Improving E-Scooter Safety:
Deployment Policy Recommendations, Design Optimization, and Training Development

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ABSTRACT

E-scooters have become an increasingly popular mode of transportation over the recent years, with many companies offering shared e-scooter fleets which are a very convenient micromobility option for a large demographic of users. However, with the increase in e-scooter use, there has been a corresponding rise in e-scooter crashes, injuries, and safety critical events. As e-scooters are easily accessible by most members of the public, there is a large variation in both proper riding techniques and knowledge of policies and regulations across users. Until recently, very little formal research has been conducted on the safety of e-scooters, and if left unaddressed, e-scooters may not continue to serve as a legitimate transportation method. The goal of this dissertation is to improve the safety of e-scooters for all riders, as well as other road users, through several approaches. The first study, *E-Scooter Safety Assessment and Campus Deployment Planning*, worked to understand the contributing factors to safety critical events involving e-scooters and identify effective policies and procedures for promoting safe e-scooter use through naturalistic data collection. During this study, it was discovered that e-scooter design may contribute to safety, which led to the second study, *E-Scooter Design: Performance and Safety Evaluation*. During this effort, the relationship between e-scooter design, rider factors, and road infrastructure was evaluated through controlled benchmark testing to identify design features with the greatest safety benefits. As the results from these two studies helped to determine vehicle, road, and policy countermeasures, the final step was to tackle safety from the perspective of the e-scooter user. From the *E-Scooter Design* study, it was observed that rider performance is highly dependent upon previous experience and general physical skill, and therefore, it was decided that the best way to assist riders is through education and training. The final study, *Development of Training for E-Scooter Riders*, aimed to develop an effective set of training materials for riders through novice rider focus group feedback and riding data collection. The results from these three studies have led to a detailed set of recommendations for improving e-scooter safety that can be implemented by policymakers and e-scooter companies. With adoption, I believe these recommendations will reduce the frequency of e-scooter crashes, injuries, and safety concerns, enabling e-scooters to serve as a safe and effective micromobility solution.

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GENERAL AUDIENCE ABSTRACT

Electric scooters, or e-scooters, have become an increasingly popular form of transportation over the recent years. However, there have been numerous reports of safety concerns, crashes, and injuries for e-scooter riders and other road users as a result of e-scooter misuse. Until recently, very little formal research has been conducted on the safety of this micromobility solution. This dissertation describes a series of studies that have investigated the contributing factors to safety concerns and identified countermeasures, such as policy recommendations, design optimization, and training, that can be implemented with an end goal of improving e-scooter safety.

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Chapter 1: Introduction

History and Current State

Electric scooters, or e-scooters, are two-wheeled scooters powered by electric motors which users typically stand on to ride. While privately owned e-scooters have been around earlier, in late 2017 many companies started releasing fleets of shared scooters in cities for use by the public. In these new systems, all that is needed to rent an e-scooter is to be above the required age specified by the local governing body and to have access to the smartphone app corresponding to the scooter brand. Largely due to their convenience, e-scooters have become an increasingly popular transportation option in the recent years, serving as a micromobility solution for first and last mile transportation and short distance trips. In addition to their accessibility, there are many advantages associated with e-scooter use, such as reducing carbon emissions and providing an affordable transportation option for a large demographic of users. Since their introduction in 2017, scooter share has overtaken bikeshare as the most popular form of micromobility, increasing the total number of shared micrmobility trips from 35 million in 2017 to 84 million in 2018 and accounting for 86 million trips in 2019 (NATCO, 2020; **Figure 1**).

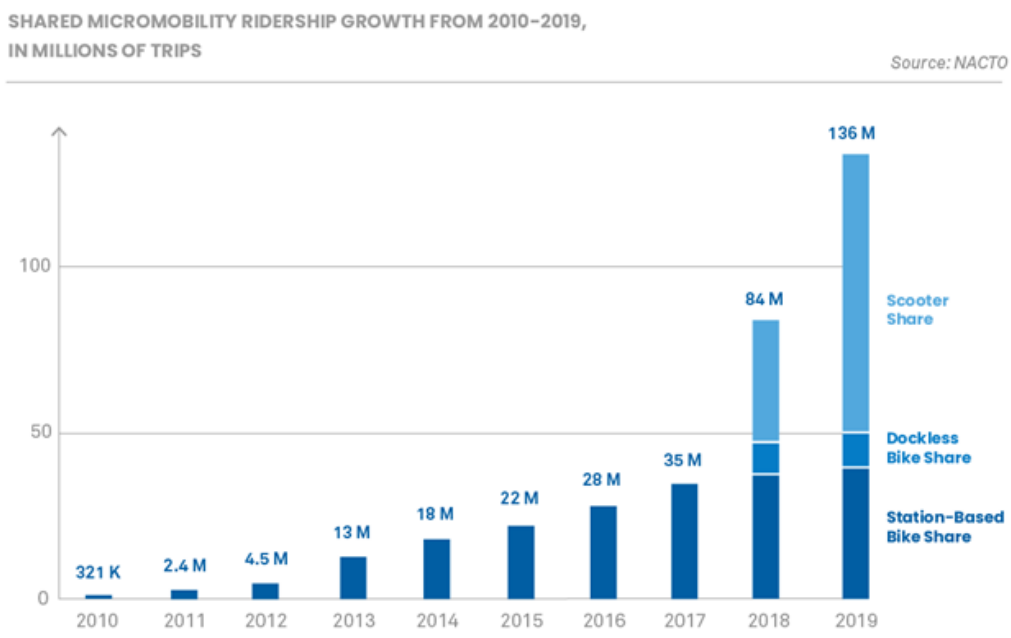


Figure 1. Shared micromobility use from 2010-2019. (Source: NATCO, 2020).

Bird was the first company to deploy a fleet of shared scooters, starting in Santa Monica, CA, with other companies such as Spin, Lime, and Skip following shortly after (DuPuis, Griess, & Klein, 2019). In these early deployments, most companies deployed their e-scooter fleets in cities without asking for permission first (DuPuis, Griess, & Klein, 2019). Local governments had varying reactions to the unexpected deployments; for instance, New York City limited operation until regulations were established, and Milwaukee, WI, impounded scooters and took legal action against the companies (DuPuis, Griess, & Klein, 2019). Conversely, some companies chose to work with cities prior to launching to avoid being issued any

cease-and-desist letters, including Spin, Skip, and GOAT. This strategy put these e-scooter vendors in a cooperative rather than adversarial relationship with the cities while also allowing cities and companies to work together on adapting the legal framework to accommodate this new form of transport (Anderson-Hall et al., 2019).

A number of cities decided to run pilot programs to work on rules and regulations in cooperation with e-scooter companies. These typically consist of companies submitting formal requests for proposals so that the cities and the company can work together to establish rules and regulations (NATCO, 2020). Washington, D.C. ran a pilot program for six e-scooter companies, and after a scooter-related fatality occurred in September 2018, the District passed regulations that required companies to apply to release scooters in the District and limited the number of scooters per provider as well as their travel speed (DuPuis, Griess, & Klein, 2019). A pilot study in Portland, OR, showed a collaboration between the Portland Bureau of Transportation and e-scooter companies to best incorporate scooters into the city. In the 120-day pilot program, there were 700,369 total trips (Eudaly et al., 2019), indicating that scooters were a popular form of transportation.

More recently, the coronavirus has affected the use of micromobility solutions. When the World Health Organization first declared coronavirus a pandemic in March 2020, the use of micromobility increased due to people choosing to avoid mass transit and seek alternative modes of transportation (Fischer, 2020). However, as lockdowns and mandatory shelter-in-place orders began, the use of micromobility solutions decreased, in part due to companies shutting down their services (Fischer, 2020). As cities began to reopen, there have been reports of increased micromobility use, as well as increased trip lengths, due to the continued need to practice social distancing during the pandemic (Fischer, 2020). Despite the slight dip in service during 2020, as of August 2021, there were 250 dockless e-scooter systems operating in cities across the U.S. (Bureau of Transportation Statistics, 2020; **Figure 2**). These trends seem to indicate that micromobility will take on a larger role in the future.

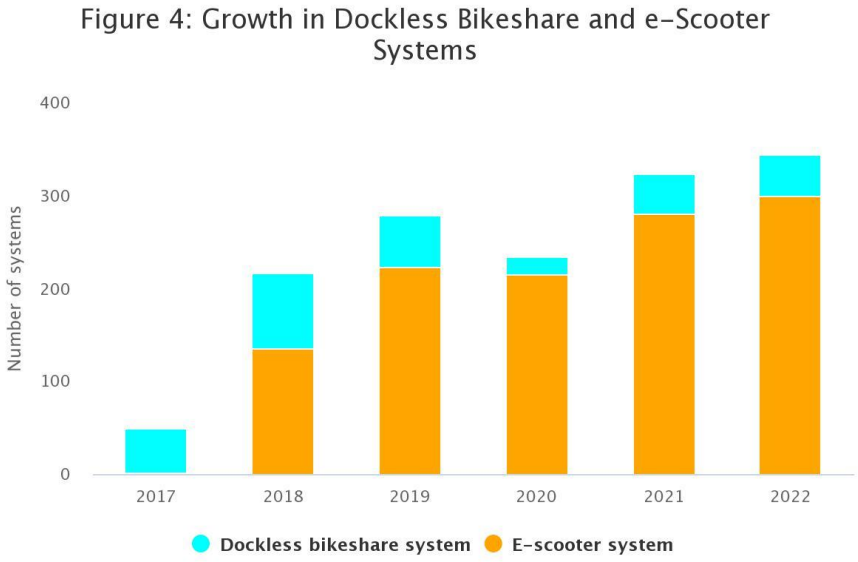


Figure 2. Bikeshare and e-scooter systems in the U.S. (Source: U.S. Department of Transportation, Bureau of Transportation Statistics, 2020).

E-Scooter Use, Rider Demographics, and Trip Patterns

To use an e-scooter, riders must have the corresponding scooter service mobile application. These applications are useful in that they allow riders to locate e-scooters in their general area. After an e-scooter has been located, the mobile device and application is used to scan a quick response (QR) code for unlocking the scooter. Typical shared e-scooters cost $1.00 to unlock and between $0.15 to $0.39 per minute to use (Riggs & Kawashima, 2020; Choron & Sakran, 2019). At the end of the ride, users are required to leave the e-scooter in a location designated by the company through either the application or by physical road markings, and some companies require users to take a picture of where they left the e-scooter as proof of proper parking (Behavioral Traffic Safety Cooperative Research Program, 2022).

E-scooter users comprise approximately 7% of the population (Populus, 2018), and typically consist of more frequent male riders than female riders (NATCO, 2020; Sanders et al., 2020). Rider age is usually between 18 and 34 (Denver Public Works, 2019; Glenn et al., 2020), indicating that e-scooters are more popular for younger populations. Most e-scooter users ride infrequently, and a large percentage have ridden only once as found in a survey conducted by the City of Chicago (2020). This was seen to vary by location, with some cities having larger populations of daily or weekly riders (Young et al., 2019). While more frequent riders have more positive perceptions of the benefits of e-scooters, they also had more negative perceptions on e-scooter safety (Sanders et al., 2020).

Trip patterns are fairly consistent across locations, with most occurring in the afternoons after work on weekdays as well as weekends starting late in the morning and lasting until early evening (Chang et al., 2019). The pilot study in Portland found that 19% of the trips occurred between 3 p.m. and 6 p.m. on weekdays and 10% of which occurred on the weekend between 2 p.m. and 5 p.m. (Eudaly et al., 2019). Ridership was seen to be the highest during the summer and the lowest during the winter (Portland Bureau of Transportation and Alta Planning & Design, 2020), possibly indicating that e-scooters are commonly used for fun rather than commuting purposes. Several surveys have also shown that e-scooters most commonly serve to replace low-carbon modes of transportation such as walking and bicycling but do also serve to replace car trips (Chang et al., 2019).

Safety Concerns, Crashes, and Injuries

With the increase in e-scooter use, safety concerns, crashes, and injuries have also been on the rise. To better understand perceptions of safety, injury patterns, and precipitating events of e-scooter crashes, the following sections cover previous e-scooter reviews and articles which have reported safety concerns and injuries caused by e-scooters.

Several studies have investigated the perceived safety and risk of e-scooters, and some of the main concerns reported by users or potential users were either hitting someone or being hit, being unsteady and falling or losing control, and not having a safe place to ride (Sanders et al., 2020). As many cities do not allow sidewalk riding to protect pedestrians, e-scooter riders are required to either ride in the street or use a bike lane if available, and riding near automotive traffic has been a major deterring factor for potential users when considering renting an e-scooter (Pimentel and Lowry, 2020). The presence of bike lanes was reported to contribute to increased perceptions of safety, especially when the bike lanes are protected (NATCO, 2020). Other road users, such as pedestrians and vehicle drivers, have also reported feeling unsafe around e-scooter riders due to previous experiences (James et al., 2019). Women had less favorable perceptions of e-scooter safety than men due to worries about hitting someone, being hit by an e-scooter, or falling (Sanders et al., 2020).

From 2017 through 2021, there have been an estimated 117,600 emergency department visits for e-scooter related injuries in the U.S, and looking at it per year, emergency department visits increased from 7,700 in 2017 to 42,200 in 2021 (Consumer Product Safety Commission, 2022). Retrospective chart reviews have been used to gain an understanding of the injury patterns and contributing factors associated with e-scooter crashes. One study found that between 2014 and 2018, e-scooter injuries and hospital admissions in the U.S. increased by 222% and 365%, respectively, and that the rate of e-scooter crashes increased from 6 per 100,000 trips to 19 per 100,000 trips (Fischer, 2020). One injury has been reported to occur for every 5,000 e-scooter trips according to the Center for Disease Control and Prevention (CDC) (Ferri, 2019). A retrospective cohort medical record review study in Southern California conducted by the University of California, Los Angeles (UCLA) monitored two emergency departments for a one-year period and found that there were 249 emergency visits for e-scooter users compared to 195 visits for bicyclists and 181 visits for pedestrians (Trivedi et al., 2019).

Studies have shown that men are more likely to be injured while riding an e-scooter than women and that most injuries occur for riders that are under the age of 40, which is in-line with ridership trends (Dwyer et al., 2021). Despite the minimum age requirement to ride a shared e-scooter, there have been several reports of injured riders under the age of 18 (Shah et al., 2021). These trends are seen in a study that analyzed operative orthopedic injuries resulting from e-scooter use in Santa Monica, CA from September 2017 to August 2019. Of the injured riders, there were 37 male patients and 36 female patients, typically young and healthy, with a mean age of 35.4 years (range of 14 to 74 years) with 4 patients under the age of 18 (**Figure 3**; Ishmael et al., 2020). Similarly, in the UCLA study, of the 249 patients that visited the emergency department, 145 were male and 104 were female, and the mean age was 33.7 years (range of 8 to 89 years) with 27 patients under the age of 18 (Trivedi et al., 2019).

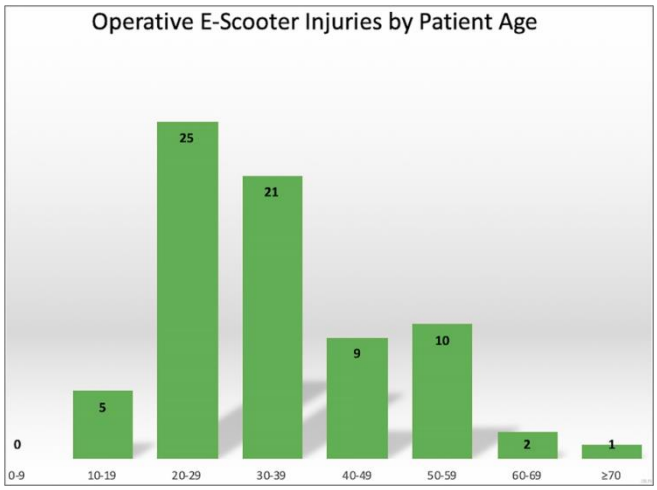


Figure 3. E-scooter crashes grouped by patient age range (Source: Ishmael et al., 2020).

Across most studies, head and upper extremity injuries are the most common injury locations with fractures and dislocations being the most common injury type (Aizpuru et al., 2019). However, other studies have found that soft tissue injuries, including abrasions, lacerations, hematomas, and contusions, were more common, especially given that they are not mutually exclusive with the orthopedic injuries (DiMaggio et al., 2019). When looking at injury severity, most e-scooter emergency department visits are due to minor injuries with low Injury Severity Scores (ISS) and Abbreviated Injury Scale (AIS) scores and do not meet the threshold to result in hospital admission, but some users are admitted for more serious

injuries, such as 6% from the UCLA study (Trivedi et al., 2019). Head injuries typically comprised the high-severity injuries, and significant increases in traumatic brain injuries and fractures resulting from e-scooter use have been observed over the recent years (Farley et al., 2020). The injuries seen during the UCLA study consisted of 79 fractures, 100 head injuries, and 69 contusions, sprains, or lacerations (Trivedi et al., 2019). During the 24-month study in Santa Monica, 73 patients had 75 orthopedic injuries with 26 of the patients being injured in July and August (Ishmael et al., 2020), corresponding to the increased e-scooter use in the summer months. Of the 75 injuries (as two riders had multiple injuries), 21% were knee injuries and 13% were elbow injures. A summary of the injuries from this study is shown in **Figure 4**.

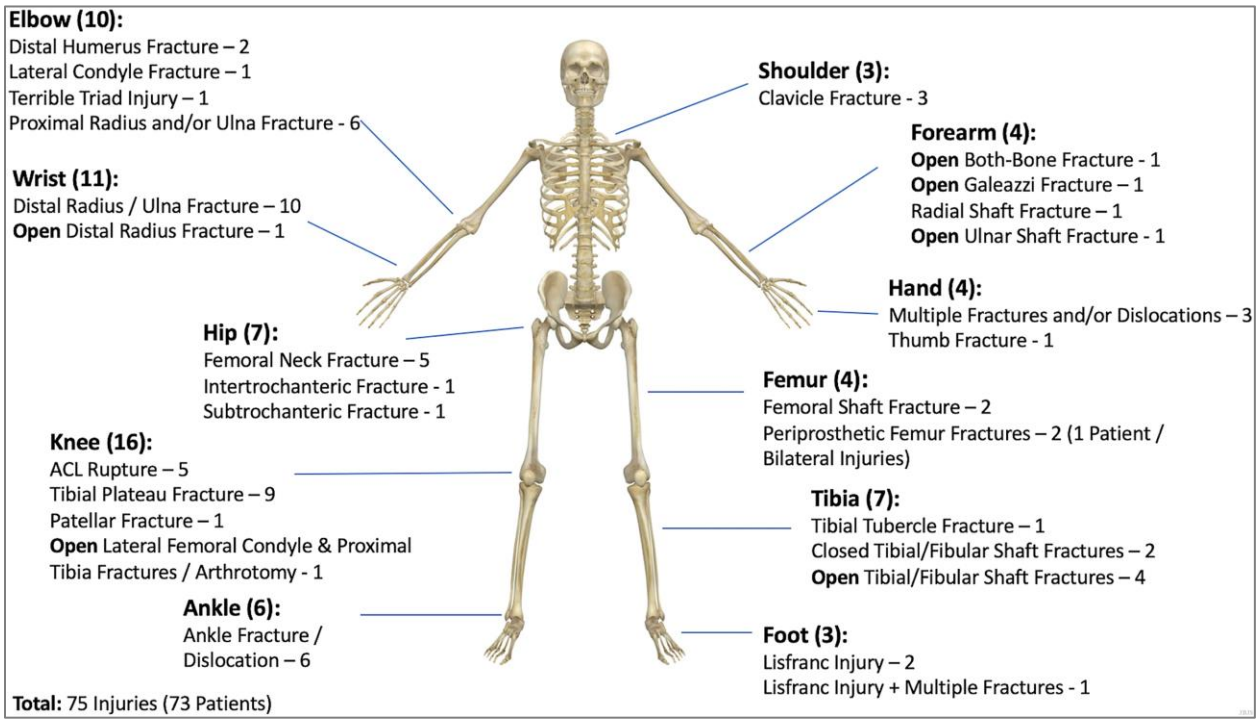


Figure 4. Anatomic location of injuries resulting from e-scooter crashes (Source: Ishmael et al., 2020).

When looking at the characteristics of e-scooter crashes and injuries, most crashes only involve the e-scooter, such that the rider fell. The UCLA study found that the common mechanisms of injuries were due to falls (183), collisions with another object (25), or being hit by a moving vehicle or object (20) (Trivedi et al., 2019). In the study in Santa Monica, eight of the riders were struck by automobiles, and 65 were individuals who had incurred falls (Ishmael et al., 2020). Only about 16% of injuries involved a motor vehicle in the Austin study, 6% of which were due to riders performing an evasive maneuver that resulted in a fall (City of Austin, 2019). Studies in Washington, D.C., San Francisco, and Portland have also all found that most reported crashes and injuries were due to falls caused by features of the roadway (Cicchino et al., 2020; Vision Zero San Francisco Injury Prevention Research Collaborative, 2019; Eudaly et al., 2019). A study in Austin reported that curbs and stationary objects such as light poles and manhole covers were the cause of the crash (City of Austin, 2019). Surface conditions have also been reported to contribute to crashes, with interviewed riders from Austin and Washington, D.C. claiming the cause of their crash was due to poor roadway conditions such as potholes, cracks, and uneven surfaces (City of Austin, 2019; Cicchino et al., 2020). Additionally, many injured riders said that excessive speed had led to the crash (City of Austin, 2019). This result may relate to e-scooter users feeling the need to get to their destination as

quickly as possible due to the cost per minute (Behavioral Traffic Safety Cooperative Research Program, 2022). Vehicle issues or malfunctions have also been seen to contribute to between 16-20% of reported crashes in several studies (Santacreu et al., 2020; Cicchino et al., 2020). Specifically, in an in-depth follow-up study conducted by the Consumer Product Safety Commission (CPSC), of 48 incidents involving e-scooters, brake issues were the reported cause for 18 occurences (Consumer Product Safety Commission, 2022).

While it is difficult to tell exactly which crash modes resulted in which injuries due to many injuries reports being anecdotal, a crash test study by Como et al. (2022) was conducted that used anthropomorphic test device (ATD) riders to gain some insight. The testing utilized an indoor pneumatic sled with an approach rail and wire-bending deceleration system. The sled was accelerated to 16 mph, and the pre-impact braking system of the sled was triggered to allow the e-scooter to release prior to impacting the target obstacle. The ATD and e-scooter were instrumented, additional side rails and an overhead gantry were used to support the ATD, and cameras were used to record the event. The three tests conducted were curb impact testing, pedestrian impact testing, and vehicle impact testing. During curb impact strikes, the ATD would commonly move forward into the stem of the handlebars and then be projected over the handlebars, which would very likely result in a head or upper-extremity orthopedic injury as well as lacerations and contusions. During pedestrian impacts, the ATD did not travel as far due to contacting the pedestrian, and potential injuries were unclear. The vehicle tests varied based upon the configuration but impacts with the front of the vehicle typically resulted in the ATD being projected onto the hood and into the windshield, which would also result in head injuries, upper extremity injuries, and potentially lower extremity injuries due to the height of the front of the car. Additional work still remains to be done with linking crash mechanisms to injuries, but this study did help to provide an initial foundation.

E-scooter crashes occur in varying locations that depend on where the e-scooters are allowed to be operated. A study by the Austin Public Health department found that 55% occurred in the street and 33% on the sidewalks, while a study in Washington, D.C. found that 58% of incidents occurred on sidewalks with only 23% occurring in the road (Behavioral Traffic Safety Cooperative Research Program, 2022). These results confirm the concerns by e-scooter users who do not prefer sidewalk riding but also do not want to ride in the street when bicycle infrastructure is lacking.

Rider factors, such as helmet use, intoxication, and aggressive riding or traffic violations, also contribute to the crashes and injuries. Despite how helmets are known to reduce the severity of head injuries, use has been seen to range from 0 to 9% in 15 separate studies (Behavioral Traffic Safety Cooperative Research Program, 2022), and injured e-scooter riders also were seen to wear helmets much less than injured bicyclists, resulting in them being three times more likely to incur a concussion (Cicchino et al., 2020). In the UCLA study, of the 249 riders, only 10 had been wearing helmets, and 12 had been intoxicated while operating the e-scooter (Trivedi et al., 2019). The UCLA study also included public observations of 193 additional e-scooter riders. Of those observed, 182 were not using helmets, 18 were not complying with traffic laws, 15 had multiple riders, and 51 were riding scooters on the sidewalk, which is not allowed in California (Trivedi et al., 2019). Holding items while riding was also seen to result in 26% of the incidents that were investigated by the CPSC (Consumer Product Safety Commission, 2022). The Austin Public Health Department also found that 29% of riders had consumed alcohol in the 12 hours prior to the incident (City of Austin, 2019) and several other studies that analyzed toxicology results found that a high percentage of injured e-scooter riders were intoxicated (Kobayashi et al., 2019). This shows the

need to either improve the public's understanding of e-scooter rules or have stricter enforcements for improper use.

There are no clear trends on peak times of the day and week when e-scooter injuries occur due to differences in hours of operation between cities. Most cities that only allow riding during the daytime saw injuries most frequently occurring on weekends when e-scooter use was the highest (City of Austin, 2019; Cicchino et al., 2020). A few studies have also shown that a large proportion of injuries occurred overnight or while it was difficult to see (City of Austin, 2019; Consumer Product Safety Commission, 2022). Additional research into night riding might be warranted.

From 2017 to 2021, there have been 68 reported scooter-related fatalities in the U.S., 14 of which have been confirmed to be associated with dockless scooter rentals (Consumer Product Safety Commission, 2022). Fifty-five of those fatally injured were male, seven were female, six were unknown, and the ages ranged from under 18 to over 60 with 44 being between the ages of 18 and 59 (Consumer Product Safety Commission, 2022). Forty-nine of the fatalities involved a motor vehicle (Consumer Product Safety Commission, 2022), which is also in line with the findings from a study conducted by the International Transport Forum (ITF) which reported that 80% of fatalities for e-scooter or bicycle riders involve a motor vehicle (Santacreu et al., 2020). This is very likely due to the lack of occupant protection provided for these vulnerable road users. Most e-scooter fatalities have also occurred during hours of darkness (Santacreu et al., 2020; Dwyer et al., 2021).

E-scooter riders are not the only ones being injured as a result of e-scooter use. There have been reports of crashes involving pedestrians due to improper e-scooter use on the sidewalk in several cities running pilot programs such as San Francisco, Portland, Washington, D.C., and Chicago (Vision Zero San Francisco Injury Prevention Research Collaborative, 2019; Eudaly et al., 2019; Cicchino et al., 2020; City of Chicago, 2020). In the Santa Monica study, 2 of the 73 injured by e-scooters were pedestrians struck by e-scooter riders (Ishmael et al., 2020), and from the UCLA study, there were 21 non-riders who sustained injuries (Trivedi et al., 2019). Additionally, improper e-scooter parking has caused not only nuisance issues for pedestrians and other road users by blocking the way but also by being a fall hazard, especially for groups with disabilities (Blomberg et al., 2019; Trivedi et al., 2019).

Unfortunately, e-scooter injuries are not tracked very well so it can be difficult to get a full picture of what injuries are occurring. Two reasons for this problem are either underreporting due to a crash not being reported to the police or not being severe enough, or misclassification of the crash since medical centers do not have a clear code for injuries involving e-scooters (Goodman et al., 2019). This is something that cities such as Charlotte are working on with their police and health departments to improve the tracking and sharing of crash and injury data (Goodman et al., 2019). By using Society of Automotive Engineers (SAE) J3194™, Taxonomy and Classification of Powered Micromobility Vehicles, as well as American National Standards Institute (ANSI) D16.1, e-scooters and other personal transportation devices are being defined, which should help authorities properly report crashes and injuries (Fischer, 2020). Additionally, the National Center for Health Statistics has approved new ICD-10-CM (International Classification of Diseases, 10th Revision, Clinical Modification) external cause codes, which will begin to be put into use in October 2020 to help health care practitioners differentiate personal transportation device injuries by the device and the cause (Fischer, 2020).

Gaps in Safety

Safety concerns, crashes, and injuries resulting from e-scooter use are becoming a major problem in cities across the United States. As e-scooters are a relatively new form of transportation, limited formal research has been conducted until recently and there remains much room for increasing the body of knowledge on e-scooter safety. To identify areas where e-scooter safety can be improved, a Haddon's matrix was utilized. A previous Haddon's matrix created for motor vehicles was adapted to fit e-scooters (**Table 1**). Aspects that are not relevant to e-scooters are eliminated with a strikethrough, and use of a helmet and protective gear was an addition.

Table 1. Haddon's Matrix for E-Scooters.

