Examination of driver behavior in response to bicyclist behaviors

SAFER SIM

SAFETY RESEARCH USING SIMULATION

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A Report on Research Sponsored by SAFER-Sim University

Transportation Center with matching funds provided by Toyota Motor Corporation

June 2016

Acknowledgements

We would like to thank National Advanced Driving Simulator staff members Alec Lavelle and David Heitbrink for their work in programming the bicycling events, Rose Schmitt and data collection staff for running participants and managing participant survey data and IRB documentation, Tim Brown for analytic support, and John Gaspar for assistance with study methodology related to final report preparation. We would also like to thank University of Iowa College of Public Health students Morgan Price and Clara Keum for their assistance with literature review and data coding. Finally, we would like to thank Susan Chrysler for her contributions to the initial concept and development of this project. This research was funded by the SAFER-Sim University Transportation Center with matching funds from Toyota Motor Company.

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Abstract

Bicyclists are at heightened vulnerability in the transportation system, compared to motor vehicle drivers, who have the advantage of being protected by the vehicle in which they drive. Intersections and trail crossings are particularly problematic, representing the majority of bicycle-motor vehicle crash locations. Non-intersections are important as well, though less frequent, as they have higher likelihood of fatalities, compared to intersection crashes. Therefore, the aim of this study was examine the influence of age, gender, and bicycle-specific infrastructure on driver performance in common bicycle-motor vehicle interactions.

This project utilized a priori literature and a naturalistic bicycling dataset to identify and develop common bicycle-motor vehicle interactions and circumstances leading to safety-critical events. These events were then tested with a between-subjects design in a high-fidelity driving simulator to examine driver performance. The tested events included an overtaking event with and without shared lane arrow markings, a right turn across path with a bicycle lane present, and a bicycle path mid-block crossing. All bicyclist avatars presented during these events were female.

A total of 48 participants completed the study. Results showed that participants in the shared lane arrows condition gave more space when overtaking, compared to the no shared lane arrow condition. Wait times and speed were found to vary by age in the right turn across path with a bicycle lane present event. No age or gender differences were found related to driving performance outcomes for the bicycle path mid-block crossing event. No collisions occurred between the bicyclist and motor vehicle for any of the three tested events. While these results are informative, further research is recommended to better understand the impact of age, bicyclist gender, and bicycle specific infrastructure, such as shared lane arrows and bicycle lanes, in relation to crash and injury outcomes.

Introduction

1.1 Background

With steady increases in bicycling in the United States and increased adoption of bicycle-specific infrastructure, it is important to understand how drivers respond to common bicyclist behaviors and bicycle-specific infrastructure. Bicycling-related hospitalizations involving motor vehicles have increased severity and burden, compared to those that do not involve motor vehicles, in terms of longer hospital stays, increased costs, and non-routine discharge dispositions and deaths (Hamann et al. 2013).

Motorist involvement in collisions with bicyclists increases the risk of fatal injury as much as 14-fold and risk of serious injuries as much as 5-fold compared to non-motor vehicle bicycle crashes (Rivara, Thompson, and Thompson 1997). Additionally, drivers are contributors in as many as 90% of all crashes (NHTSA 2015). Therefore, understanding driver behavior is paramount to the prevention of bicycle-motor vehicle crashes.

The primary objective of this project was to gain a better understanding of driver response to bicyclist behaviors through the convergence of epidemiological and naturalistic data to create simulated events to test driver performance. The project specifically focused on the impact of different infrastructure (bicycle lanes, shared lane markings, and bicycle paths) on driver response to bicyclists in typical settings and circumstances common to safety-critical events. Naturalistic bicycling data were coded and considered, along with a priori epidemiologic and observational studies, to identify these common settings and circumstances. From these data sources, three events were developed to examine driver response.

1.2 Research Objectives

1. Conduct a literature review to better understand bicycle-motor vehicle crash typologies and identify gaps in research.

2. Analyze a naturalistic bicycling dataset of Iowa bicyclists to understand how Iowa bicycling aligns with a priori literature, in terms of safety-critical events, and to gather relevant detail from these real-world data to be used in the design of the simulator events.

3. Develop and test driver performance in common safety-relevant bicycle-motor vehicle interactions and impact of bicycle-specific roadway design treatments.

Literature Review

A literature review was conducted to identify common crash characteristics of bicycle-motor vehicle crashes and key gaps in knowledge in this research area. The literature review is organized into the following sections: crash types, contributing crash factors, bicycle-specific infrastructure, and gaps in the literature.

2.1 Common Types of Bicycle Crashes

Several different crash typologies have been identified for categorizing bicycle crashes to allow for easier interpretation of crash characteristics and trends, as well as allowing for ease in developing and applying countermeasures. Cross and Fisher (1977) defined seven classes and 36 problem types for bicycle-motor vehicle crashes. Classes refer to the common crashes at the most general level, while the problem types are variations within each class. The most common class found was D, collisions that occur when a motorist overtakes a bicyclist travelling in the same direction. In the variety of problem types that made up class D, the motorist failed to judge the distance and passed too closely and in the process collided with the bicyclist. This class made up almost 38% of all fatal cases, and 10.5% of all non-fatal cases (Cross and Fisher 1977).

Of the 36 problems types, there were seven that made up 49% of fatal cases and 52% of non-fatal cases (Cross and Fisher 1977): 1) the most common and important problem type observed, making up almost 25% of all fatalities--motorists and bicyclists traveling in the same direction, motorist passes bicyclist to overtake, collision results mostly from poor bicycle lighting, alcohol impairment, and high passing; 2) cyclist fails to yield to a stop sign at an intersection, the cyclist is traveling at or above average speed, and fails to slow down or stop, the motorist does not look in the direction of the bicyclist or assumes that the cyclist will stop, which results in collision; 3) motorist enters roadway or driveway junction without observing cyclist approaching from roadway or sidewalk from the right or left, the bicyclist assumes that motorist will stop until they have passed through the junction; 4) crashes that occur at intersections and mostly in poor lighting environments, motorist enters into an intersection and collides with a cyclist approaching from a wrong direction; 5) velocity junction of a roadway and a residential driveway or alley, the cyclist drives out of the driveway or alley and collides with a motorist who is approaching from the left near lane or right far lane, the motorist usually fails to look in the cyclist's direction, and the bicyclist fails to slow down and search for traffic; 6) overtaking event, the motorist and bicyclist are traveling in the same direction, with the motorist positioned on the right hand side, the bicyclist turns left abruptly without adequately searching behind, and collides with an overtaking motorist; 7) motorist is making a left turn at an intersection, with the bicyclist approaching the intersection at a high speed, the motorist fails to yield, and the bicyclist assumes that the motorist will not turn into their path (Cross and Fisher 1977).

In the 1980s, the National Highway Traffic Safety Administration (NHTSA) created a handbook for crash typing that identified 45 bicyclist-motorist crash types, examples are motorist driving out from a driveway or alley, cyclist turning left in front of traffic, motorist turning left facing the cyclist, and cyclist riding out from a stop sign (NHTSA 1983). Hunter, Pein, and Stutts (1995) applied the NHTSA bicycle typing to update the distribution of crash types. They identified three main crash types: 1) 57% crossing paths, 2) 36% parallel paths, and 3) 6% specific circumstances. For crossing paths, the motorist and cyclist were on intersecting paths; bicyclist and motorist approached each other either on parallel paths in the same or opposite direction for the parallel paths type; and specific circumstances included motorist backing, parking lot location crashes, and 'weird' crashes (e.g., cyclist falling). Nearly one quarter (22%) of crossing path crashes involved motorist failure to yield to cyclist, 17% were bicyclist failure to yield at an intersection, and 12% of the crashes occurred when a bicyclist failed to yield mid-block. In the parallel path crashes, 12% of cases were motorist turning into the bicyclist's path, 9% of crashes occurred when motorist overtook the bicyclist, and 7% were when a cyclist turned into a motorist's path.

Räsänen and Summala (1998) further studied bicycle crash typologies, this time focusing on attention of both bicyclists and motorists among 188 bicycle-motorist crashes in four cities in Finland. They used an accident investigation team consisting of four members: a traffic engineer, a physician, a vehicle engineer, and a police officer. They found two common underlying characteristics in collisions: one was lack of detection (e.g., motorist did not observe bicyclist in time to avoid collision when bicyclist came from an unexpected direction) and the second was incorrect expectations about other road user’s behavior (e.g., cyclist expected that motorist would give way).

The results showed that only 11% of drivers observed the bicyclist before a collision occurred, while 68% of bicyclists noticed the motorist before a collision. However, 92% of the bicyclists who noticed the motorist had expected that the driver would give way (Räsänen and Summala 1998). They also identified four major crash types: 1) car turns, cycle path crosses street before road crossing; 2) car turns, cycle track crosses after road crossing; 3) car drives straight, cyclist comes from the left; 4) car drives straight ahead, cyclist comes from the right. The most common type was category 1: the motorist turned right, and the bicyclist was coming from the right. These types of collisions mostly occurred at the intersection of a collector road and a residential road and, in most of the cases, the cyclist had seen the driver and assumed the driver would give way but did not have enough time to prevent the collision. In almost all the cases, the driver did not notice the bicyclist (Räsänen and Summala 1998).

Based on the various typologies, the most common crashes are motorist overtaking bicyclist traveling in the same direction, motorist turns right or left into the path of bicyclist going in the same or opposite direction, motorist drives straight and bicyclist comes from the right or left, motorist drives into roadway from driveway or alley, and bicyclist drives in the wrong direction. The common factors contributing to collision as identified by these studies included failure of motorist to notice or observe bicyclist (lack of detection), incorrect expectations, visual obstruction, poor or inadequate lighting, and inadequate judgment on passing distances between motorist and bicyclist.

2.2 Contributing Crash Factors

In a cross-sectional study examining bicycle-motor vehicle (BMV) crashes in Iowa, 57% of crashes occurred at an intersection and 93.1% occurred in an urban area (Hamann et al. 2015). In rural areas, non-intersection crashes were more frequent (82%) compared to intersection crashes (18%). BMV crashes at intersections were more likely to involve bicyclist or motorist failure-to-yield-right-of–way and motorist turning (left, right, or U-turn). Crashes at non-intersections were more likely to involve driver vision obscurement, young bicyclists below age 10, and rural areas characterized, for example, by no lighting on roadway (Hamann et al. 2015).

A recent study conducted in Oregon (Hurwitz et al. 2015) examining statewide crash data found that 12% of all BMV crashes were motorist turning right or ‘right hook’ type. Of those, 74% happened at signalized intersections, and 26% at driveways. Among the intersection crashes, 59% had no right turn lane but did have bike lane, and 25% had no right turn lane and no bike lane. In their simulation experiment to assess behavior of right-turning motorist in crash-likely scenarios, they found that male participants had higher number of right-hook crashes than females and participants with some college degree also had higher crash rates. Their data also showed that 66% of motorists failed to check mirrors before turning right and failed to observe the bicyclist, and 15% of crashes were attributed to ‘look but did not see’ failure (Hurwitz et al. 2015). Failure-to-yield-right-of-way accounted for 19% of BMV crashes, and in most cases, motorists observed the bicyclist but poorly projected that they would turn completely before the bicyclist reached the intersection, which resulted in collisions (Hurwitz et al. 2015).

As part of the same project, Hurwitz et al. (2015) also conducted a driving simulator study to specifically examine right-hook-turn BMV crashes, focused on signalized intersections and specific factors, such as: oncoming traffic turning left, a pedestrian present in conflicting crosswalk, a variety of pavement markings, and positions of the bicyclist in adjacent bike lane. They observed that motorists' attention depended on the factors present: motorists frequently noticed bicyclists riding ahead more than bicyclists approaching from behind; the presence of a pedestrian prevented motorists from noticing bicyclists approaching from behind; in the presence of oncoming traffic, motorists ignored other components, but in the absence of oncoming traffic they scanned for traffic signals, bicyclist riding ahead, and pedestrians. They concluded that conflicts such as oncoming traffic turning left, pedestrian in crosswalk, and bicyclist coming from behind motorist in the blind spot contribute to right-hook crash because motorists fail to detect bicyclist as a result of reduced attention to the bicyclist.

A study of bicyclist and motorist collisions at T-intersections used video cameras to observe the head movements of drivers as they approached intersection, and showed that when the bicyclist comes from the right and the motorist is turning right, drivers were less likely to scan the right leg of the T-intersection, and most often looked to the left to check for oncoming cars, failing to see bicyclists in time enough to avoid a collision (Summala et al. 1996).This event accounted for 70% of the crashes. These results are similar to that found by Räsänen and Summala (1998), which found that only 11% of motorists observed bicyclists before collision because they looked only left. A larger percentage (68%) of bicyclists detected the motorist but incorrectly expected the driver to give way and could not stop in time to avoid crash.

A study conducted in Palo Alto, California, (Wachtel and Lewiston 1994) using police reports analyzed crashes by the age, sex, direction of travel, and position in the road of bicyclists. 74% (233 of 314) of bicycle-motor vehicle collisions occurred at intersections, 1.6% (5 of 314) of collisions were overtaking events where the motorist and bicyclist were riding in the same direction, and motorist hit bicyclist from behind. Collisions that occurred when the motorist was turning right at an intersection and failed to detect the bicyclist approaching from right was one of the most common bicycle-motor vehicle crashes. They also observed that the risk of collision was slightly greater in male bicyclists than female bicyclists, but this result was not consistent and likely due to varied exposure. They concluded that bicyclist’s sex does not have an effect on bicycle-motor vehicle collisions.

2.3 The Role of Infrastructure in Bicycle Safety

Literature in the area of bicycle-specific infrastructure has been steadily increasing in recent years in the United States, and results generally show safety benefits (Hamann and Peek-Asa 2013, Reynolds et al. 2009, Mead et al. 2014). However, research is still limited, and when separated by specific facility type, results are often mixed and/or demonstrate varied impact (Reynolds et al. 2009). Also, previous research on bicycle safety in the United States has often focused on helmet use, design, education, and policies to reduce the severity of injuries when a crash occurs (Cook and Sheikh 2003, Thompson, Rivara, and Thompson 1989) and have only more recently involved study of bicycle-specific infrastructure (Reynolds et al. 2009).

The rate and safety of bicycling has a relationship with the built environment. For example, research has shown that higher rates of bicycle crashes and increased severity accompany roads with poor lighting at night relative to daylight conditions (Klop and Khattak 1999). Previous research has observed that bicycling volume increases with the addition or expansion of bicycle lanes (Barnes, Thompson, and Krizek 2006, Chen et al. 2012).

