If “Yes” to Question 3, answer Question 4, 5, if no skip to Question 6]

3. Where have you previously seen or learned about this unique, orange/purple shuttle?
    - Media or news
    - Rode on the shuttle
    - Have seen it while I was driving

- Have seen it while I was walking
- Other (please specify)

4. Where did you see, ride on, or drive near the shuttle in the past?
    - Minneapolis, MN
    - Saint Paul, MN
    - White Bear Lake, MN
    - Rochester, MN
    - Duluth, MN
    - Grand Rapids, MN
    - Other locations

5. Do you think the shuttle is a good idea?
    - Absolutely
    - Probably
    - Unsure
    - Probably Not
    - Definitely Not

6. Can you describe your interpretation of the following scenarios, what you would do as a driver following each shuttle, and fill out the system usability scale:

(the order of scenarios A, B, and C will be presented at random)

***Scenario A*:** The shuttle approaches a signalized intersection in which the right light on the back of the vehicle begins to flash. The vehicle then stops prior to turning through the intersection.

What do you think the shuttle is doing?

- Turning
- Emergency braking
- Parking
- Loading/Unloading
- Yielding/Stopping for a pedestrian
- Malfunctioning
- Other (please specify)

You intend to turn right at the intersection. What would you do next as a driver?

- Wait behind the shuttle until it begins to move
- Pause a few seconds and then go around the shuttle
- Go around the shuttle
- Other (please specify)

Scenario A - Signage Usability Scale (SUS)

1. I think that I would like to use this system frequently

1 Strongly Disagree	2	3	4	5 Strongly Agree

2. I found the system unnecessarily complex

1 Strongly Disagree	2	3	4	5 Strongly Agree

3. I thought the system was easy to use

1 Strongly Disagree	2	3	4	5 Strongly Agree

4. I think that I would need the support of a technical person to be able to use this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

5. I found the various function in this system were well integrated

1 Strongly Disagree	2	3	4	5 Strongly Agree

6. I thought there was too much inconsistency in this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

7. I would imagine that most people would learn to use this system very quickly

1 Strongly Disagree	2	3	4	5 Strongly Agree

8. I found the system very cumbersome to use

1	2	3	4	5
Strongly Disagree				Strongly Agree

9. I felt very confident using the system

1	2	3	4	5
Strongly Disagree				Strongly Agree

10. I needed to learn a lot of things before I could get going with this system

1	2	3	4	5
Strongly Disagree				Strongly Agree

***Scenario B*:** The shuttle approaches a signalized intersection in which the right light on the back of the vehicle begins to flash. As the vehicle stops prior to turning through the intersection, both rear lights begin to flash.

What do you think the shuttle is doing?

- Turning
- Emergency braking
- Parking
- Loading/Unloading
- Yielding/Stopping for a pedestrian
- Malfunctioning
- Other (please specify)

You intend to turn right at the intersection. What would you do next as a driver?

- Wait behind the shuttle until it begins to move

- Pause a few seconds and then go around the shuttle
- Go around the shuttle
- Other (please specify)

Scenario B - Signage Usability Scale (SUS)

11. I think that I would like to use this system frequently

1 Strongly Disagree	2	3	4	5 Strongly Agree

12. I found the system unnecessarily complex

1 Strongly Disagree	2	3	4	5 Strongly Agree

13. I thought the system was easy to use

1 Strongly Disagree	2	3	4	5 Strongly Agree

14. I think that I would need the support of a technical person to be able to use this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

15. I found the various function in this system were well integrated

1 Strongly Disagree	2	3	4	5 Strongly Agree

I thought there was too much inconsistency in this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

17. I would imagine that most people would learn to use this system very quickly

1 Strongly Disagree	2	3	4	5 Strongly Agree

18. I found the system very cumbersome to use

1 Strongly Disagree	2	3	4	5 Strongly Agree

19. I felt very confident using the system

1 Strongly Disagree	2	3	4	5 Strongly Agree

20. I needed to learn a lot of things before I could get going with this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

***Scenario C*:** The shuttle approaches a signalized intersection in which the right light on the back of the vehicle begins to flash. As the vehicle stops prior to turning through the intersection, the LCD screen in the back changes to show the following message and icon:

What do you think the shuttle is doing?

- Turning
- Emergency braking
- Parking
- Loading/Unloading
- Yielding/Stopping for a pedestrian
- Malfunctioning
- Other (please specify)

You intend to turn right at the intersection. What would you do next as a driver?

- Wait behind the shuttle until it begins to move
- Pause a few seconds and then go around the shuttle
- Go around the shuttle
- Other (please specify)

Scenario C - Signage Usability Scale (SUS)

21. I think that I would like to use this system frequently

1	2	3	4	5
Strongly Disagree				Strongly Agree

22. I found the system unnecessarily complex

1	2	3	4	5
Strongly Disagree				Strongly Agree

23. I thought the system was easy to use

1 Strongly Disagree	2	3	4	5 Strongly Agree

24. I think that I would need the support of a technical person to be able to use this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

25. I found the various function in this system were well integrated

1 Strongly Disagree	2	3	4	5 Strongly Agree

26. I thought there was too much inconsistency in this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

27. I would imagine that most people would learn to use this system very quickly

1 Strongly Disagree	2	3	4	5 Strongly Agree

28. I found the system very cumbersome to use

1 Strongly Disagree	2	3	4	5 Strongly Agree

29. I felt very confident using the system

1 Strongly Disagree	2	3	4	5 Strongly Agree

30. I needed to learn a lot of things before I could get going with this system

1 Strongly Disagree	2	3	4	5 Strongly Agree

Appendix E: Driving Simulation Signaling Systems

Figure E1. Double flashing signaling system (ON) at unsignalized intersection

Figure E2. Double flashing signaling system (OFF) at unsignalized intersection

Figure E3. Double flashing signaling system (ON) at signalized intersection

Figure E4. Double flashing signaling system (OFF) at signalized intersection

Figure E5. Single/No flashing signaling system at unsignalized intersection

Figure E6. Single/No flashing signaling system at (ON) signalized intersection

Figure E7. Text/Icon signaling system at unsignalized intersection

Figure E8. Text/Icon signaling system (turn signal - ON) at signalized intersection

Figure E8. Text/Icon signaling system (turn signal - OFF) at signalized intersection