Phase	Goal	Factors Affecting System Component			
		Road User	*Vehicle*	*Environment*	*Policy and Organizational Change*
Pre-Crash	*Crash Prevention*	~~Licensing~~, Training/ Education, Enforcement and Driver State	Inspection and Design, ~~Crash Avoidance Systems~~, Alert Systems	Riding Location Design/Layout, Road Features/Infrastructure, Separation from other Road Users, Speed	Standard Features, Policies/Laws
Crash	*Injury Prevention and Reduction of Injury Severity*	~~Use of Restraints~~, Use of Helmet and Protective Gear, Impairment	~~Occupant Restraints, Air Bags, Crash Absorption, Safety Class, Padded Interiors~~	~~Crash Absorption Barriers, Breakaway Poles,~~ Elimination of Hazards	Mandatory Features
Post-Crash	*Injury Treatment, Life Preservation*	Medical Treatment and Evacuation	~~Ease of Extraction~~, Fire Prevention	Rescue Facilities, Evacuation Lanes, Traffic Control Procedures	Response Policies/Laws

As can be seen from the Haddon's matrix, many countermeasures overlap between motor vehicles and e-scooters, although some are not applicable. For instance, unlike motor vehicles, e-scooter riders are not required to take a formal education course and pass an evaluation to obtain a license. In the current scooter-share systems, aside from providing identification that verifies that the user is the legal age to be operating the e-scooter, the education that e-scooter riders receive is the training through in-app safety instructions that they review prior to renting an e-scooter. However, given the large number of reports of misuse, it is possible that these materials need improvement. Formal education or training could be an option, but one of the main attractions of e-scooters is their convenience, and therefore incorporating a formal course in the current system is a difficult countermeasure to implement in a practical manner. E-scooters do not offer restraints for riders, and while e-scooter users are encouraged to wear helmets and other protective gear, these are not included with most shared e-scooters. Laws and policies requiring helmet use are not consistent and there is very little enforcement. Design standards for e-scooters have recently been introduced by SAE, but e-scooter providers continue to advance new designs, and it is unclear if their compatibility with the real-world riding environment has been tested or is fully understood by users, as well as if true riding behaviors have been taken into consideration. At the current state, e-scooter technologies do not include crash avoidance systems, and alert systems are slowly being introduced. Due to the design of the e-scooter, other crash mitigators such as air bags are not currently possible at this time. The number of reports of surface conditions and features contributing to crashes

and injuries indicates that the interaction of road features and infrastructure with the e-scooter needs to be better understood. As there have been reported collisions of e-scooter riders with pedestrians and other road users, cities need to continue to work on identifying and clearly communicating where e-scooters should be operated. E-scooters are not designed to withstand crashes and therefore road features are not designed for crash-compatibility, but cities could work to remove hazards that contribute to crashes and injuries. Policies, laws, and standards are behind due to the unexpected introduction of e-scooters to the public but are slowly being developed with assistance from the pilot programs held between cities and providers. However, inconsistencies between locations can cause confusion for users.

The areas that I believe to provide the greatest and most practical opportunities for improving e-scooter safety are providing deployment and policy recommendations, evaluating the relationship between e-scooter design, rider factors, and road infrastructure to identify design features with the greatest safety benefits, and improving rider education on safe riding techniques. The goals of this dissertation are to expand upon the current state of knowledge for e-scooters and improve the safety of e-scooters. This includes the following items:

- Suggesting the best practices and methods for studying e-scooter safety
- Identifying specific factors that contribute to safety concerns
- Recommending deployment policy changes to address safety concerns
- Developing reliable test methods and metrics for evaluating e-scooter performance and safety
- Making recommendations for the optimal design of e-scooters
- Studying rider factors that affect performance and safety
- Proposing safety training materials to improve rider education and promote safe riding

To effectively implement these goals and work towards improving e-scooter safety, the van Mechelen (1992) injury prevention model was utilized in this dissertation, which can be seen in **Figure 5**.

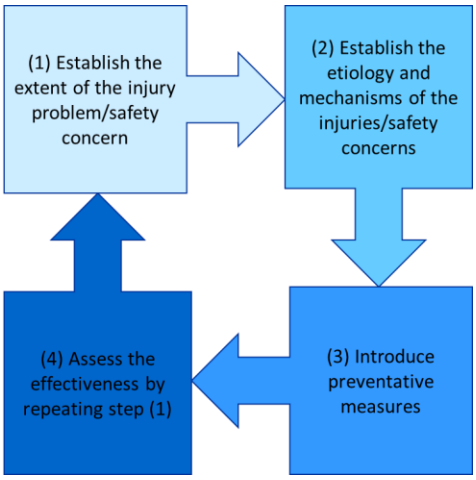


Figure 5. Injury prevention model adapted from van Mechelen (1992).

Numerous media reports of safety concerns and injuries related to e-scooter use have highlighted that there is a safety issue that needs to be addressed. To begin establishing the causes of these safety concerns, the previous literature review has been conducted. While this has provided some initial insight to the problem, much of this information has been collected from anecdotal reports of safety concerns, crashes, and injuries, which are unable to capture the full context of the incidents. To better understand

the mechanisms and contributing factors to e-scooter crashes and injuries, a naturalistic study on the campus of the Virginia Polytechnic Institute and State University (Virginia Tech) was conducted. The Virginia Tech Transportation Institute (VTTI) specializes in naturalistic driving studies in which a vehicle is instrumented with a data acquisition system (DAS) in which a user can operate the vehicle under normal conditions. This non-invasive method allows for the collection of unbiased data which captures true driving behaviors. The *E-Scooter Safety Assessment and Campus Deployment Planning* study, described in chapter 2, utilized this technique through a research program in which a fleet of instrumented e-scooters was deployed on the Virginia Tech campus to collect naturalistic riding data. The results of this study helped to inform us of the safety concerns associated with e-scooter use. The *E-Scooter Design: Performance and Safety Evaluation* study, described in chapter 3, investigated the issues of the riding environment and the design of the e-scooter through a controlled participant study. In this study, participants rode multiple e-scooter models with various designs and features through a series of benchmark tests that included the specific infrastructure factors that were observed to contribute to safety concerns. The results of this study allowed us to further understand road factors that are incompatible with e-scooters, as well as to identify the optimal e-scooter design. Additionally, rider factors such as age, gender, experience, posture, and strategy were studied to understand their relation to riding performance and safety. In the *Development of Training for E-Scooter Riders* study, described in chapter 4, a participant focus group study was conducted to compare various training methods and identify solutions that are effective in reducing safety concerns caused by the e-scooter rider. Additionally, novice rider behavior was studied. The results from these three studies can be used to provide recommendations, described in chapter 5, to cities, policymakers, and e-scooter providers which can be implemented and evaluated in future deployments. Ultimately, the goal of this dissertation is to improve e-scooter safety by reducing crash and injury rates and safety concerns through the incorporation of the identified countermeasures. I believe that future investigations will find that these measures can help to improve e-scooter safety.

Chapter 2: E-Scooter Safety Assessment and Campus Deployment Planning Study

Abstract

E-scooters are a popular new service for short distance trips, but there are reports of safety concerns for riders and other users of rights of way. Until recently, little formal research has been conducted on e-scooter safety or the optimal deployment strategy to decrease nuisance issues created by this mode of transportation. To address this, the Virginia Tech Transportation Institute (VTTI) and Spin deployed a fleet of e-scooters on the Virginia Polytechnic Institute and State University (Virginia Tech) campus through an exclusive, controlled research program. Through on-scooter data acquisition systems, fixed infrastructure cameras, anecdotal injury reports, and surveys, data was collected to assess safety impact as well as to understand beneficial and problematic user behaviors and patterns for subsequent countermeasure development and deployment recommendations. Overall, e-scooters were viewed favorably by the community. Throughout the deployment there was a crash rate of 0.94 per 100 trips and an injury rate of 3 per 10,000 trips. The most common conflict type for crashes and near-crashes was a simple fall-over or bailout (67%), followed by an impact with an infrastructure element (25%). Group riding, aggressive riding, trick riding, and excessive speed were major contributing factors. While 99% of riders did not wear helmets, 86% did follow parking policies. These results can be used to inform future design and policy mitigation strategies.

Introduction

E-scooters have become a highly used micromobility solution for providing first and last-mile transportation, and it has been seen that they have the potential to replace short-distance car trips and make transit more palatable. According to a survey of 7,000 people in six major cities where e-scooters have been deployed, 70% of survey participants viewed scooters positively (Richter, 2018). In San Francisco, for example, in the first 30 days of e-scooter deployment, 1,600 scooters were deployed resulting in 95,000 rides by 32,000 different people (Richter, 2018). E-scooters are a legitimate transportation option with dockless operation that support last mile transportation and are replacing car trips, resulting in benefits such as increased car parking availability and reduction in carbon. According to the U.S. Department of Transportation, short trips make up the majority of trips taken with almost 60% of trips taken in 2017 consisting of less than six miles (U.S. Department of Transportation, 2018). These statistics show that e-scooters are a viable option for our country's current transportation needs and are likely to be deployed in more and more communities over time.

In addition to all the benefits of e-scooters, there are also many negatives associated with e-scooter deployments. There are reports of safety concerns for riders and other users of rights of way in areas where e-scooters are already deployed. According to a JAMA study in Southern California that monitored UCLA and the UCLA Santa Monica ER for a one-year period, there were 249 ER visits for scooter users as compared to 195 visits for bicyclists and 181 visits for pedestrians (Trivedi et al., 2019). Among the scooter visits, most were due to minor injuries but 6% were admitted for more serious injuries (Trivedi et al., 2019). Until recently, very little formal research has been conducted on the safety of this form of transportation as well as the optimal approach to deployment to decrease nuisance issues.

To first get a better understanding of the safety concerns associated with e-scooter use, our team at VTTI, in collaboration with Spin, decided to conduct a controlled research program on Virginia Tech's campus.

During this effort, a fleet of up to 300 shared e-scooters were deployed for approximately seven months between September 2019 and March 2020. On average Spin deployed between 150-200 e-scooters, and a subset of 52 of these e-scooters were instrumented with micro data acquisition systems (microDASs) that collected naturalistic riding data through an inertial measurement unit (IMU), GPS, and forward video. Fixed video cameras were also strategically installed on infrastructure around Virginia Tech's campus to capture interactions between road users, and subjective pre- and post-deployment surveys were administered. Data was also collected through Spin's smartphone application, and anecdotal, de-identified injury reports were shared from the Virginia Tech Police Department and the health center on Virginia Tech's campus. The data collection and deployment effort occurred in two phases that aligned with a change in e-scooter model. Phase 1 occurred between September 2019 and November 2019, during which the Segway Ninebot ES4 e-scooter model was deployed. Phase 2 occurred between November 2019, and March 2020, during which the Segway Ninebot Max e-scooter model was deployed. The end goal of this study was to identify safety concerns and recommend deployment policies.

As this was a large-scale, complex study, a sizable project team was required to ensure its smooth operation and to tackle the different aspects of the study. While I did not serve as the lead researcher, I was a key team member with core contributions such as instrumentation and maintenance of the scooter microDASs, development of the reduction protocols and sampling plans, data reduction and analysis, literature review, and final reporting. I worked closely with the full team to ensure this industry-funded work fully informed the remainder of my research and led to the subsequent studies in which I did serve as the lead researcher. To capture the full essence of the naturalistic study, all components have been concisely included in this chapter with appropriate attributes documented at its conclusion.

The following sections include a literature review on current deployment policies and regulations as well as the methods and results from the study.

Literature Review: E-Scooter Policies

E-scooters are a relatively new mode of transportation, and therefore policies regarding proper use are not well established. A quick literature review was conducted to understand how cities are currently handling the deployments and to compare policies and regulations between locations. The following section includes the results from that review.

E-Scooter Policies

Rules and regulations regarding e-scooter use currently vary by locale, making it difficult for riders and other road users to understand the rules and regulations for operating an e-scooter and for enforcement officials to regulate their use (Fischer, 2020). The Governors Highway Safety Association surveyed the 54 State and Territorial Highway Safety Offices (HSOs) to understand their involvement in micromobility, asking about such topics as laws and pilot programs. Thirty of the states responded to the survey, 17 of which said that they have some laws addressing certain aspects of micromobility, most pertaining to e-scooters, and 16 of which had pilot programs in the state (Fischer, 2020). The HSOs that were not involved did not think that e-scooters counted as motor vehicles and therefore they were precluded from regulating them, and/or stated that they believed micromobility to be a local issue (Fischer, 2020).

Cities such as San Francisco, CA; Nashville, TN; Denver, CO; Scottsdale, AZ; Charlotte, NC; and Honolulu, HI have already written cease and desist letters to e-scooter vendors operating in their cities due to riders not obeying local laws, parking issues, or illegal launches (Anderson-Hall et al., 2019). Some of these cities

have been working on pilot programs or creating new legislation to allow scooters back on the streets. Arlington County, VA used the results of their pilot program to update their state motor vehicle code defining e-scooters and where they can be operated, as well as added signage to roads to enhance e-scooter use (Fischer, 2020).

Some cities have banned e-scooters altogether because they do not comply with regulations for allowable forms of transportation. Honolulu, for example, has classified e-scooters as mopeds. However, the scooters do not comply with existing moped laws, and therefore anyone using an e-scooter is subject to a fine and possible jail time (Anderson-Hall et al., 2019).

As cities develop and implement rules and regulations, enforcement that can potentially reduce dangerous riding will likely improve. Once there are set laws, it will be easier to train officials on how to enforce safe riding (Fischer, 2020). Community support will also be key in reporting any violations or unsafe riding practices (Fischer, 2020).

Riding Location

Localities and policymakers have debated where e-scooter riders should be permitted, taking into account both nuisance and safety considerations. A majority of cities have made riding scooters on sidewalks illegal, yet due to the large number of new users being unfamiliar with their cities' rules, as well as the differing rules from city to city, these issues continue to occur (Anderson-Hall et al., 2019; DuPuis, Griess, & Klein, 2019). The rules on sidewalk riding are also ambiguous in some cities, which allow sidewalk riding if done appropriately (City of Austin, n.d.) or if there are no bike lanes present (City of Denver, 2021). However, this can result in confusion for riders who travel between cities and are unaware of the inconsistences in riding policies. A Southern California study found that 52% of pedestrians seeking medical treatment had been hit by an e-scooter and 24% had tripped over a e-scooter on the sidewalk (Fischer, 2020).

However, other cities, such as Denver, CO, do not allow e-scooter riders on the roadway (except for intersections) or in bike lanes, but they are allowed to be ridden on sidewalks (Anderson-Hall et al., 2019). California recently passed Active Assembly Bill 2989, which only allows e-scooters on streets with speed limits of up to 35 mph (Choron & Sakran, 2019), while in Scottsdale, AZ, it is illegal to ride an e-scooter on roads where the speed limit is more than 25 mph (Anderson-Hall et al., 2019).

Conversely, the injuries that could occur if a rider were to crash on a high-speed or high-volume road could be much more severe and is one reason why some localities prefer e-scooter riding on sidewalks (Fischer, 2020). For localities that do allow scooters to ride in lanes shared with automobiles, because of the limited infrastructure to accommodate scooters, motorists do not expect to share travel lanes with e-scooters, making cars dangerous to scooters in a similar way that scooters are dangerous to pedestrians on sidewalks (DuPuis, Griess, & Klein, 2019). In a study conducted in Austin, TX, researchers found that 16% of the total e-scooter incidents were due to motor vehicles, but only 10% of these actually involved a collision with the motor vehicle (Fischer, 2020). Most crashes (50%) were due to roadway conditions such as potholes and cracks (Fischer, 2020).

Some communities have started to address the uncertainty of where e-scooters are permitted by creating designated infrastructure such as additional bike lanes that will make it clear for both e-scooter riders and other road users as to where designated travel areas are (DuPuis, Griess & Klein, 2019). The National Association of City Transportation Officials and the North American Bikeshare Association have also called

for more bike lanes, paths, and other marked areas that are safe for riders; this would help return the sidewalk back to primarily pedestrian use and make everyone feel safe (Fischer, 2020). A survey in Austin found that e-scooter riders were most comfortable on protected bike lanes, followed by paved urban trails, painted bike lanes, and residential streets without road markings, and that e-scooter riders were most uncomfortable on sidewalks adjoining multi-lane roads, surface trails, and multi-lane streets with road markings (Fischer, 2020). Separating infrastructure also made drivers feel more comfortable and has been shown to reduce fatality and injury rates (Fischer, 2020), which shows that infrastructure that separates e-scooter riders from motorists will improve safety.

Setting up a virtual perimeter to restrict e-scooter operation to certain areas (i.e., geofencing) is another way to prevent riders from using e-scooters in locations that could be unsafe for either them or other road users, and in certain locations, the speed may be reduced to improve safety (Fischer, 2020). Geofences are also used to define service boundaries and prevent theft of the devices, and they will work by stopping the e-scooters shortly after they exit the area (City of Chicago, 2020). There have been reports of these geofences causing the scooters to decelerate too quickly, resulting in jolting experiences for the riders, and therefore companies have worked to find safe deceleration rates (Portland Bureau of Transportation and Alta Planning and Design, 2020).

Speed Limits

Top speed is another factor that some cities have chosen to regulate. California's Active Assembly Bill 2989 limits the top speed of e-scooters to 20 mph, and Chicago, IL, is working on a pilot e-scooter program where the maximum allowable speed will also be 20 mph (Anderson-Hall et al., 2019). Arlington, VA and Washington, DC set jurisdictional speed limits of 10 mph in 2019 (Cicchino et al., 2020). Most cities have arrived at limiting the speed to 15 mph, but this still varies based upon the cities needs as well as feedback from the surrounding communities and frequent users. According to Choron and Sakran (2019) e-scooters pose a danger to riders due to their high travel speeds of up to 18 mph and minimal occupant protection.

Many scooters in these shared services are equipped with speed governors or speed limiting software. This allows the geofences to communicate with and prevent scooters from reaching speeds over a specific limit based upon the riding location (Baltimore City Department of Transportation, 2019). However, there still have been reports of riders traveling at excessive speeds due to roadways with large decline grades, indicating the need for improvements in this technology.

Parking

Many cities have received complaints of scooters blocking sidewalks and other areas of the roadway. Although e-scooters fleets are intended to be a dockless system such that they can be left anywhere, many users do leave them in inappropriate locations that cause either blocking or tripping hazards, especially for those with low vision or disabilities. To address this issue, some cities have required e-scooter vendors to apply for spaces within sidewalk furniture zones that act as a parking zone (Anderson-Hall et al., 2019). A short-term option is to paint an area for this zone, but e-scooters could still fall or be knocked over within these areas which would damage the e-scooter or surrounding objects and block the sidewalk, so long-term options might include creating physical parking infrastructure similar to bike racks (Anderson-Hall et al., 2019). Some e-scooter providers have implemented a requirement for riders to take a picture of where they have parked the e-scooter using the rental app. The photo is then reviewed, and if a user continues to leave the e-scooter in inappropriate places, the company can suspend their account and prevent them from riding in the future (DuPuis, Griess, & Klein). Cities have also created laws that

prohibit e-scooters to block sidewalks or other walkway features. Unfortunately, the issues with this are that many users are unaware of these laws and there is limited enforcement. Few studies have investigated proper parking, but most that did found that improper parking was under 5% (Brown et al., 2020; Fang et al., 2018).

Service Hours

Service hours have also been a criterion set by some locales and e-scooter service providers. For instance, Lime and Razor have service hours between 7 a.m. until 8 p.m., compared to Lyft, which has scooters available 2 hours before sunrise until 2 hours after sunset (Anderson-Hall et al., 2019). These rules are in place to allow operations and maintenance teams to collect and charge scooters, as well as to improve safety since riding an e-scooter in limited light can affect a rider's visibility to other road users (Anderson-Hall et al., 2019). Most cities do not allow the scooters to be unlocked during nighttime hours due to the increased numbers of injuries and fatalities that have been reported to occur (City of Austin, 2019). Weather and special events also affect service hours, as most companies will remove their scooters if they predict higher rates of misuse or injuries, as well as to prevent damage to the devices (City of Chicago, 2020).

Lock-to technology

Lock-to technology is another requirement that cities such as Chicago, Austin, Boulder, and Bloomington have made mandatory to prevent vandalism to scooters, clutter around the streets, and community backlash (Anderson-Hall et al., 2019). Lock-to ensures e-scooters lock to fixed objects, potentially reducing improper parking that blocks rights-of-way. Spin is one company that has agreed to implement this technology if so required (Anderson-Hall et al., 2019). A similar option to lock-to technology is tethering technology, which keeps unused scooters in an upright position and can be unhooked in the case of an emergency or if the row of scooters falls over (Anderson-Hall et al., 2019).

Maintenance

Due to heavy use, scooters need to frequently be serviced. When a device issue is noticed, the scooter will be disabled so that they can be collected, inspected, and fixed by the company (Baltimore City Department of Transportation, 2019). If device issues go unfixed, it can cause issues with the performance of the scooter, which has been reported by several injured e-scooter riders who blame device failure for the crash (Cicchino et al., 2020; City of Austin, 2019).

Helmet Use

Helmet use is a less established requirement across cities, possibly due to many users not planning in advance to take an e-scooter trip and thus not bringing a helmet with them (Behavioral Traffic Safety Cooperative Research Program, 2022). Many locations do have traditional helmet requirements for riders under a certain age, but that age can still vary by state (Pimentel and Lowry, 2020; City of Santa Monica, 2019). In a study of nine cities across the U.S., only Spokane, WA had a mandatory helmet requirement for e-scooter riders (Goodman et al., 2019), despite overwhelming statistics that the rate of head trauma for e-scooter riders has been seen to be double that for bicyclists (Fischer, 2020). Another study conducted by Austin, TX's Public Health Department found that 45% of people interviewed with injuries relating to e-scooter use involved head injuries and 15% of those were traumatic brain injuries, which could be due in part to less than 1% of e-scooter riders using helmets (Fischer, 2020).

One very clear safety solution that could help to mitigate head injuries is to wear a helmet. Very few riders have been seen to use helmets, and head injuries have been involved in almost 40% of the e-scooter

injuries in emergency departments (Goodman et al., 2019). Cities need to either pass new regulations making helmet use mandatory, or they need to improve enforcement of helmet use while operating an e-scooter (Ishmael et al., 2020; Ferri, 2019). Companies such as Wheels are planning to implement scooters that come with attached helmets, and liners will also be included to address hygiene concerns, particularly the spread of the coronavirus (Ferri, 2019). The helmet would be unlocked through the Wheels app, and a sensor would be able to recognize if the helmet is being used (Fischer, 2020).

Countermeasures by Brand

E-scooter and service characteristics are important for cities when considering which brand(s) of scooters to allow (Anderson-Hall et al., 2019). There are several differences between e-scooter providers, such as motor wattage, maximum speed, mile range, license requirement, lock-to technology, handlebar adjustment, free helmet, gyroscope sensor, and accelerometer sensor, and these may have safety implications for the users.

Overall, while countermeasures and policies exist, they are inconsistent between locations and scooter fleet operators with a tendency for rare enforcement. This study aims to gain further understanding of the policies in place and provide recommendations on how to better implement them to improve safety.

Methods

The research team at VTTI partnered with Spin to deploy a fleet of e-scooters on the Virginia Tech campus through an exclusive, controlled research program. A data acquisition system was added to a subset of scooters to collect data to assess safety impact, behaviors that are exhibited that may be beneficial or problematic, and ways in which kinematic and other data may be used to predict risky behavior for developing subsequent countermeasures. In addition, fixed cameras were installed to evaluate a variety of behavioral measures through a classification system developed as part of the project. The resulting data was used to assess impacts on safety, nuisance, and mobility, identify unique countermeasures to problems associated with e-scooter deployments where possible, and generate deployment requirements and guidelines for future open competition.

This project focused on addressing the following research questions:

1. What are the safety concerns associated with e-scooters (multiple passengers, dangerous behavior, one-handed riding, phone usage, food/drink holding, headphone wearing, impairment, obstacles, stunts, pedestrian/vehicle interaction, etc.)?
2. Will an e-scooter deployment in Virginia Tech result in nuisance concerns (scooter parking location, parking style, blocking access) and how can these concerns be mitigated locally and for future deployments in other parts of the country?
3. What are the utilization patterns (day/time, trip length and destination, replacing what types of trips, etc.) of e-scooters on the Virginia Tech campus?
4. How can e-scooter deployments be controlled in order to reduce safety and nuisance concerns?

Stakeholder Involvement and Policy Development

The VTTI team managed the overall technical program to ensure that the project achieved its objectives within the designated timeframe and with the allocated resources. A project kickoff meeting with relevant project stakeholders was held where the research objectives, research and deployment plans, the work plan tasks, and issues related to program governance were discussed. The team facilitated getting all necessary approvals and buy-in from all local governing bodies including Virginia Tech, the Town of

Blacksburg, and Virginia Tech Institutional Review Board (IRB) authorities. Leading up to deployment, a stakeholder group was created that included members from the following Virginia Tech departments: police, legal, risk management, communications, parking and transportation, alternative transportation, and operations. During these pre-deployment stakeholder meetings, many operational constraints were discussed and agreed upon with the goal of a safe deployment on the Virginia Tech campus. These operational constraints included:

- Geofencing
  - Scooters were restricted to the limits of the Virginia Tech campus and certain high-pedestrian areas were off limits.
  - Scooters were not allowed in the Town of Blacksburg.
- Scooter speed limits
  - Scooter speeds were governed to 12 mph, and reduced speeds of 4 mph were enforced in certain high-pedestrian areas.
- Weather
  - During service hours, **IF** more than 50% of the hourly predictions exceeded 50% probability of precipitation **AND** (total forecast accumulation of rain during the hours of operation was expected to exceed 0.5" **OR** the forecast precipitation was snow/ice) according to the National Weather Service, the day's deployment was cancelled.
  - Deployment and operations were suspended while winds were greater than 30 mph.
  - Deployment and operations were suspended while there was observable snow and ice coverage on campus sidewalks and streets.
- Special events on campus
  - Deployment would not occur on special event days with high volumes of traffic.
- Time of service
  - Scooter service started at 7am and ended at civil twilight (30 minutes after dusk). Scooters were removed from campus by Spin employees every night for charging.

Biweekly project status meetings were held with campus stakeholders during the e-scooter deployment on campus to discuss and resolve any safety or logistical concerns.

Data Collection

With the goal of becoming the first living-laboratory for dockless e-scooters, VTTI led the effort to gather comprehensive research data about the e-scooter deployment. This dataset included four main data sources, each of which are described in more detail later in this section:

1. Naturalistic data collected from e-scooters equipped with VTTI's microDAS;
2. Observational data collected by 14 external cameras installed in high-traffic areas around the Virginia Tech campus;
3. Subjective data collected by optional post-ride surveys within the Spin smartphone application as well as more comprehensive surveys regarding the campus deployment;
4. Spin smartphone application data;
5. Photographs taken at the conclusion of each e-scooter ride using the Spin smartphone application; and
6. Anecdotal, de-identified injury reports provided by the Spin application, the Virginia Tech Police Department (VTPD), and Virginia Tech's on-campus health center.

Data was collected over 134 deployment days (**Table 2**), resulting in a rich dataset that could be used to develop safety countermeasures and to provide guidance to communities on improving infrastructure and policies to better accommodate micromobility transportation with the goal of encouraging livable communities. The two phases were also marked by a shift in the e-scooter model from the Segway Ninebot ES4 to the Segway Ninebot Max.

Table 2. Deployment Statistics.

Deployment Statistics	Phase 1	Phase 2	Total
Total # of deployment days	51	83	134
Days with inclement weather	7	19	26

Figure 6. VTTI's e-scooter microDAS installed on a Spin scooter.

MicroDAS

The VTTI team developed a data acquisition system specifically for the Spin e-scooter platform, referred to as a microDAS (**Figure 6**) to capture naturalistic riding data. The microDAS was encapsulated in a custom waterproof enclosure mounted on Spin's standard internet of things (IoT) box which is installed on the stalk of the e-scooter. Fifty-two (52) of Spin's e-scooters were modified to facilitate such instrumentation. The microDAS collected several data sources, all at 10Hz, including:

- Video stream – high definition (HD) video of the area in front of the rider
- Accelerometers – a multi-axis (x, y, z) accelerometer collected kinematic behavior, including hard *g*-force stops, starts, and turns. When combined with the video data it enabled analysis of riding behaviors that may be associated with risky outcomes.
- GPS – a GPS sensor collected speed and high-precision positioning of the e-scooter to enable analysis of trip-level rider behavior and usage patterns.

The on-scooter DAS was designed to collect anonymous rider data (i.e., only forward video and GPS traces). This enabled collection of data from anyone who rode the scooters, providing a more robust base of data without concerns over participant recruitment, human subject informed consent, and compensation. The data collection effort resulted in slightly over 9,000 trips collected by the DAS. The e-scooters were configured to securely offload the data to a VTTI server when the scooters were located within a predetermined geofence.

Fixed Cameras

A fixed observation video system package was also developed to complement the data collected by the microDAS. The VTTI team managed the procurement and installation of 14 stationary video cameras on the Virginia Tech campus at strategically placed, public locations to facilitate the collection of aggregate data on rider and pedestrian interactions and rider behavior in general that could not be captured by the microDAS's forward video. These cameras also captured specific infrastructure factors of interest. The cameras were configured to stream video to enable remote storage on secure VTTI servers and to record during hours of e-scooter deployment (approximately 6am to 8pm daily). The views of the fixed cameras can be seen in Appendix A-5.

Surveys

The final modality of VTTI's data collection included subjective surveys to obtain opinion and preference data from e-scooter users, pedestrians, cyclists, and members of the town and university community. There were two main forms of subjective surveys: one long-form survey that consisted of up to 31 questions, and a short, three-question optional survey that was presented in the Spin mobile app to riders after each ride. IRB approval was obtained prior to the distribution of all surveys (IRB #19-581).

Long-Form Perception Surveys

The long-form surveys focused on opinions about e-scooters in general, the specific implementation associated with this project, and ways that riders and non-riders could envision improvements in safety, distribution, and usefulness. A similar survey was referenced which had been conducted by a project team member in Arlington, VA when developing the survey instruments for this project (Buehler, 2019).

Two versions of the survey were developed and administered prior to the deployment and one month into deployment to understand any shifts in attitudes and opinions of the e-scooter deployment on campus as exposure increased. Qualtrics surveys were administered online and via tablets in person on campus at locations with high commuter foot traffic. For the pre-deployment survey, 428 responses were received, and for the follow-up survey, 465 responses were received.

Survey recruitment instruments were developed in conjunction with the VTTI and Virginia Tech Communications teams. Recruiting methods included social media posts on VTTI and Virginia Tech Twitter, Facebook, and Instagram accounts, electronic bulletins around campus, Virginia daily news emails (which are sent to current employees and students as well as alumni) and fliers handed out in person on campus. One out of 50 survey respondents were randomly chosen to receive a $50 check for their participation. The results from these surveys can be seen in Appendix A-8.

Post-Ride In-App Surveys

An optional short three-question survey was designed and presented to every Spin e-scooter rider at the conclusion of their ride within the Spin application. This survey allowed more e-scooter riders to be reached and to understand changes over time throughout the deployment. The three questions that were included in this survey were:

1. What was the purpose of your trip?
2. If not by e-scooter, how would you have taken this trip?
3. Why did you choose to ride an e-scooter for this trip?