2.3.1 Bicycle Lanes

Early research on bicycle lanes compared the collision frequency of bicycles on roads with and without bicycle lanes. Researchers showed that BMV crash frequencies were reduced in five different classes of collisions: bicycle leaving driveway, motorist leaving driveway, motorist overtaking bicyclist, motorist making improper turns, and bicyclist on the wrong side of the road. They concluded that bicycle lanes improved safety and reduced the frequency of crashes overall (Lott and Lott 1976).

A comparative analysis studied the effects of bicycle lanes and wide curb lanes on safety and reported that significantly more motor vehicles passed bicycles on the left and encroached on adjacent traffic lane in wide curb lanes (17%) than in bicycle lane situations (7%), even though there was no conflict with oncoming motor vehicle. At intersections, bicyclists were found to obey traffic stop signs more at bike lane sites than at wide curb lane sites. More bicycle/bicycle conflicts occurred in bike lanes, while more bicycle/pedestrian conflicts occurred in wide curb lanes. (Hunter et al. 1999). In addition, results showed that the frequency of bicycling increased more in roads with bike lanes compared to wide curb lanes.

In a study evaluating the before and after crash rates of installing bicycle tracks and marked bicycle lanes in Copenhagen, Denmark, the installation of bike lanes resulted in an increase in bicycle traffic and a decrease in motor vehicle traffic (Jensen 2008). Cycle tracks and bicycle lanes are shown to increase safety effects in experiencing crash and injuries. However, bicyclist safety at intersections and on roads with marked bicycle lanes significantly worsened. The authors hypothesized that this may have been due to an increase in traffic; in addition, detailed traffic and design conditions were not studied.

A more recent observational study, conducted by Duthie et al. (2010) at 48 sites in three cities in Texas, analyzed the effects of bicycle lanes on lateral position of bicyclists and motorist passing distances in overtaking events. They showed that in the presence of bicycle lanes, bicyclists felt safer and more comfortable in the riding environment, and the risk of a bicyclist being hit by an opening car door also reduced due to the presence of a buffer between bicyclists and parked cars.

Chen et al. (2012) carried out a quasi-experimental design in New York City, assessing crashes in both a control group and treatment group, before and after the installation of bicycle lanes. They found that the presence of bicycle lanes did not increase the occurrence of crashes even though the volume of bicycling increased during the period. Although they found that the number of bicycle-motor vehicle crashes at intersections increased overall, this may have been because the study did not involve design changes and markings at intersections.

2.3.2 Shared Lane Arrow Markings

Shared lane arrow markings, also known as sharrows, have been shown to improve safety of bicyclists and motorists on roads (Pol et al. 2015, Brady, Loskorn, and Mills 2011, Brady et al. 2010, Hunter et al. 2011). They have increased in use throughout the United States since their addition to the MUTCD in 2009 (FHWA 2012). However, being fairly new to the collection of standard pavement markings, they are often not fully understood by road users (Boot et al. 2013), and the safety effectiveness has been debated (Ferenchak and Marshall 2016).

One study in Austin, Texas examined the impact of shared lane arrows to determine if they led to safer conditions. They defined a safe motorist condition by two factors: one was that motorists made complete lane changes when passing, and two was that motorists did not encroach on adjacent lanes when passing. A safe bicyclist condition was defined by two factors: bicyclist did not ride outside of the lane, either on sidewalk or empty parking spaces, and bicyclist rode at the position indicated by the sharrow. They showed that bicyclists exhibited safer behaviors after the installation of shared lane markings; they rode less outside of full lane and did not bypass queue of parked vehicles frequently. Motorists also showed safer behaviors; they passed bicyclists less often and gave adequate distance (Brady, Loskorn, and Mills 2011).

A study of the before and after evaluation of shared lane arrow markings in Cambridge, Massachusetts found that there were decreases in motorist lane changing and speed; the percentage of motorists yielding to bicyclist increased, there was increased spacing between motor vehicles in travel lane and parked motor vehicles, and motorists gave sufficient room to bicyclists. (Hunter et al. 2011).

Pein, Hunter, and Stewart (1999) measured the distance of bicycles and motorists from each other and from the curb before and after shared lane arrow markings in Gainesville, Florida. They reported that the volume of bicyclists increased after the addition of the sharrows, the percentage of bicyclists using the roadway instead of sidewalks increased significantly, and the mean distance between the bicycle and the curb increased from 1.58 feet to 1.83 feet, However, the mean distance between motorists and bicyclists did not vary much before sharrows (6.00 feet) versus after installation (6.13 feet).

Despite these previous studies of how the presence of shared lane arrow markings impact the interaction of motorists and bicyclists, there is limited research on the role of shared lane arrows on bicyclist-motorist interactions that evaluates the role of motorist age and gender.

2.3.3 Bicycle Trail Crossings

Gårder, Leden, and Pulkkinen (1998) evaluated the effect of raising urban bicycle crossings by 4 cm to 12 cm in a before and after study. They found that raised crossings attract an increased volume of bicyclists by more than 50% and led to reduced speed of motor vehicles. In a Portland, Oregon study examining the interaction of motorists and bicyclists at colored crossings, researchers discovered that bicyclists felt very safe when using colored bike paths and did not often look out for traffic; however, motorists were more willing to slow down and yield to bicyclists (Hunter et al. 2000).

Fitzpatrick et al. (2011) investigated the daytime and nighttime visibility of three crosswalk marking patterns in Texas: transverse lines, continental markings, and bar pair markings. At sites where crosswalk markings were newly installed, the detection distances to bar pairs and continental markings were significantly longer than the detection distances to transverse markings both during the day and at night. They also found that age was a significant factor during the day in existing crosswalk sites.

Knoblauch and Raymond (2000) in their before and after evaluation study of the effect of crosswalk markings on vehicle speeds in Maryland, Virginia, and Arizona found a significant reduction in the speed of drivers as drivers appeared to respond to crosswalk markings by slowing down slightly whether or not a pedestrian was present. Another before and after evaluation of crosswalk markings conducted at 11 locations in 4 cities in the United States found that the use of crosswalks increased after installation, and vehicles slowed down as they approached crosswalk (Knoblauch, Nitzburg, and Seifert 2001).

2.4 Gaps in the Literature

Several gaps in the literature were identified, including how driver age and gender impact response to bicycle-specific infrastructure (shared lane arrows, bicycle lane), female bicyclists, and bicycle paths in common crash type scenarios. There has been some examination of driver response to bicyclists by gender in the real-world setting, but this has not included the impact of bicycle-specific infrastructure. In one study, the results showed that riders gave more passing distance when they thought the rider was female compared to males (Walker 2007). Probable explanations for this behavior were that motorists, in general, assume that female bicyclists are less experienced and more unpredictable than male bicyclists (Walker 2007). A few studies have identified how the presence or absence of shared lane arrow markings affect the volume, behavior, and aggressiveness of motorists and bicyclists on the road (Brady, Loskorn, and Mills 2011, Hunter et al. 2011), but few studies have evaluated the passing distances in the presence and absence of shared lane arrow markings. In addition, research on the effect of infrastructure such as bicycle lanes and trail crossings have shown mixed results, suggesting that further safety research evaluating bike lanes and shared lane arrow markings are warranted.

Iowa Naturalistic Bicycling Data Analysis

3.1 Overview

To augment the literature review, a naturalistic dataset with 261 bicycling trips collected from 10 adults and 10 children (aged 10 to 13) in Iowa was utilized. These data came from a separate independently funded project conducted by the PI and colleagues (Hamann, Peek-Asa, and McGehee 2014). Safety-critical events (crashes, near crashes, errors, traffic violations) were previously identified as part of that project. The data were collected using a GPS-enabled helmet camera, and each of the 20 bicyclists were asked to record all of their bicycling trips for one week. Data collection took place in Johnson County, Iowa between August and October 2013.

As part of the current project, the safety-critical events from that dataset were coded in greater detail to determine common characteristics. Specifically, the following variables were coded: visual obstructions, bicyclist lane position (left, center, right), land use in area (housing, recreation, commercial, etc.), infrastructure type (paved street, paved street with bicycle facility, off-road bicycle path, gravel road, sidewalk, other), traffic volume, site configuration (4-way intersection, T-intersection, non-intersection, alley, roundabout), parking, traffic controls (traffic light, stop sign, unregulated, other), number of lanes, roadway grade (flat, slight hill, steep hill) and rurality (urban, rural). These safety-critical event details and the general characteristics from the 261 trips were utilized to identify and develop the selected events.

3.2 Results

From the safety-critical event data, we found that the majority of events (93.7%) were due to errors or traffic violations. These included incomplete stops (61.0%), failure to stop or yield (28.9%), reckless riding toward another bicyclist or pedestrian (1.6%), and riding against traffic (1.1%). Only 1.1% of the safety-critical events involved motorist errors that involved direct interaction or direct impact to the bicyclist. We did not code other motorist errors that did not involve the bicyclist. All the motorist errors identified involved failure-to-yield-right-of-way. The majority of safety-critical events occurred when the bicyclist was traveling forward (45.8%), followed by turning right (31.3%). The most common bicyclist position during safety-critical events was to the right side of the lane (73.7%).

We also examined general trip characteristics from this dataset and found that many of the participant bicyclists utilized local bicycle paths, which often intersected low traffic residential roads at mid-block. Intersections were the most problematic overall, but being overtaken by a motor vehicle was a very common occurrence as well. Passing distance allotted by the motorists varied widely.

Methodology

4.1 Event Selection

Based on our naturalistic dataset and the literature review, we created a list of potential events to be tested in the simulator. Next, we reordered the list based on priority in terms of frequency of occurrence when bicycling, potential crash or injury risk, and gaps in the literature. From this list, we eliminated any events that could not be feasibly recreated in a simulation setting or could not easily be incorporated into the larger study in which these scenarios would be nested. For example, we eliminated the scenario where the bicyclist would be traveling on an off-road bicycle/multi-use path and cross a driveway where a car was exiting. This type of scenario was not feasible because there was not a reasonable time point to incorporate the driver entering/exiting a parking lot or driveway during the test drive.

Finally, we were limited to adding three scenarios to the larger study in which the bicycle scenarios were nested; therefore, we chose the top three based on these limitations and feasibility. The final three scenarios chosen were: 1) overtaking with and without shared lane arrow markings, 2) right turn across bicyclist in bicycle lane, and 3) bicyclist coming from the right on path, crossing perpendicular in front of driver at mid-block. The larger study, to which these bicycle events were added, was focused on creating and validating computational models of driver behavior related to potential forward collisions, lane departures, and crashes with pedestrians. Therefore, the larger study contained several pedestrian encounters and also included distraction tasks.

4.2 Definition and Development of Scenarios

For all three events the cyclist was depicted as female, no helmet, riding a road bike, and dressed in casual clothes: shorts and a t-shirt. The bicyclist was set at a fairly slow fixed speed of 15 km/hr (9.3 mph). The posted speed limit for the overtaking event was 35 mph, 40 mph for the right turn across path event, and 30 mph for the bicycle path crossing event.

In Event 1, overtaking, drivers encountered a bicyclist on the road either with or without shared lane arrows and with the bicyclist positioned to the right side of the lane on a two-lane road. Figures 4.1 to 4.5 show this event from diagram, naturalistic, and final simulation perspectives. The bicycle was triggered to start moving at 6 seconds to the estimated minimum distance between the bicyclist and motor vehicle.

The shared lane arrow markings were presented in accordance to minimum MUTCD guidelines (MUTCD figure 9C-9) at greater than 4 feet from the edge line to the apex of the chevrons (FHWA 2012). The shared lane markings were placed 200 feet apart, and the drivers saw at least one of these markings before the bicyclist was visible and saw several before they overtook the bicyclist. The bicyclist was positioned 2 feet from the center of the lane or 4 feet from the right edge of the lane.

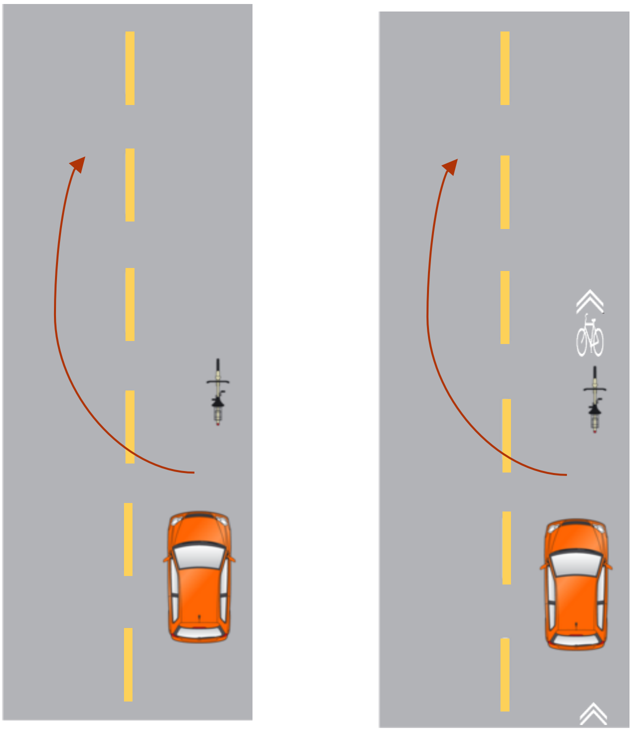

Figure 4.1 - Event 1: Overtaking bicyclist with and without shared lane markings

Figures 4.2 and 4.3 are example overtaking events found in the naturalistic dataset and used to guide development of the simulated events. Figure 4.2 shows a motorist passing closely to the bicyclist, while Figure 4.3 shows a vehicle that makes a complete lane change to pass.

Figure 4.2 - Motorist overtaking a bicyclist on a 30 mph road with shared lane arrows, bicyclist perspective, Iowa naturalistic bicycling dataset

Figure 4.3 - Motorist overtaking a bicyclist on a rural two-lane highway just outside a small town, bicyclist perspective, Iowa naturalistic bicycling dataset

Figures 4.4 and 4.5 show the finalized overtaking event conditions: with shared lane arrows and without. In the shared lane arrow condition, the driver was traveling from the urban to the residential area, while participants in the no shared lane arrow condition were traveling from the residential area to the urban area. This difference was due to counterbalancing and was taken into account in our analysis.