The results from this in-app survey can be seen in Appendix A-9.

Spin Application Data

Spin collected data throughout deployment using their typical onboard systems at 5Hz as well as through the mobile applications that all riders must use to lock and unlock a Spin e-scooter. Spin provided start and stop times and locations of each ride for analysis purposes, which totaled over 120,000 rides. This data did not include personally identifiable information (PII) since all Spin e-scooters were geofenced to the Virginia Tech's campus boundaries wherein all campus buildings host a large number of students/employees.

At the end of each ride, Spin riders were presented with a screen in the Spin application asking if they wanted to consent to sharing their full trip GPS data and take a short survey. Approximately 12,000 rides

resulted in the rider choosing to consent to share their trip data and approximately 11,000 of those had completed in-application survey questions. Spin de-identified the responses to these surveys and provided the data to VTTI researchers along with the full GPS traces of those rides where users agreed to data sharing.

Parking Photos

As part of Spin's normal processes, riders are required to upload a picture of the parked e-scooter to end their ride within the mobile application. Spin shared approximately 67,000 final parking photos with the research team to analyze parking compliance over time.

Injury Reports

The research team also collected anecdotal, de-identified injury reports through the Spin application, as well as by contacting the Virginia Tech Police Department and Virginia Tech's on-campus health center.

Data Analysis

The goals of the analysis were to answer the project's research questions by identifying safety critical events and behaviors, as well as understanding typical e-scooter usage and parking patterns. To accomplish these goals, algorithms needed to be developed to pull these events from the dataset, and classification schemes were created to characterize conflict and baseline events and behaviors. The following sections detail the development of the analyses.

Develop Conflict Trigger Algorithms

During this study, an algorithm was created to detect certain riding behaviors and events. While full development of such an algorithm was not within the scope of the current effort, the theoretical groundwork was laid. Three main trigger algorithms were developed based on the reduced forward video and kinematic data to detect fallover events, forward impact events, and near miss events. Each of these algorithms are described in further detail below. These algorithms were then run across the DAS data to easily identify behaviors and events of interest.

Fall-Over Events

To detect instances where the e-scooter fell over, which was when part of the e-scooter (other than the wheels) made contact with the ground, an algorithm was developed to find instances where the Z-axis of the accelerometer approached or reached zero and was sustained for a duration of at least one second. The resulting algorithm utilized the following threshold criteria:

- 0.3 g <= *accel_z* <= -0.3 g
- *accel_z* window duration: 1 second

Forward Impact Events

To detect instances where the e-scooter made a forward impact with an object, an algorithm was developed to find instances where a large longitudinal acceleration was followed by a sustained 0 speed. The resulting algorithm utilized the following threshold criteria:

- Filtered x-accel using a moving average over 3 consecutive data points
- When values ≥ 0.3g are found in the data, the corresponding speed data are reviewed to look for a speed of 0 for ≥ 3s

Near-Miss Events

In order to identify potential near-miss events of interest, kinematic signals were analyzed to identify anomalous swerving maneuvers. These swerving maneuvers were extracted from the yaw rate signal (z-axis gyroscope) obtained from the IMU. Potential swerve events were identified by executing an extremum search of the yaw rate signal. At each of the identified extrema points, a set of summary metrics were calculated, and these summary metrics were later used to identify the cases of interest. Two types of events were identified for further review, those where there was a sharp yaw rate change followed by the rider coming to a stop, and those with a sharp yaw rate where the rider did not stop. These two event types were selected due to the differences in the kinematic signature associated with stopping.

In order to identify cases where the rider stopped after a detected swerve event, a set of logical criteria were enforced on the summary measures generated from each of the potential swerve maneuvers. The resulting algorithm utilized the following threshold criteria:

- Speed in the 5 seconds following the yaw rate change was greater the 2 m/s
- Speed 5 seconds after the detected swerve maneuver was less than 0.75 m/s
- Absolute lateral acceleration was greater than 0.4g
- Peak to peak yaw rate change of greater than 70 deg/s

To identify cases where the rider kept on riding after a detected swerve event, a set of logical criteria were enforced on the summary measures generated from each of the potential swerve maneuvers. The resulting algorithm utilized the following threshold criteria:

- Speed in the 5 seconds following the yaw rate change was greater the 2 m/s,
- Speed 5 seconds after the detected swerve maneuver was greater than 1 m/s.
- Absolute lateral acceleration was greater than 0.2g
- Peak to peak yaw rate change of greater than 70 deg/s

Develop Conflict/Behavior Classification Schemes

During this task, a classification scheme was developed to systematically identify and categorize the types of behaviors that e-scooter riders engaged in relative to the infrastructure, trafficway, environmental factors and other road users. This classification scheme included two variants called data reduction protocols: one for on-scooter DAS analyses and one for fixed-camera analyses. Both variants defined events of interest as 1) crashes, 2) near crashes, or 3) crash relevant. In addition to classifying those events of interest, the classification schemes also included questions aimed at baseline events, which are epochs of data randomly selected from the entire dataset. The inclusion of baseline event reduction allowed for conclusions to be drawn during analyses about the prevalence of certain behaviors and the level of risk associated with those behaviors. The data reduction protocols were modeled after existing schemes, particularly the Researcher Dictionary for Safety Critical Even Video Reduction Data (Virginia Tech Transportation Institute, 2015), but were altered to account for behaviors unique to e-scooter riders. This classification scheme was completed prior to data reduction and analysis, and can be seen in Appendix A-1, Appendix A-2, and Appendix A-3.

Develop Parking Classification Scheme

Similarly, a classification scheme was developed to enable analysis of e-scooter parking compliance and behaviors. The data reduction protocol included only four questions focusing on parking compliance and further classification of the e-scooter parking location and whether it was blocking access to anything that

would be considered a nuisance (e.g., ADA ramps, sidewalks, stairs, sidewalk furniture, etc.). This protocol can be seen in Appendix A-4.

Data Sampling and Reduction

MicroDAS and Fixed Cameras Sampling and Reduction

VTTI's statisticians completed power analyses to determine adequate baseline sample sizes to answer the study's main research questions. For the DAS dataset, the baseline sample size was determined through a power analysis which found that a sample size of 800 events per phase of deployment would sufficiently detect a 15-20% difference in prevalence of certain behaviors/elements.

The fixed camera data was used to answer to main research questions, and therefore had a different sampling strategy. To answer questions surrounding the prevalence of certain behaviors across all 14 fixed camera sites (e.g., helmet usage, handheld item, etc.), 46 samples were reduced per fixed camera for a total of 644 samples. To answer questions related to specific elements in certain camera views of interest, 9 of the 14 cameras were oversampled as they had high to moderate exposure to vehicle interactions and the following infrastructure elements of interest:

- Shared lanes (9 sites) – 1,032 samples
- Bike lanes (2 sites) – 400 samples
- Intersections (5 sites) – 593 samples
- Roundabouts (3 sites) – 400 samples
- Crosswalks (8 sites) – 939 samples

Once the data reduction protocols and sampling plans were finalized, VTTI's trained Data Reduction team integrated the DAS and fixed camera protocol questions and response options into their toolsets. Events of interest that were identified by the triggers (i.e., fall-overs, forward impacts, and near crashes) and baseline events were also queued up in the data reduction toolsets to facilitate the coding of video data for each event of interest and baseline event. Human reductionists then coded each event epoch by viewing the video segment (the duration of which was defined in the respective protocol) and coding the behaviors and elements that were present in the video during the selected timeframe. In parallel, the data reduction team also completed standard quality control practices to ensure consistency amongst reductionists and coding practices to the extent possible.

Parking Photo Sampling and Reduction

To understand e-scooter parking patterns and prevalence, a total sample of 826 parking photos were analyzed, stratified proportionally to the number of rides taken by week of deployment. A power analysis was completed with a significance of 0.05, determining that a sample size of 800 would provide an estimated statistical power of ±97.85%.

Each parking photo was categorized to determine if the e-scooter was parked 1) according to Virginia Tech policy (Virginia Tech Policy No. 5005: e-scooters must be parked within 5 feet of an approved bicycle rack or at designated zones on campus, cannot block ADA pathways, ADA ramps, or building entrances or exits), 2) not according to policy, but acceptable, and 3) not according to policy, and not acceptable.

As the parking photo dataset included still photos rather than video data, a simpler reduction process was followed to code the parking photos. The parking photos were imported into a VTTI tool that allowed the reductionist to quickly scroll through the photos and answer the applicable questions about each photo

per the reduction protocol. Again, due to the relative simplicity of this process and the protocol, quality control processes were less rigorous, with only 5% of photos being verified by a second reductionist.

Analysis Plan

Analyses were performed upon the reduced/coded data, which allowed us to address the questions motivating the study, including rider behavior, factors associated with risk, riding and parking patterns, and other issues surrounding the safe deployment of a fleet of electric scooters on college campuses. Summary statistics were compiled for each of the four datasets. Odds ratios were calculated for the microDAS data to inform the level of risk associated with various factors encountered during e-scooter rides on campus. The frequencies of certain factors encountered during e-scooter conflicts (crashes, crash-relevant conflicts, and near misses) were compared to the frequencies of those same factors being present during baseline events. This comparison allowed us to draw conclusions about the prevalence of those factors occurring during conflicts and baseline events to determine the odds ratios.

Results

MicroDAS Results

Table 3 summarizes information about the e-scooter trips such as the number of Spin and DAS trips, as well as the mean trip duration.

Table 3. Trip Information by Deployment Phase.

		Phase 1	Phase 2	Total
Entire e-scooter fleet (*data source: Spin onboard unit)	# Spin Trips	72,315	48,321	120,636
	Mean trip duration (mins)	7.8	6.5	7.3
VTTI DAS-equipped scooters (*data source: DAS)	# DAS Trips	3,106	5,981	9,087
	Mean trip duration (min)	6.1	4.0	4.8

Of the VTTI instrumented scooters, there were a total of 85 crashes out of 9,087 trips, showing that 0.94% of the trips resulted in a crash. For Phase 1 of the deployment, there were 51 crashes out of 3,106 trips which is a crash rate of 1.64 per 100 trips, and for Phase 2 of the deployment, there 34 crashes out of 5,981 trips which is a crash rate of 0.57 per 100 trips. **Table 4** shows a further breakdown of the crashes by phase. Near misses were another type of safety-critical event that were reduced and analyzed in further detail. Near misses include near-crashes and crash relevant events which are also shown in **Table 4.**

Table 4. Safety-Critical Events by Deployment Phase.

DAS Results	Phase 1	Phase 2	Total
Crashes	51	34	85
Crash rate per 100 trips	1.64	0.57	0.94
1 crash per X hours of riding	6.2	11.8	8.5
Near crashes	52	17	69
Total safety-critical events	103	51	154
Total safety-critical event rate per 100 trips	3.32	0.85	1.69

The tables below include summary statistics of the crash and non-crash conflicts based on the data reduction results for each event. Some conflicts may fall into multiple categories and be counted multiple times. Therefore, the number of conflicts for each data representation may be greater than the total 154 conflicts. (Additional results from the DAS dataset are included in Appendix A-6).

Crashes were characterized as being a simple fall-over/bailout (where the e-scooter made contact with the ground), which was the most common crash type (71%), or an impact event (where the e-scooter made contact with another object) accounting for 29% of crashes (**Table 5**). Crashes were also characterized by the status of the ride after the crash, and the e-scooter rider stopped the ride in only 9 cases (10.5% of crashes). In all other cases (89.4%) the rider either stopped briefly and then continued riding or continued riding without stopping at all.

Table 5. Crash Type and Ride Status.

	Summary		Post Ride Status (Count)	
Crash Type	Count	Percent	Stopped	Stopped briefly/ continued riding
Simple fall-over/bailout	60	70.6%	4	56
Impact with infrastructure element	19	22.4%	3	16
Impact with another scooter	2	2.4%	0	2
Impact with pedestrian	1	1.2%	0	1
Impact with vehicle	1	1.2%	1	0
Impact with a plant	2	2.4%	1	1
Total	**85**	**100%**	**9**	**76**

The frequency, prevalence, and odds ratio associated with various infrastructure, environmental, and behavioral factors can be seen in **Table 6**. The factors below were determined to have significant effects on riding risk. Conditions with an odds ratio <1 had a lower risk and included riding on a non-shared path, riding on surfaces that are not dry, and riding in traffic flow. Factors with an odds ratio >1 had a higher risk, and included riding in non-daylight conditions, riding off-road, on the grass or on a loose surface (gravel, grass, dirt, mulch, sand), group riding, riding behavior characterized as aggressive, excessive speed, or trick riding, and "non-normal" behaviors of other road users (includes aggressive, distracted, or unexpected actions made by pedestrians, bicyclists, vehicles, other e-scooter riders, etc.).

Table 6. Frequency, Prevalence, and Odds Ratio of Safety Critical Events.

	Frequency				Prevalence		Odds Ratio
	SCEs: Comparison group	SCEs: Reference group	Baselines: Comparison group	Baselines: Reference group	SCEs	Baselines	
Infrastructure Factors							
[1]Riding location: Non-Shared Path vs. shared-use path	59	95	695	639	38%	52%	**0.57 [0.41, 0.80]**
Riding location: No designated path (off-road) vs. others	65	219	42	2119	23%	2%	**14.97 [9.92, 22.61]**

Environmental Factors							
Lighting: Non-daylight vs. daylight	11	143	19	1579	7%	1%	**6.39 [2.98, 13.70]**
[2]Surface condition: Others vs. dry	44	148	618	1455	23%	30%	**0.70 [0.49, 0.99]**
Surface type: loose surface vs. solid surface	35	191	17	1852	15%	1%	**19.96 [10.98, 36.31]**
Surface type: grass vs. solid surface	50	191	34	1852	21%	2%	**14.26 [9.00, 22.60]**
Behavioral Factors							
Grouping: group riding vs. ride alone	29	125	145	1459	19%	9%	**2.33 [1.51, 3.62]**
[3]Riding behavior: others vs. normal	87	67	227	1374	56%	14%	**7.86 [5.55, 11.13]**
Riding behavior: aggressive vs. normal	74	67	149	1374	52%	10%	**10.18 [7.03, 14.76]**
[4]Other actor behavior: others vs. normal	31	123	26	1308	20%	2%	**13.20 [7.73, 14.76]**
[5]Flow direction: In traffic flow vs. not applicable	34	120	439	895	22%	33%	**0.58 [0.39, 0.86]**

1. "non-shared path" includes unpaved path, parking lane, shoulder, ADA access ramp, bike lane, crosswalk, parking lot, roadway, no designated path, and sidewalk.
2. Surface condition is based on worst case scenario, i.e., if rode though both wet and dry surface, it will be classified as wet condition.
3. "other riding behaviors" including excessive speed, trick riding, and aggressive driving.
4. "other actor behavior" includes aggressive, possibly distracted, or unexpected movements by vehicles/drivers or other road users (scooters, pedestrians, bicyclists, etc.)
5. In traffic flow includes: in pedestrian traffic, with flow, slower; incorrect direction in a bike lane; incorrect direction in a shared vehicle lane; against pedestrian traffic flow; correct direction in a bike lane; same speed as pedestrian flow; correct direction in a shared vehicle lane; in pedestrian traffic flow with a faster speed. "Not applicable" means the rider was not in a traffic flow.

Fixed Camera Results

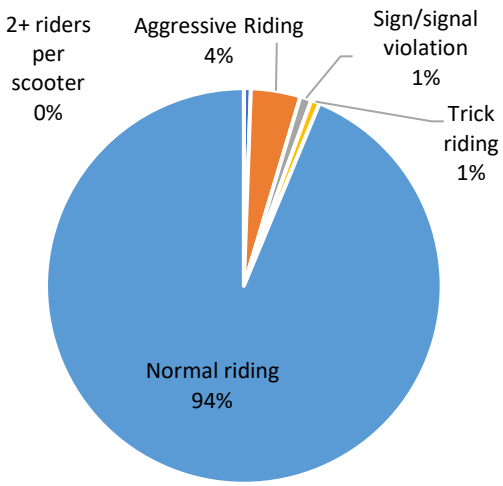
A total of 1,406 fixed camera baseline samples were reduced by VTTI's data reduction team. Of those, 10 conflicts were identified, 1 of which was a crash and 9 of which were deemed crash relevant. The single crash identified occurred while the subject rider was trying to pass a group of pedestrians on a sidewalk which resulted in an impact with a fixed infrastructure element.

The sections below include summary statistics of the fixed camera reduction results. (Additional results from the fixed camera dataset are included in Appendix A-7)

Prevalence of Rider Behaviors

When looking at the distribution of e-scooter riders by gender, 73% of the rides captured by the fixed cameras had male riders and 27% had female riders. Helmet use was also studied by the fixed cameras. Only 1% of riders were wearing helmets. Riders were also seen to frequently wear bags (79%) and infrequently carry items (2%) or hang items on the handlebars (5%) while using e-scooters.

In addition to be captured by the DAS, riding behavior was also captured by the fixed cameras (**Figure 7**) which captured more of the environment surrounding the e-scooter riders, rather than just the forward view. Most of the riders rode in a normal manner (94%), followed by some aggressive riding (4%), trick riding (1%), sign/signal violation (1%), and double riding (<1%), where more than one person was witnessed on the same scooter.



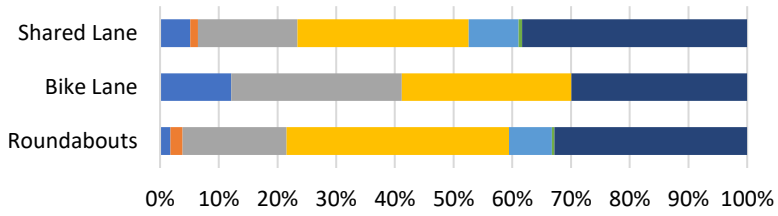
Riding Behavior	Count
2+ riders per scooter	8
Aggressive riding	57
Sign/signal violation	13
Trick riding	10
Normal riding	1,318
Total	1,406

Figure 7. Riding behavior captured by fixed cameras.

Riding stance was another factor of interest. A rider's center of gravity was determined by looking at their hip location relative to the scooter's handlebars. If there was approximately 2" of space or less between the rider's hips and the scooter stalk, their center of gravity was characterized as towards the front of the scooter, and if there was approximately more than 2" of space between the rider's hips and the scooter stalk, their center of gravity was characterized as towards the center or back of the scooter. From this, it was seen that 41% of riders had their center of gravity more towards the front of the scooter, and 59% had their center of gravity towards the center or back of the scooter. Foot placement was also examined. Seventy-five percent (75%) of riders had their feet placed in the fore and aft of the scooter, 22% rode with their feet side to side, and 3% rode with one foot on and one foot off.

Infrastructure-Specific Results

The second research question focused on specific types of infrastructure. For the fixed camera locations that had a shared roadway lane (11), bike lanes (2), and roundabouts (3), the actual riding locations chosen by the subject riders are indicated in **Figure 8**.



	Roundabouts	Bike Lane	Shared Lane
Bike lane	12	79	80
Parking lot	14	0	21
Crosswalk	119	189	264
Sidewalk	255	188	455
Shared-use Path	49	0	133
No designated path (off road)	3	0	9
Roadway (Shared Lane)	221	195	598

Figure 8. Riding locations used by infrastructure type.

Figure 9 shows the percentage of aggressive riding for each infrastructure type present in a fixed camera field of view. Aggressive riding, defined in the data reduction protocol as including aggressive/dangerous weaving or speeding, intentionally causing close/unsafe proximity to other users, etc., was seen most frequently in parking lots, followed by roundabouts and intersections.

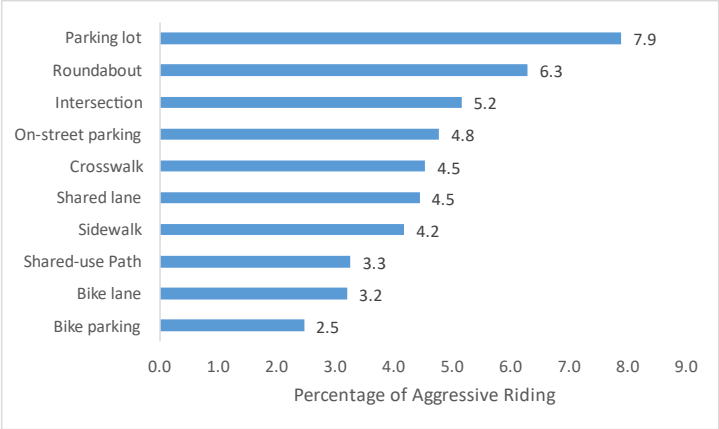


Figure 9. Percentage of aggressive riding by infrastructure type present.

Survey Results

Information of e-scooter perceptions through the pre- and post-deployment surveys was also gathered, including anticipated and actual trip replacement. Sixty-eight percent (68%) of pre-deployment respondents and 81% of post-deployment respondents stated that e-scooters would replace walking trips. This was consistent with the in-app survey results where 68% of respondents in Phase 1 and 76% of respondents in Phase 2 indicated e-scooter trips replaced walking trips.

The long-form survey also gauged impressions of e-scooters on campus before and after the deployment. Most of the impressions were favorable: 70% of pre-deployment respondents and 49% of post-deployment respondents viewed such deployments as favorable to moderately favorable, with only 8%

of pre-deployment and 16% of post-deployment respondents viewing the deployment as unfavorable. (Full perception survey results are included in Appendix A-8 and Appendix A-9.)

Parking Photo Results

Of the parking photos analyzed, 39% were parked according to the Virginia Tech policy and additional 46% was classified as being parked "acceptably" (i.e., not blocking access to pedestrian or vehicle rights-of-way). Thus, a total of 86% were parked acceptably while 14% were blocking access to something and would likely be considered a "nuisance". E-scooters parked acceptably increased from an average of 80% to 90% over the course of the 20-week deployment. Of the unacceptably parked scooters, only 8% were blocking access to either a sidewalk (n=64) or ADA ramp (n=2). Detailed parking photo results, including detailed characterizations of unacceptable parking jobs, are included in Appendix A-9.

Injury Report Results

Regarding the e-scooter injuries that occurred on campus, there were between 26 and 36 injuries reported, either through the Spin mobile application, the VTPD and/or the on-campus health center, as detailed in **Table 7**. It is unknown whether each injury occurred on a Spin e-scooter or a personally owned scooter. It was also unclear whether any the injuries that were reported by Spin or VTPD overlapped with the data that was provided by the health center, but it is unlikely that they overlap when considering incident date, time, location, and description of the crash. Assuming that 36 known injuries occurred across the 120,636 total trips, this is an injury rate of 3 injuries per 10,000 trips.

Table 7. Injuries Reported on the Virginia Tech Campus.

Source of Injury Report	Injuries Reported	Additional Injury Information
Spin application	5	• 1 crashed in intersection, leg lacerations
VTPD	7	• 2 transported to local hospital (1 resulted in overnight stay) – 1 concussion, 1 arm injury • 1 caused crash between bicyclist and pedestrian • 1 crash with vehicle in parking lot • 3 crashes with likely injuries
Virginia Tech Health Center	24	• 4 wrist fractures; one required surgery • 2 dislocated shoulders • 2 with abrasions on knees • 1 injury to face/shoulder • 1 facial fracture; loss of tooth • 14 miscellaneous injuries

Discussion

E-scooters are a relatively new mode of transportation to both users as well as the cities in which they operate. There have been reports of safety concerns for e-scooter riders and other road users. The data collected during this study provides a more comprehensive look at e-scooter utilization patterns as well as safety and nuisance concerns to inform best practices around future deployments.

Crash rates were observed to decrease from 1.64% in Phase 1 to 0.57% in Phase 2. This decrease in crash rate could be the result of a training effect or learning curve: when riders gain more experience riding the e-scooters, they also became safer at operating them. Additionally, there were e-scooter design changes

seen during the shift from the ES4 e-scooter model in Phase 1 to the Max model in Phase 2. The ES4 had smaller, non-pneumatic tires and weighed 31 lbs., and the Max model had larger pneumatic tires and weighed 42 lbs. There was also a change in the braking systems between the two models. These design changes could have resulted in added safety benefits. The overall crash rate was 0.94 per 100 trips, or 940 crashes per 100,000 trips. While this crash rate is higher than findings from other studies, which reported rates between 6 and 19 crashes per 100,000 trips (Fischer, 2020), it is also likely a more accurate representation. Other studies only collected information about crashes and injuries from hospital admissions or self-reports; comparatively, in this study the microDAS captured additional information which allowed for all crashes to be detected.

The most common conflict types for crashes were simple fall-overs and bailouts (71%) or impacts with infrastructure (22%), although there were a few other impacts with plants, vehicles, pedestrians, and other scooters. These crash trends appear to be in line with results from a study by Trivedi et al., which found that 73% of injured riders had fallen (2019). Fall-overs and bailouts are events caused by loss of control or the rider intentionally abandoning the e-scooter in an attempt to avoid a crash. Many e-scooter riders are first-time users, and lack of experience has resulted in a number of crashes and injuries, as seen in a study in Austin, Texas, which reported that 1/3 of injured e-scooter users were first-time riders and approximately 60% of injured users had ridden an e-scooter less than 9 times (City of Austin, 2019).

Several factors were identified to contribute to higher risk levels for e-scooter riders. Riding behavior significantly impacts the risk of a safety critical event occurrence. Group riding was involved in 19% of the safety critical events and increases the risk of a safety critical event by 2.33 when compared to riding alone. While reviewing the microDAS forward camera footage from these group riding events, it became apparent that riders were more likely to perform unsafe maneuvers and trick riding when traveling with other riders, many of which led to the safety critical events. Other riding behaviors such as aggressive riding, excessive speed riding, and trick riding had large effects on safety critical event risk. Eighty-seven (87) of the 154 safety critical events, or 56%, involved one of these riding behaviors. Breaking this down further, 74 of those events involved aggressive riding, resulting in a 10.18 times higher risk of a safety critical event compared to normal riding. The study at UCLA also found that aggressive behaviors and traffic violations were frequently observed (Trivedi et al., 2019). Aggressive behavior is not only a factor in e-scooter crashes but also contributes to a number of motor vehicle collisions (U.S. Department of Transportation, 2008). However, e-scooter fleet services present a unique opportunity such that algorithms can be developed and incorporated into the e-scooter software that can be used to detect aggressive riding and either give feedback or limit services for users that continue to ride in a dangerous manner.

Other road user actions that were characterized as aggressive, distracted, or unexpected also affected risk, as there was a 13.20 times higher risk of a safety critical event occurrence when other road users acted in any of these manners. Interactions with other road users continue to be a major safety concern, and several studies have noted how both e-scooter riders and other road users feel unsafe interacting with each other (Sanders et al., 2020; Pimentel and Lowry, 2020; James et al., 2019). This signifies the importance for all road users to be educated on traffic laws. One environmental factor that impacted risk was lighting. Riding during non-daylight conditions had a 6.39 greater risk of a safety critical event when compared to riding during daylight conditions. Studies by the City of Austin (2019) and the Consumer Product Safety Commission (2022) also observed an increased proportion of crashes and injuries during conditions where it was difficult to see. Spin e-scooters are equipped with headlights, yet several crashes

and near crashes occurred, indicating the need for either improved headlights or additional road lighting to help riders detect hazards that may not be easily visible. Additionally, riding on non-solid surfaces such as grass, gravel, dirt, sand, and mulch were also seen to result in a higher safety critical event risk. Most e-scooters are designed for travel on flat pavement or asphalt, and perhaps due to the selection or design of tires, they do not traverse well over off-road surfaces. To reduce the number of conflicts, either more emphasis needs to be placed on the appropriate operating domains so that e-scooter users understand not to ride in these conditions, or tires designed for off-roading should be added to the e-scooter design.

A few conditions were observed to have a lower risk. Riding on a non-shared path when compared to a shared-use path was seen to have approximately half of the risk, likely due to fewer interactions with other pedestrians, cyclists, and vehicles, which has been seen to lend to comfort (NATCO, 2020). Riding in traffic flow when compared to riding against traffic flow or in areas without a clear flow direction was also less risky. This could indicate that users tend to ride in a safer manner when it is clear as to where they are supposed to ride, demonstrating the need for additional signage for e-scooter riders and improved education regarding traffic laws. Riding on wet surfaces or surfaces with standing water, snow, or ice compared to dry surfaces also had lower risk. While these might seem counterintuitive, it can be hypothesized that due to these conditions being perceived as more dangerous, riders operated with caution to ensure that they did not crash.

The fixed camera results showed that a majority of riders operated e-scooters in a normal riding behavior (1318 observations or 94%), yet there were some aggressive riders (57 observations or 4%) and some instances of sign or signal violation (13 observations or 1%), trick riding (10 observations or 1%), and multiple riders per e-scooter (8 observations or <1%), which are also in line with the results from Trivedi et al. (2019). The fixed cameras were also able to capture aggressive riding by infrastructure type. Aggressive riding was most commonly observed in parking lots, roundabouts, and intersections. Two similarities between these locations are that there is not a defined flow direction and that there is typically pedestrian traffic. Given the context of these locations, e-scooter riders were most likely traveling at higher speeds relative to the surrounding foot-traffic and had to weave between pedestrians walking in multiple directions, causing them to become unsafely close. While these actions may not have been intentionally aggressive, it remains a safety concern for e-scooters to be operating in domains without clear flow or with slower moving traffic. In a South California study, 52% of pedestrians that were injured had been struck by e-scooters (Fischer, 2020), and these injuries are serious due to disparities in speed and overall energy. Identifying safe locations for e-scooters to travel could be a solution to reduce aggressive behaviors.