Figure 4.4 - Overtaking event with shared lane arrow markings present

Figure 4.5 - Overtaking event without shared lane arrows

In Event 2, the driver was instructed to turn right at a four-lane intersection with a traffic light. The light turned red when the driver approached the intersection. The driver first passed the bicyclist, parallel, in a bicycle lane. They then came upon the intersection where the traffic light was red. While slowing to a stop and right before the light turned green, the bicyclist reappeared from behind the car. The bicyclist was traveling forward, therefore it became necessary for the driver to yield to the bicyclist as they are turning right. This event trigger (start of event) occurred one second after the driver first passed the bicyclist.

This event corresponds to the common bicycle crash type, motorist right turn (FHWA 1996), often called a right hook. This event, however, was programmed so that the driver would have adequate time to recognize and yield to the cyclist in order to avoid collision. Figures 4.6 and 4.7 show the diagram created during development and the final simulated event. The vehicle lane was set at 12 feet and the bicycle lane was 7.33 feet.

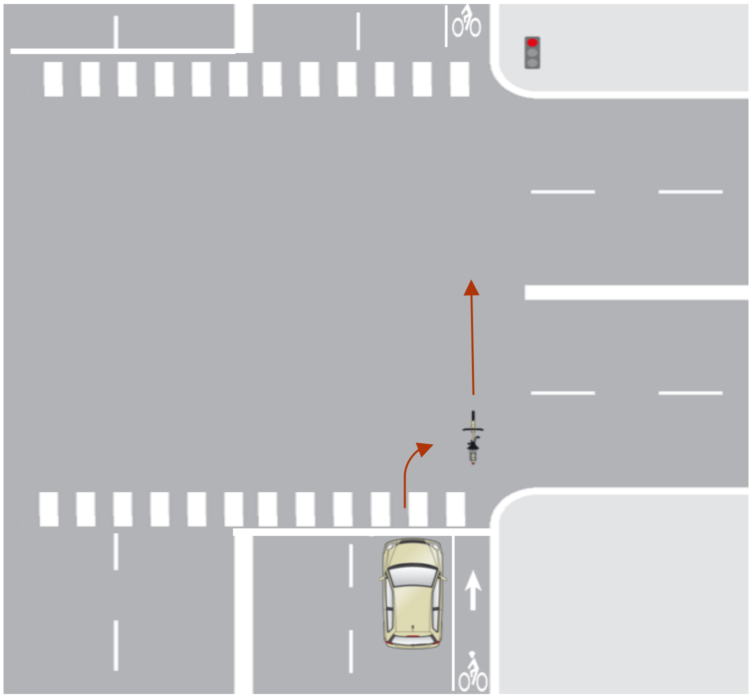

Figure 4.6 - Event 2: Right turn across path

Figure 4.7 - Right turn across path event before car passes bicyclist (top) and as car waits while bicyclist crosses through intersection (bottom)

In Event 3, the driver was traveling straight forward when a bicyclist crossed the driver’s path from the right side. The bicyclist was on a bike path and the path had a marked crosswalk where it crossed the road. The bicyclist was visually obstructed by a fence until the last few feet when they were revealed, and there was a clear sight line (Figures 4.9 and 4.10). The start of this event (trigger) was at the point when the bicyclist first became visible to the driver, which did not necessarily correspond to the first gaze of the driver to the bicyclist.

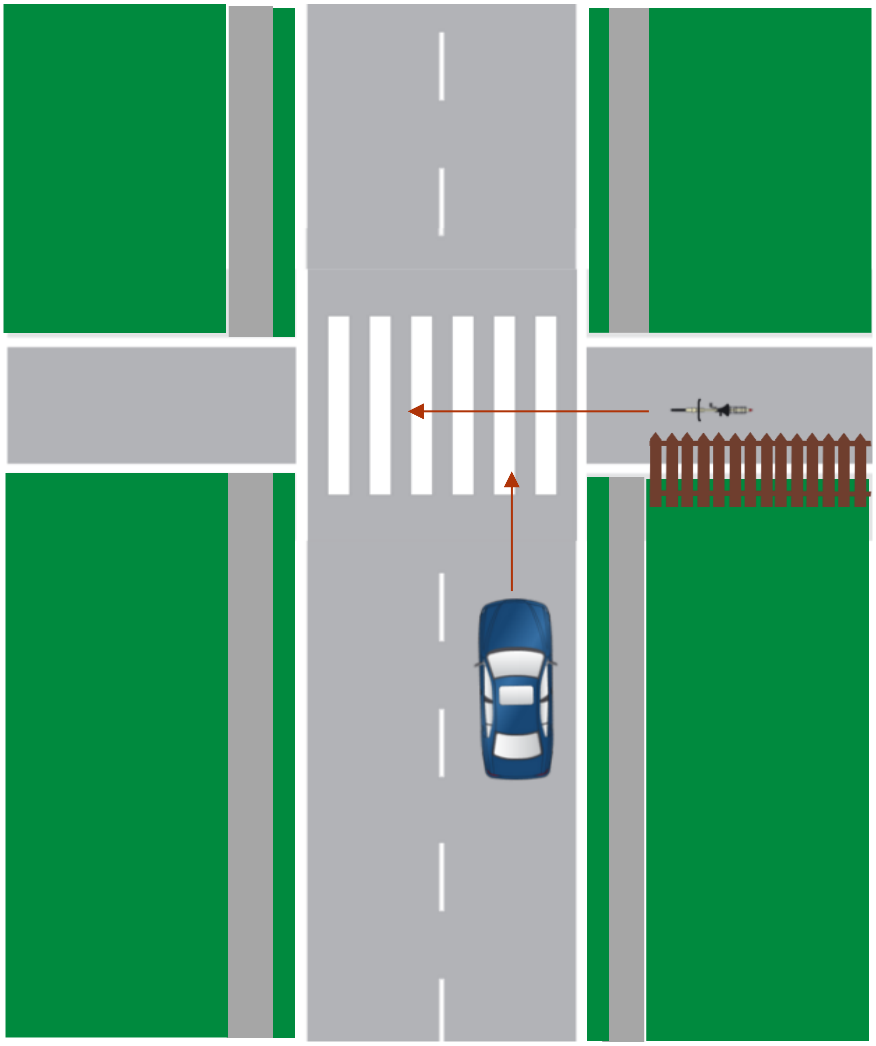

Figure 4.8 - Event 3: Bicycle path crossing with fence obstruction of sight line

Figure 4.9 depicts a view from the real-world naturalistic data that shows a bicycle path crossing a residential roadway. It shows a common circumstance where a fence or foliage are blocking the sight line to the trail until a few feet from the crossing.

Figure 4.9 - Mid-block bicycle path crossing from real-world naturalistic data

The bicycle path crossing event was modeled after real-world naturalistic data circumstances, such as that seen in Figure 4.6. This event was placed in a residential area, which happened to be a school zone, and included a fence that obscured the bicyclist just before they crossed the road (Figure 4.10). An identical fence was placed earlier in the scenario as well, with no bike event, to familiarize the driver with the presence of such a structure.

Figure 4.10 - Bicycle path crossing event

4.3 Participants

A total of 59 participants were enrolled in the study. Eleven of those had to be replaced due to simulator sickness (*n* = 4) or performance issues related to not properly engaging in the task (*n* = 7). A total of 48 participants completed the study, with equal proportions in each age (novice: 18-25, young: 26-40, middle: 41-60, older: 61-80) and gender (male, female) group. Mean ages for each age group were as follows: novice 22.8 (*SD* = 1.7), young 33.4 (*SD* = 4.3), middle 49.8 (*SD* = 4.7), and older 71.4 (*SD* = 4.5).

The majority of participants (95.8%) started driving by age 16 or earlier, with the exception of two female participants (one middle age group, one older age group) who started driving between ages 18 and 22. Most participants reported driving at least once daily (85.4%). Nearly one third (*N* = 13, 27.1%) of participants reported having had a crash in the past five years. This was higher in the novice and young age groups (33.3% and 50%) compared to middle and older age groups (8.3% and 16.7%), although not a statistically significant difference (*p* = 0.12). Among the 13 participants who reported a crash, 5 (38.5%) reported the crash was primarily their responsibility, and this did not vary significantly by age or gender groups.

Additional driving-related characteristics of the study population can be found in Tables 5.1 to 5.3. These tables also demonstrate that the sampling and random assignment of participants to study conditions were successful in achieving equal balance, as there were no significant differences between groups on driving characteristics, with one exception. The middle and older age groups' average ratings of realism were slightly higher than younger age groups, and males scored the realism slightly higher than females. However, all participants rated the realism high, as the scale ranged from 0 (not at all realistic) to 7 (completely realistic). The overall average realism for participants was 5.8 (*SD* = 0.7).

Table 4.1 - Participant driving characteristics by age group

Characteristic	**Total**	**Novice (18-25)**	**Young (26-40)**	**Middle (41-60)**	**Older (61-80)**	***p*-value**
	***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	
Driving start age						0.44
10-14	21 (43.75)	7 (58.33)	3 (25.00)	5 (41.67)	6 (50.00)	
15-16	25 (52.08)	5 (41.67)	9 (75.00)	6 (50.00)	5 (41.67)	
18-22	2 (4.17)	0 (0)	0 (0)	1 (8.33)	1 (8.33)	
Driving frequency						0.47
At least once weekly	7 (14.58)	3 (25.00)	2 (16.67)	0 (0)	2 (16.67)	
At least once daily	41 (85.42)	9 (75.00)	10 (83.33)	12 (100.00)	10 (83.33)	
Driver improvement courses						0.36
Yes	5 (10.42)	1 (8.33)	3 (25.00)	0 (0)	1 (8.33)	
No	43 (89.58)	11 (91.67)	9 (75.00)	12 (100.00)	11 (91.67)	
Frequency of exceeding speed limit						0.30
Occasionally	21 (43.75)	4 (33.33)	4 (33.33)	5 (41.67)	8 (66.67)	
Always	27 (56.25)	8 (66.67)	8 (66.67)	7 (58.33)	4 (33.33)	
Seat belt use						1.00
Frequently	1 (2.08)	0 (0)	0 (0)	1 (8.33)	0 (0)	
Always	47 (97.92)	12 (100.00)	12 (100.00)	11 (91.67)	12 (100.00)	
Comfortable overtaking						0.36
Slightly uncomfortable	5 (10.42)	1 (8.33)	1 (8.33)	3 (25.00)	0 (0)	
Very comfortable	43 (89.58)	11 (91.67)	11 (91.67)	9 (75.00)	12 (100.00)	
Comfortable changing lanes						0.60
Slightly uncomfortable	3 (6.25)	0 (0)	1 (8.33)	2 (16.67)	0 (0)	
Very comfortable	45 (93.75)	12 (100.00)	11 (91.67)	10 (83.33)	12 (100.00)	
Accident in the past five years						0.12
Yes	35 (72.92)	8 (66.67)	6 (50.00)	11 (91.67)	10 (83.33)	
No	13 (27.08)	4 (33.33)	6 (50.00)	1 (8.33)	2 (16.67)	
Accident responsibility (of those with accident in past 5 years)						1.00
Yes	5 (38.46)	2 (50.00)	2 (33.33)	0 (0)	1 (50.00)	
No	8 (61.54)	2 (50.00)	4 (66.67)	1 (100.00)	1 (50.00)	
Average realism, Mean (*SD*)	5.8 (0.71)	5.6 (0.62)	5.5 (0.78)	6.1 (0.45)	5.8 (0.78)	0.01

Table 4.2 - Participant driving characteristics by gender

Characteristic	**Total (*N* = 48)**	**Female (*N* = 24)**	**Male (*N* = 24)**	***p*-value**
Driving start age				0.61
10-14	21 (43.75)	10 (41.67)	11 (45.83)	
15-16	25 (52.08)	12 (50.00)	13 (54.07)	
18-22	2 (4.17)	2 (8.33)	0 (0)	
Driving frequency				0.41
At least once weekly	7 (14.58)	2 (8.33)	5 (20.83)	
At least once daily	41 (85.42)	22 (91.67)	19 (79.17)	
Driver improvement courses				0.34
Yes	5 (10.42)	1 (4.17)	4 (16.67)	
No	43 (89.58)	23 (95.83)	20 (83.33)	
Frequency of exceeding speed limit				0.14
Occasionally	21 (43.75)	8 (33.33)	13 (54.17)	
Always	27 (56.25)	16 (66.67)	11 (45.83)	
Frequency of seat belt use				1.00
Frequently	1 (2.08)	1 (4.17)	0	
Always	47 (97.92)	23 (95.83)	24 (100.00)	
Comfortable overtaking				0.34
Slightly uncomfortable	5 (10.42)	4 (16.67)	1 (4.17)	
Very comfortable	43 (89.58)	20 (83.33)	23 (95.83)	
Comfortable changing lanes				1.00
Slightly uncomfortable	3 (6.25)	2 (8.33)	1 (4.17)	
Very comfortable	45 (93.75)	22 (91.67)	23 (95.83)	
Accident in the past five years				0.74
Yes	13 (27.08)	6 (25.00)	7 (29.17)	
No	35 (72.92)	18 (75.00)	17 (70.83)	
Accident responsibility (of those with accident in past 5 years)				0.59
Yes	5 (38.46)	3 (50.00)	2 (28.57)	
No	8 (61.54)	3 (50.00)	5 (71.43)	
Average realism, Mean (*SD*)	5.8 (0.71)	5.6 (0.77)	5.9 (0.62)	0.05

Table 4.3 - Participant driving characteristics by overtaking event condition

(shared lane arrows, no shared lane arrows)

Characteristic	**Total**	**Shared lane arrows**	**No shared lane arrows**	***p*-value**
Driving start age				
10-14	21 (43.75)	10 (41.67)	11 (45.83)	0.49
15-16	25 (52.08)	14 (58.33)	11 (45.83)	
18-22	2 (4.17)	0 (0)	2 (8.33)	
Driving frequency				
At least once weekly	7 (14.58)	4 (16.67)	3 (12.50)	1.00
At least once daily	41 (85.42)	20 (83.33)	21 (87.50)	
Driver improvement courses				
Yes	5 (10.42)	2 (8.33)	3(12.50)	1.00
No	43 (89.58)	22 (91.67)	21 (87.50)	
Frequency of exceeding speed limit				
Occasionally	21(43.75)	10 (41.67)	11 (45.83)	0.77
Always	27 (56.25)	14 (58.33)	13 (54.17)	
Frequency of seat belt use				
Frequently	1 (2.08)	0 (0)	1 (4.17)	1.00
Always	47 (97.92)	24 (100.00)	23(95.83)	
Comfortable overtaking				
Slightly uncomfortable	5 (10.42)	4 (16.67)	1 (4.17)	0.34
Very comfortable	43 (89.58)	20 (83.33)	23(95.83)	
Comfortable changing lanes				
Slightly uncomfortable	3 (6.25)	2 (8.33)	1 (4.17)	1.00
Very comfortable	45 (93.75)	22 (91.67)	23(95.83)	
Accident in the past five years				
No	35 (72.92)	17 (70.83)	18 (75.00)	0.74
Yes	13 (27.08)	7(29.17)	6 (25.00)	
Accident responsibility				
Yes	5 (38.46)	3 (42.86)	2 (33.33)	1.00
No	8 (61.54)	4 (57.14)	4 (66.67)	
Average realism, Mean (*SD*)	5.8 (0.71)	5.8 (0.80)	5.8 (0.61)	0.49

4.4 Driving Simulator

The National Advanced Driving Simulator (NADS-1) was used to test and collect data for the bicycle events. NADS-1 is a high-fidelity, motion-based simulator with 13 degrees of freedom of motion. A 24 foot-diameter dome sits upon the motion base and houses the cab for this study, which was a Chevy Malibu sedan with a Toyota steering wheel. Eye glance behavior was captured using the Face Lab 5.0 device (Seeing Machines, Canberra, Australia), mounted in the cab of the simulator above the steering wheel. This eye tracking system captured gaze and eye position at a rate of 60 Hz.