The injury rate during this study was 3 injuries for every 10,000 trips, which is in line with the results from the studies in Portland (Eudaly et al., 2019) and Austin, Texas (City of Austin, 2019). While only a maximum of 36 injuries were reported, there were also only 85 crashes captured by the DAS. It is unclear if the injuries resulted from these crashes or if they were separate events, possibly involving non-Spin scooters. Regardless, it appears that the likelihood of being injured as a result of an e-scooter crash is relatively high due to the limited occupant protection offered by the scooter. Despite the high injury risk, severe injuries were not commonly observed. Only 9 of the 85 crashes resulted in riders completely stopping, a possible indication that they suffered an injury that prevented them from continuing the ride. This also likely indicates that in the rest of the crash cases, riders were either unharmed or they did not sustain an injury that was severe enough to limit their ability to ride an e-scooter. According to the National Transportation Safety Board's definition of severe injuries (1995), the 4 wrist fractures and 1 facial fracture that occurred

during this study would be classified as severe. Overall, this demonstrates that while e-scooter riders can be at risk to sustain serious injuries, severe injuries occur less often. All of the injured riders reported that they were not wearing a helmet at the time of the crash, and there were a few head injuries which could have possibly been mitigated if helmets were used. This indicates that enforcement of helmet use should be considered as it may possibly help to reduce the severity and occurrence of head injuries. The fixed camera results only help to strengthen the need to consider enforcement of helmet use, as 99% of the observed riders were not wearing helmets. Observations from the Behavioral Traffic Safety Cooperative Research Program (2022) also found that helmet use ranged from 0 to 9%, and that only 10 of 249 injured riders in the UCLA study had been wearing a helmet (Trivedi et al., 2019). While helmet use was not a required policy during this deployment, it is known that use of helmets reduces the severity and incidence of head injuries. However, helmets are not included with shared scooters and most e-scooter trips are unplanned (Behavioral Traffic Safety Cooperative Research Program, 2022), making this a difficult policy to enforce. Therefore, it is apparent that new solutions need to be implemented to increase helmet use.

An additional concern, aside from lack of helmet use, has been carrying items. It is not surprising that many riders were carrying items as this study was conducted on the Virginia Tech campus where the majority of riders were students. However, carrying items can still impact safety because it affects the rider and scooter's center of mass and distribution of weight which could have implications for maintaining balance, turning, and steering. A study by the Consumer Product Safety Commission (2022) found that holding items contributed to 26% of the investigated incidents. Policies might need to be put in place to govern carrying items.

Riding stance was also observed from the fixed cameras as there can be safety implications associated with a rider's posture. For e-scooters, it is typically recommended that riders have their center of gravity more towards center to back of the e-scooter to balance the weight of the e-scooter which is located mostly towards the front with the handlebars, which is why it was interesting to observe that 41% of riders had their center of gravity towards the front of the scooter. Additionally, the recommended foot placement is fore and aft. Twenty-two percent (22%) rode with their feet side to side, which is surprising given that the e-scooter deck is not wide enough for both feet to fully fit. These results point to the need for instructions or tutorials on proper riding stance.

Riding location was also captured by the fixed cameras. For the fixed camera locations that had a shared roadway lane, most e-scooter riders chose to also ride in the shared lane (38%) followed by the sidewalk (29%) and the crosswalk (17%). For the locations with bike lanes, the least common location to ride was in the bike lane (12%), with the most common still being the shared lane (30%), followed closely by the crosswalk (29%) and the sidewalk (29%). This result seems to contradict safety perception data collected in a study by NATCO et al. (2020), which reported that the presence of a bike lane increased perceptions of safety. At roundabouts, most riders were observed to travel on the sidewalk (38%), followed by the shared lane (33%) and the crosswalk (18%).

When looking at the trip information, the total number of trip miles decreased from Phase 1 to Phase 2, despite Phase 2 having 32 more days than Phase 1. While the operational hours for a majority of the weeks in Phase 2 were shorter than in Phase 1 due to constraints by daylight, another possible explanation for this trend could be that e-scooters are a less popular transportation option in the lower-temperature months, which was a similar finding in a study conducted by the Portland Bureau of Transportation and Alta Planning & Design (2020). Mean trip duration also decreased during Phase 2. Given that this

deployment occurred on a college campus, this could indicate that due to the changes in temperature, trips were primarily used for travel to classes and less for recreational purposes and enjoyment.

The parking photo results showed that parking according to Virginia Tech policy, and in a manner that was deemed acceptable due to the e-scooter not blocking access, improved by about 10% from 80% to 90% over the course of the deployment. This could mean that e-scooter riders became more experienced and compliant with the parking policies over time. A study by Fang et al. (2018) also found that scooters were parked improperly around 2% of the time, which is similar to the above finding. This indicates that the parking policies that were in place were effective.

According to the survey results, e-scooters were reported to replace walking trips. Given that their intended use is for first- and last-mile transportation, it appears that users also agree with their purpose. Surveys from Chang et al. (2019) also found that e-scooters were primarily used to replace low-carbon modes of transportation such as walking. Many respondents to the survey had favorable views of e-scooters both pre- and post-deployment. Some of the respondents to the post-deployment survey had never used an e-scooter at VT, indicating that many people have positive perceptions of e-scooters despite not having used them. However, post-deployment impressions were less favorable than pre-deployment, which could be a sign that e-scooters on campus became a nuisance for other road users.

Conclusions and Recommendations

E-scooter programs are a work in progress that require further refinement. While e-scooters are an exciting opportunity due to being an affordable, convenient, low-emission method of transportation, there remain safety and nuisance concerns that need to be addressed for e-scooters to be more widely accepted as a legitimate transportation option. The results from this study have helped to identify the successes from the e-scooter deployment on the Virginia Tech campus, as well as the concerns that require attention. Based upon the results, the following recommendations are provided:

- Limiting hours of operation to daylight or improving lighting in the riding environment or on the scooter. It was seen that conflicts were more likely to occur at times with partial light to darkness.
- Improving e-scooter rider education on where e-scooters fit into the current transportation model. Several crashes and near crashes resulted from conflicts with other road users. E-scooter riders need to be instructed on proper riding location and right-of-way regulations.
- Development of methods for training novice e-scooter users or designing e-scooters with added safety benefits. The leading safety critical event that occurred was a simple fall-over or bailout resulting from loss of control without the involvement of another actor, indicating that user error was the cause. Unconventional rider stances observed by the fixed cameras could be a contributing factor. Some form of training or incorporation of a safer model could help to mitigate these events. It was seen that the change from the ES4 to the Max model resulted in lower crash and injury rates due to improvements in the e-scooter design.
- Implementation of software algorithms to flag improper riding behaviors such as aggressive, excessive speed, and trick riding which were seen to contribute to several safety critical events. Placing holds on the accounts of riders who display these behaviors could reduce conflicts.
- Clarification of regulations for e-scooter riders through easy-to-find resources and on-road signage. Many e-scooter riders are either unaware or unclear of the traffic laws regarding proper e-scooter use due to lack of resources and discrepancies between jurisdictions. It is important to

make these rules of operation clear, and incorporation of signs on the road could be an easy way to make riders aware of speed limits and proper riding locations.

- Providing clear instructions on parking, such as the ones provided during this deployment. Parking nuisances can be reduced if riders understand how and where to acceptably park their scooters.
- Consider enforcement of helmet use. Although helmets were not required during this deployment, only 1% of riders were observed to use helmets during the deployment, and several serious head injuries occurred which the use of helmets could have mitigated. E-scooters can reach speeds that become dangerous for the riders given the minimal protection that e-scooters offer riders. Helmets at a minimum should be required. As they are not included with shared scooters due to sanitary or theft issues, additional solutions should be investigated, such as nearby helmet rentals or rewards to motivate helmet use.
- Monitoring item carrying while using e-scooters. Riders were observed to carry items which can affect control of the e-scooter as well as rider balance and dexterity, leading to safety concerns. If conflicts are seen to result from carrying items, regulations should be put into place.

As the needs for individual cities and locations do vary, these recommendations should be selected accordingly. However, these recommendations were developed to address the safety critical events observed during this deployment, and similar findings have been observed in several other deployments throughout the country, which helps to validate the needs for inclusion of these policy recommendations. Incorporation of the above recommendations into future deployments can help to improve e-scooters from not only being a popular transportation option, but also a safe and reliable one.

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Chapter 3: E-Scooter Design: Performance and Safety Evaluation

Abstract

Over the recent years, e-scooters have become an increasingly popular and convenient micromobility solution for short-distance trips for a wide demographic of users. Due to their accessibility, knowledge regarding proper e-scooter use and level of operating experience can vary widely. With the increase in use, there has been a rise in injuries for e-scooter riders and other road users. One possible cause is that the true performance capabilities of e-scooters vary based upon their designs; users are unaware of these differences or how to accommodate their riding behavior to retain a safe experience. This relationship between safety outcomes and scooter design attribute has yet to be established. Until recently, very little formal research has been conducted on the safety of this form of transportation or on the optimal design for e-scooters. Safety concerns may limit the widespread adoption of e-scooters as a legitimate transportation option. To address this concern, the Virginia Tech Transportation Institute (VTTI), in collaboration with Ford Motor Company and Spin, conducted a controlled participant study on the Virginia Smart Roads to evaluate and compare various e-scooter designs and study how rider specific factors contribute to performance and safety. The results from this study will be used to inform e-scooter companies and manufacturers on design recommendations for improved e-scooter safety.

Introduction

Electric scooters, or e-scooters, are two-wheeled scooters powered by electric motors which users typically stand on to ride. In late 2017 many companies started releasing fleets of shared scooters in cities for shared use by the public. In these new systems, all that is needed to rent an e-scooter is to be above the required age specified by the local governing body and to have access to the smartphone app corresponding to the scooter brand. Largely due to their convenience, e-scooters have become an increasingly popular transportation option in the recent years, serving as a micromobility solution for first and last mile transportation and short distance trips. In addition to their accessibility, there are many advantages associated with e-scooter use, such as reducing carbon emissions and providing an affordable transportation option for a large demographic of users. Since their introduction in 2017, scooter share has overtaken bike share as the most popular form of micromobility, increasing the total number of shared micrmobility trips from 35 million in 2017 to 84 million in 2018 and accounting for 86 million trips in 2019 (NATCO, 2020).

However, along with the increase in e-scooter use, there has also been a rise in e-scooter related injuries. As of March 2021, there have been 36 reported e-scooter related fatalities in the United States (Dwyer et al., 2021). Additionally, since the introduction of scooter fleet systems in 2017, emergency department visits for e-scooter users have increased from 7,700 to 25,400 in 2020 (United States Consumer Product Safety Commission, 2021). A study was also conducted in a UCLA Emergency Room where visits were monitored over a one-year period, and it was observed that there were 249 visits for e-scooter riders compared to 195 for bicyclists and 181 for pedestrians (Trivedi et al., 2019). This trend seems to indicate that while convenient, e-scooters have also become a large safety concern.

There are several possible reasons for these increased safety risks. The first is that policies on proper e-scooter use are not well-established or consistent between various locations or service providers. This makes it difficult for e-scooter users to understand where they fit into the transportation system. Another possible cause is that the optimal design for an e-scooter has yet to be determined and tested. E-scooter manufacturers continue to release new e-scooter models with different features, indicating that the

design is still evolving to find the best balance between cost, performance, and safety. Finally, due to ease of access to rent an e-scooter, there is a large variation in knowledge regarding proper e-scooter use and level of operating experience. There have been many reports of unsafe riding, injuries, and nuisance issues, and until recently, little formal research has been conducted on e-scooter safety.

The first naturalistic e-scooter study was conducted on the Virginia Polytechnic Institute and State University (Virginia Tech) campus and was a collaboration between VTTI and Spin. During this effort, a fleet of shared e-scooters was deployed to understand how policies impact riding safety as well as to investigate factors that contribute to crashes and injuries. A subset of the fleet was instrumented with VTTI's micro-data acquisition system (microDAS) to capture naturalistic data. For the first phase of the study, the ES4 e-scooter model was used which had small diameter, solid tires, utilized a single front-wheel brake, and did not have any kind of suspension. The ES4 scooters were replaced in the second phase of the study with the Max e-scooter model which had larger diameter, pneumatic tires, and utilized a dual-wheel braking system. Despite the increase in trips during the second phase of the study, the rate of conflicts such as crashes, fallovers, bailouts, and near crashes decreased (**Figure 10**). This result seems to indicate that the shift in scooter model may have improved rider safety, and that it is worth investigating which design features contributed to the lower conflict rate.

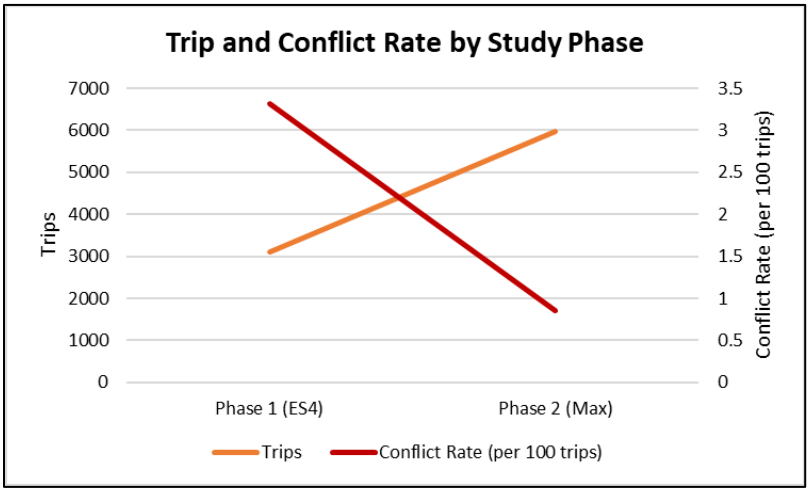

Figure 10. Trip and Conflict Rate by Study Phase. (Source: E-Scooter Safety Assessment and Campus Deployment Planning study)

During the study, the conflict events were also analyzed, and it was observed that the most common two precipitating events were loss of control due to an infrastructure element or conflict with a fixed infrastructure element (**Figure 11**). Some of these infrastructure elements and surface features that contributed to the conflict events can be seen in **Figure 12** and **Figure 13**. This shows that scooter compatibility with infrastructure needs to be studied further.

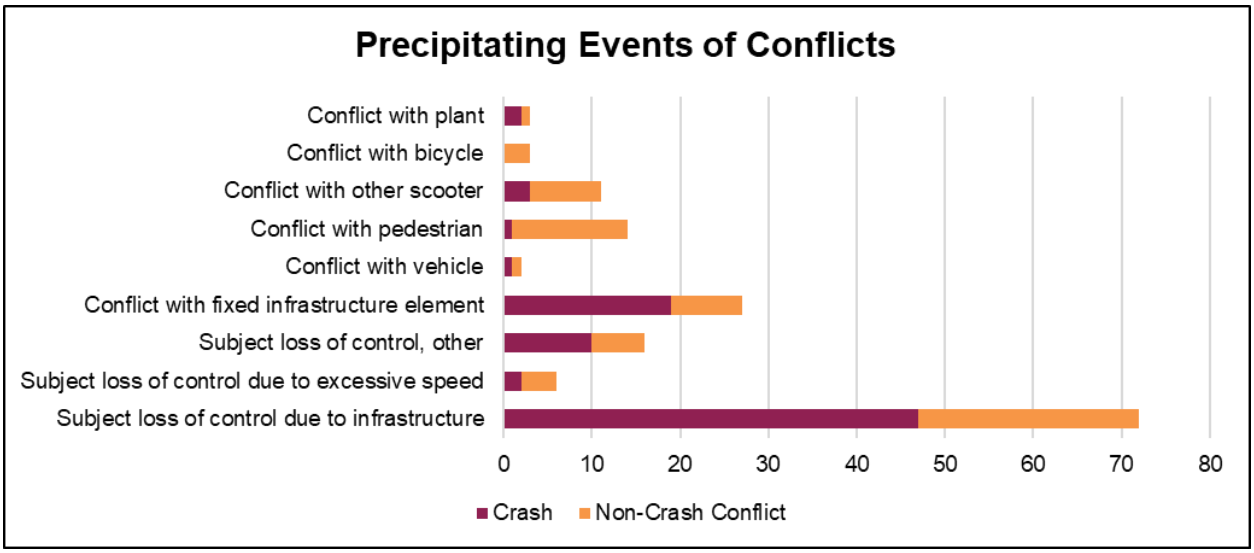

Figure 11. Precipitating Events of Conflicts. (Source: E-Scooter Safety Assessment and Campus Deployment Planning study)

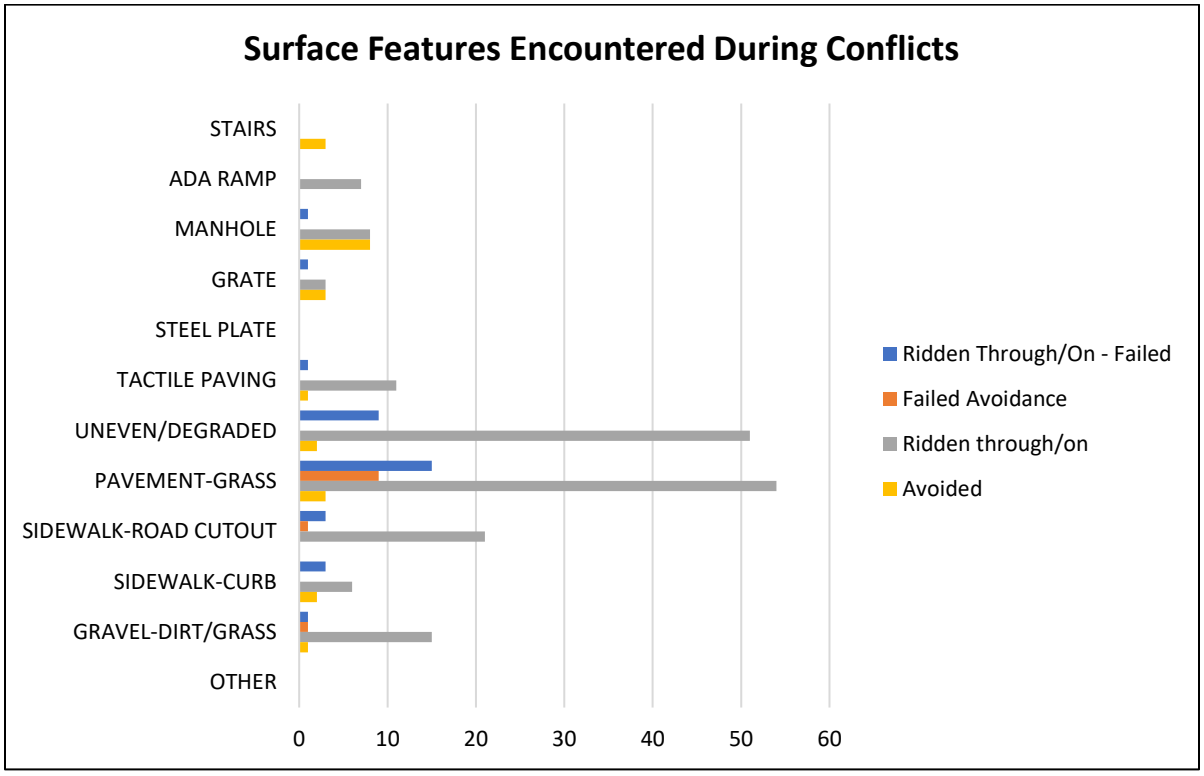

Figure 12. Surface features encountered during conflict events. (Source: E-Scooter Safety Assessment and Campus Deployment Planning study)

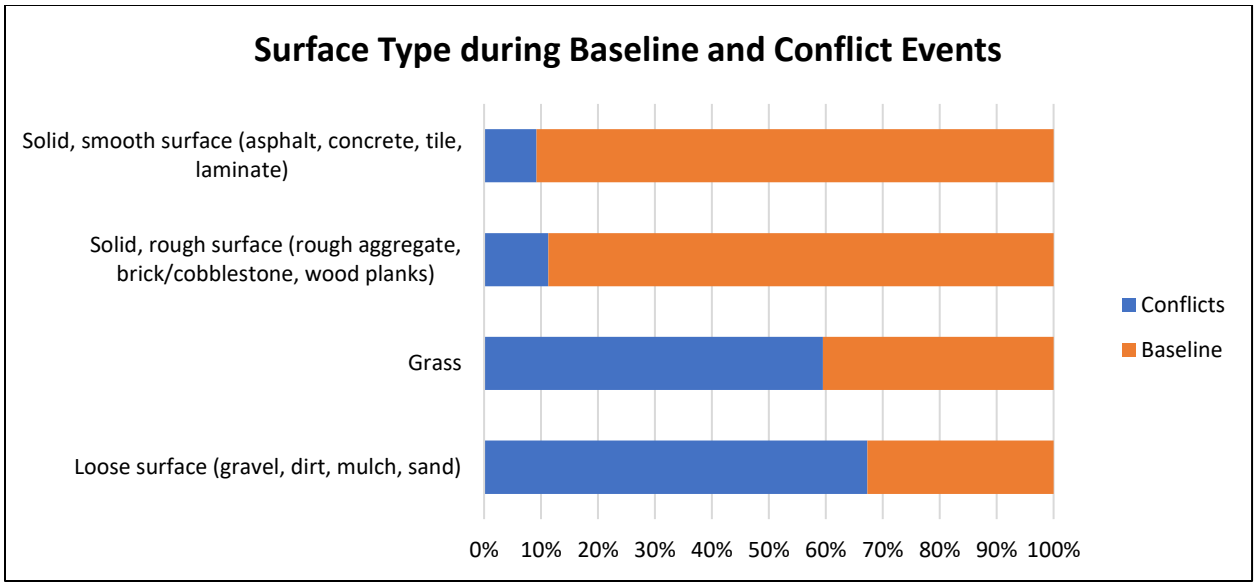

Figure 13. Surface type during baseline and conflict events. (Source: E-Scooter Safety Assessment and Campus Deployment Planning study)

The results from this study on Virginia Tech's campus point to the fact that the true capabilities of e-scooters are not well known. Manufacturer testing may be based upon limited testing conditions that do not reflect real-world use. There is a need to better understand the relationship between e-scooter design and the associated compatibility with road features and infrastructure to improve safety. Therefore, this study, a collaboration between VTTI, and Ford Motor Company, and Spin, aims to investigate safety as a function e-scooter design. There are two main objectives:

1. To evaluate and compare the performance and safety of various e-scooter designs and features through benchmark testing which will incorporate riding tasks and conditions that are representative of real-world use.
2. To understand rider-specific factors (age, gender, anthropometrics, approach/strategy, posture, etc.) that contribute to performance and safety.

Literature Review: Design and Testing of Two-Wheel Vehicles and E-Scooters

To understand how specific design features affect the performance of the e-scooter, I conducted a brief literature review on the design considerations and standards of two-wheeled vehicles and on design concepts that could be implemented to improve e-scooter safety. Additionally, previous relevant test methods and metrics were identified. The following section includes the results from that literature review.

Design of Two-Wheel Vehicles and E-Scooters

The following sections provide information on design considerations for all types of two-wheeled vehicles, design standards for e-scooters and the development processes involved in e-scooter designs.

Design Considerations for Two-Wheel Vehicles

An important aspect of designing two-wheeled vehicles is to ensure that the center of gravity (COG) is at a location that lends to the stability of the vehicle. For e-scooters specifically, this location should be as centered between the wheels as possible and as low to the ground as possible. To assist with this, the

foot platform should have a large mass relative to the stem or steering column. Accordingly, steering components such as handlebars should be relatively lightweight compared to the rest of the e-scooter assembly in order to prevent the COG from being located too high or too far forward, which would lead to a more unstable design. Having a lower deck height also assists with lowering the COG (Ringer, 2019). Riders add height to the COG, which is why it is critical for the vertical component of the e-scooter's COG to be as low as possible.

Creating a more minimalistic handlebar design has it challenges, considering the user needs to control the scooter's speed with this mechanism. Both the throttle and brake are present on either side of the handlebar where the user would place their hands. Finding a new method to control the acceleration of the device that still has the convenience of the current system will need to be considered in any alternate designs. Alternatively, a more streamlined electrical system can be created to greatly reduce the weight of the handlebars due to the throttle and brake.

Wheelbase is another important design aspect for e-scooters and other two-wheeled vehicles. Wheelbase is defined as the horizontal distance between the centers or points of ground contact of the front and rear wheels of the vehicle, as seen in **Figure 14**. Wheelbase contributes to the longitudinal stability of a vehicle, with longer wheelbases improving stability and shorter wheelbases leading to sharper handling (Anderson, 1999). E-scooters are balanced with their wheelbase, as they have stability in the longitudinal direction, assuming that the center of mass is close to the middle of the scooter, and they also have decent handling. However, due to the narrow design in the lateral direction, lateral stability can be a challenge.

Wheel size also affects the stability of a two-wheeled vehicle. When wheels rotate, they have angular momentum, which causes them to act as gyroscopes and helps to stabilize the vehicle, although not by a significant amount. Larger wheels have a larger inertia due to increased size and typically, mass, and therefore the increased momentum will help them to go straight. However, if a rider leans, the torque that is produced by this motion will be in the rearward direction of the vehicle's path of travel, and the rearward change in the angular momentum vector will cause the vehicle to turn in the same direction as the lean (Anderson, 1999). This gyroscopic torque contributes to a rider's stability because the centrifugal force associated with the turn assists a rider in changing the angle of the vehicle back to a vertical, upright orientation (Jones, 1970).

Steering axis angle, trail, fork offset, and fork length are other factors which are commonly used to assist with the steering design of bicycles and motorcycles but are also applicable to e-scooter designs. Steering axis angle, also called caster, is the angle that the steering head makes with the vertical or horizontal axis (Anderson, 1999). This is the axis around which the steering mechanism pivots. For bikes, this is also called head angle or head tube angle, and for motorcycles this is called rake angle, or fork angle. The steering axis angle tends to contribute to the length of the wheelbase and the trail, with more horizontal steering axis angles having larger wheelbases and trails (Anderson, 1999). Trail is the horizontal distance from where the front wheel contacts the ground to the intersection of the steering axis (Anderson, 1999). Trail is also called caster for some vehicles. Because steering axis angle and trail are related, a more horizontal steering axis angle will cause a larger trail. A larger trail causes the vehicle to turn less easily, and a shorter trail makes the vehicle easier and more responsive to turn, but also more unstable (Anderson, 1999). Trail also varies as the vehicle leans, such that trail decreases as vehicle lean increases (Anderson, 1999). Fork offset is the perpendicular distance from the steering axis to the center of the front wheel and is sometimes known as fork rake for bikes. These variables, along with wheel diameter, all influence each

other and a vehicle's steering performance. Fork length, also known as head tube length, is the length of the steering tube, and a longer fork length affects a rider's posture by causing them to be more upright, moving the center of gravity up in the vertical direction and closer to the front in the horizontal direction, and it reduces the vehicle's aerodynamics. **Figure 14** illustrates steering axis angle, trail, fork offset, and fork length.

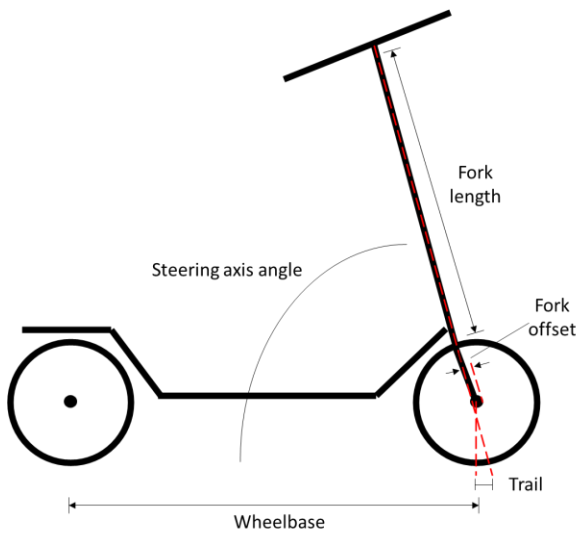

Figure 14. Visual representation of scooter steering geometry and wheelbase.

The handling of a vehicle is largely dependent upon this design geometry. Handling is the amount of effort required to control a bike while also keeping it stable (Anderson, 1999). Handling can be affected by the speed at which a vehicle travels or if the front wheel is deflected by an object, which can cause a phenomenon called caster flutter or shimmy and makes it difficult to control the vehicle, sometimes leading to crashes (Ringwood & Feng, 2007). This occurs as the downward force on the steering column and the resistance force from the ground cancel out and prevent the wheel from rotating in the opposite direction, and instead cause it to rotate around its axis. By adjusting the steering column from a vertical to rearward angle, the wheel is now able to move in the opposite direction (Zimmerman, 2016).

Wheel flop is another variable that is affected by the steering geometry of a vehicle, defined as the tendency of a wheel to turn or flop when the handlebars are rotated and the vehicle is leaned, causing the front end of the vehicle to lower (Bansal et al., 2013). This is affected by the steering axis angle and trail, both of which can be influenced by fork offset. The equation for flop is $f = b \sin(\partial) \cos(\partial)$, where f is the wheel flop factor, b is trail and ∂ is steering axis or head angle measured with reference to the horizontal axis, so increasing the trail or decreasing the steering axis angle will cause the flop factor to increase.

When applying these geometrical design considerations to e-scooters, it can be concluded that the steering columns of e-scooters are close to the vertical, meaning minimal trail. E-scooters do not appear to include any fork offset, otherwise any trail would be minimized. This lack of steering axis angle could potentially cause some caster flutter when the speed increases or when the e-scooter wheel is deflected by an object, which is potentially why increasing the wheel size has been seen to be effective in improving riding safety. The steeper head angle and larger trail makes steering easier and more responsive and reduces wheel flop.

The uncertain nature of the operator is also in play. E-scooter riders use varying stances, and the location of the COG will change depending on stance. This will therefore require a more robust design that keeps individual operator preference in mind.

Design Standards for E-Scooters

A primary standard for powered scooters exists in the American Society for Testing and Materials (ASTM) standard F2641 (American Society for Testing and Materials, 2015). This standard includes both powered scooters intended for use by children ages 8–12, and more importantly, those intended for use by riders aged 13 and above. It is not meant for scooters intended for adult use only. The standard defines terminology used in powered, or e-scooter design and gives requirements for testing and design. Some of these requirements apply to the craftmanship of exposed components being free of sharp edges and burrs. There are specifications for electrical systems, brakes, latches, folding mechanisms, hinges, clearances, fasteners, plastics, shields and guards, paint, materials, access points, and labels and warnings. The standard also defines specific and rigorous test methods, including a finger probe to test clearances and pinch points.