NADS-1 is also equipped with an audio subsystem that plays engine, road, and wind noise, as well as noise from other vehicles.

Figure 4.11 - NADS-1 high fidelity driving simulator exterior view (left) and interior dome view (right)

4.4.1 Road Network

The road network used for this study had a total of approximately 4.9 square miles and included urban, residential, and freeway areas. Figure 4.12 shows the urban and residential areas and the connector between the two, as well as the locations of the bicycle events for group A. Group B did the same drive and encountered the same bicycle events, but in opposite order, which was part of the study design to counterbalance the order in which the events were presented to participants. A standard roadway lane width of 12 feet was utilized throughout the entire driving scenario.

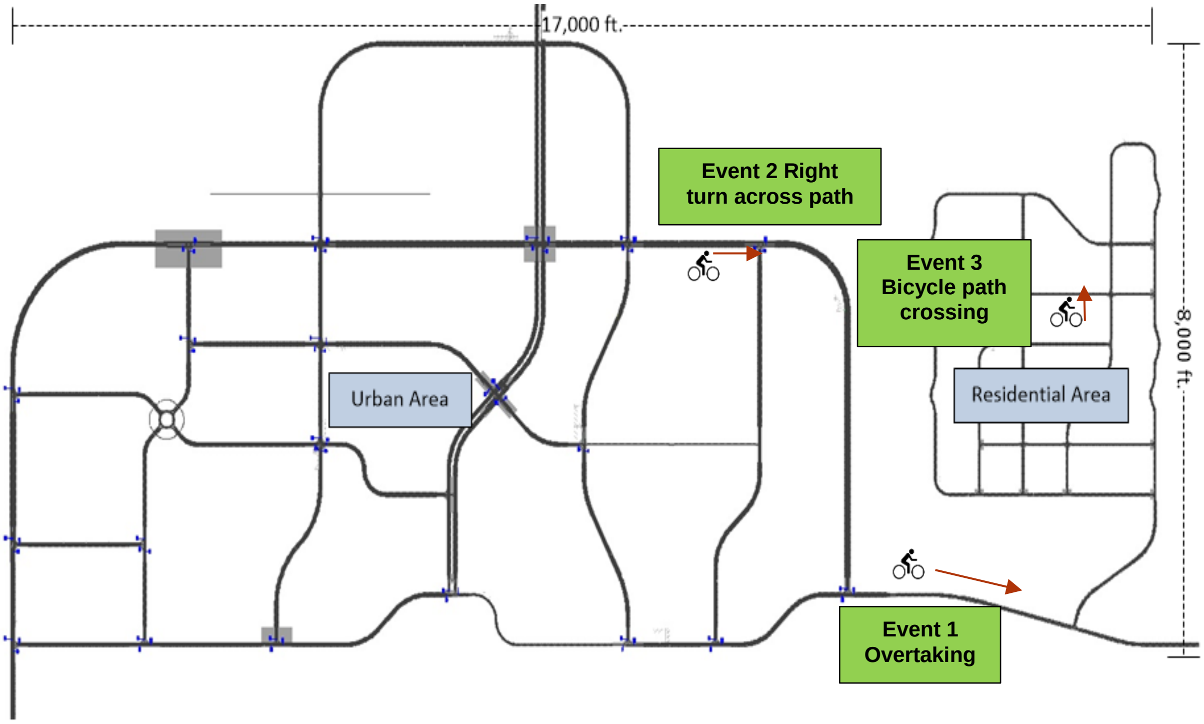

Figure 4.12 - Roadway network utilized and locations of study bicycle events, group A

4.5 Research Design

We determined primary research questions and corresponding performance measures for each of the three scenarios that were identified and prioritized from the naturalistic data and a priori literature.

For Event 1, overtaking, the main research questions included: 1) Is the minimum overtaking distance (closest approach) given to the bicyclist by the driver impacted by the presence of shared lane arrow markings? and 2) Does the presence of shared lane arrow markings increase the number of complete lane changes when overtaking the bicyclist?

For Event 2, right turn across path, our research questions included: 1) How does the timing of visual attention (gaze) to the bicyclist vary by driver age and gender?, 2) Does driver wait time for bicyclist to cross differ by age or gender?, and 3) Does the minimum distance between driver and bicyclist (closest approach) differ by driver age or gender?

For Event 3, bicycle path crossing, our main research questions included: 1) Does braking and deceleration reaction (brake force and brake reaction time, first response, deceleration) vary by age or gender of the driver? and 2) Does the time spent on collision course with the bicyclist and minimum time to collision with the bicyclist (min TTC, TETTC) vary by age and gender of the driver?

4.5.1 Independent Variables

Independent variables included shared lane arrow presence (for overtaking event only), age (Novice: 18-25, Young: 26-40, Middle: 41-60, Older: 61-80), and gender (male, female).

4.5.2 Dependent Variables

Table 4.1 lists the dependent measures considered for the three bicycle events. Not all of the dependent measures applied to each event.

Table 4.4 - Dependent measures

Variable	**Definition**	**Format**	**Event ***
Braked	Yes or No, Did the participant brake during the event?	Binary	1,3
BrakeDist	Distance to bicycle at point of brake response	Feet	3
BrakePressRT	Response time to brake press from beginning of event	Seconds	3
BrakeTCA	Time of closest approach at point of brake response	seconds	1,2,3
Change in Speed	Initial event speed minus minimum speed during the event	Miles per hour	1,2,3
Closest Approach	Minimum distance to bicycle during event	Feet	1,2,3
ClosestApproachInTurn	Minimum distance to bike after the driver begins their right turn in Right Turn Across Path event	Feet	2
Collision	Collision or no	Binary	1,2,3
First response	Type of first response: throttle release, brake press, steer or none	Categorical	1,2,3
GlanceRT	Response time from stopping at the stop line to when the driver looks toward the bike in the Right Turn Across Path event	Seconds	2
InitSpeed	Initial distance to the bicyclist at start of event	Miles per hour	2
LaneChange	Yes or No, defining lane change as the car fully entering the left lane	Binary	1
LaneDepart	Lane departure or no	Binary	1,3
MaxAccelInTurn	The maximum acceleration after the driver begins their right turn in Right Turn Across Path event	G	2
MaxBrake	Maximum braking force	lbf	2,3
MaxDecel	Maximum deceleration during the event	G	1,3
MaxLaneDevLeft	Maximum lane deviation to the left	feet	1,3
MaxLaneDevRight	Maximum lane deviation to the right	feet	1,3
MinSpeed	Minimum speed during the event	Miles per hour	1,3
MinTTC	Minimum time to collision during event	Seconds	1,2,3
Passing Distance	Distance between motor vehicle and bicycles when the car is alongside the bike in the overtaking event	Feet	1
RelativeSpeedAtPassing	Magnitude of the vector speed difference between the driver's vehicle and the bicycle at the moment the driver passes the bicycle	Feet per second	1
Speeding	Yes or No, was the initial speed at the start of the event over or under the posted speed limit?	Binary	1,2,3
Steer RT	Response time to first steer input	Seconds	2
TETTC	Time exposed to total time to collision less than the critical value of 20 seconds	Seconds	1,2,3
ThrottleReleased	Yes or No, Did the participant release the throttle during the event?	Binary	1,3
ThrottleReleaseRT	Response time to throttle release from the beginning of event	Seconds	3
TimeLaneDepart	The time at which the lane departure occurred	Seconds	1
WaitTime	Time spent waiting at the stop line in the Right Turn Across Path event	Seconds	2

*Indicates to which event the dependent measures corresponded. 1 = Overtaking,

2 = Right turn across path, 3 = Bicycle path crossing

4.5.3 Analysis

Distributions of participant demographics and driving-related characteristics (driving frequency, crash history, etc.) were examined overall. Distributions of age and gender for each of the dependent measures were also examined by event. Non-parametric descriptive statistics (Kruskal-Wallis and Wilcoxon Mann-Whitney) were computed for continuous dependent variables and Chi-square or Fisher's exact tests were used for categorical dependent measures.

We further examined dependent measures that had a *p*-value of <0.15 by building adjusted ANOVA and logistic regression models. Specifically, factorial ANOVA models were built to examine equality of means between main factors and continuous dependent measures. Multivariable logistic regression models were built to examine relationships between independent variables and dependent outcome measures. All analyses were conducted using SAS 9.4 software (SAS Institute Inc. 2002-2012).

4.5.4 Counterbalancing

In order to account for any carryover effects resulting from encountering a bicyclist in the simulator, as well as from driving through different environments, the order of the three events were counterbalanced across two groups. Group A drove through the urban area, followed by residential, followed by freeway, while group B drove freeway, followed by residential, then urban. The overtaking event took place between the urban and residential areas, the right turn across path event was in the urban part of the drive, and the bicycle path crossing was in the residential portion of the drive.

4.5.5 Event 1: Overtaking

For the overtaking event, the main factor examined was treatment (shared lane arrows, no shared lane arrows), and this was between-subjects. Other main factors included gender and age.

Dependent variables modeled included: ThrottleReleaseRT, TETTC, ClosestApproach, MaxLaneDevLeft, MaxLaneDevRight, Braked (Yes or No), lane change (Yes or No), and ThrottleRelease (Yes or No).

4.5.6 Event 2: Right Turn Across Path

All participants viewed the same right turn across path event, therefore there was no variation in roadway treatment. The main factors of interest were gender and age. We adjusted for group (A or B) to account for the counterbalancing of events throughout the drive.

Dependent variables modeled included: min speed, mean speed, initial speed, wait time, closest approach in turn, change in speed, and first response.

4.5.7 Event 3: Bicycle Path Crossing

All participants viewed the same bicycle path crossing event. Age and gender were the two main factors examined for the bicycle path crossing event. The group (A or B) was included as a covariate to account for possible effects of the event counterbalancing.

Dependent variables modeled included: Max Deceleration, BrakePressRT, MaxBrake, Change in Speed (Initial Speed minus Min Speed).

4.6 Experimental Protocol

4.6.1 Inclusion and Exclusion Criteria

To be included in the study, participants had to be between ages 18 and 80, have a valid U.S. driver’s license, no driver’s license restrictions beyond vision correction, drive a minimum of 2,000 miles per year, ability to drive without any special equipment (e.g., pedal extensions, hand brake or throttle, spinner wheel knobs, or other non-standard equipment), and must have been able to meet the study timeline.

Exclusion criteria included: pregnancy, diagnosis with a current serious illness, diabetes (Type I or uncontrolled Type II), heart condition (history of ventricular flutter or fibrillation, systole requiring cardioversion that is unstable, heart attack, or a pacemaker implanted within the last 6 months), brain damage (from a stroke within the last 6 months, active tumor, head injury, infection, or any symptoms that still exist), diagnosed with seizures or epilepsy, Meniere's Disease (or any inner ear, dizziness, vertigo, hearing, or balance problems), untreated sleep apnea, diagnosis of narcolepsy, chronic fatigue syndrome, migraine or tension headaches that require medication daily, untreated depression, anxiety disorder or episodes of hyperventilation or anxiety attacks, ADHD, claustrophobia, motion sickness (where one single mode of transport is high and present or more than 2-3 episodes where intensity is moderate or above), medications that stimulate or induce drowsiness, current skeletal, muscular, or neurological problems in neck or back regions, chronic neck and back pain, pinched nerves in neck or back or back surgery in past year, or mobility issues that would make climbing down a short ladder or walking on a narrow walkway without assistance difficult to perform safely.

4.6.2 Recruitment

Participants were recruited primarily via email sent to eligible individuals (based on age and gender) in the National Advanced Driving Simulator Registry, which contains approximately 9000 people. A web ad was also posted on drivingstudies.com, which is a NADS recruiting web site.

4.6.3 Informed Consent and Compensation

A research assistant discussed the study and addressed any questions with interested persons via phone prior to the participant agreeing to participate. The phone screening included an overview of the study, determination of the potential participant meeting initial study criteria (inclusion criteria and no exclusion criteria). The screening included questions on driving qualifications, health history, current health status, and medications. Study appointments were then made with eligible participants who were willing to participate.

At the study appointment, which lasted approximately one hour each, study staff completed the informed consent process with each participant, in-person, at the NADS facility. Each participant was preliminarily assigned a study condition (A or B) at the time they were scheduled. This was finalized after enrollment into the study.

The purpose of the study was withheld from the participants so that their driving behaviors were not altered and a realistic naturalistic response could be obtained, retaining the element of surprise. They were told that the purpose of the study was to provide feedback on modifications to a new scenario, but the real purpose was to evaluate their responses to potential collision situations. A debriefing statement was given to participants at the end of the study, and any questions or concerns they had were addressed as part of the end of study procedures. This study was approved by the University of Iowa Institutional Review Board.

Compensation of $45, in the form of an e-voucher, was given to participants who completed the entire study. Pro-rated compensation was given to participants who withdrew early from the study, at a rate of $10 for every 30 minutes of participation, with a $10 minimum.

4.6.4 Study Procedures

Each participant study visit took approximately one hour to complete. Upon arrival, a member of the research team confirmed that the participant had a valid driver’s license and asked them to complete a video release statement. Next, each participant watched a presentation on a computer, which provided them an overview of the simulator cab and drive and the purpose of the study.

Participants were instructed to drive as if they were in their own vehicle and told that they may experience a variety of driving hazards, road conditions, and times of day. Although not part of the bicycle events, participants in this study were asked to complete secondary message tasks while driving and instructions for how to do that were given.

Participants heard a word and were then asked to immediately type the word on a keypad on a task screen that was attached to the center console.

Each participant completed two practice drives of up to 10 minutes total in order to assess their ability to orient within the simulator and complete the message task. After the practice drive, the participants completed a wellness survey to evaluate status regarding simulator sickness. If the participant experienced any negative symptoms during the practice drives, their participation was ended, and they were escorted out. If there were no negative symptoms and they felt comfortable, the study drive began.

The drive included rural, urban, and residential areas and took approximately 35 minutes to complete. Participants were given navigation instructions via audio prompts for this study. For each turning instruction, participants were given two prompts: one 10 seconds before the intersection (e.g., “Turn right at the next intersection”) and one 5 seconds before (e.g., “Turn right now”).

After the study drive, participants completed another wellness survey, a realism survey, and were read a debriefing statement, which explained the real purpose of the study and why they were deceived. The last step was completion of the compensation voucher by the research staff.

4.7 Data Reduction

Video/audio recordings captured the participant face, interaction with the displays, and the driving view. These video data play a large role in verifying the reduced simulator data. Additionally, over a hundred variables were collected from the simulator and used to calculate reduced measures. The data reduction process aggregated signals over an entire event into a scalar measures. These measures made up the dependent variables listed in Table 4.1.

Matlab software from The Mathworks, Inc. was used to perform the data reduction. Matlab scripts were written to trim the data down to the events of interest, obtain variables regarding other objects of interest (i.e., bicycles), and compute dependent variable values. The reduced data was exported into an Excel spreadsheet with one row per event and used for subsequent analyses.

Several of the dependent variables relate to a common measure called Time-To-Collision (TTC). This measure is often used in collision situations but becomes less useful when objects are not on a collision path. Its computation is also more complicated when the objects are not on the same path but are coming from different angles of approach. An alternate measure, called Time to Closest Approach (TCA) was used to provide a meaningful measure when the objects are not on a collision path. The TCA measure and computational techniques are documented in Schwarz (2014).

Experimental Results

5.1 Event 1: Overtaking

The majority (81.25%) of participants did not make a complete lane change in order to overtake the bicyclist, and this did not vary by presence of shared lane arrow markings. Conversely, none of the shared lane arrow condition drivers had closest approach distances of less than 3 feet, compared to 37.5% of those in the no shared lane arrow condition. Mean closest approach was 5.8 feet (*SD* = 1.8) for the shared lane arrow condition and 4.1 feet (*SD* = 2.0) without shared lane arrows. Additionally, results for passing distance (distance between bicyclist and motorist when car is alongside bicyclist during overtaking) were very similar to closest approach, meaning that for most participants, the closest they came to the bicyclist during the event was when they were parallel and overtaking, rather than approaching from behind or returning to their lane after overtaking (Table 5.1). These results suggest that shared lane arrows help a driver more precisely manage their positioning around a bicyclist, resulting in more space given throughout the entire event, but less extremes (complete lane change).

There were significant effects on closest approach for condition (shared lane arrows vs. no shared lane arrows), $F(1,39) = 10.58$, $p < 0.01$, $\eta_p^2 = 0.21$ and for the interaction of age and condition $F(3,39) = 3.86$, $p = 0.02$, $\eta_p^2 = 0.23$. Closest approaches did not vary significantly by age among those in the shared lane arrow group but did have an impact on the no shared lane arrow group. The older age group in the no shared lane arrow condition gave an average of only 2.7 feet (*SD* = 1.0) closest approach, while the young age group gave an average of 6 feet (*SD* = 2.7). Novice and middle age groups in the no shared lane arrow condition gave 3.8 feet (*SD* = 1.5) and 3.6 feet (*SD* = 0.6), respectively. Closest approach for the shared lane arrow condition was larger for all age groups compared to the no shared lane arrow condition (Table 5.4).

No collisions were observed, and all participants at least partially departed their lane to overtake the bicyclist for this event. The most common first response for participants was braking (39.58%), but the majority (95.83%) of participants braked at less than 0.4 G, meaning they did not hard brake. Average throttle release reaction times were longer in the no shared lane arrow group (1.4 seconds, *SD* = 2.6), compared to the shared lane arrow group (0.6 seconds, *SD* = 1.7), which was a significant difference ($p = 0.03$, Table 5.1). However, after adjusting for age and gender, this effect was lost, $F(1,32) = 0.96$, $p = 0.33$, $\eta_p^2 = 0.03$.

The total time exposed time to collision (TETTC), in other words the time spent on a collision course with the bicyclist was much higher for the no shared lane arrow group (4 seconds, *SD* = 3.6) compared to the shared lane arrow group (0.1 seconds, *SD* = 0.03, $p < 0.01$). In fact, only three participants in the shared lane arrow group spent any time on a collision course with the bicyclist in the event, and all of those were male. Condition (presence or absence of shared lane arrows) was found to have a significant effect on TETTC, after adjusting for age and gender, $F(1,42) = 34.03$, $p < 0.0001$, $\eta_p^2 = 0.45$. However, the roadway geometry may have contributed somewhat to this difference. The road curvature bends slightly away from the path of travel for the shared lane arrow condition, but slightly toward the path of travel in the no shared lane arrow condition. This is because the drivers are driving in opposite directions on the connector road between urban and residential areas in the two conditions, due to counter balancing (urban to residential versus residential to urban).

Max deceleration did not independently vary by condition or gender, but was found to vary by age (Tables 5.1 & 5.2). Novice drivers were found to have greater mean deceleration (0.2 G, *SD* = 0.1), compared to the other age groups which all had means of 0.1 G (*SD* = 0.1), $p = 0.01$. However, when stratified by condition, the age effect only remained statistically significant among the no shared lane arrow group (Table 5.4). Novice drivers in the shared lane arrow group had mean max deceleration of 0.3 G

(*SD* = 0.2) compared to 0.0 G (*SD* = 0.0) for young and 0.1 G (*SD* = 0.1) for middle and older age groups. Although not significant at the $p < 0.05$ level, novice drivers in the shared lane arrow group did have higher mean decelerations than the young, middle, and older age groups ($p = 0.27$). These results suggest that the shared lane arrows helped to mitigate some of the fast decelerations among novice drivers (age 18-25). However, this interaction of age and scenario did not remain significant in the factorial ANOVA model. After adjusting for gender and scenario, the main effect of age yielded an *F* ratio of $F(3,39) = 5.89$, $p = 0.002$, $\eta_p^2 = 0.31$.

Average max lane deviation left was slightly larger for those in the shared lane arrow group (8.1 feet, *SD* = 1.9) compared to those in the no shared lane arrow group (7.5 feet, *SD* = 0.6; $p < 0.11$). Average max lane deviation right averaged 0.4 feet (*SD* = 1.2) for shared lane arrow group compared to 0.9 feet (*SD* = 0.6) for the no shared lane arrow group ($p < 0.11$).

Max lane deviation left and right did not vary significantly by gender (Table 5.3), but was found to decrease by age for max deviation left ($p = 0.04$). However, when stratified by both age and shared lane arrow presence, this decrease in max lane deviation left only remained significant among those in the no shared lane arrow group ($p = 0.04$). Conversely, max lane deviation right did not significantly vary by age or the combination of age and shared lane arrow group.

Table 5.1 - Overtaking event characteristics by condition

	Total	**Shared lane arrow**	**No shared lane arrow**	
Performance measure	***N* (%)**	***N* (%)**	***N* (%)**	***p*-value**
Hard deceleration, G				
<0.4	46 (95.83)	24 (100.00)	22 (91.67)	0.48
>=0.4	2 (4.17)	0 (0)	2 (8.33)	
Lane change				
False	39 (81.25)	19 (79.17)	20 (83.33)	1.00
True	9 (18.75)	5 (20.83)	4 (16.67)	
First response				
Brake Press	19 (39.58)	12 (50.00)	7 (29.17)	0.33
Throttle Release	17 (35.42)	7 (29.17)	10 (41.67)	
Steer	12 (25.00)	5 (20.83)	7 (29.17)	
Initial speed				
<35mph	24 (50.00)	11 (45.83)	13 (54.17)	0.56
≥35mph	24 (50.00)	13 (54.17)	11 (45.83)	
Throttle release				
No	33 (68.75)	19 (79.17)	14 (58.33)	0.11
Yes	15 (31.25)	5 (20.83)	10 (41.67)	
Braked				
No	21 (43.75)	9 (37.50)	12 (50.00)	0.38
Yes	27 (56.25)	15 (62.50)	12 (50.00)	
	Total	**Shared lane arrow**	**No shared lane arrow**	
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**
Max Brake, G	8.0 (8.8)	7.7 (6.8)	8.3 (10.6)	0.59
Max Deceleration, G	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.46
Max Acceleration, G	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.89
Max Speed, mph	38.8 (5.3)	39.2 (4.7)	38.4 (5.9)	0.46
Min Speed, mph	26.7 (10.5)	28.1 (9.3)	25.3 (11.6)	0.41
Mean Speed, mph	31.9 (7.4)	32.6 (6.5)	31.2 (8.3)	0.67
Initial Speed, mph	34.9 (8.4)	35.3 (7.4)	34.4 (9.4)	0.87
Initial dist (feet)	259.9 (73.5)	264.1 (65.0)	255.6 (82.3)	0.82
Throttle Release Reaction Time	1.0 (2.2)	0.6 (1.7)	1.4 (2.6)	0.03
Brake Press Reaction Time	0.5 (0.8)	0.6 (0.8)	0.5 (0.7)	0.85
Brake TCA	5.5 (0.7)	5.5 (0.7)	5.5 (0.6)	0.54
Brake Dist	256.7 (62.8)	252.9 (66.8)	261.5 (59.9)	0.44
Steer RT	4.8 (4.5)	5.0 (5.1)	4.7 (4.0)	0.53
TETTC	2.1 (3.2)	0.1 (0.3)	4.0 (3.6)	<0.01
Closest Approach	4.9 (2.0)	5.7 (1.8)	4.1 (2.0)	<0.01
Passing Distance	4.9 (2.0)	5.7 (1.8)	4.1 (2.0)	<0.01
Relative Speed At Passing	37.6 (10.8)	38.8 (8.4)	36.4 (12.8)	0.64
Max Lane Dev Left	7.8 (1.9)	8.1 (1.9)	7.5 (2.0)	0.11
Max Lane Dev Right	0.6 (1.0)	0.4 (1.2)	0.9 (0.6)	0.11

Table 5.2 - Overtaking event characteristics by age

Performance measure	**Total**	**Novice**	**Young**	**Middle**	**Older**	
Max deceleration	***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	***p*-value**
<0.4	46 (95.83)	10 (83.33)	12 (100.00)	12 (100.00)	12 (100.00)	0.23
>=0.4	2 (4.17)	2 (16.67)	0 (0)	0 (0)	0 (0)	
Lane change						
False	39 (81.25)	8 (66.67)	9 (75.00)	10 (83.33)	12 (100.00)	0.19
True	9 (18.75)	4 (33.33)	3 (25.00)	2 (16.67)	0 (0)	
First response						
Brake	19 (39.58)	5 (41.67)	4 (33.33)	6 (50.00)	4 (33.33)	0.10
Steer	17 (35.42)	0 (0)	6 (50.00)	2 (16.67)	4 (33.33)	
Throttle	12 (25.00)	7 (58.33)	2 (16.67)	4 (33.33)	4 (33.33)	
Initial speed						
<35	24 (50.00)	6 (50.00)	5 (41.67)	8 (66.67)	5 (41.67)	0.57
>=35	24 (50.00)	6 (50.00)	7 (58.33)	4 (33.33)	7 (58.33)	
Throttle release						
No	33 (68.75)	6 (50.00)	9 (75.00)	9 (75.00)	9 (75.00)	0.55
Yes	15 (31.25)	6 (50.00)	3 (25.00)	3 (25.00)	3 (25.00)	
Braked						
No	21 (43.75)	2 (16.67)	8 (66.67)	6 (50.00)	5 (41.67)	0.09
Yes	27 (56.25)	10 (83.33)	4 (33.33)	6 (50.00)	7 (58.33)	
	Total	**Novice**	**Young**	**Middle**	**Older**	
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**
Max Brake	8.0 (8.8)	15.5 (11.4)	3.6 (5.3)	6.2 (5.6)	6.6 (7.5)	0.04
Max Deceleration	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.01
Max Acceleration	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.11
Max Speed	38.8 (5.3)	39.9 (6.9)	40.3 (6.1)	36.9 (2.8)	38.0 (4.3)	0.72
Min Speed	26.7 (10.5)	20.5 (11.9)	30.1 (10.6)	27.6 (8.7)	28.6 (9.1)	0.05
Mean Speed	31.9 (7.4)	28.5 (9.1)	34.8 (7.8)	31.3 (6.0)	32.8 (5.6)	0.22
Initial Speed	34.9 (8.4)	36.0 (10.8)	34.7 (9.1)	34.1 (4.7)	34.7 (8.6)	0.83
Initial Dist	259.9 (73.5)	269.7 (95.5)	258.2 (79.9)	253.3 (41.3)	258.2 (75.5)	0.84
Throttle Release Reaction Time	1.0 (2.2)	1.6 (3.2)	0.8 (1.5)	0.9 (2.0)	0.3 (0.6)	0.83
Brake Press Reaction Time	0.5 (0.8)	0.8 (0.9)	0.7 (0.9)	0.2 (0.6)	0.4 (0.6)	0.39
Brake TCA	5.5 (0.7)	5.3 (0.8)	5.3 (0.9)	5.8 (0.5)	5.7 (0.5)	0.42
Brake Dist	256.7 (62.8)	257.2 (80.2)	254.1 (60.3)	244.0 (58.3)	268.4 (49.5)	0.79
Steer RT	4.8 (4.5)	8.3 (7.4)	3.8 (2.4)	3.7 (2.4)	3.7 (2.7)	0.10
TETTC	2.1 (3.2)	4.0 (5.0)	0.9 (1.2)	1.6 (2.2)	1.8 (2.8)	0.50
Closest Approach	4.9 (2.0)	5.1 (2.3)	5.4 (2.0)	4.7 (2.0)	4.2 (1.8)	0.44
Passing Distance		5.2 (2.2)	5.4 (2.0)	4.7 (2.0)	4.3 (1.8)	0.47
Relative Speed At Passing	37.6 (10.8)	30.7 (11.7)	42.8 (11.7)	37.8 (7.9)	39.2 (8.6)	0.09
Max Lane Dev Left	7.8 (1.9)	9.0 (1.9)	8.0 (2.1)	7.4 (1.9)	7.0 (1.4)	0.04
Max Lane Dev Right	0.6 (1.0)	0.5 (1.2)	0.5 (0.8)	0.7 (0.7)	0.8 (1.2)	0.89
Time Lane Depart	5.8 (5.1)	9.5 (8.1)	4.5 (2.5)	4.9 (3.4)	4.1 (3.1)	0.05
Time Max Lane Dev Left	8.5 (4.8)	11.9 (8.0)	7.1 (2.3)	8.1 (2.8)	7.0 (2.4)	0.06
Change in speed	8.2 (9.1)	15.5 (12.3)	4.6 (5.9)	6.5 (6.1)	6.1 (7.0)	0.09