In 2019, the Society of Automotive Engineers (SAE) developed standards for classifying micromobility devices in the Taxonomy and Classification of Powered Mobility Vehicles to assist with crash reporting, policy making, and emergency department data. E-scooters were defined as "powered standing scooters", and their design components consisted of: a center column and handlebar for rider stability, steering, and acceleration and braking controls; a platform for a single rider to stand on; a frame that contained either two or three wheels; and a power source of an electric motor (SAE International, 2019). The e-scooter must not weigh more than 500 lbs. and may not travel at speeds greater than 30 mph. Additionally, the Powered Standing Scooter should be designed primarily for paved roadways or paths. Specifications can be seen in **Figure 15**.

TYPES OF POWERED MICROMOBILITY VEHICLES[1]

	Powered Bicycle	Powered Standing Scooter	Powered Seated Scooter	Powered Self-Balancing Board	Powered Non-Self-Balancing Board	Powered Skates
Center column	Y	Y	Y	Possible	N	N
Seat	Y	N	Y	N	N	N
Operable pedals	Y	N	N	N	N	N
Floorboard / foot pegs	Possible	Y	Y	Y	Y	Y
Self-balancing[2]	N	N	N	Y	N	Possible

[1]All vehicles typically designed for one person, except for those specifically designed to accommodate additional passenger(s)
[2]Self-balancing refers to dynamic stabilization achieved via a combination of sensors and gyroscopes contained in/on the vehicle

Figure 15. SAE J3194™ Taxonomy and Classification of Powered Micromobility Vehicles. (Source: SAE International from SAE J3194™ Standard - TAXONOMY & CLASSIFICATION OF POWERED MICROMOBILITY VEHICLES. https://www.sae.org/standards/content/j3194_201911/).

Development of E-Scooter Design

E-scooters have been undergoing iterative improvements over the years of their service. Within the micromobility arena, regulatory pressure for a "form-factor" standing e-scooter design exists. Standing e-scooter designs have remained relatively constant, with the major propulsion and power components located along the foot platform and lower portion of the steering column, and with the hand-control system along the handlebars (Behavioral Traffic Safety Cooperative Research Program, 2022). Some of the more widespread changes seen in e-scooter design include those of the wheels and tires. To aid in overcoming obstacles in the road, such as small curbs, bumps, cracks, and uneven pavement, the diameter of the wheels and tires have been increased. This larger diameter allows for the tires to easily climb over these obstacles and prevent a sudden stop that could topple the rider. Another change is that of the tires transitioning from a hard polymer to a softer rubber or even pneumatic tires in some cases. This softer rubber cushions the ride and provides suspension between the rider and the road so that inconsistencies are not translated into the handlebars, causing the controls to be more difficult to operate, with pneumatic tires amplifying this benefit further. These pneumatic tires also aid in overcoming obstacles, as the softer tires with a larger sidewall are more pliable and therefore able to easily deform over obstacles, providing more traction and stability. However, these more pliable pneumatic tires are less durable as their solid rubber counterparts. The softer, air-filled rubber wears down from the road surface much faster than a solid tire. Pneumatic tires are also vulnerable to puncture (Behavioral Traffic Safety Cooperative Research Program, 2022).

Another common change is the addition of handlebar brakes. The original, non-powered scooter often had a stomp brake on the rear tire, which was applied by the rider using their rear foot to depress a hinged or flexible panel down onto the surface of the tire tread. This would induce friction and slow or stop the scooter dependent upon the amount of force exerted by the rider's foot. This is a simple braking solution; however, it introduces safety concerns as the rider must relocate one of their feet to the back of the scooter and control it independently of their other foot. This can be difficult for an untrained rider to do in an emergency and may introduce instability as the rider's feet are not planted fully on the footboard. In powered e-scooters, the braking system is replaced with a handlebar brake, not unlike that on a standard bicycle. The rider uses their hand to grab a large lever, which is squeezed against the handlebar. This operates, via a cable or electrical signal and motor, a brake on the rear wheel. This brake is either rim type or disk type. The rim type brake uses two hard rubber pads on either side of the metal wheel that are compressed and introduce friction to slow or stop the scooter. The disk type brake is similar; however, the pads are ceramic or composite based and compress against a dedicated, machined disk separate from the wheel. The disk type brake provides a more robust and reliable braking system but is more costly to produce and implement.

Potential Physical Design Concepts

The following sections discuss potential e-scooter design concepts. Many of these concepts have already been implemented by e-scooter companies, and a discussion of the potential benefits of each concept is included.

Self-Balancing

Self-balancing e-scooters (i.e., e-scooters that remain upright while stationary, without a rider, and on mostly level ground) could help inexperienced riders maintain control over the e-scooter and would eliminate the need for a kickstand, thus reducing the number of high-drag components (those that protrude and can easily snag and/or break off). This design could be accomplished with wider tires than

currently deployed models and a fork wide enough to accommodate wider tires. The rake angle may also need to be increased to accommodate a wider front tire, which would move the front tire away from the footboard and increase the wheelbase of the scooter, thus improving stability but also increasing the turning radius.

Another change is to rework the arrangement of the internal components of the scooter, namely the battery. If the battery pack cells were placed horizontally to produce a longer, thinner battery, the thickness of the box frame could be reduced. This would allow the footboard, and in turn the COG, to be lower to the ground without reducing the ground clearance (which could cause imbalance and fall-overs).

Additional Wheels

Adding more points of contact (i.e., wheels) between the scooter and the ground can also increase stability. Added wheels would create a balanced system without the need for a kickstand. However, Huston (1982) noted that despite more points of contact, instability can be created while in motion due to the rider being unaware of the consequences of adding an extra tire and attempting to ride normally. Three different options of adding an additional wheel are discussed below, and each had their own advantages and disadvantages.

Adding a tire to the front section is often referred to as a 'tadpole' design and is more stable than adding a rear tire, also known as a 'delta' design, as discussed later. With the addition of a front tire, the vehicle can be prone to understeering (Van Valkenburgh et al., 1982). This occurs when the front tires slip on the ground due to extra momentum causing the tires to resist turning and instead continue in their original direction (Bundorf, 1968). This becomes an issue when trying to avoid obstacles and could potentially increase crash rates. However, Zandieh (2014) found that vehicles with an additional wheel in the front have the potential to increase the rollover threshold while turning. The higher a vehicle's rollover threshold, the less likely it is to fall over while in motion. If a user brakes while they are turning a 'tadpole' designed scooter, they will exert an acceleration in the opposite direction of the current acceleration.

While this configuration is useful when used properly, if the user fails to brake while turning or accelerates while turning, this tire configuration is very unstable. Keeping a constant speed is also dangerous on this type of vehicle because the original lateral force will cause it to roll over (Zandieh, 2014). This type of configuration requires prior knowledge of the mechanics in order to be ridden safely. Due to the need for this vehicle to be used by many people easily and without difficulty, this tire configuration would not be ideal.

To avoid problems with an additional front wheel, the additional wheel can instead be moved to the rear. This allows for the control rod to move with more freedom, but keeps the stability gained by introducing a third point of contact. However, one of the biggest issues stemming from the addition of the rear wheel is its instability while being ridden. The 'delta' configuration has a high center of gravity due to its geometry which can lead to the vehicle tipping in a sideways motion with a high roll angle (Ranpariya, 2019). It has also been observed that this wheel configuration leads to oversteering which can cause the user to lose control and crash.

Seat Implementation

E-scooters with seats have lower centers of gravity and riders remain relatively still as compared to standing riders, providing more stability. Seats can also be more comfortable for riders and provide options for riders who may not be able to stand due to physical limitations or injuries.

These advantages are heavily outweighed by the loss of dexterity and increased crash severity associated with the seat. If the e-scooter were to become unstable during the ride and enter a "death wobble," a seated operator would have a hard time recovering while a standing one would not. There are also the problems associated with a crash event, where a seated operator will have a higher chance of being trapped and would not be able to bail from the e-scooter as easily as if they were standing.

Suspension

The addition of a suspension system is an option which many e-scooter companies are incorporating in their designs to reduce the transmission of shock to the handlebars, and thus the rider's hands, when the e-scooter travels over objects or rough terrain. A design similar to a bicycle suspension, comprised of two front forks with a spring-damper system inside of them, would be relatively unsusceptible to damage. Another option for suspension design utilizes a single spring-damper system attached to the rear of the e-scooter, where the rear wheel would be on a single-pivot linkage attached to the shock on the opposing linkage end. This assembly would be located on one side of the scooter, moving the COG off to the side, which would present issues if the e-scooter were self-balancing. This configuration is bulkier and would be more susceptible to damage from rider abuse and during transport of the e-scooters.

Test Methods and Metrics for Two-Wheel Vehicles

To properly assess the safety benefits of e-scooter designs, previous research was reviewed to identify appropriate metrics that could be used for evaluation. As there has been minimal testing of e-scooters, methods for evaluating other two-wheel vehicles were also explored. E-bike testing was found to be helpful due to the wide availability of information that has been acquired through multiple studies. Both designs rely on the user to balance on two wheels placed linearly in the sagittal plane, giving them similar dynamics.

A recent study found that placing participants on a course allowed for the collection of quantifiable measurements such as acceleration, velocity, roll angle, and steering angle, while also being able to repeat the process, resulting in similar data between participants (Garman et al., 2020). It was stated in this study that a rider's stability can be studied by observing the position of the rider's body, their interaction with the handlebars and foot platform, and the inputs to the brake and throttle. The load applied to the stem, steer angle, and roll angle were measured using various devices, including accelerometers, load cells, potentiometers, and GPS trackers to quantify the previously mentioned metrics (Garman et al., 2020). Steer angle is defined as how far the handlebars are rotated when the user is turning while roll angle is defined by the tilt the scooter experiences in the coronal plane.

A study by Chi (2005) stated that the center of gravity changed when a user rode a bicycle along an incline due to the point of contact the wheels made with the ground. It was found that as a user traveled uphill, the center of gravity would move from the center of the contact line towards the back wheel; moving downhill resulted in the center of gravity being more towards the front wheel. The contact line in this study was the distance between the point of contact of the two wheels. Measuring the position of the center of gravity proved to be important because as the center of gravity moved from the center of the contact line to either wheel, the bicycle became more unstable and required the user to self-adjust.

The method for testing from Garman et al. (2020) allowed participants to use the scooters in a manner similar to how they would be used outside of testing. In addition, various metrics were identified, including roll angle, steer angle, and load applied to the handlebars. This, combined with the focus of center of

gravity changes on different elevations, would encompass most of the expected environmental terrain the scooters would be traveling on.

In one mechanical study, a test track was set up with turns and obstacles. The scooters had strain gauges applied to them and ran through many trials with different riders of different weights. The main finding was that the stem had the highest load during braking and the lowest load during acceleration. Furthermore, the average braking distance was 3.3 ± 1.5 m, and the highest speed reached was 19.4 kph (Garman et al., 2020). The study also evaluated the different acceleration and deceleration times, maximum steering angle, rider lean angle, and head longitude acceleration (Garman et al., 2020).

Therefore, with a better understanding on the design of e-scooters and two-wheel vehicles, design standards, and potential design concepts, our research team moved on to developing methods to evaluate the performance and safety of the various designs while utilizing some of the previous relevant testing that had been conducted.

Methods

The following sections detail the design of this study, including the e-scooters used during testing, testing procedures, and demographics information for the participants. The data that is collected and the analysis protocols are also described.

E-Scooter Models

Four different e-scooter models were evaluated during this study, which can be seen in **Figure 16**. **Table 8** compares each of the models and their designs.

Figure 16. E-Scooter Models. From left to right: Segway Ninebot Max 2.3, Spin S-100T, Okai ES400B, and Segway Ninebot Max 2.0 with a seat attachment.

These four e-scooters were provided by the sponsor company, Spin, and were identified for testing due to prior use in deployments across the U.S. The Max 2.3, S-100T, and Okai units had very limited previous use, but due to the Max 2.0 being an older model, a brand-new unit was not acquired. Instead, a unit that had been deployed during the *E-Scooter Safety Assessment and Campus Deployment Planning* study was

used during this effort as it was the only unit available. Each of the models had the capability to travel up to a speed of 15 mph, and this speed was also governed by Spin software and geofencing technologies. The scooters were maintained after each participant session.

Table 8. E-Scooter Model Specifications.

	Segway Ninebot Max 2.3	Spin S-100T	Okai ES400B	Segway Ninebot Max 2.0 w/ Seat Attachment
Previous Use	20 trips	0 trips	0 trips	399 trips
Weight	61.3 lbs.	62.0 lbs.	75.0 lbs.	49.9 lbs.
Dimensions	47.6” x 20.3” x 44.8”	46.0” x 19.0” x 46.0”	47.2” x 20.5” x 48.0”	45.9” x 18.6” x 47.4”
Steering axis angle	72.5 deg	75.0 deg	75.0 deg	76.5 deg
Handlebar height from deck	37.75”	37.63”	39.25”	38”
Handlebar diameter	1.56”	1.56”	1.56”	1.56”
Handlebar length	20.25” (4.18” left, 4.69” right)	23.25” (5.06” both)	20.56” (4.88” both)	18.5” (4.18” left, 4.69” right)
Brake type(s)	Front drum brake, rear wheel anti-lock electronic brake, regenerative braking	Front drum brake, rear stomp brake, regenerative braking	Front drum brake, rear wheel anti-lock electronic brake, regenerative braking	Simultaneous front wheel drum brake, rear wheel anti-lock electronic brake, regenerative braking
Brake controls and locations	Hand brake levers - left and right handlebars	Hand brake lever - left handlebar, and rear stomp brake	Hand brake levers - left and right handlebars	Hand brake lever - left handlebar
Accelerator controls and locations	Thumb throttle-right handlebar	Thumb throttle-right handlebar	Thumb throttle-right handlebar	Thumb throttle-right handlebar
Maximum speed (governed)	15 mph	15 mph	15 mph	15 mph
Deck height	7.00”	6.50”	7.00”	5.75”
Ground clearance	2.63”	2.00”	3.25”	2.25”
Deck length	19.25”	19.88”	16.75”	19.19” (14.25” usable)
Deck width	7.00”	6.75”	7.25”	6.75”
Wheelbase	36.25”	36.50”	36.50”	35.25”
Tire diameter	9.5”	9.5”	11.0” front, 10.0” rear	9.0”
Tire width	2.25”	2.69”	2.31”	2.38”
Tire type	Pneumatic	Pneumatic	Solid	Pneumatic
Shock Absorber	Front hydraulic suspension	-	Front hydraulic suspension	-
Motor	350 W, Rear wheel drive	500 W, Rear wheel drive	350 W, Rear wheel drive	350 W, Rear wheel drive
Seat	No	No	No	Yes

Testing Procedures

Three separate evaluations were conducted during this study: the Speed, Acceleration, and Braking test (SAB), the Handling, Stability, and Maneuverability test (HSM), and the Geofence test. Each of these three tests were designed to evaluate and compare how specific design factors of each of the e-scooters performed throughout a series of tasks and testing conditions. Prior to the tests, riders were required to pass a pre-testing evaluation that consisted of basic riding tasks to ensure that they could operate an e-scooter in a safe manner (Appendix B-1).

Speed, Acceleration, and Braking Test

The first evaluation was the Speed, Acceleration, and Braking test. This test was conducted on the Rural section of the Virginia Smart Roads. The purpose was to compare the true maximum speed of each of the e-scooter models to the advertised maximum speed for a variety of road conditions. Additionally, the acceleration and braking capabilities of each of the scooters would be analyzed, and the performance of each of the e-scooters would be compared. In total, there were 9 road conditions, which can be seen in **Table 9**.

Table 9. Road conditions for SAB test.

Condition Number	Slope	Terrain
1	Flat	Pavement
2	Flat	Loose gravel over grass
3	Flat	Wet pavement
4	Incline	Pavement
5	Incline	Loose gravel over grass
6	Incline	Wet pavement
7	Decline	Pavement
8	Decline	Loose gravel over grass
9	Decline	Wet pavement

For the course setup, cones were placed at the beginning of each of the 9 road condition sections that would serve as the starting point for each trial. The participant would begin between the start cones, accelerate to the top speed that the scooter would allow or a speed that they were comfortable with, and ride approximately 200 feet down the road. At this point there would be a second set of cones to signify when to begin braking. When the front wheel of the e-scooter passed between these cones, the participant was instructed to brake as hard as they could or were comfortable with. After the e-scooter comes to a stop, the participant would step off and wait while a researcher used a measuring wheel to record the braking distance, defined as the distance from the braking cones to the front wheel of where the e-scooter came to a stop. A final set of cones was placed approximately 50 feet past the braking cones to mark the end of the braking zone. This setup can be seen in **Figure 17**.

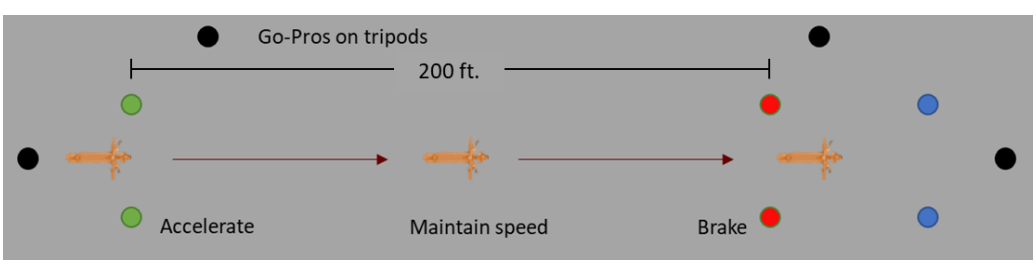

Figure 17. Speed, Acceleration, and Braking test setup.

This procedure would be repeated for each of the 4 e-scooter models on all 9 road conditions for a total of 36 trials per participant. The order of road conditions was the same for all participants, but the order that the participants would use each of the e-scooters was counterbalanced and randomly assigned.

Handling, Stability, and Maneuverability Test

The second evaluation was the Handling, Stability, and Maneuverability test. This test was conducted on the Highway section of the Virginia Smart Roads. The purpose was to evaluate and compare the performance and safety of each e-scooter model when completing various use cases at low speeds. These use cases were identified during the study on Virginia Tech's campus as having possibly contributed to the conflicts. In total, there were 22 tasks included in the course, which can be seen in **Figure 18**. Additional images of the obstacles can be found in Appendix B-2.

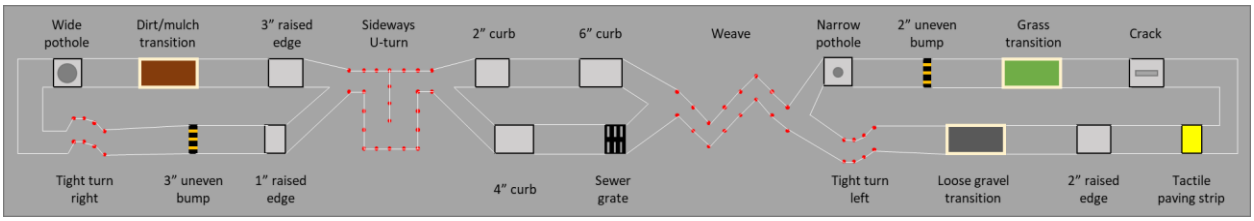

Figure 18. Handling, Stability, and Maneuverability course.

Spray chalk was used to mark out a 6-foot-wide lane to help guide participants through the course, and markings went from solid to dashed lines around the tasks to let participants know that they could ride or walk around the tasks if needed. Additionally, the markings were used to assist with data reduction. The tasks were spaced approximately 50 feet apart to allow participants to gather themselves and regain speed between tasks. For the test, the participant would be randomly assigned to 1 of 4 start locations within the course. They would complete the entire course for a single trial and could pause between each of the sections if needed. The participants were instructed that they could complete the tasks in any way possible and were also told that they could choose to opt-out of any tasks during the trial that they were not comfortable performing. This procedure was performed on each of the e-scooters, and the order that the participants would use each of the e-scooters was counterbalanced and randomly assigned.

Geofence Test

The third evaluation was the Geofence test. This test was conducted on the Highway section of the Virginia Smart Roads adjacent to the HSM test. The purpose was to evaluate the GPS accuracy of geofences and understand how e-scooters handle when riding through them. It was also of interest to understand participants' perceptions of the audible geofence notifications from the e-scooter as well as how they think the e-scooter handled while traveling through the geofences.

Figure 19 shows where the geofences were set up on the Smart Roads. There is a no-ride zone geofence on both ends of the road with a slow zone geofence in the middle of the road. The no-ride zone brings the e-scooter to a stop, and the slow zone reduces the speed of the e-scooter to approximately 7 mph. The road has a slight slope to understand how the scooters respond while riding on inclines and declines.

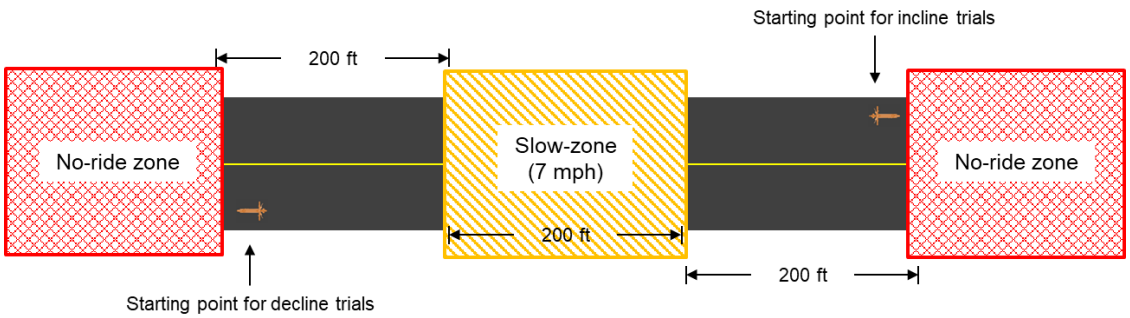

Figure 19. Geofence test setup.

The first trial was a surprise trial, such that the participant was unaware of the geofences. The participant would start just outside of either of the no-ride zone geofences, closer to the slow zone geofence, and would be instructed to ride on the road so that additional data could be collected and so that additional perceptions could be gathered on the e-scooters. Once the participant reached the other slow zone, the trial ended, and the participant was asked what they thought happened. They were then debriefed on the purpose of the test. Participants next completed 12 more trials, 6 on the Max 2.3 e-scooter and 6 on the Max 2.0 e-scooter with a seat, as these were the only two scooters that had internet of things (IoT) boxes that communicated with the geofences. An approach speed (10, 12, or 15 mph) was assigned, and the trials would be performed while riding down the decline and up the incline. The starting location (top of the road or bottom of the road) and the order that participants used the e-scooters was counterbalanced and randomized. Cones were placed near each of the geofences to assist with data reduction.

Participants

To understand user perceptions of the various e-scooter models, participants were recruited for this study. There were two groups of participants: a group of 8 experienced e-scooter riders followed by a group of 16 novice e-scooter riders. The experienced rider group was required to have ridden an e-scooter at least 9 times previously, with the most experienced riders selected for the study, and the novice rider group was required to have ridden an e-scooter 3 times or less previously. These criteria were selected based upon input from Spin's subject matter experts as well as findings from the City of Austin (2019). The experienced rider group served two purposes: to generate data that would allow for the most reliable comparisons on the performance between each of the scooters, as it was anticipated that their previous experience and comfort with using the scooters would better demonstrate the true capabilities of each model, as well as to provide recommendations on tasks that they thought might not be appropriate for the novice riders to attempt. All participants were screened prior to the sessions. **Table 10** shows the breakdown of the participants that were eligible and recruited for the study.

Table 10. Participant demographic breakdown.

Experienced Rider Group					Novice Rider Group				
Experience	9 or more previous trips				**Experience**	3 or less previous trips			
Gender	5 male, 3 female				**Gender**	8 male, 8 female			
	Avg.	Std.	Min.	Max.		Avg.	Std.	Min.	Max.
Age (yrs.)	20.5	0.71	20	22	**Age (yrs.)**	33.6	12.9	20	59
Weight (lbs.)	174.2	26.2	120	213	**Weight (lbs.)**	153.2	23.9	115	200
Height (in.)	70.9	3.1	66	74	**Height (in.)**	67.4	4.6	60	73

The two groups had slightly different research procedures. The experienced rider group completed all 3 of the tests, and the novice rider group only completed the HSM test. For the HSM test, the experienced rider group only performed 1 trial on each e-scooter while the novice rider group performed 2 trials on each e-scooter.

Participants were paid at a rate of $30 per hour. Experienced riders were paid $150 for participation across two, 2.5-hour sessions, and novice riders were paid $60 for their participation in a single 2-hour session. This study was approved by Virginia Tech's Institutional Review Board (IRB #21-378 and #22-219).

Data Collection

MicroDAS

Each of the four e-scooters were instrumented with VTTI's microDAS (**Figure 20**) with a customized weather-resistant enclosure for scooter installation. The microDAS collected forward-facing video, GPS data such as speed and trip or path tracking, and has multi-axis accelerometers to measure longitudinal, lateral, and vertical acceleration as well as pitch, yaw, and roll rates. Data is collected in this system at a rate of 10 Hz, and the coordinate system is aligned with respect to the stem of the scooter, which can be seen in **Figure 20**. As the origin of the microDAS rotates with respect to the deck of the scooter when the rider steers, measures were taken relative to a timepoint when the steering was approximately straight. While the four scooters had slightly different steering axis angles which could have resulted in small differences in the alignments of the microDAS units on the scooter stems, these were assumed to be insignificant for the selected metrics.

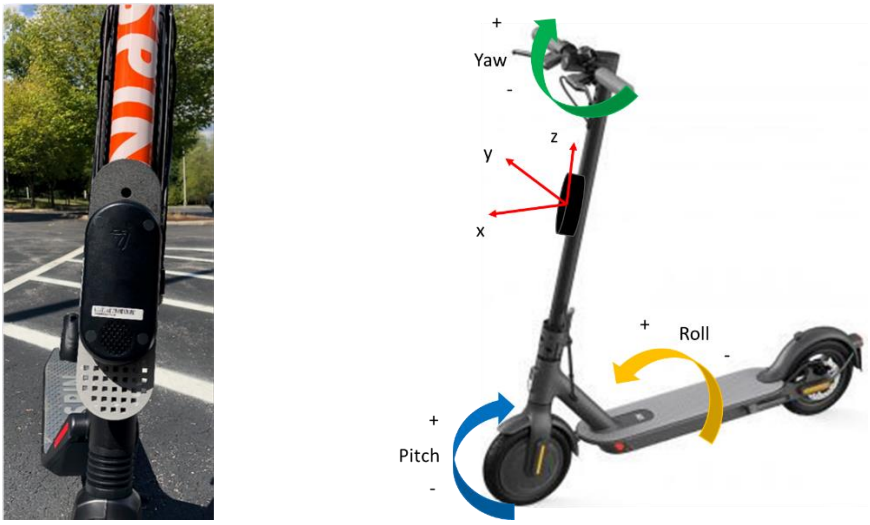

Figure 20. VTTI's microDAS (left) and alignment of microDAS on scooter stem (right).

The data was automatically offloaded to VTTI's secure server following each session. Examples of the data collected can be seen in **Figure 21** and **Figure 23**.

Fixed Cameras

To understand if there were any rider factors that also contributed to e-scooter performance and safety, Go-Pro cameras on tripods were set up alongside each of the three test courses to capture information regarding rider posture, strategy, and behavior.

For the Speed, Acceleration, and Braking test, a total of four Go-Pros were used. Two of the Go-Pros were located at the start of the course to capture rider posture during acceleration. One of these cameras was placed behind the rider, and the second camera was placed to the side of the rider. Similarly, two Go-Pros were located at the end of the course to capture rider posture during braking. One of these cameras were placed behind the braking zone, and the second camera was placed to the side of the braking zone. These views can be seen in **Figure 22**.

For the HSM test, a total of six Go-Pro cameras were used. These cameras were placed safely along the side of the course and were strategically located to focus on tasks of interest as well as to capture as many tasks as possible in the field of view. An example of these views can be seen in **Figure 24**.

Surveys

Qualtrics electronic surveys were developed for participants to share their perceptions on each of the e-scooters. During the test sessions, surveys were administered to participants on a tablet. Full versions of the surveys can be seen in Appendix B-4.

Pre-Session Questionnaire

A pre-session questionnaire was administered to each participant to collect demographics information as well as to understand prior experiences with e-scooters. The novice rider group was also asked questions to understand their level of physical activity and athleticism, prior experience with e-scooters or similar devices, and initial perceptions on e-scooter safety. The results can be seen in Appendix B-5.

Speed, Acceleration, and Braking Test Surveys

Three surveys were developed for the SAB test (Appendix B-4). The first survey was given to the participant after completing a single road condition on each of the 4 e-scooter models. Participants would complete this survey nine times throughout the course of the session. For this survey, participants were asked to rank the e-scooters on their acceleration and braking in the order for which they thought the e-scooters performed during the condition.

Following completion of all trials of the SAB test, two additional surveys were administered. The first survey asked participants to rate each of the e-scooter's acceleration and braking performance on a scale from 1 to 5 for several criteria. Additionally, participants were asked to select the e-scooter model that they preferred for accelerating, braking, and overall for the entire test.

The final survey was intended to understand which of the testing conditions would not be appropriate for less experienced riders to attempt. Experienced riders would select any of the nine conditions, and for the conditions that they selected, they would be asked to explain why they believed the condition would not be appropriate by choosing reasons from a list of choices.