Table 5.3 Overtaking event characteristics by gender

Performance measure	**Total *N* (%)**	**Female *N* (%)**	**Male *N* (%)**	***p*-value**
Max deceleration, G				
<0.4	46 (95.83)	24 (100.00)	22 (91.67)	0.48
>=0.4	2 (4.17)	0 (0)	2 (8.33)	
Lane change				
False	39 (81.25)	19 (79.17)	20 (83.33)	1.00
True	9 (18.75)	5 (20.83)	4 (16.67)	
First response				
Brake Press	19 (39.58)	10 (41.67)	9 (37.50)	0.63
Throttle Release	17 (35.42)	7 (29.17)	10 (41.67)	
Steer	12 (25.00)	7 (29.17)	5 (20.83)	
Initial speed, mph				
<35	24 (50.00)	13 (54.17)	11 (45.83)	0.56
>=35	24 (50.00)	11 (45.83)	13 (54.17)	
Throttle release				
No	33 (68.75)	18 (75.00)	15 (62.50)	0.35
Yes	15 (31.25)	6 (25.00)	9 (37.50)	
Braked				
No	21 (43.75)	10 (41.67)	11 (45.83)	0.77
Yes	27 (56.25)	14 (58.33)	13 (54.17)	
	Total	**Female**	**Male**	
	Mean (*SD*)	***N* (%)**	***N* (%)**	***p*-value**
Max Brake, G	8.0 (8.8)	7.0 (7.8)	8.9 (9.9)	0.52
Max Deceleration, G	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.91
Max Acceleration, G	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.97
Max Speed, mph	38.8 (5.3)	39.1 (5.8)	38.4 (4.85)	0.59
Min Speed, mph	26.7 (10.5)	27.2 (9.2)	26.2 (11.9)	0.92
Mean Speed, mph	31.9 (7.4)	32.3 (6.3)	31.4 (8.4)	0.86
Initial Speed, mph	34.9 (8.4)	34.3 (9.8)	35.4 (6.8)	0.74
Initial dist (feet)	259.9 (73.5)	255.3 (86.0)	264.4 (60.0)	0.71
Throttle Release Reaction Time	1.0 (2.2)	1.0 (2.2)	0.9 (2.2)	0.44
Brake Press Reaction Time	0.5 (0.8)	0.5 (0.8)	**0.6 (**0.8)	0.97
Brake TCA	5.5 (0.7)	5.5 (0.7)	5.5 (0.7)	0.90
Brake Dist	256.7 (62.8)	255.8 (72.1)	257.7 (53.9)	0.75
Steer RT	4.8 (4.5)	3.9 (2.4)	5.7 (5.8)	0.53
TETTC	2.1 (3.2)	1.8 (2.7)	2.3 (3.7)	0.62
Closest Approach	4.9 (2.0)	5.1 (2.2)	4.6 (1.8)	0.40
Passing Distance	4.9 (2.0)	5.2 (2.2)	4.7 (1.8)	0.39
Relative Speed At Passing	37.6 (10.8)	37.5 (9.9)	37.8 (11.8)	0.99
Max Lane Dev Left	7.8 (1.9)	7.9 (2.0)	7.8 (1.9)	0.82
Max Lane Dev Right	0.6 (1.0)	0.6 (1.0)	0.6 (0.9)	0.86
Time Lane Depart	5.8 (5.1)	4.8 (3.1)	6.7 (6.5)	0.45
Time Max Lane Dev Left	8.5 (4.8)	7.6 (2.9)	9.4 (6.2)	0.74
Change in speed	8.2 (9.1)	7.2 (8.1)	9.2 (10.1)	0.64

Table 5.4 - Overtaking by age and condition

Characteristic	Total		Shared Lane Arrows					No Shared Lane Arrows				
	Shared Lane Arrows	**No Shared Lane Arrows**	**Novice (18-25)**	**Young (26-40)**	**Middle (41-60)**	**Older (61-80)**	**Kruskal-wallis *p*-value**	**Novice (18-25)**	**Young (26-40)**	**Middle (41-60)**	**Older (61-80)**	**Kruskal-wallis *p*-value**
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**		**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	
Max Brake	7.7 (6.8)	8.3 (10.6)	11.5 (9.1)	4.7 (6.9)	8.6 (4.9)	6.0 (5.2)	0.42	19.6 (12.8)	2.5 (3.3)	3.9 (5.6)	7.2 (7.2)	0.15
Max Deceleration	0.1 (0.1)	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.27	0.3 (0.2)	0.0 (0.0)	0.1 (0.1)	0.1 (0.1)	0.04
Max Acceleration	0.1 (0.1)	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.0)	0.49	0.2 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.29
Max Speed	39.2 (4.7)	38.4 (5.9)	40.9 (7.2)	39.2 (4.8)	37.1 (0.8)	39.5 (3.7)	0.76	39.0 (7.0)	41.3 (7.5)	36.8 (4.1)	36.5 (4.6)	0.66
Min Speed	28.1 (9.3)	25.3 (11.6)	23.6 (12.4)	28.5 (10.9)	27.7 (8.2)	32.6 (2.4)	0.47	17.3 (11.5)	31.7 (11.0)	27.4 (10.0)	24.7 (11.8)	0.09
Mean Speed	32.6 (6.5)	31.2 (8.3)	30.6 (9.5)	33.1 (7.6)	31.4 (5.1)	35.1 (2.5)	0.68	26.4 (8.9)	36.5 (8.4)	31.2 (7.3)	30.4 (7.1)	0.23
Initial Speed	35.3 (7.4)	34.4 (9.4)	34.3 (14.2)	34.5 (3.3)	35.5 (2.4)	36.9 (5.1)	0.94	37.6 (7.0)	34.8 (13.1)	32.7 (6.2)	32.5 (11.2)	0.60
Initial Dist	264.1 (65.0)	255.6 (82.3)	255.5 (125.5)	257.1 (28.8)	265.9 (21.4)	277.9 (45.1)	0.92	283.8 (61.8)	259.4 (114.9)	240.7 (54.0)	238.5 (97.9)	0.60
Throttle Release Reaction Time	0.6 (1.7)	1.4 (2.6)	1.3 (2.9)	1.0 (2.1)	0.1 (0.3)	0.1 (0.2)	0.87	1.9 (3.8)	0.4 (0.5)	2.1 (2.9)	0.6 (0.8)	0.97
Brake Press Reaction Time	0.6 (0.8)	0.5 (0.7)	1.1 (1.1)	0.5 (0.7)	0.4 (0.7)	0.2 (0.3)	0.50	0.5 (0.6)	0.9 (1.3)	0.0 (0.0)	0.6 (0.8)	0.57
Brake TCA	5.5 (0.7)	5.5 (0.6)	5.0 (1.0)	5.6 (0.6)	5.7 (0.6)	5.8 (0.3)	0.65	5.5 (0.5)	5.1 (1.3)	6.0 (0.0)	5.4 (0.7)	0.83
Brake Dist	252.9 (66.8)	261.5 (59.9)	249.6 (104.9)	209.6 (0.2)	252.9 (28.3)	278.7 (56.4)	0.16	264.7 (57.8)	298.7 (54.5)	226.3 (116.8)	254.6 (45.4)	0.73
Steer RT	5.0 (5.1)	4.7 (4.0)	8.6 (10.2)	4.8 (2.9)	4.2 (1.8)	3.0 (0.7)	0.19	8.0 (5.0)	2.7 (1.2)	3.1 (3.0)	4.6 (4.0)	0.12
TETTC	0.1 (0.3)	4.0 (3.6)	0.4 (0.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.23	7.6 (4.8)	1.9 (0.9)	3.2 (2.1)	3.6 (3.0)	0.06
Closest Approach	5.7 (1.8)	4.1 (2.0)	6.4 (2.2)	4.8 (0.7)	5.7 (2.5)	5.8 (0.9)	0.30	3.8 (1.5)	6.0 (2.7)	3.6 (0.6)	2.7 (1.0)	0.02
Passing Distance	5.7 (1.8)	4.1 (2.0)	6.4 (2.2)	4.8 (0.7)	5.7 (2.5)	5.8 (0.9)	0.31	3.9 (1.5)	6.1 (2.7)	3.7 (0.5)	2.8 (1.0)	0.03
Relative Speed At Passing	38.8 (8.4)	36.4 (12.8)	34.6 (9.2)	40.9 (10.5)	36.8 (7.4)	43.1 (4.2)	0.29	26.9 (13.5)	44.7 (13.6)	38.9 (9.0)	35.3 (10.4)	0.16
Max Lane Dev Left	8.1 (1.9)	7.5 (2.0)	9.7 (1.9)	7.0 (0.4)	7.9 (2.6)	7.9 (0.8)	0.02	8.2 (1.7)	9.0 (2.7)	6.8 (0.7)	6.2 (1.4)	0.04
Max Lane Dev Right	0.4 (1.2)	0.9 (0.6)	0.3 (1.5)	0.4 (1.0)	0.4 (0.9)	0.4 (1.5)	0.99	0.7 (0.8)	0.7 (0.7)	0.9 (0.4)	1.1 (0.7)	0.71
Time Lane Depart	5.8 (5.7)	5.7 (4.6)	9.0 (10.5)	5.8 (3.0)	5.0 (3.2)	3.5 (1.0)	0.25	10.1 (5.6)	3.3 (1.0)	4.8 (4.0)	4.7 (4.3)	0.11
Time Max Lane Dev Left	8.7 (5.5)	8.3 (4.2)	11.3 (10.6)	8.1 (2.7)	8.5 (2.4)	7.0 (0.8)	0.46	12.4 (5.4)	6.1 (1.2)	7.7 (3.2)	7.1 (3.4)	0.14
Change in speed	7.2 (7.5)	9.1 (10.5)	10.8 (10.5)	6.1 (8.0)	7.8 (6.5)	4.3 (3.8)	0.42	20.3 (13.0)	3.1 (3.0)	5.3 (5.9)	7.8 (9.3)	0.13

Table 5.5 - Overtaking performance measures by gender and condition

	Total		**Shared lane arrows**			**No shared lane arrows**		
	Shared lane arrow	**No shared lane arrow**	**Female**	**Male**	**Wilcoxon**	**Female**	**Male**	**Wilcoxon**
Performance Measure	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**
Max Brake	7.7 (6.8)	8.3 (10.6)	7.0 (7.0)	8.3 (6.9)	0.47	7.1 (8.8)	9.5 (12.4)	0.75
Max Deceleration	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.97	0.1 (0.1)	0.1 (0.2)	0.89
Max Acceleration	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.83	0.1 (0.1)	0.1 (0.1)	1.00
Max Speed	39.2 (4.7)	38.4 (5.9)	39.6 (5.3)	38.7 (4.2)	0.54	38.7 (6.6)	38.1 (5.5)	0.83
Min Speed	28.1 (9.3)	25.3 (11.6)	29.1 (7.5)	27.0 (11.0)	0.97	25.2 (10.6)	25.4 (13.1)	0.83
Mean Speed	32.6 (6.5)	31.2 (8.3)	33.7 (4.1)	31.5 (8.3)	0.79	31.0 (8.0)	31.3 (8.9)	0.88
Initial Speed	35.3 (7.4)	34.4 (9.4)	34.7 (9.7)	35.9 (4.3)	0.83	33.9 (10.3)	34.9 (8.8)	0.79
Initial dist	264.1 (65.0)	255.6 (82.3)	258.9 (85.9)	269.3 (37.6)	0.83	251.7 (89.9)	259.6 (77.7)	0.79
Throttle Release Reaction Time	0.6 (1.7)	1.4 (2.6)	1.0 (2.3)	0.2 (0.3)	0.84	1.1 (2.3)	1.6 (2.9)	0.33
Brake Press Reaction Time	0.6 (0.8)	0.5 (0.7)	0.7 (0.9)	0.4 (0.8)	0.47	0.4 (0.6)	0.7 (0.8)	0.44
Brake TCA	5.5 (0.7)	5.5 (0.6)	5.4 (0.8)	5.6 (0.7)	0.68	5.6 (0.6)	5.3 (0.7)	0.37
Brake Dist	252.9 (66.8)	261.5 (59.9)	253.7 (77.3)	252.0 (58.6)	0.95	258.5 (71.6)	264.4 (52.5)	0.81
Steer RT	5.0 (5.1)	4.7 (4.0)	3.6 (1.1)	6.3 (6.9)	0.26	4.3 (3.3)	5.1 (4.7)	1.00
TETTC	0.1 (0.3)	4.0 (3.6)	0.0 (0.0)	0.2 (0.5)	0.07	3.6 (2.9)	4.5 (4.3)	0.90
Closest Approach	5.7 (1.8)	4.1 (2.0)	5.9 (1.7)	5.4 (1.8)	0.28	4.3 (2.4)	3.8 (1.5)	0.79
Passing Distance	5.7 (1.8)	4.1 (2.0)	6.0 (1.7)	5.4 (1.8)	0.27	4.4 (2.4)	3.9 (1.5)	0.77
Relative Speed At Passing	38.8 (8.4)	36.4 (12.8)	39.3 (7.2)	38.4 (9.7)	0.83	35.7 (12.1)	37.2 (14.0)	0.83
Max Lane Dev Left	8.1 (1.9)	7.5 (2.0)	8.3 (1.8)	7.9 (2.0)	0.54	7.5 (2.3)	7.6 (1.8)	0.44
Max Lane Dev Right	0.4 (1.2)	0.9 (0.6)	0.3 (1.2)	0.5 (1.1)	0.50	0.9 (0.5)	0.8 (0.7)	0.62
Time Lane Depart	5.8 (5.7)	5.7 (4.6)	4.1 (1.8)	7.6 (7.7)	0.19	5.5 (4.1)	5.9 (5.3)	1.00
Time Max Lane Dev Left	8.7 (5.5)	8.3 (4.2)	7.3 (1.5)	10.2 (7.5)	0.79	8.0 (3.8)	8.6 (4.7)	0.97
Change in speed	7.2 (7.5)	9.1 (10.5)	5.6 (6.0)	8.9 (8.7)	0.58	8.8 (9.8)	9.5 (11.7)	0.86

Figures 5.1 and 5.2 show the overtaking trajectories for all participants. From these figures it looks like those in the no shared lane arrow condition were more likely to slow and turn around the bike, likely making a complete lane change in the process, when overtaking compared to those in the shared lane arrow condition. It can also be seen that those in the shared lane arrow condition (see Figure 5.1) were less likely to be on a collision path with the bicyclist during all points in the event time period. However, the geometry of the road may be a possible contributor to this difference. In the shared lane arrow condition, the road bends slightly away from the path of travel, making it less likely that the two would be on a collision path. However, in the no shared lane arrow condition (see Figure 5.2), the road bends slightly toward the path of travel of the driver's vehicle, making it more likely that the two were on a collision path for some period of time.