Handling, Stability, and Maneuverability Test Surveys

Three surveys were also developed for the HSM test (Appendix B-4). The first survey was given to the participant after each trial. Participants would complete this survey 4 times throughout the course of the session. For this survey, participants were given a survey and asked to rate each of the e-scooter's performance on a scale from 1 to 5 for turning, riding over raised edges and bumps, riding off curbs, and riding across other obstacles and terrain. If participants did not complete any of the tasks, they would select "not applicable." Additionally, the novice rider group was asked about tasks that they chose to avoid

and reasons for avoiding them, as well as tasks that they chose to attempt after previously not attempting them and reasons for the change.

Following all trials of the HSM test, two additional surveys were administered. The first survey asked participants to rank the e-scooters in the order for which they thought the e-scooters performed each task. They were also asked to select the e-scooter model that they preferred for turning and maneuvering, riding over or off of obstacles, stability, riding across different surface types, and overall for the test.

The final survey was only completed by the experienced rider group and was intended to understand which of the tasks would not be appropriate for the novice riders to attempt. Participants would select any of the tasks, and for the tasks that they selected, they would be asked to explain why they believed the task would not be appropriate by choosing reasons from a list of choices.

Geofence Test Surveys

After the surprise trial, participants were asked what they thought happened and why the e-scooter slowed down and came to a stop. Following the test, they were then asked to rate the e-scooters on a scale of 1 to 5 on the deceleration rate after entering slow zone geofence, acceleration rate back to full speed after exiting slow zone geofence, stopping rate after entering no-ride zone geofence, volume level of audible notification, tone of audible notification, and effectiveness of audible notification. They were also asked which of the two e-scooters responded better to the slow zone and no-ride zone geofences.

Overall Study Surveys

At the end of the study, two final surveys were administered (Appendix B-4). Participants were asked to indicate how much they agreed with a series of statements on a scale from 1 to 5 for each of the e-scooter models.

The final survey asked participants to select the e-scooter that they preferred across the two sessions of testing and to select the factors that contributed to their selection. These results can be seen in Appendix B-8.

Data Reduction and Analysis

Data reduction protocols were developed for the DAS data and the Go-Pro videos. These protocols can be seen in Appendix B-3.

Speed, Acceleration, and Braking Test Reduction and Analysis

SAB MicroDAS Reduction and Analysis

VTTI's Data Reduction team used Hawkeye, a custom data-viewing software suite developed by VTTI, to identify timestamps for each of the trials corresponding to the start of the trial, end of the trial, and when the subject started to brake. The forward video from the microDAS along with GPS speed data was used for this (**Figure 21**).

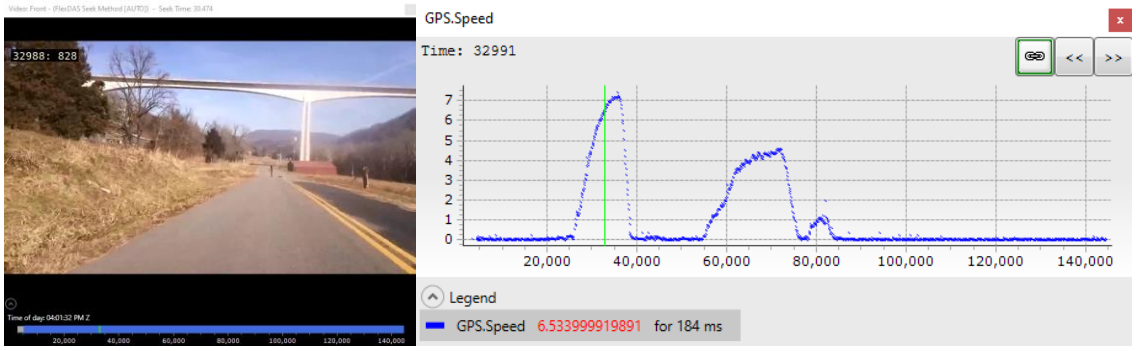

Figure 21. Forward camera view (left) and GPS speed data (right) collected by VTTI's microDAS during SAB test.

A script was then developed to filter the data and collect the following variables:

- Maximum speed and timestamp of maximum speed
- Speed at braking timestamp
- Average pitch rate between braking timestamp and trial end timestamp

The reduced variables and timestamps were used to determine the top speed of the scooter for each trial, as well as to calculate the acceleration rate and braking distance. Kinematics equations were used for these calculations, which can be seen below:

$$\text{Average acceleration rate} = \frac{v_{max}}{t_{v_{max}} - t_{start}}$$

$$\text{Braking distance} = \frac{v_{braking}^2}{2 \times a_{braking}} \quad \text{where} \quad a_{braking} = \frac{v_{braking}}{t_{end} - t_{braking}}$$

where v_{max} is the maximum speed during the trial, t_{vmax} is the timestamp corresponding to the maximum speed, t_{start} is the trial start timestamp, $v_{braking}$ is the speed at the braking timestamp, t_{end} is the trial end timestamp, $t_{braking}$ is the braking timestamp, and $a_{braking}$ is the braking rate.

During the test, the braking distance of the Max 2.3 unit was significantly longer than the other models. Given that this scooter was one of the newer models and should have had one of the best braking systems, the research team decided to investigate why this result was seen. It was hypothesized that the scooter was not braking as well as it should have been due to possible mechanical issues or wear. To test this hypothesis, four other Max 2.3 units were evaluated against the Max 2.3 scooter that was used for testing. Two of the units were provided by Spin, and the other two were acquired from the fleet deployed on Virginia Tech's campus. The testing was conducted on flat pavement, and there were five trials for each scooter. The braking distance was recorded after each trial, and the results showed that on average, the Max 2.3 unit from testing was braking in 14.16 feet, while the average of the other four units was 11.32 feet, indicating that the unit that was being used for testing was braking at 80% capacity. To account for this in the data, an adjustment factor was added. Additionally, after this result was seen and following the conclusion of the SAB test, the Max 2.3 unit was switched with another unit which was used for the HSM test and Geofence test. This example shows the importance of servicing brakes, which may not occur as often for large fleets of e-scooters.

A factorial analysis of variance (ANOVA) was used to analyze differences in performance between the scooters, with additional factors of the condition slope and terrain, trial number, participant gender,

participant weight, and participant height included in the analysis, as well as interaction effects between the scooter and these factors. Group differences were identified by post-hoc analysis using Tukey's honestly significant difference (HSD) test, and results were deemed significant if their p-value was less than 0.05.

A follow-up analysis was conducted to study trends in performance based upon e-scooter features, and regressions were performed to generate correlation values and equations of fit.

SAB Fixed Camera Reduction and Analysis

A protocol was developed for analyzing the Go-Pro videos. For each trial, VTTI's Data Reduction team answered a series of questions regarding the rider's posture while accelerating and braking, such as their initial acceleration posture, acceleration posture change, initial braking posture, and braking posture change (**Figure 22**). The data was analyzed using descriptive statistics and grouped by scooter model.

Figure 22. Go-Pro views from SAB test. Top left: acceleration side view. Top right: acceleration rear view. Bottom left: braking side view. Bottom right: braking front view.

Handling, Stability, and Maneuverability Test Reduction and Analysis

HSM MicroDAS Reduction and Analysis

Similar to the SAB test, VTTI's Data Reduction team identified timestamps for each task of the HSM test corresponding to when the subject approached each task, when the subject started each task, and when the subject completed each task. This was also completed by using the forward video or accelerometer data (**Figure 23**).

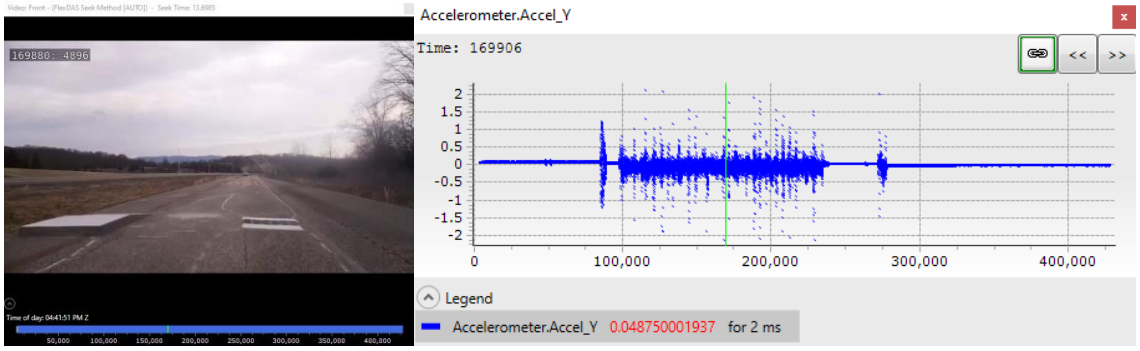

Figure 23. Forward video (left) and accelerometer data (right) collected by VTTI's microDAS during HSM test.

A script was developed to filter the data and collect the following variables:

- Speed when subject approaches obstacle
- Speed when subject begins obstacle
- Maximum speed between start of task and completion of obstacle
- Average speed between start of task and completion of obstacle
- Maximum longitudinal, lateral, and vertical acceleration between start of task and completion of obstacle
- Maximum pitch, yaw, and roll rate between start of task and completion of obstacle
- Time to complete course

Speed differences were also calculated using the above data. Given that there were 22 individual obstacles, the obstacles were placed into groups such as lateral maneuvers, riding into raised surfaces, riding off raised surfaces, and terrain transitions. For each group, a factorial ANOVA was used to analyze differences in relevant performance metrics between the scooters, with additional factors of the trial number, start location, experience level, participant gender, participant weight, and participant height included in the analysis, as well as interaction effects between the scooter and these factors. Group differences were identified by post-hoc analysis using Tukey's HSD test, and results were deemed significant if their p-value was less than 0.05.

HSM Fixed Camera Reduction and Analysis

A second protocol was developed for analyzing the Go-Pro videos for the HSM test. For each trial, VTTI's Data Reduction team answered the following questions regarding the rider's initial posture approaching each task and any posture changes or strategies that they used while completing each task (**Figure 24**). The data was analyzed using descriptive statistics and grouped by scooter model and experience level for each obstacle type.

Figure 24. Go-Pro view to observe rider initial posture and change in posture for riding off 4" curb during HSM test.

Additionally, for the sideways U-turn obstacle and obstacles that involved riding into a raised surface (excluding the 1" raised edge), a logistic regression was performed for if the scooter was able to complete the obstacle with or without assistance (i.e., rider using their feet or lifting the front of the scooter using the handlebars). This data was coded as a binary variable with 1 corresponding to completing the obstacle and 0 corresponding to either not being able to complete the obstacle for the lateral maneuvers or getting stuck while attempting the obstacle for riding over raised surfaces. Scooter features were also added to the analysis to understand if there were trends in scooter designs that correspond to compatibility with completing these types of obstacles, and experience and gender were also investigated to look for differences between the groups.

Geofence Test Reduction and Analysis

Geofence MicroDAS Reduction and Analysis

For each trial, the following timestamps were identified by using the forward-video:

- Scooter enters the slow zone geofence
- Scooter begins to decelerate after entering the slow zone geofence
- Scooter reaches reduced speed in slow zone geofence
- Scooter exits the slow zone geofence
- Scooter begins to accelerate after exiting the slow zone geofence
- Scooter enters no-ride zone geofence
- Scooter begins to decelerate after entering the no-ride zone geofence

Corresponding latitudes, longitudes, and speeds were taken for each of the timestamps. The following metrics were calculated for each trial using the reduced timestamps, GPS locations, and corresponding speeds:

- Time and distance until the speed begins to decrease after entering the slow-zone
- Time and distance to reach the reduced speed after entering the slow-zone
- Time and distance to reach the reduced speed after the speed begins to decrease
- Difference between the actual reduced speed and the expected reduced speed
- Time and distance until the speed begins to increase after exiting the slow-zone
- Time and distance until the speed begins to decrease after entering the no-ride zone

A factorial ANOVA was used to analyze differences in performance between the scooters, with additional factors of the slope and speed at the beginning timestamp included in the analysis, as well as interaction

effects. Group differences were identified by post-hoc analysis using Tukey's honestly HSD test, and results were deemed significant if their p-value was less than 0.05. No follow-up analyses on scooter features were performed as only two e-scooters were included in this testing.

Survey Analysis

All survey data was analyzed using descriptive statistics.

Safety Critical Event Analysis

A third protocol was developed for reducing safety critical events. Safety critical events were defined as:

- Full fall over – a part of the scooter contacts the ground (other than wheels) and a part of the rider contacts the ground (other than feet).
- Bailout with fall over – a part of the scooter contacts the ground (other than wheels), but the rider's foot catches their fall or the rider successfully aborts without falling.
- Bailout no fall over – only the rider's feet catch their fall and the rider also prevents the scooter from contacting the ground.
- Forward impact – the scooter impacts an object or surface.

An "Other" category was also used to capture circumstances that did not fit into the defined categories Each event was characterized by the type of event and the post-event action of the rider. A narrative was also written for each event.

Results

The following sections include the results from each of the three tests and is broken down by the specific measures collected by the microDAS, the fixed camera results, and the survey results.

Speed, Acceleration, and Braking Test Results

SAB MicroDAS Results

Top Speed Results

The top speed that the four e-scooter models were able to reach during each trial was recorded, and these results can be seen in **Figure 25**. When averaging the top speed by scooter, the Max 2.3, S-100T, and Okai scooter models reached speeds around 12.5 mph (12.6 mph, 12.5 mph, and 12.2 mph, respectively), which were slightly below the governed top speed of 15 mph, while the Max 2.0 model reached a speed of around 10.2 mph, which was significantly different from the other three models ($p<0.0001$). The top speed that each e-scooter was able to reach also varied by slope. When averaging the top speed of all four scooter models by slope, the scooters were able to reach a speed of 14.0 mph on the decline slope, 11.8 mph on the flat slope, and 9.6 mph on the incline slope. There were significant differences in top speed between the decline and flat slopes ($p<0.0001$), decline and incline slopes ($p<0.0001$), and flat and incline slopes ($p<0.0001$). Differences between the scooters were less significant on the decline slope. There were also differences in top speed by terrain. When averaging the top speed of all four scooter models by terrain, the scooters were able to reach a speed of 13.0 mph on pavement, 12.8 mph on wet pavement, and 9.5 mph on off-road. There were significant differences between the pavement and off-road terrains ($p<0.0001$) and the wet pavement and off-road terrains ($p<0.0001$). For the off-road terrain, the S-100T reached significantly greater top speeds than the Okai ($p=0.0190$) and the Max 2.0 ($p<0.0001$).

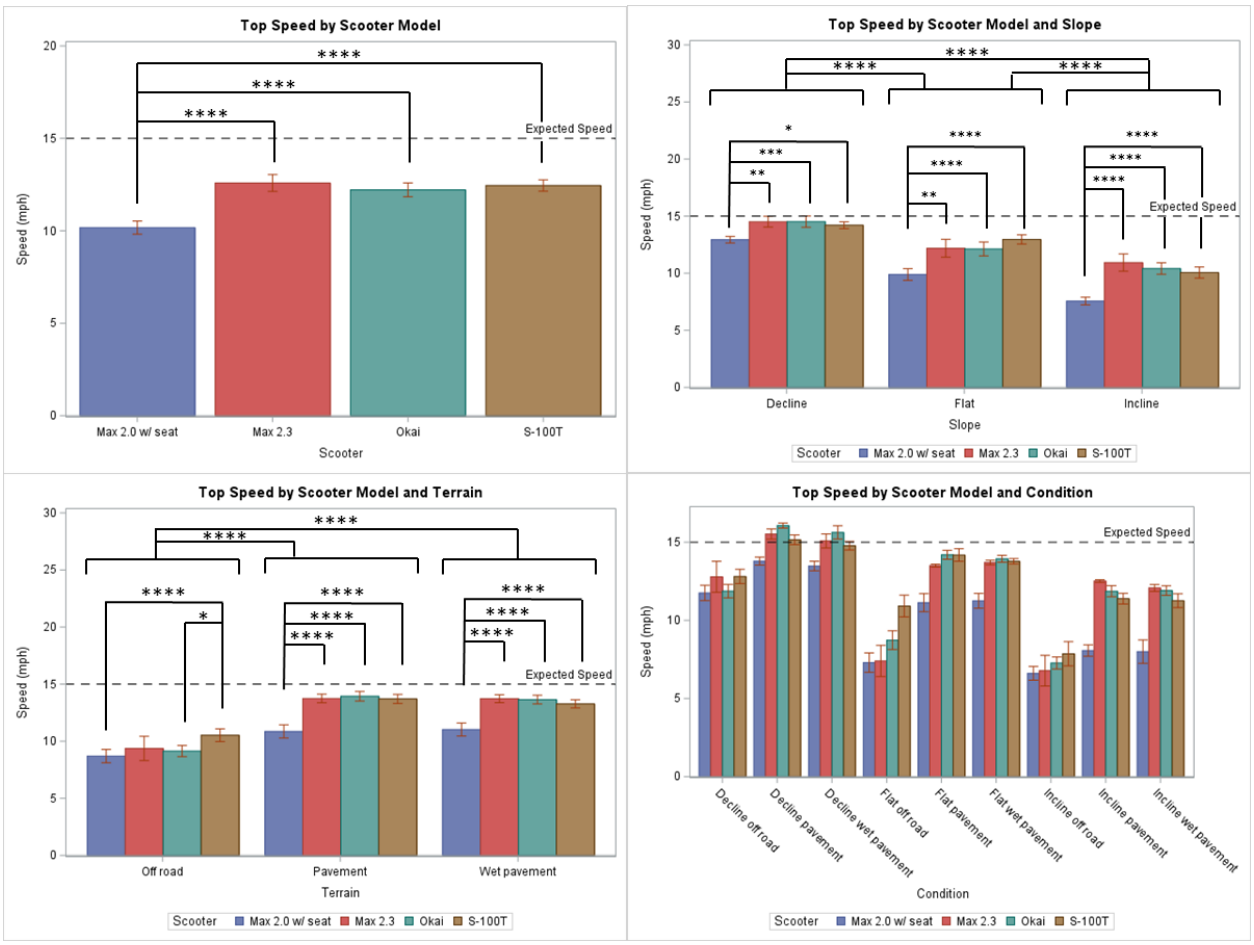

Figure 25. Top speeds from the SAB test. Top left: top speed by scooter model. Top right: top speed by scooter model and slope. Bottom left: top speed by scooter model and terrain. Bottom right: top speed by scooter model and condition. (*-p<0.05, **-p<0.01, ***-p<0.001, *-p<0.0001)***

The effects of gender and rider weight on top speed were also investigated, which can be seen in **Figure 26**. Averaging the top speed of all four scooters, female riders were able to reach speeds of 12.6 mph while male riders reached speeds of 11.4 mph, which was significant (p=0.0459). Rider weight was seen to have a significant effect on the top speed that the Max 2.0 was able to reach (p<0.0149).

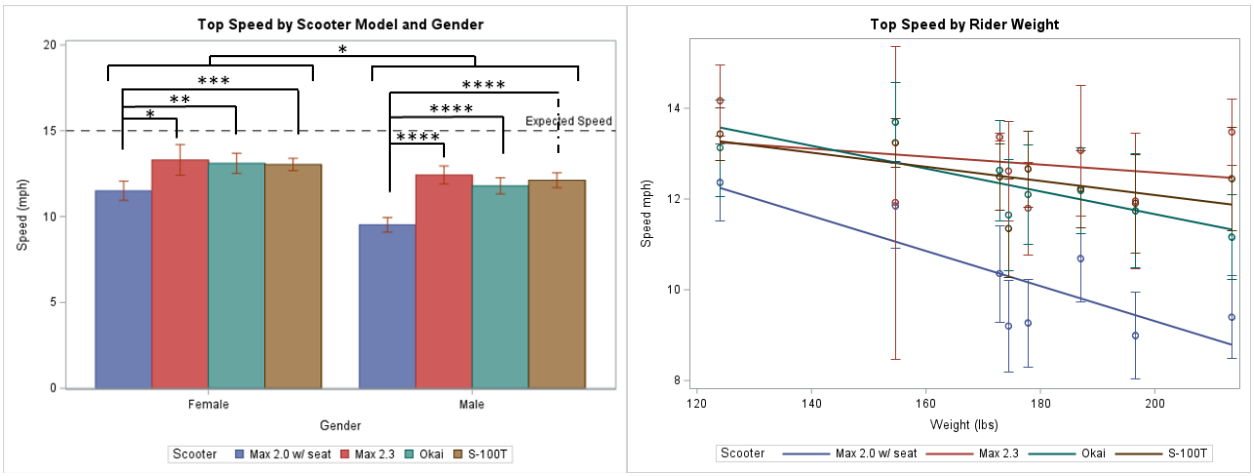

Figure 26. Top speed by scooter model and gender (left) and by scooter model and rider weight (right). (*-p<0.05, **-p<0.01, ***-p<0.001, *-p<0.0001)***

Acceleration Rate Results

The acceleration rate from the start of the trial to the time at which the top speed was reached was calculated for each of the four scooters, and the results can be seen in **Figure 27**. When averaging the acceleration rate by scooter for all slopes and terrains, the S-100T had the fastest acceleration rate of 1.95 ft/s^2, followed by the Max 2.3 with 1.85 ft/s^2, then the Okai with 1.64 ft/s^2, and the Max 2.0 with 1.23 ft/s^2. The acceleration rate of the Max 2.0 was significantly different than the other three e-scooters ($p<0.0001$), and the acceleration rate of the S-100T was significantly different than the Okai ($p<0.0001$). Similar to the top speed results, acceleration rate varied by slope: when averaging the acceleration rate of all scooters by slope, the decline slope had an average rate of 2.40 ft/s^2, followed by the flat slope with a rate of 1.64 ft/s^2, and the incline slope had the slowest average acceleration rate of 0.98 ft/s^2. The acceleration rates were significantly different between the decline and flat slopes ($p<0.0001$), the decline and incline slopes ($p<0.0001$), and the flat and incline slopes ($p<0.0001$). The acceleration rate on pavement was an average of 1.87 ft/s^2 for all four scooters and 1.89 ft/s^2 for wet pavement, both of which were significantly different than the acceleration rate on the off-road terrain which was 1.13 ft/s^2 ($p<0.0001$). Only the acceleration rate of the S-100T was significantly faster than the acceleration rate of the Max 2.0 on the off-road terrain ($p=0.0002$).

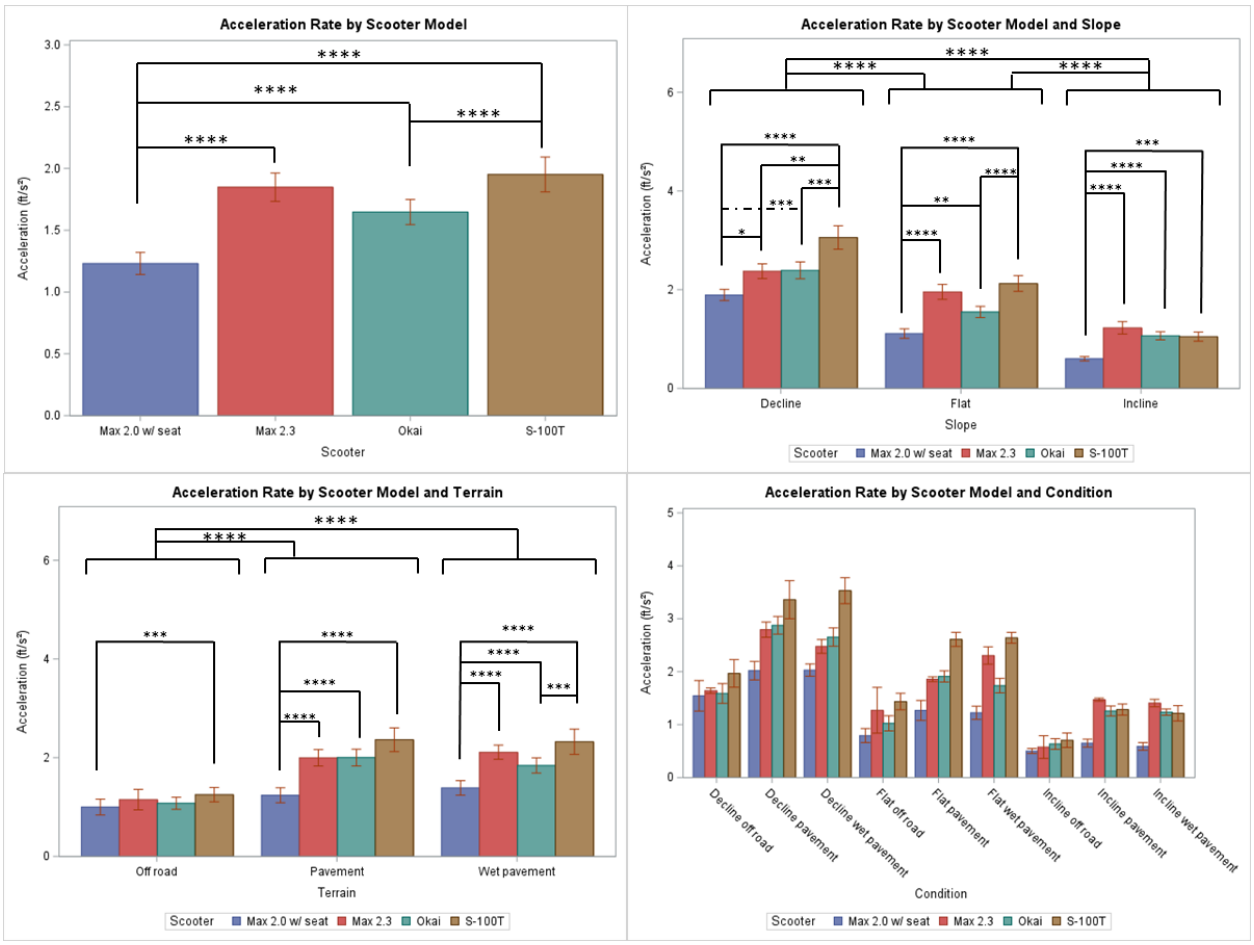

Figure 27. Acceleration rates from the SAB test. Top left: acceleration by scooter model. Top right: acceleration by scooter model and slope. Bottom left: acceleration by scooter model and terrain. Bottom right: acceleration by scooter model and condition. (*-p<0.05, **-p<0.01, ***-p<0.001, *-p<0.0001)***

The effect of gender and rider weight and on acceleration rate was also analyzed, which can be seen in **Figure 28**. There was not a significant difference in acceleration between gender, but rider weight was once again seen to have a significant effect on acceleration rate for the Max 2.0 (p=0.0097).

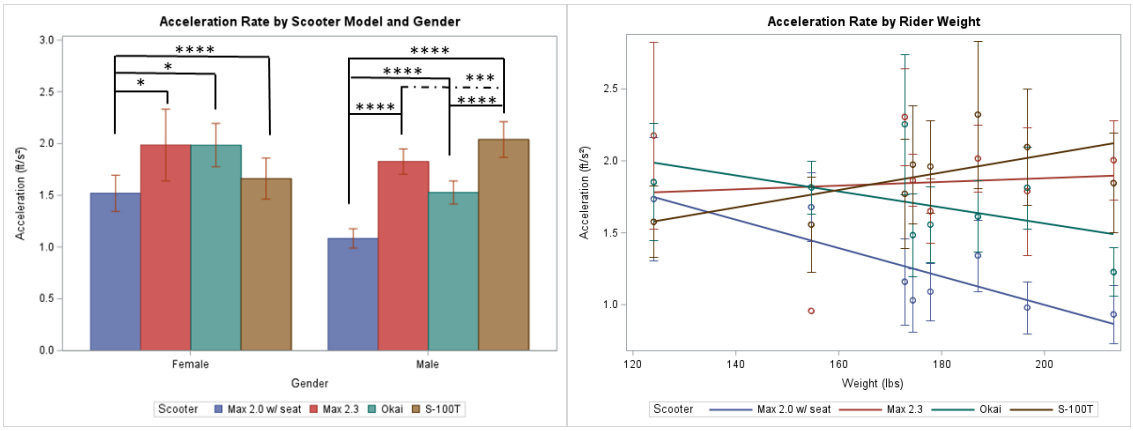

Figure 28. Acceleration rate by scooter model and gender (left) and scooter model and rider weight (right). (*-p<0.05, ***-p<0.001, *-p<0.0001)***

Braking Distance Results

Braking distances were also calculated for each of the trials, and the results can be seen in **Figure 29**. Speed before braking was also included as a factor in this analysis. The Max 2.3 had an average braking distance of 18.7 ft, the S-100T had an average braking distance of 15.5 ft, the Okai had an average braking distance of 16.8 ft, and the Max 2.0 had an average braking distance of 11.7 ft. There were significant differences in the braking distances by slope, with the decline slope having an average braking distance of 19.8 ft, followed by the flat slope with 16.2 ft, and the incline slope with 10.4 ft. The braking distance on the incline slope was significantly different than the braking distance on the flat slope (p=0.0043) and the decline slope (p=0.0437). There were also non-significant differences in the braking distance between different terrains, with the average braking distance on the off-road terrain being 9.6 ft, 17.7 ft on the pavement terrain, and 17.7 ft on the wet pavement terrain.