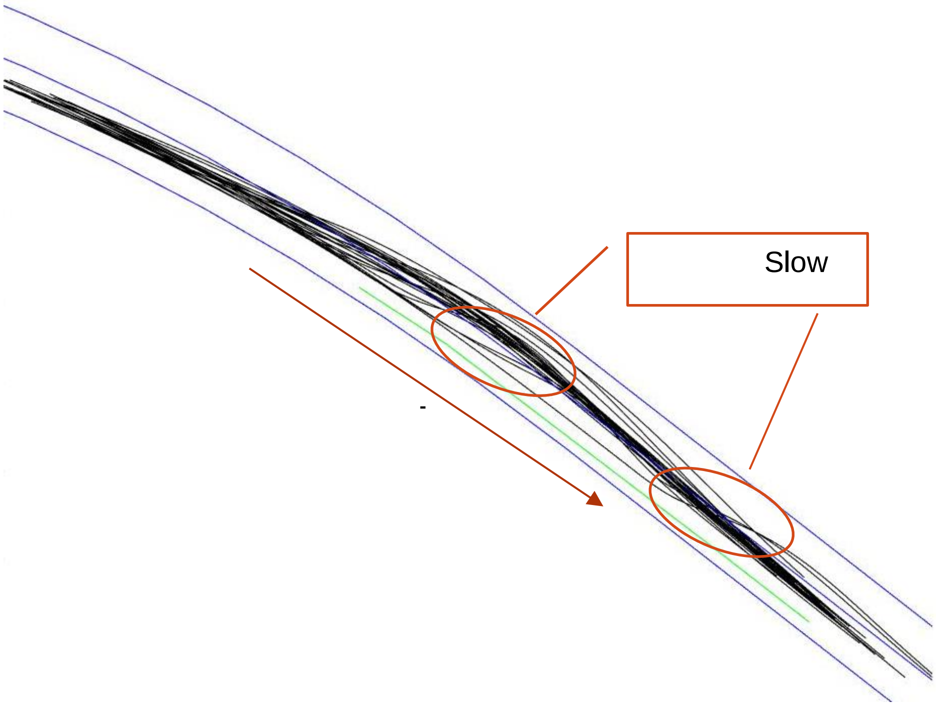

Figure 5.1 - Motorist overtaking patterns, shared lane arrows present. Bike paths shown in green, vehicle paths in black

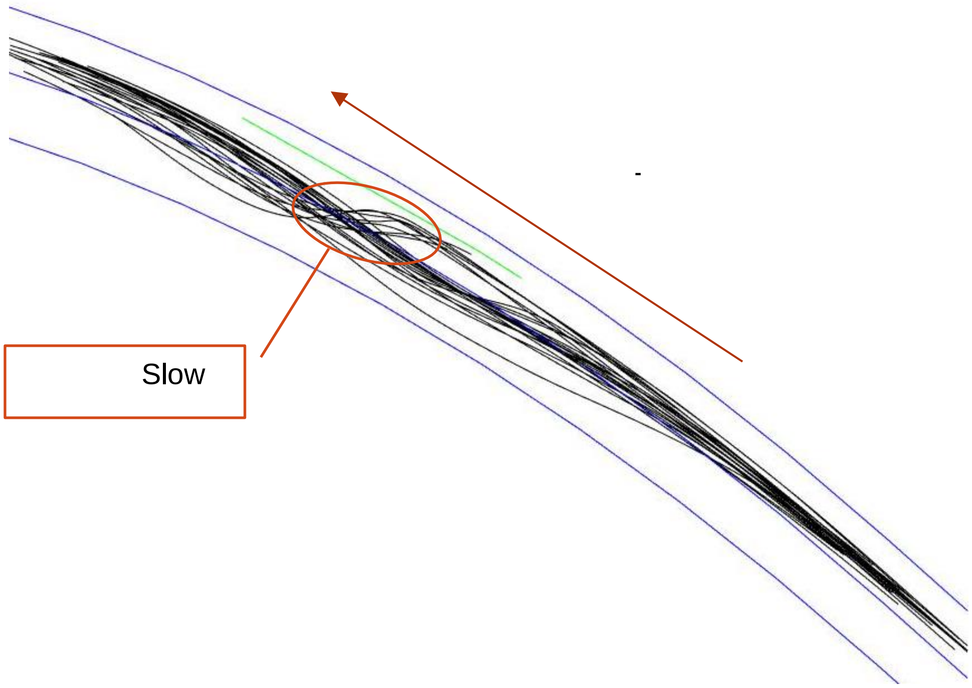

Figure 5.2 Motorist overtaking patterns, shared lane arrows absent. Bicycle path shown in green, vehicle paths in black

5.2 Event 2: Right Turn Across Path

The mean amount of wait time, which was the time spent waiting at the stop line before the bicyclist passed through the intersection, significantly decreased with age for this right turn across path (RTAP) event (Table 5.6). Novice drivers had a mean wait time of 4.9 seconds (*SD* = 2.3) compared to older drivers, which was 1.8 seconds (*SD* = 1.9). For wait time, the main effect for age was significant, yielding an *F* ratio of $F(3,42) = 4.27$, $p = 0.01$, $\eta_p^2 = 0.23$, after adjusting for group and gender.

Higher mean speed and initial speed were found to be negatively correlated with wait time (mean speed $r = -0.53$, $p = <0.01$, initial speed $r = -0.32$, $p = 0.03$), overall. Results showed that mean speeds increased with each age group ($p = 0.02$); however, initial speeds were lower in the novice (Mean = 13.4 mph) and middle (Mean = 18.7

mph) age groups, compared to young (Mean = 24.1 mph) and older (Mean = 26.6 mph). Minimum speeds were lower among the younger age groups compared to the older age groups (p = 0.03). For minimum and mean speeds the main effect of age was significant, yielding F ratios (adjusted for gender and group) of $F(3,42) = 3.20$, $p = 0.03$, $\eta_p^2 = 0.19$ and $F(3,42) = 3.22$, $p = 0.03$, $\eta_p^2 = 0.19$.

Mean glance reaction times were longer for males (0.6 seconds, *SD* = 0.9) compared to females (0.3 seconds, *SD* = 0.5), but this was not statistically significant (p = 0.28) given the large variance. Glance reaction times did not vary by age, and there were no collisions or hard accelerations in the turn (>0.4 G) observed for this right turn across path event. Distributions by gender did not vary significantly for any of the performance measures that were examined (Table 5.7).

Table 5.6 - Right turn across path event driving performance measures by age

	Total	**Novice (18-25)**	**Young (26-40)**	**Middle (41-60)**	**Older (61-80)**	**Kruskal - Wallis**
Performance Measure	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**
Max Brake, G	17.5 (7.0)	16.9 (7.3)	17.4 (7.3)	18.5 (8.0)	17.4 (6.1)	0.85
Max Deceleration, G	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.79
Max Speed, mph	24.7 (9.4)	19.5 (6.6)	27.3 (10.9)	24.1 (8.0)	27.9 (9.9)	0.17
Min Speed, mph	2.5 (2.4)	1.5 (1.9)	1.7 (1.5)	2.6 (2.8)	4.0 (2.4)	0.03
Mean Speed, mph	9.9 (3.5)	7.6 (3.3)	10.2 (4.1)	10.1 (3.2)	11.7 (2.3)	0.02
Initial Speed, mph	20.7 (12.9)	13.4 (9.4)	24.1 (14.7)	18.7 (12.3)	26.6 (11.8)	0.07
Wait time, seconds	3.5 (2.4)	4.9 (2.3)	3.8 (1.2)	3.6 (2.7)	1.8 (1.9)	0.01
Max Accel in Turn, G	0.2 (0.1)	0.2 (0.1)	0.2 (0.0)	0.3 (0.1)	0.2 (0.1)	0.40
Closest Approach in Turn, feet	9.2 (4.1)	10.4 (4.5)	10.3 (4.5)	9.3 (3.3)	6.9 (3.5)	0.17
Brake TCA, seconds	1.9 (4.5)	1.6 (3.0)	1.7 (6.6)	0.9 (2.8)	4.4 (2.9)	0.26
Brake Dist, feet	137.6 (151.6)	87.0 (135.9)	170.8 (158.6)	74.4 (151.0)	230.3 (148.5)	0.34
Steer RT, seconds	10.0 (6.2)	7.4 (5.7)	11.9 (5.8)	10.5 (7.4)	10.3 (5.8)	0.35
Min TTC, seconds	4.0 (5.4)	2.9 (2.2)	5.8 (7.5)	2.6 (1.3)	4.4 (7.4)	0.90
TETTC, seconds	1.4 (3.3)	0.6 (0.7)	0.5 (0.5)	0.4 (0.5)	4.1 (5.9)	0.26
Closest Approach, feet	6.7 (2.6)	6.7 (2.6)	7.4 (3.3)	6.5 (1.6)	6.2 (3.0)	0.61
Relative Speed At Passing, mph	14.0 (3.4)	14.8 (3.7)	13.1 (3.3)	14.9 (4.3)	13.1 (2.2)	0.61
Glance RT, seconds	0.5 (0.7)	0.6 (0.8)	0.5 (1.0)	0.4 (0.6)	0.4 (0.5)	0.88
Change in speed, mph	18.2 (6.9)	11.9 (9.7)	22.4 (14.1)	16.1 (12.3)	22.6 (11.9)	0.15
First response, ***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	***N* (%)**	0.10
Brake	20 (41.67)	7 (58.33)	7 (58.33)	4 (33.33)	2 (16.67)	
Throttle	28 (58.33)	5 (41.67)	5 (41.67)	8 (66.67)	10 (83.33)	

Table 5.7 - Right turn across path event driving performance measures by gender

Characteristic	Total Mean (*SD*)	Male Mean (*SD*)	Female Mean (*SD*)	Wilcoxon *p*-value
Max Brake, lbf	17.5 (7.0)	17.3 (7.2)	17.8 (7.0)	0.70
Max Deceleration, G	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.62
Max Speed, mph	24.7 (9.4)	24.6 (8.3)	24.9 (10.5)	0.95
Min Speed, mph	2.5 (2.4)	2.0 (2.0)	2.9 (2.6)	0.23
Mean Speed, mph	9.9 (3.5)	9.7 (3.3)	10.1 (3.8)	0.41
Initial Speed, mph	20.7 (12.9)	20.0 (12.3)	21.4 (13.7)	0.76
Wait time, seconds	3.5 (2.4)	3.6 (2.2)	3.4 (2.6)	0.78
Max Accel in Turn, G	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.79
Closest Approach in Turn, feet	9.2 (4.1)	9.7 (4.4)	8.8 (3.8)	0.48
Brake TCA, seconds	1.9 (4.5)	1.2 (5.7)	2.6 (3.1)	0.76
Brake Dist	137.6 (151.6)	129.5 (152.3)	145.0 (156.8)	0.49
Steer RT, seconds	10.0 (6.2)	10.7 (5.9)	9.3 (6.5)	0.32
Min TTC, seconds	4.0 (5.4)	4.1 (5.9)	3.8 (5.0)	0.78
TETTC, seconds	1.4 (3.3)	1.1 (2.1)	1.6 (4.2)	0.49
Closest Approach, feet	6.7 (2.6)	6.7 (3.0)	6.7 (2.2)	0.82
Relative Speed At Passing, mph	14.0 (3.4)	14.1 (3.7)	13.8 (3.2)	0.61
Time Lane Depart	14.3 (6.5)	14.8 (6.4)	13.8 (6.7)	0.48
GlanceRT, seconds	0.5 (0.7)	0.6 (0.9)	0.3 (0.5)	0.28
Change in speed, mph	18.2 (6.9)	18.0 (12.3)	18.5 (13.1)	1.00
First response	***N* (%)**	***N* (%)**	***N* (%)**	1.00
Brake Press	20 (41.67)	10 (41.67)	10 (41.67)	
Throttle Release	28 (58.33)	14 (58.33)	14 (58.33)	

5.3 Event 3: Bike Path Crossing

No collisions or lane departures were observed during the bicycle path crossing event. Additionally, only one participant had a value for time to collision, meaning almost all of the participants (97.9%) were never on a collision course with the bicyclist. The mean minimum projected distance at the time of closest approach for all participants was 8.0 feet (*SD* = 2.5) and this did not vary significantly by age or gender. This measure is a prediction of the minimum distance between the motor vehicle and bicyclist, which is found using all the TCA values (which are calculated at every frame) and finding the minimum projected distance among all of those. The minimum projected distances were smaller than the actual closest approach Mean = 18.6 (*SD* = 8.1), showing that participants did, in fact, respond to the bicyclist by slowing down.