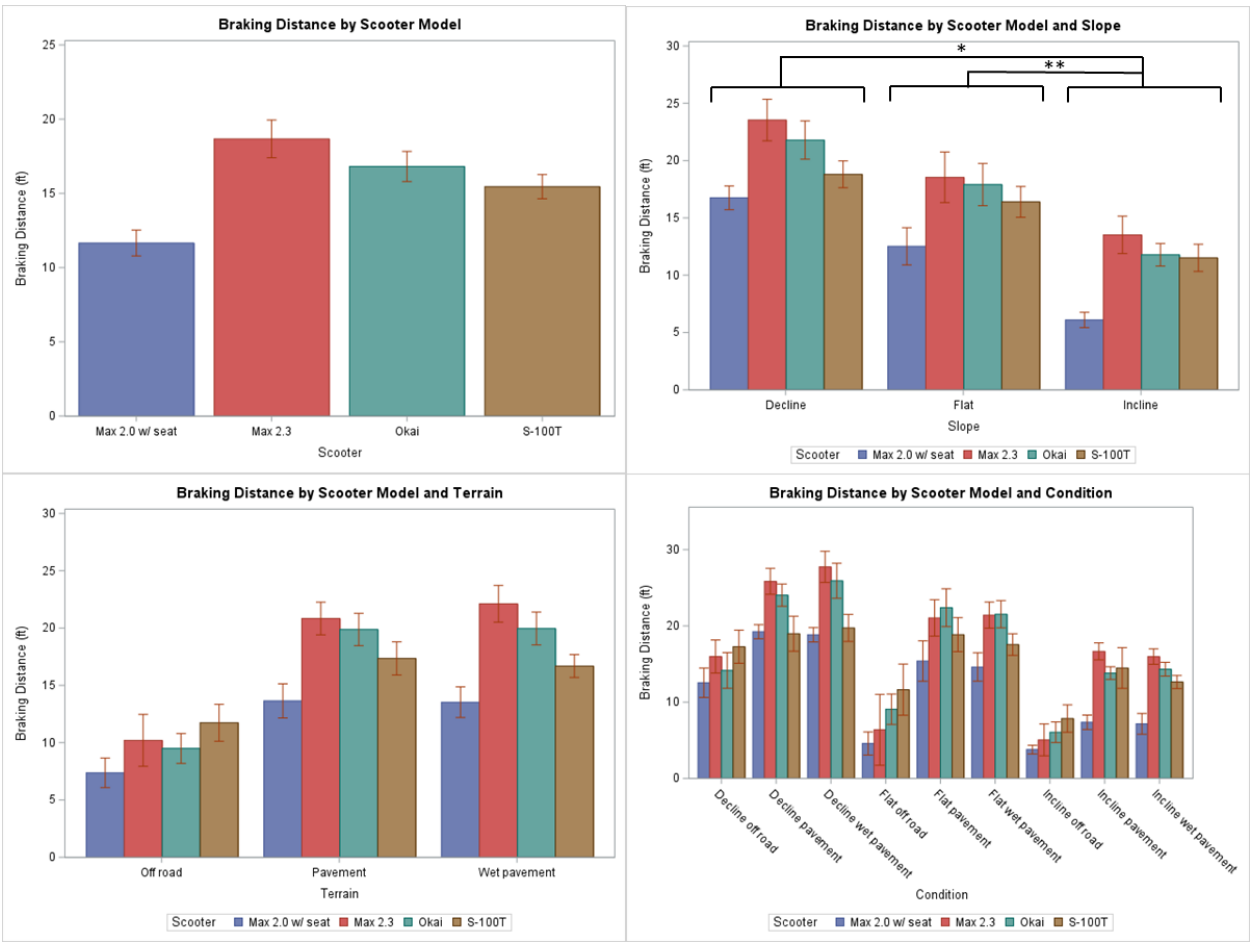

Figure 29. Braking distance from the SAB test. Top left: braking distance by scooter model. Top right: braking distance by scooter model and slope. Bottom left: braking distance by scooter model and terrain. Bottom right: braking distance by scooter model and condition. (*-p<0.05, **-p<0.01)

Speed before braking was seen to have a signficant effect on braking distance (p<0.0001). As can be seen in **Figure 30**, braking distance was highly correlated with speed before braking (R^2=0.80) and also varied largely based upon slope and terrain.

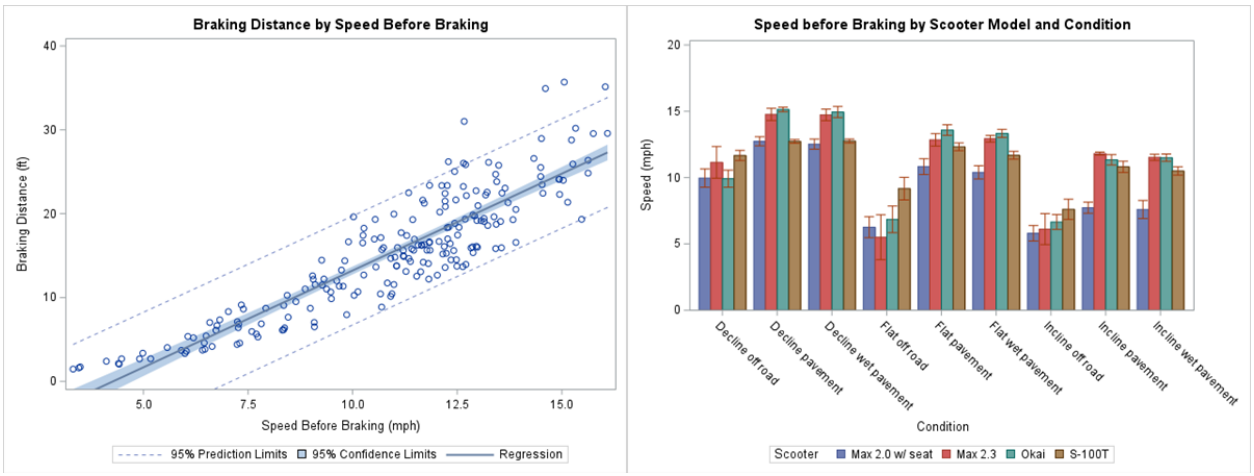

Figure 30. Braking distance by speed before braking (left) and by scooter model and condition (right).

To have more standardized data to compare the braking distances between the scooter models and across the different slopes and terrains, a predicted braking distance was calculated using 15 mph as the speed at the braking timestamp and the previously calculated braking rate. These results can be seen in **Figure 31**. The scooters all had very similar predicted braking distances (Max 2.3: 28.2 ft, S-100T: 27.4 ft, Okai: 26.6 ft, Max 2.0: 27.7 ft). These results were relatively consistent across all slopes and terrains. There was a slight significant difference in the predicted braking distance between the flat slope and incline slope (flat: 29.0 ft, incline: 26.2 ft, p=0.0296).

Gender and rider weight also had an effect on the predicted braking distance. While on average female riders were predicted to brake in 27.2 ft and male riders were predicted to brake in 27.5 ft, Tukey's adjustment accounting for factors rider weight and height predicted distances of 29.6 ft for female riders and 26.7 ft for male riders (p=0.0334). Rider weight significantly affected the braking distance for the Max 2.3 model (p=0.0113). These results can be seen in **Figure 32**.

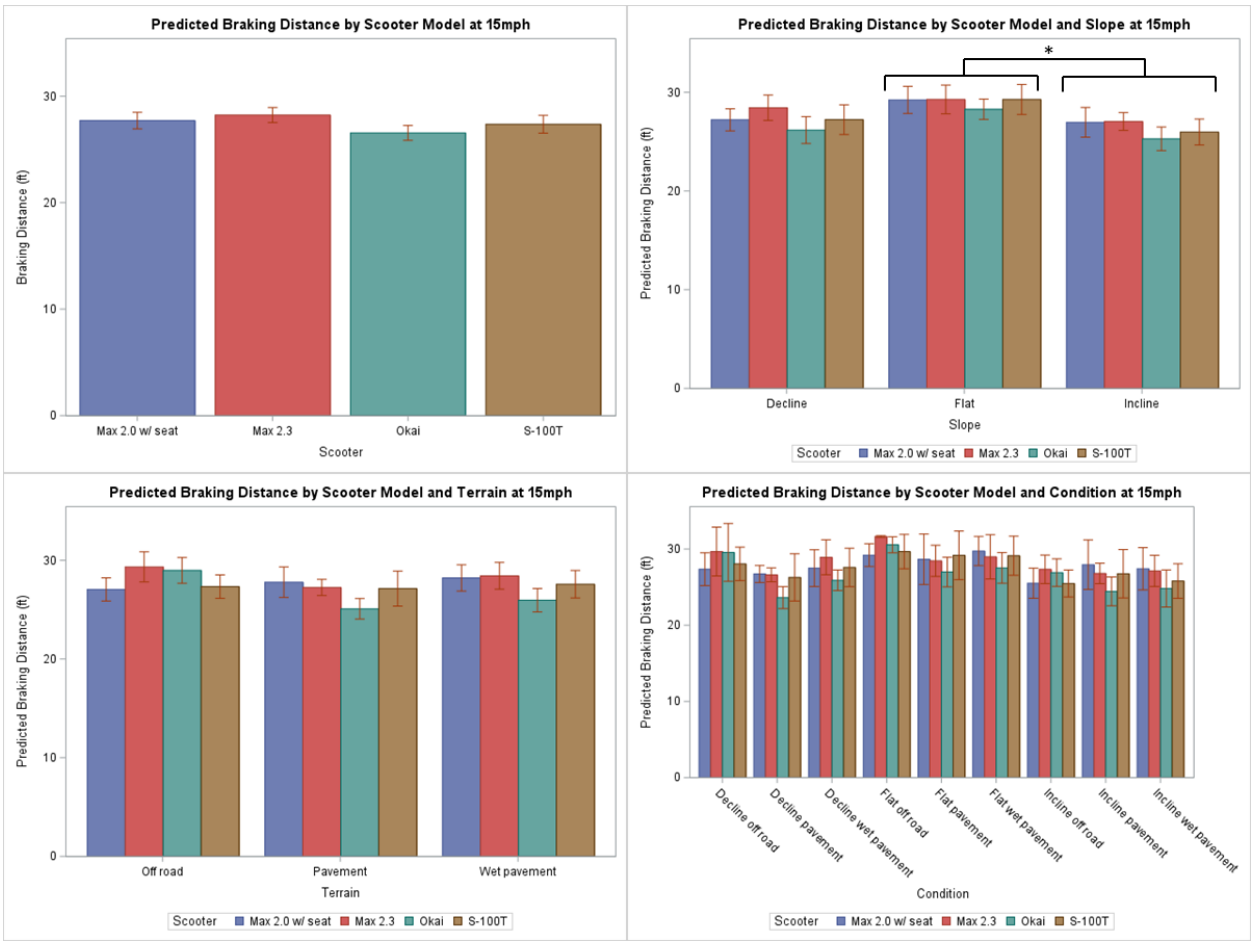

Figure 31. Predicted braking distances for the SAB test. Top left: braking distance by scooter model. Top right: braking distance by scooter model and slope. Bottom left: braking distance by scooter model and terrain. Bottom right: braking distance by scooter model and condition. (*-p<0.05)

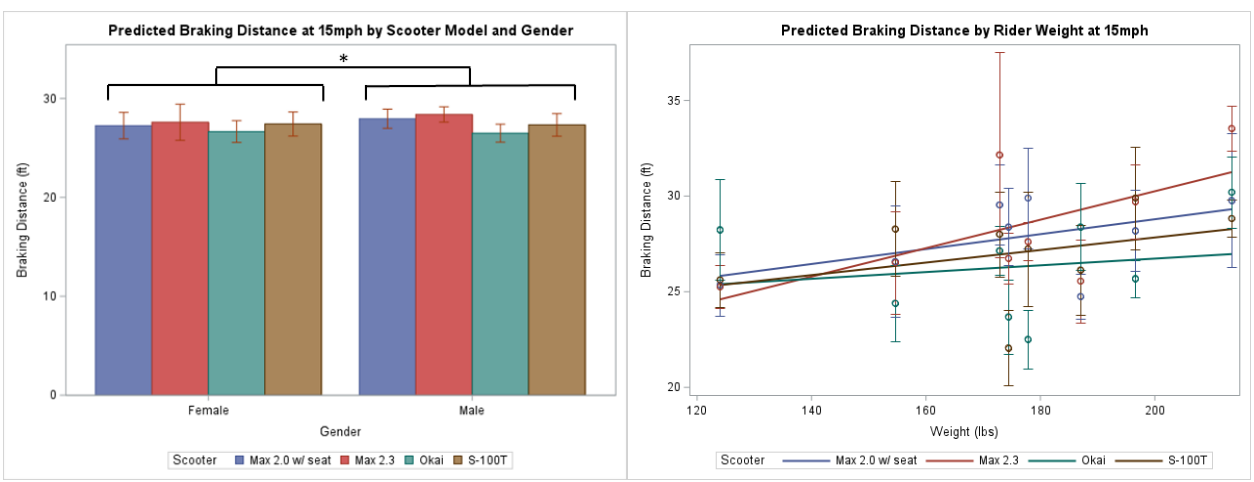

Figure 32. Predicted braking distance by scooter model and gender (left) and scooter model and rider weight (right). (*-p<0.05)

SAB Survey Results

Participant rankings on their perceptions of the acceleration and braking capabilities for each of the scooters after each trial can be seen in **Figure 33**. Across all trials, the S-100T was ranked first for acceleration rate (34 selections), acceleration stability (33 selections), braking rate (34 selections), and braking stability (31 selections). The Okai was ranked last for acceleration rate (31 selections) and acceleration stability (31 selections) followed closely by the Max 2.0 (27 selections for acceleration rate and 26 selections for acceleration stability). The Okai was also ranked last on braking stability (26 selections). The Max 2.0 had the second greatest number of selections for being ranked first on braking rate (19 selections) and braking stability (22 selections). The Max 2.3 had the lowest rankings for braking rate (33 selections).

Participant ratings on their perceptions of the acceleration and braking capabilities for each of the scooters after the test can be seen in **Figure 34**. Participants thought that the acceleration rates for the Max 2.3 and S-100T were appropriate, while the Max 2.0 was too slow, and the Okai was too fast. Only the Okai was ranked under a 3 for acceleration feel. Participants found the S-100T to have the most effective accelerator controls, followed by the Max 2.3, Okai, and Max 2.0. The Okai was rated slightly lower than the other scooter models for accelerator control placement. For braking rate, participants thought that the Max 2.0 had the most appropriate rate, with the S-100T and Okai having rates that were too fast and the Max 2.3 braking at a rate that was too slow. The Max 2.0 was also rated the best for braking feel, followed by the Max 2.3, S-100T, and Okai. Participants thought that the brake controls were more effective for the S-100T and Okai and less effective for the Max 2.3 and Max 2.0. There were very little differences in ratings for the brake control placement between scooters.

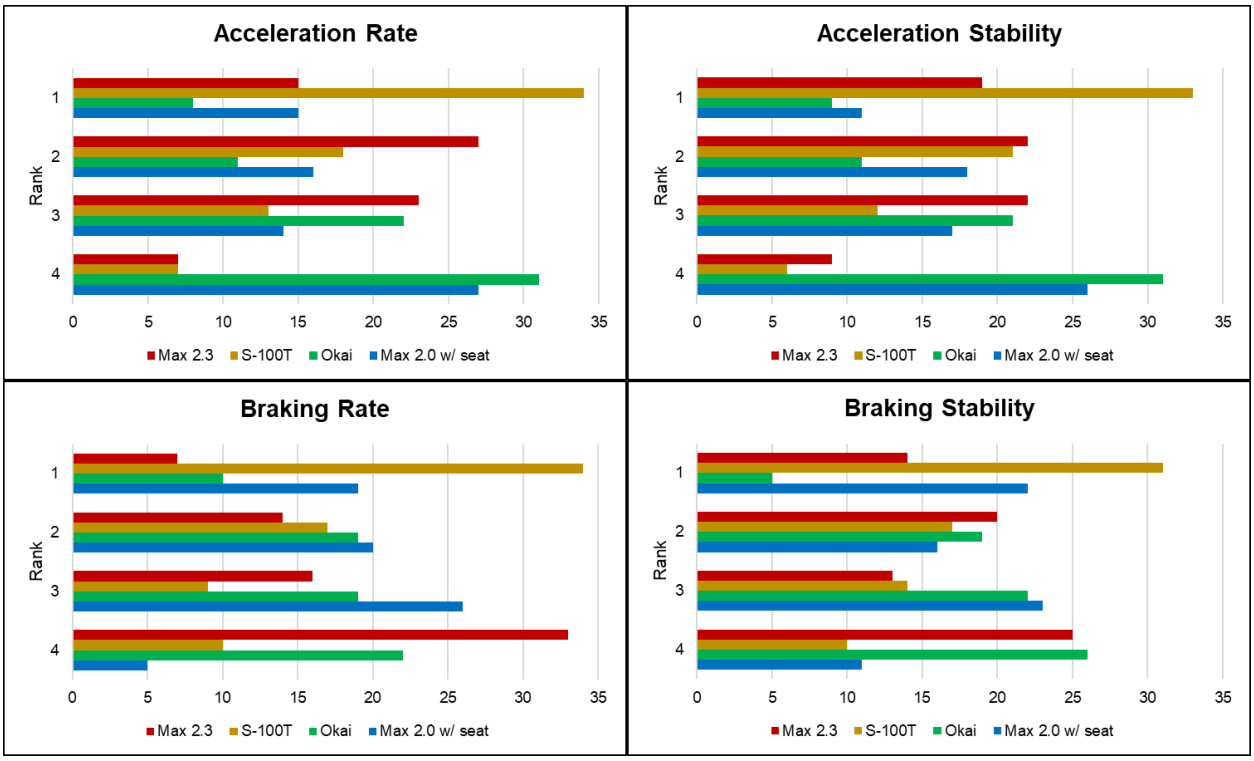

Figure 33. Post-trial survey results. Participants ranked the scooters from 1-4 for each trial. The figure shows the number of participants to give the scooter each rank for all trials combined.

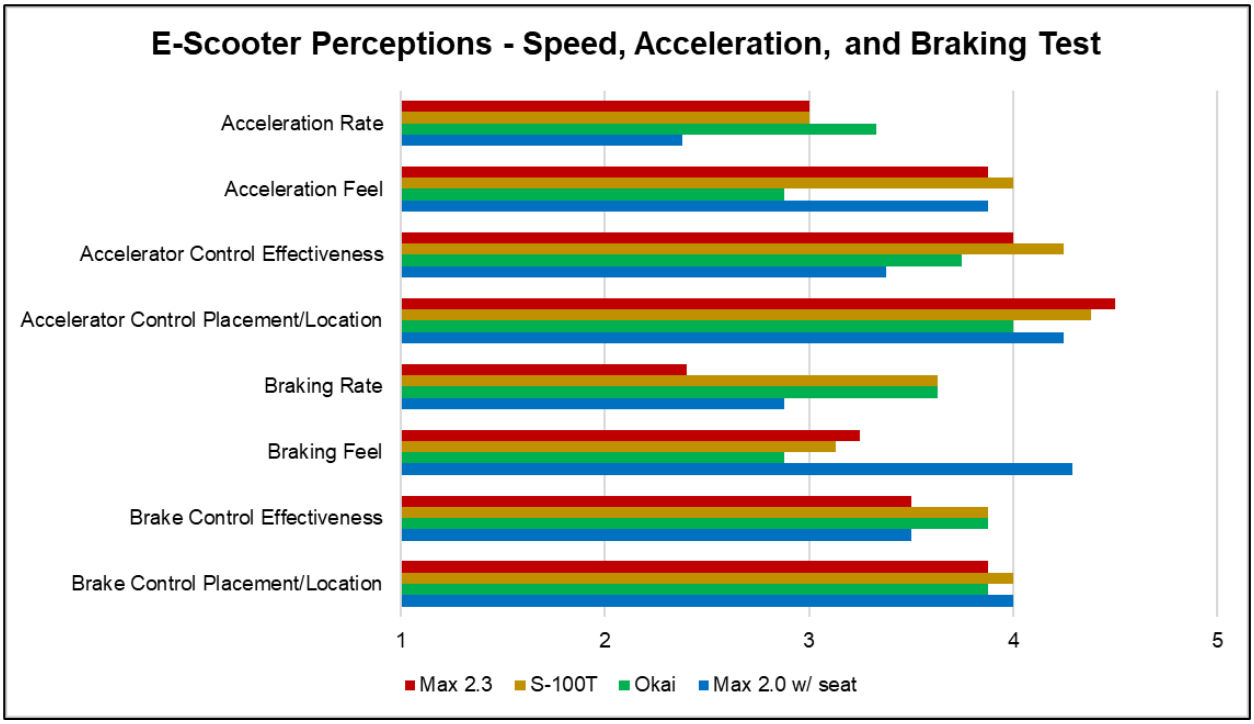

Figure 34. Post-test survey results. Participants would rate scooters on a scale from 1-5. The figure shows the average ratings. Acceleration/braking rate: 1 – too slow, 5 – too fast. Acceleration/braking feel: 1 – unstable, wobbly, 5 – stable, smooth. Acceleration/braking control effectiveness: 1 – not effective (hard squeezing to accelerate), 5 – effective (easy squeezing to accelerate). Accelerator/braking control placement/location: 1 – uncomfortable, 5 – comfortable.

Additional survey results can be seen in Appendix B-6.

SAB Fixed Camera Results

The initial acceleration posture and acceleration posture change by scooter and slope can be seen in **Figure 35** and by scooter and terrain in **Figure 36**, and the initial braking posture and braking posture change by scooter and slope can be seen in **Figure 37** and by scooter and terrain in **Figure 38**. Aside from the seated Max 2.0, the most common initial acceleration posture was legs bent, body leaning forward. The most common acceleration posture changes were to return the body to a neutral front/back position or to straighten the legs. Aside from the seated Max 2.0, the most common initial braking postures were legs either bent or straight, no body lean or body leaning forward. Most participants did not change their posture while braking. The second most common action was to lean backward. There were no major differences or trends in acceleration or braking initial postures or posture changes with scooters, slopes, or terrains.

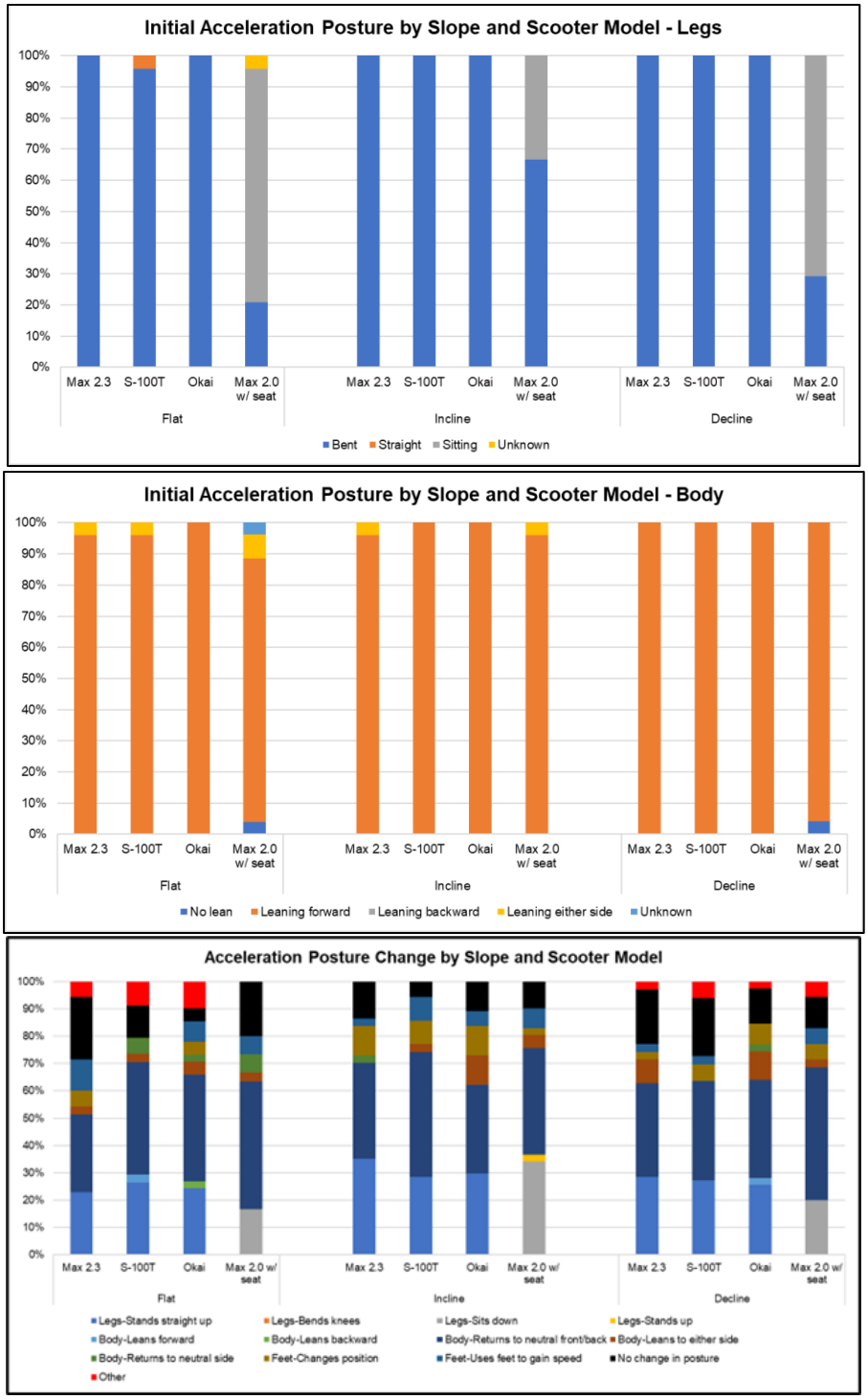

Figure 35. Acceleration posture by slope. Top: initial acceleration body posture. Middle: initial acceleration legs posture. Bottom: acceleration posture change.

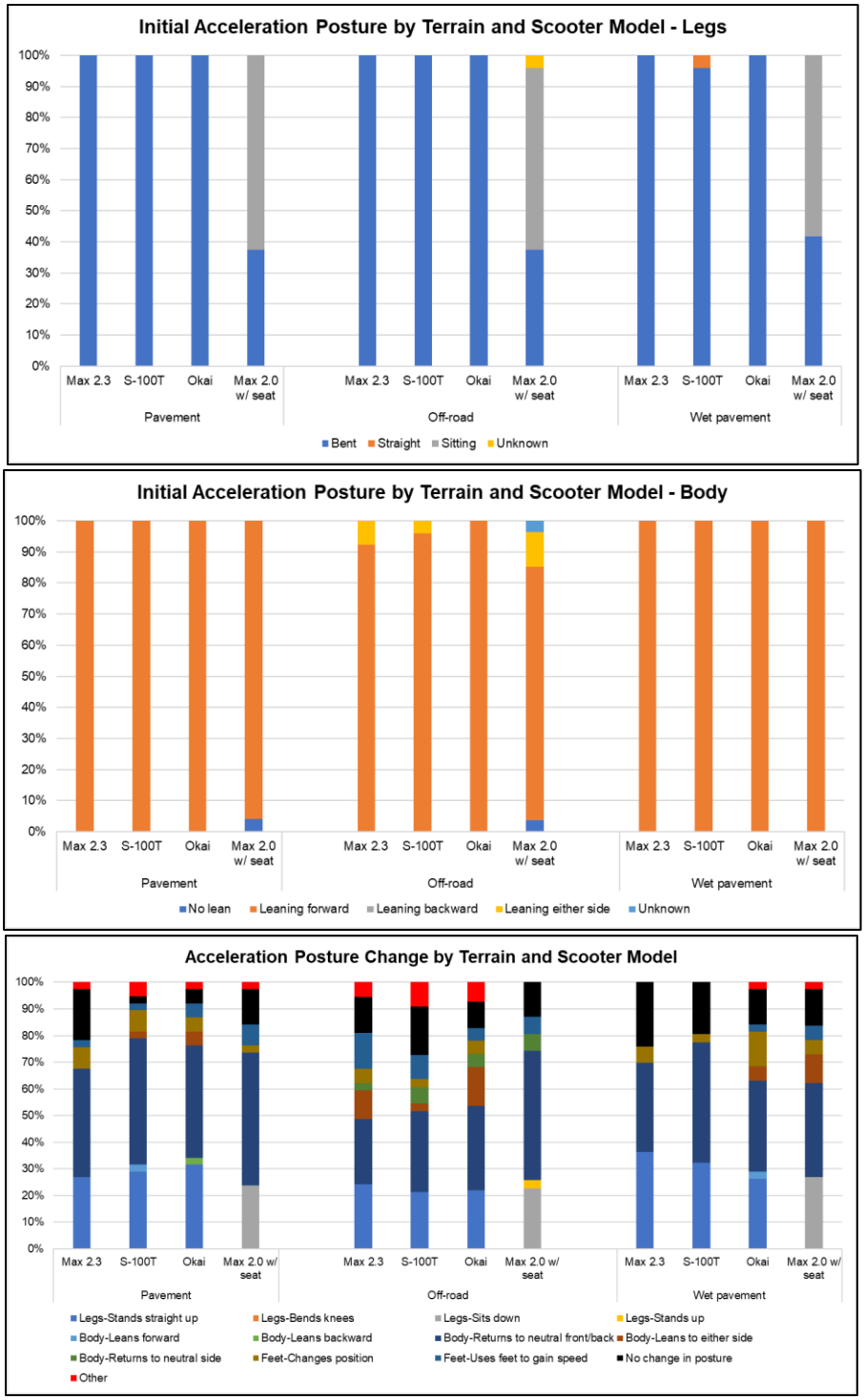

Figure 36. Acceleration posture by terrain. Top: initial acceleration body posture. Middle: initial acceleration legs posture. Bottom: acceleration posture change.