Descriptive statistics did not reveal any statistically significant differences by age or gender in relation to dependent measures for this bike path crossing event (Tables 5.8 & 5.9). However, 10 (20.8%) participants had max decelerations greater than or equal to 0.4 G, and 8 (16.7%) of those were in the middle or older age groups. Higher mean maximum brake forces (lbf) were also found in the middle (*M* = 27.7, *SD* = 15.3) and older (*M* = 28.8, *SD* = 15.6) age groups but this was not a statistically significant difference (*p* = 0.11). These results suggest reactions might have been slower in older age groups, which revealed itself in the need to brake harder.

Factorial ANOVAs, comparing the main effects of age and gender on max deceleration, mean brake press reaction times, maximum brake force, and change in speed were not significant at the 0.05 level, indicating no significant mean differences. For max deceleration, the main effects for age and gender yielded *F* ratios of *F*(3,42) = 1.22, *p* = 0.31 and *F*(1,42) = 0.07, *p* = 0.79. For brake press reaction times, the main effects for age and gender yielded *F* ratios of *F*(3,40) = 0.96, *p* = 0.42 and *F*(1,40) = 0.06, *p* = 0.81. For maximum brake force, the main effects for age and gender yielded *F* ratio tests of *F*(3,42) = 1.28, *p* = 0.29 and *F*(1,42) = 0.06, 0.80. Change in speed main effects for age and gender yielded *F* ratio tests of *F*(3,42) = 1.95, *p* = 0.14 and *F*(1,42) = 0.25, *p* = 0.62.

Table 5.8 - Bicycle path crossing event driving performance measures by age

Performance measure	Total	Novice (18-25)	Young (26-40)	Middle (41-60)	Older (61-80)	Kruskal-Wallis
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**
Max Braking Force, lbf	24.8 (13.6)	18.9 (4.6)	23.9 (14.8)	27.7 (15.3)	28.8 (15.6)	0.11
Max Deceleration, G	0.3 (0.1)	0.3 (0.1)	0.3 (0.2)	0.4 (0.2)	0.4 (0.2)	0.11
Max Speed, mph	29.8 (3.1)	29.1 (3.7)	29.9 1.8)	30.9 (2.7)	29.2 (4.0)	0.59
Min Speed, mph	14.8 (7.7)	17.1 (5.8)	16.7 (8.0)	13.4 (8.4)	12.0 (8.2)	0.31
Mean Speed, mph	20.8 (5.4)	21.9 (4.8)	22.2 (4.9	20.1 (5.6)	18.9 (6.1)	0.49
Initial Speed, mph	29.6 (3.2)	29.1 (3.7)	29.6 (2.0)	30.8 (2.8)	28.9 (4.1)	0.57
Initial Distance, feet	150.2 (21.0)	149.9 (22.1)	148.5 (14.9)	155.5 (24.2)	146.8 (23.1)	0.52
Throttle Release RT, seconds	0.6 (0.4)	0.5 (0.4)	0.7 (0.4)	0.5 (0.3)	0.6 (0.5)	0.39
Brake Press RT, seconds	1.0 (0.4)	1.0 (0.3)	1.1 (0.4)	0.8 (0.2)	1.0 (0.5)	0.14
Brake TCA, Seconds	2.4 (0.5)	2.5 (0.4)	2.2 (0.5)	2.5 (0.3)	2.4 (0.7)	0.21
Brake Distance, feet	107.1 (21.4)	108.5 (19.3)	98.4 (22.1)	117.4 (20.1)	103.4 (21.9)	0.16
Closest Approach, feet	18.6 (8.1)	17.1 (7.0)	16.4 (6.6)	20.6 (7.8)	20.4 (10.4)	0.60
Relative Speed At Passing, mph	25.9 (8.7)	27.7 (7.6)	28.7 (8.7)	24.4 (9.1)	22.7 (8.8)	0.20
Max Lane Dev Left, feet	1.1 (0.7)	0.9 (0.6)	1.2 (0.6)	1.2 (0.8)	1.0 (0.8)	0.35
Max Lane Dev Right, feet	-0.5 (0.6)	-0.3 (0.5)	-0.6 (0.6)	-0.6 (0.8)	-0.3 (0.7)	0.34
Change in speed, mph	14.8 (6.9)	11.9 (3.7)	12.9 (7.4)	17.4 (8.1)	16.9 (6.7)	0.15
Minimum projected distance, feet	8.0 (2.5)	8.7 (2.1)	7.3 (1.8)	7.6 (3.1)	8.4 (2.8)	0.29
	Total *N* (%)	**Novice *N* (%)**	**Young *N* (%)**	**Middle *N* (%)**	**Older *N* (%)**	***p*-value**
Max deceleration						0.12
<0.4	38 (79.17)	12 (100.00)	10 (83.33)	8 (66.67)	8 (66.67)	
>=0.4	10 (20.83)	0 (0)	2 (16.67)	4 (33.33)	4 (33.33)	
First response						0.23
Brake Press	2 (4.17)	0 (0)	0 (0)	0 (0)	2 (16.67)	
Throttle Release	46 (95.83)	12 (100.00)	12 (100.00)	12 (100.00)	10 (83.33)	
Initial speed, mph						0.66
<30	23 (47.92)	6 (50.00)	7 (58.33)	4 (33.33)	6 (50.00)	
≥30	25 (52.08)	6 (50.00)	5 (41.67)	8 (66.67)	6 (50.00)	
Throttle released						0.47
No	12 (25.00)	4 (33.33)	1 (8.33)	3 (25.00)	4 (33.33)	
Yes	36 (75.00)	8 (66.67)	11 (91.67)	9 (75.00)	8 (66.67)	
Braked						1.00
No	2 (4.17)	1(8.33)	1(8.33)	0 (0)	0 (0)	
Yes	46 (95.83)	11 (91.67)	11 (91.67)	12 (100.00)	12 (100.00)	

Table 5.9 - Bicycle path crossing event driving performance measures by gender

	Total	**Male**	**Female**	**Wilcoxon**
Performance measure	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	***p*-value**
Max Brake	24.8 (13.6)	25.2 (13.2)	24.3 (14.1)	0.57
Max Deceleration	0.3 (0.1)	0.3 (0.1)	0.3 (0.2)	0.61
Max Speed	29.8 (3.1)	29.9 (2.9)	29.7 (3.4)	0.86
Min Speed	14.8 (7.7)	14.5 (7.5)	15.1 (8.1)	0.70
Mean Speed	20.8 (5.4)	20.5 (5.1)	21.0 (5.7)	0.76
Initial Speed	29.6 (3.2)	29.8 (3.0)	29.4 (3.5)	0.74
Initial dist	150.2 (21.0)	152.3 (18.9)	148.1 (23.0)	0.54
Throttle Release RT	0.6 (0.4)	0.6 (0.4)	0.6 (0.4)	0.89
Brake Press RT	1.0 (0.4)	0.9 (0.4)	1.0 (0.4)	0.84
Brake TCA	2.4 (0.5)	2.5 (0.4)	2.3 (0.5)	0.36
Brake Dist	107.1 (21.4)	109.5 (18.7)	104.7 (24.0)	0.56
Closest Approach	18.6 (8.1)	19.0 (8.1)	18.2 (8.1)	0.79
Relative Speed At Passing	25.9 (8.7)	25.1 (8.7)	26.6 (8.7)	0.64
Max Lane Dev Left	1.1 (0.7)	1.2 (0.6)	0.9 (0.7)	0.18
Max Lane Dev Right	-0.5 (0.6)	-0.6 (0.6)	-0.3 (0.6)	0.11
Change in speed	14.8 (6.9)	15.3 (7.3)	14.3 (6.6)	0.61
Minimum projected distance	8.0 (2.5)	8.2 (2.0)	7.8 (2.9)	0.57
	Total ***N* (%)**	**Female** ***N* (%)**	**Male** ***N* (%)**	***p*-value**
Max deceleration, G				
<0.4	38 (79.17)	20 (83.33)	18 (75.00)	0.47
>=0.4	10 (20.83)	4 (16.67)	6 (25.00)	
First response				
Brake Press	2 (4.17)	1 (4.17)	1 (4.17)	1.00
Throttle Release	46 (95.83)	23 (95.83)	23 (95.83)	
Initial speed				
<30	23 (47.92)	12 (50.00)	11 (45.83)	0.77
≥30	25 (52.08)	12 (50.00)	13 (54.17)	
Throttle release				
No	12 (25.00)	6(25.00)	6(25.00)	1.00
Yes	36(75.00)	18 (75.00)	18(75.00)	
Braked				
No	2 (4.17)	1 (4.17)	1 (4.17)	1.00
Yes	46 (95.83)	23 (95.83)	23 (95.83)	

Discussion and Conclusions

The purpose of the research was to better understand and fill gaps related to driver performance in common circumstances leading to bicycle-motor vehicle collisions, as well as the impact of bicycle-specific infrastructure (bicycle lanes, bicycle paths, and shared lane arrow markings) and variations by age and gender. To accomplish this goal, the aims of the study were to, first, conduct a thorough literature review and analysis of unique naturalistic bicycling data to identify key gaps in the literature and develop events to be tested using a high-fidelity driving simulator. Based on the literature review and naturalistic bicycling data analyses, we developed three bicycling events, which were added to a larger driving scenario that was focused on the impact of distraction tasks in response to pedestrians. These three events included: 1) overtaking with and without shared lane arrow markings present, 2) right turn across path event with bicycle lane present, and 3) mid-block bicycle path crossing.

6.1 Event 1: Overtaking

Shared lane arrow markings have become increasingly popular throughout the United States, especially since their official addition to the Manual of Uniform Traffic Control Devices(FHWA 2012) in 2009. Shared lane arrow markings are intended to guide bicyclists out of the door zone, assist with position of bicyclists in line with traffic rather than side-by-side on narrow roads, alert motorists that bicyclists may be present, and reduce wrong-way riding. They are also often used in areas where the roadway is too narrow to accommodate both a motor vehicle travel lane and a bicycle lane. However, road users (both motorists and bicyclists) often do not understand these markings, sometimes interpreting them as warning of an upcoming crossing or bicycle lane (Boot et al. 2013).

Our results indicated that motorists were likely interpreting the shared lane arrow markings as bicycle lanes, given that those in the shared lane arrow condition gave more passing distance and less total time exposed to collision. In other words, the shared lane arrows successfully realigned the motorist positioning throughout the event to avoid a collision course.

Comparatively, although we did not directly measure passing distance for bike lanes, as that was not a primary focus, our results showed only one participant had a closest approach value of less than three feet for the parallel bike lane overtaking part of the right turn across path event. Average closest approach for right turn across path (bicycle lane present) was 6.7 feet (*SD* = 2.6), compared to 5.7 feet (*SD* = 1.8) for shared lane arrows and 4.1 feet (*SD* = 2.0) for no shared lane arrows. These results suggest that although those in the shared lane arrow condition gave more room than no shared lane arrow condition, passing distance for bicycle lanes is even greater.

6.2 Event 2: Right Turn Across Path

Right turn across path crashes, also often referred to as ‘right hook’, are one of the most common bicycle-motor vehicle crash types and the influence of bicycle lane presence, age, and gender on these events is not fully understood. Therefore, we examined the main effects of age and gender on a right turn across path event with a bicycle lane present.

Age was found to be an important factor in the right turn across path event in terms of wait time before turning and speed. This event included a bicycle lane, which was present for all participants. The amount of wait time, time spent waiting at the stop line before completing the turn, decreased with age. The mean speed and minimum speed also increased with age.

6.3 Event 3: Bike Path Crossing

Design of bicycle paths often result in mid-block crossings and crossings with partial visual obstruction due to foliage, fencing, houses, buildings, etc. It is not uncommon for bicycle path crossings to occur in residential areas with low traffic volume, therefore a bicyclist might encounter a crossing on a daily basis and rarely at the same time as a vehicle is approaching. The mid-block path crossing with no traffic present was a circumstance we found often in our naturalistic bicycling dataset, and we found that bicyclists often did not fully look or slow in anticipation of vehicles in these areas, especially when on a route they frequently rode. Therefore, we chose to test a mid-block bicycle path crossing with visual obstruction and timing so that the motor vehicle had to respond to the bicyclist by slowing.

We did not find any significant differences in driving performance by age or gender related to a bicyclist coming from the right, crossing perpendicularly on a bike path in front of the motorist. All participants successfully slowed to avoid the bicyclist. This event also included a visual obstruction along the bike path, in form of a fence, so the drivers were not able to detect the bicyclist until they approached the road edge. However, this event was designed so that the drivers would have enough time to react and avoid collision. Further work is recommended to examine different bicycle path crossing configurations (e.g., with and without painted crosswalk markings at the junction or mid-block vs intersection crossings).

6.4 Limitations

For the overtaking event, the posted speed limit on the road was 35 mph, which is outside the recommended less than 35 mph speed limits for shared lane arrows (FHWA 2012). We were not able to change the speed limit or find an alternate two-lane road location with a lower speed limit, as these bicycle events were being added to an already existing driving scenario which was full of other events. Therefore, this was a compromise. However, we hypothesized that the passing behaviors at, for example, 30 mph vs. 35 mph posted speed limits were likely to be similar. We also believe this is useful information, as it is common for urban-rural connector roads to have posted speed limits of 35 mph, especially speed transition areas.

The generalizability of results from this study are somewhat limited, given the small sample size and the fact that all participants are Iowa residents who likely have less experience encountering bicyclists and bicycle-specific infrastructure relative to other geographic areas with higher concentrations of bicyclists and specific infrastructure for bicyclists. However, our results are still able to give insight into driver decision-making and response, regardless of experience. Additionally, given that roadway design is largely uniform throughout the United States, responses captured are likely to be similar in other geographic areas if the same infrastructure and bicyclist behaviors were presented.

6.5 Conclusions

Simulation is a valuable tool for the study of bicycle-motor vehicle interactions, as it allows for the same events to be presented to all drivers for an objective evaluation of variation in infrastructure design and demographic characteristics. Results from this study indicated beneficial aspects for shared lane arrow markings, including greater passing separation distances, compared to no shared lane arrow markings. Additionally, we did not find any significant variation in driving performance by gender for any of our events but did find differences in speed, wait times, and braking forces by age group. Older drivers had smaller closest approach values but had lower deceleration values, compared to younger age groups.

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