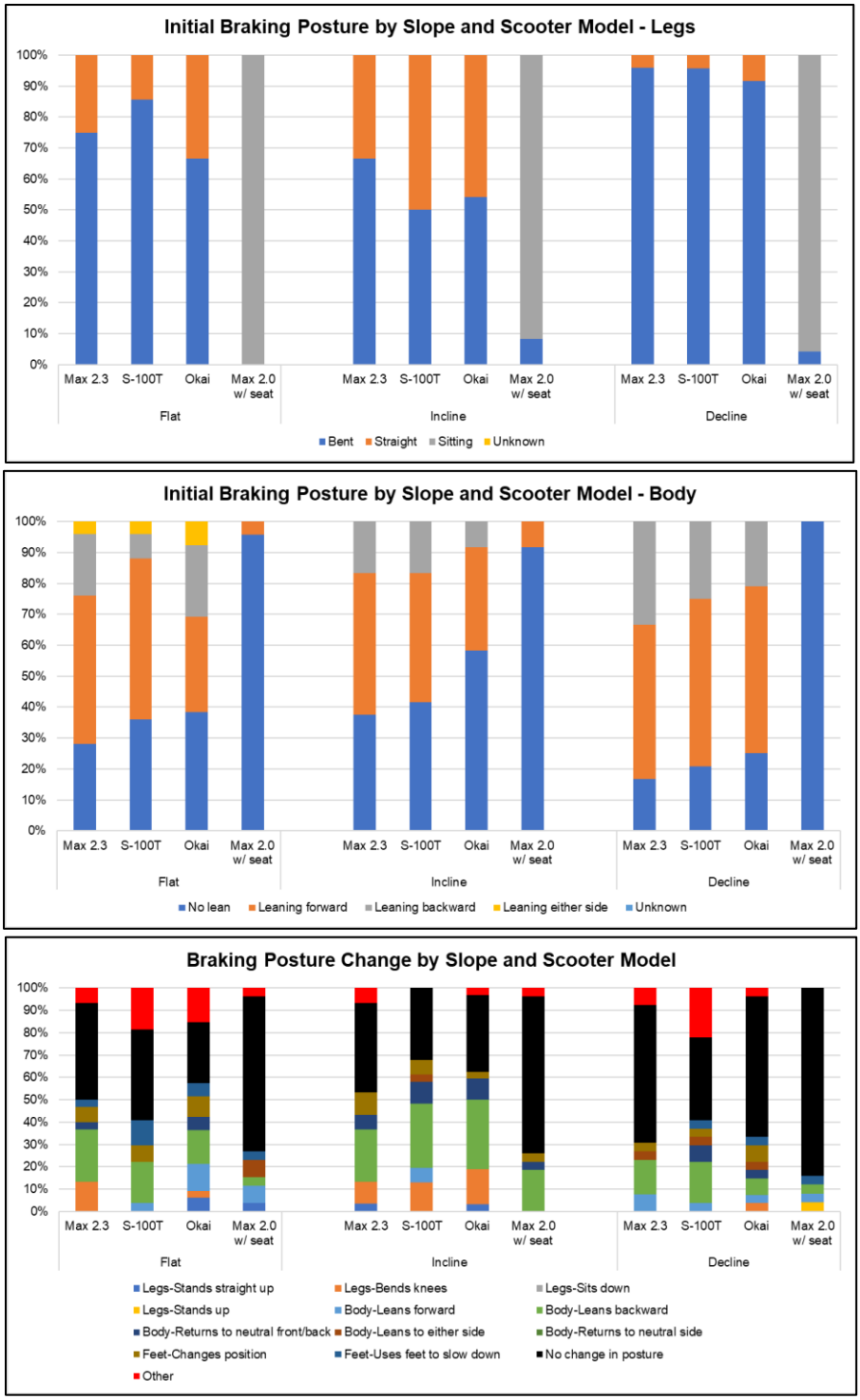

Figure 37. Braking posture by slope. Top: initial braking body posture. Middle: initial braking legs posture. Bottom: braking posture change.

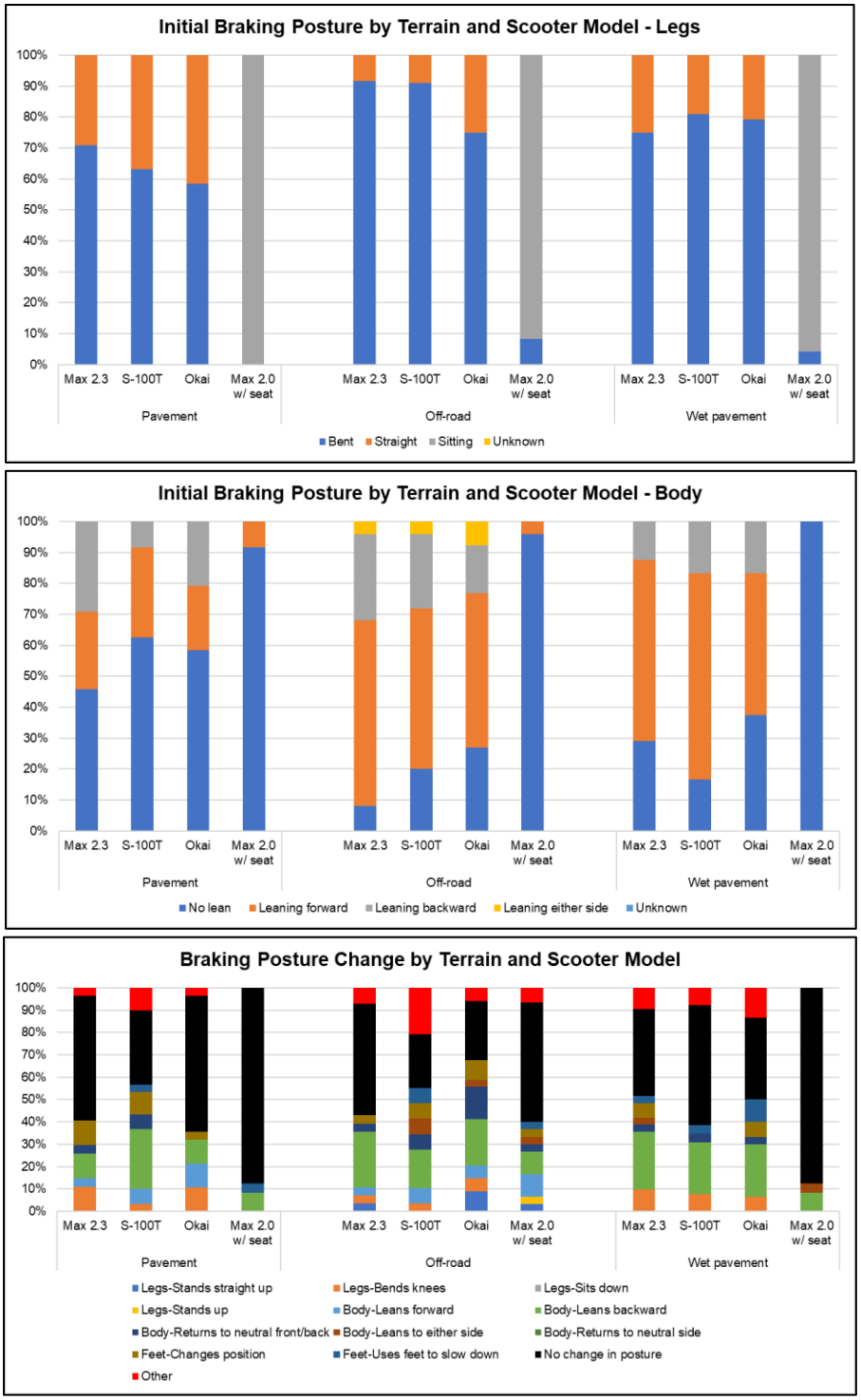

Figure 38. Braking posture by terrain. Top: initial braking body posture. Middle: initial braking legs posture. Bottom: braking posture change.

SAB Safety Critical Event Results

The safety critical events are summarized in **Figure 39**. Most safety critical events occurred while braking and on the flat, off-road condition, and the S-100T had the most safety critical events. The most common crash type was a bailout, and most safety critical events happened on either the first or third trials.

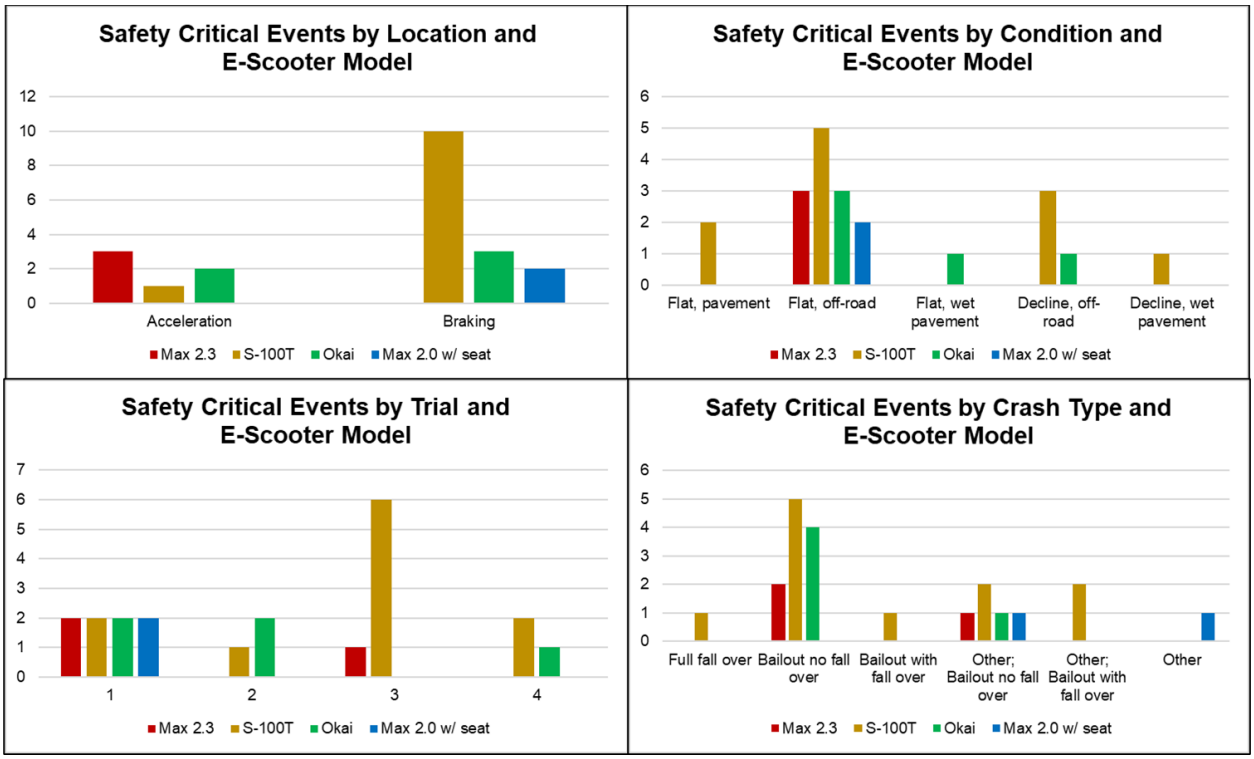

Figure 39. Safety critical event frequency occurring during the SAB test. Top left: SCEs by location and scooter model. Top right: SCEs by condition and scooter model. Bottom left: SCEs by trial and scooter model. Bottom right: SCEs by crash type and scooter model.

Handling, Stability, and Maneuverability Test Results

HSM MicroDAS Results

Lateral Maneuver Results

The first metric that was investigated for lateral maneuvers was speed change, in which a lower speed change would indicate greater ability to maintain speed. These results can be seen in **Figure 40**. The average speed changes were -1.15 mph for the Max 2.0, -1.74 mph for the Max 2.3, -1.92 mph for the Okai, and -1.69 mph for the S-100T. However, no significant differences were observed between the scooters, likely due to incorporating speed before the obstacle, in which a general trend was observed where approaching the obstacle with a greater speed also required a greater speed decrease to pass through the obstacle ($p<0.0001$). There were significant differences observed in the speed change between experience groups, with the experienced riders on average reducing their speed by 2.60 mph and the novice riders reducing their speed by 1.36 mph ($p<0.0416$). Female riders were also seen to maintain their speed better than male riders, with speed changes of -1.14 mph compared to -2.02 mph.

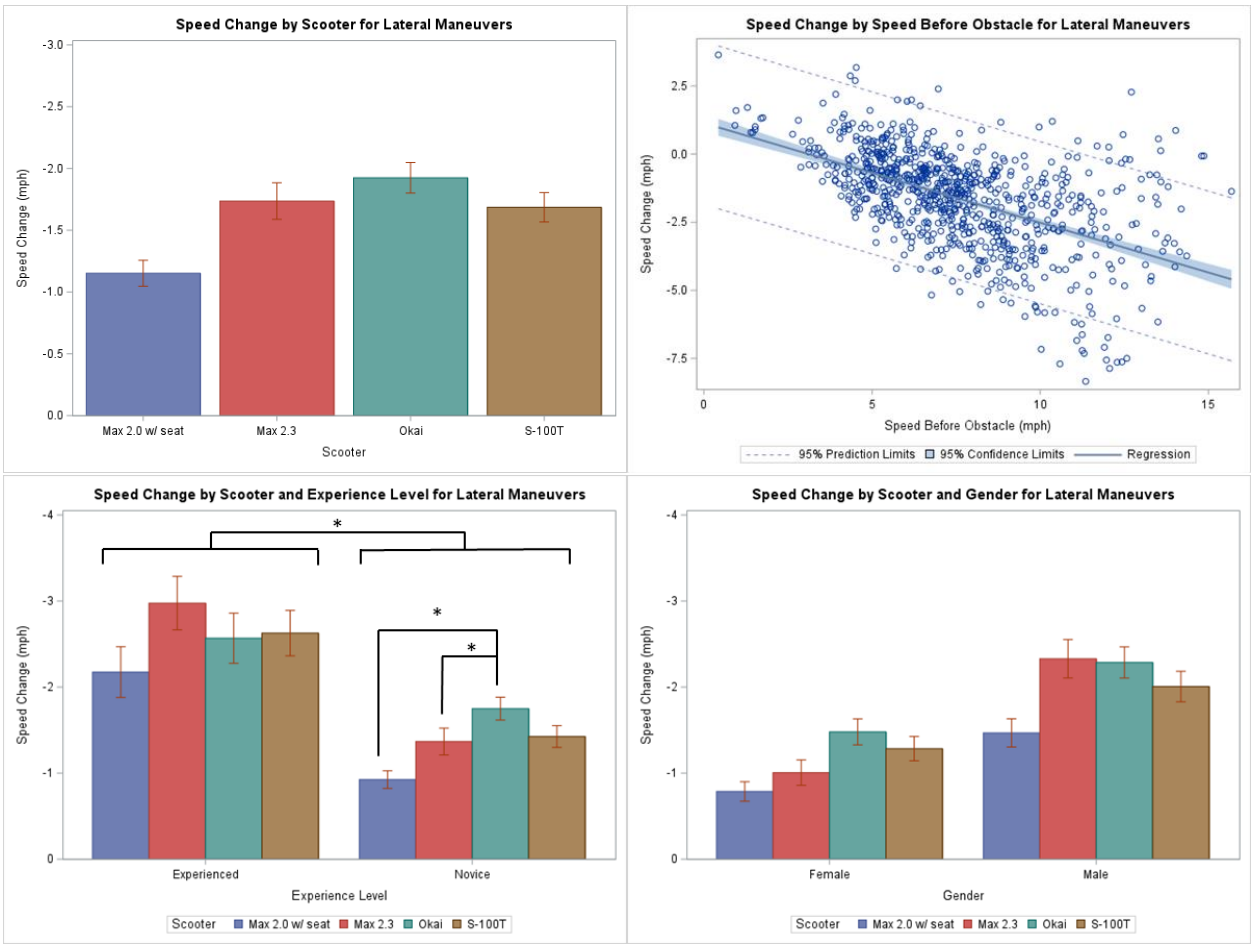

Figure 40. Speed change for lateral maneuvers. Top left: speed change by scooter. Top right: speed change by speed before the obstacle. Bottom left: speed change by scooter and experience level. Bottom right: speed change by scooter and gender. (*-p<0.05)

Significant trends were also observed with specific scooter features. As can be seen in **Figure 41**, increasing scooter weight, deck height, wheelbase, and tire diameter also resulted in greater speed decreases ($p<0.0001$).

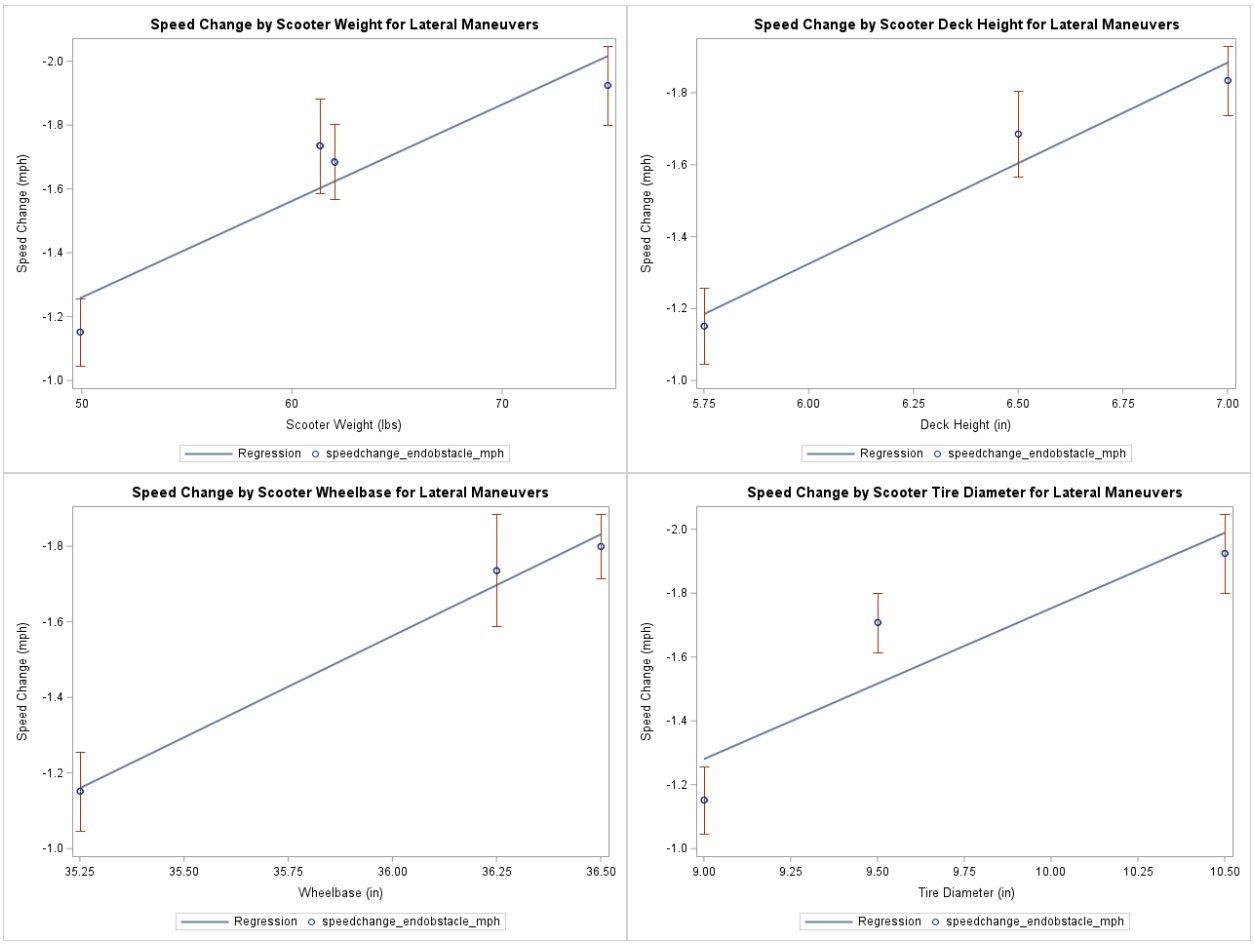

Figure 41. Effect of specific scooter features on speed change. Top left: speed change by scooter weight. Top right: speed change by deck height. Bottom left: speed change by wheelbase. Bottom left: speed change by tire diameter.

The maximum roll rate that the scooters experienced during the lateral maneuver obstacles was also analyzed, and these results can be seen in **Figure 42**. The Max 2.3 and Okai experienced higher maximum roll rates of 46.4 deg/s and 44.5 deg/s, respectively, when compared to the S-100T and Max 2.0 that experienced respective roll rates of 41.7 deg/s and 39.0 deg/s. Significant differences were observed between the Max 2.3 and S-100T ($p=0.0133$), Max 2.3 and Max 2.0 ($p=0.0002$), and the Okai and Max 2.0 ($p=0.0138$). There was an observable trend with the maximum roll rate and the mean speed, such that higher mean speeds resulted in higher roll rates ($p<0.0001$). Novice riders had smaller maximum roll rates than experienced riders (41.8 deg/s and 46.7 deg/s, respectively), and female riders had smaller maximum roll rates than male riders (35.1 deg/s and 49.2 deg/s, respectively).

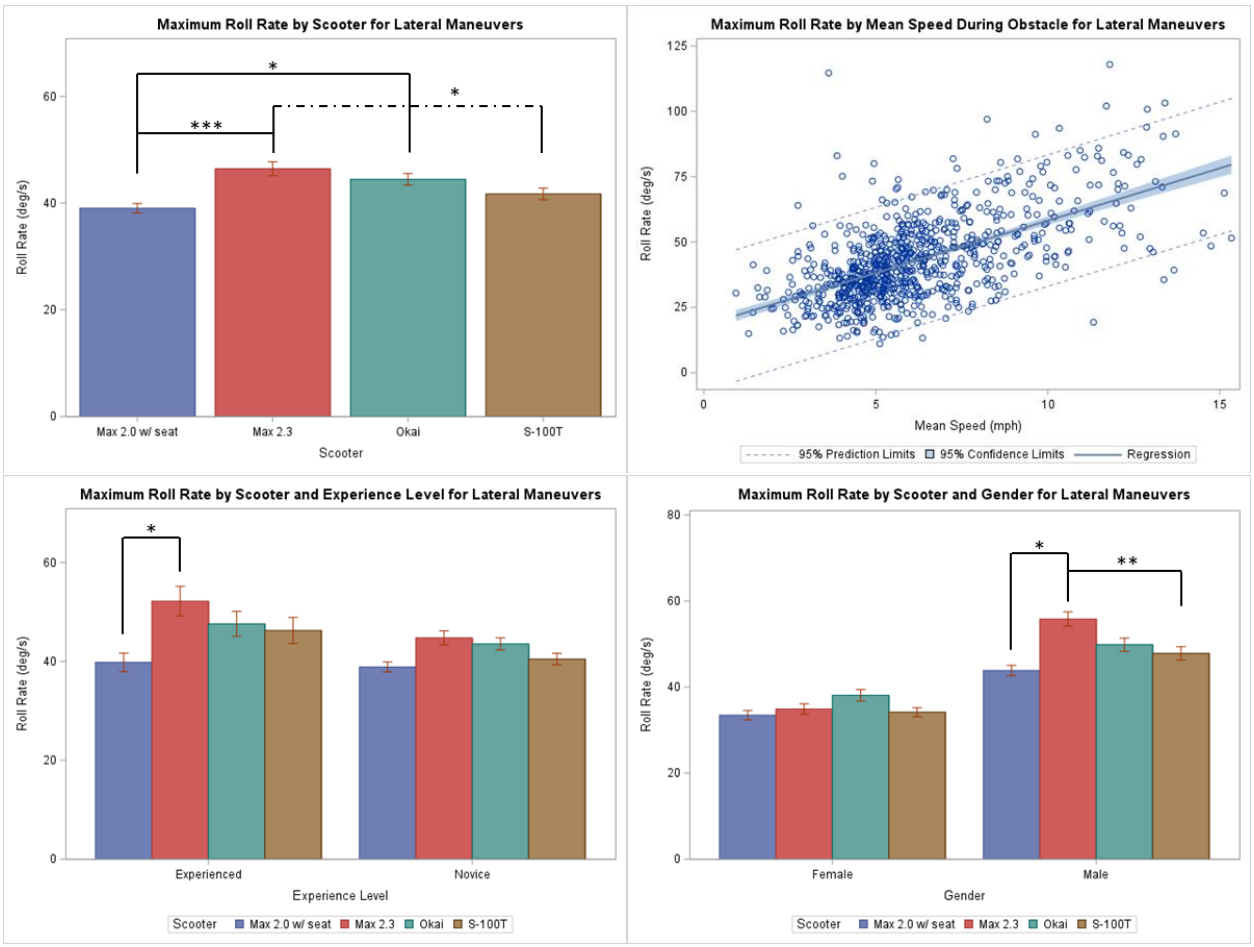

Figure 42. Maximum roll rate for lateral maneuvers. Top left: roll rate by scooter. Top right: roll rate by mean speed during obstacle. Bottom left: roll rate by scooter and experience level. Bottom right: roll rate by scooter and gender. (*-p<0.05, **-p<0.01, ***-p<0.001)

Rider weight had a significant effect in determining roll rate for the Max 2.3 (p=0.0005), Okai (p=0.0014), and S-100T (p<0.0001), and rider height was significant for all scooters (p<0.0001) (**Figure 43**).

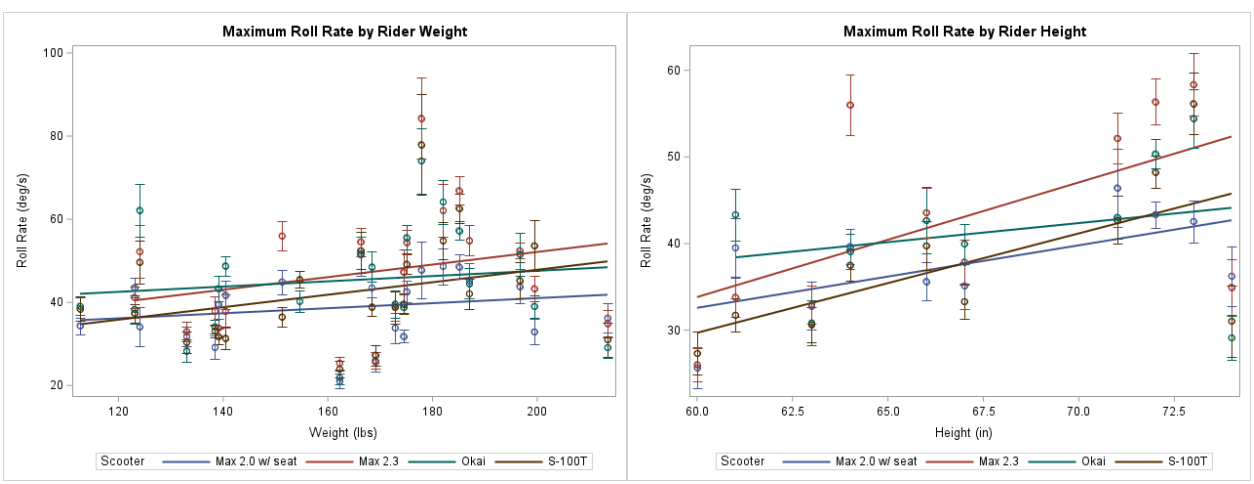

Figure 43. Maximum roll rate by rider weight (left) and by rider height (right).

Additionally, scooter steering axis and deck height were seen to have significant effects on the maximum roll rate during lateral maneuvers, with a steeper steering axis resulting in less roll (p<0.0001) and a taller deck height resulting in more roll (p<0.0001) (**Figure 44**).

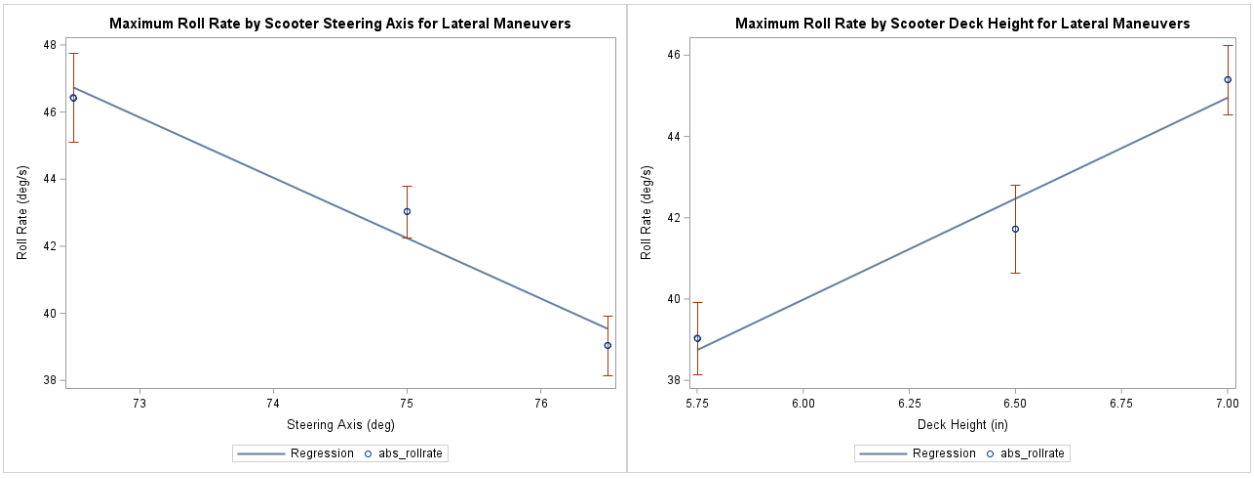

Figure 44. Effect of specific scooter features on roll rate. Left: roll rate by steering axis. Right: roll rate by deck height.

Maximum yaw rate was the final metric investigated during the lateral maneuver obstacles. These results can be seen in **Figure 45**. On average, the Max 2.0 had a maximum yaw rate of 144.2 deg/s, 153.6 deg/s for the Max 2.3, 160.0 deg/s for the Okai, and 139.4 deg/s for the S-100T. Significant differences were observed between the Max 2.3 and the S-100T (p<0.0001), the Max 2.3 and the Max 2.0 (p<0.0001), the Okai and the S-100T (p=0.0005, and the Okai and the Max 2.0 (p=0.0011). There was an observable trend with the maximum yaw rate and the mean speed, such that higher mean speeds resulted in lower yaw rates (p<0.0001). There were also significant differences in the maximum yaw rate between experienced and novice riders (167.6 deg/s and 143.9 deg/s, respectively; p=0.0042) as well as male and female riders (157.8 deg/s and 138.3 deg/s, respectively; p=0.0041).

Maximum yaw rate was also seen to be significantly affected by rider weight for the S-100T (p=0.0087) and rider height for the Max 2.0 (p=0.0011), the Max 2.3 (p=0.0398), and the S-100T (0.0013) (**Figure 46**).

Similar to roll rate, a trend was seen with yaw rate and steering axis in that scooters with a steeper steering axis experienced less yaw, which can be seen in **Figure 47**.

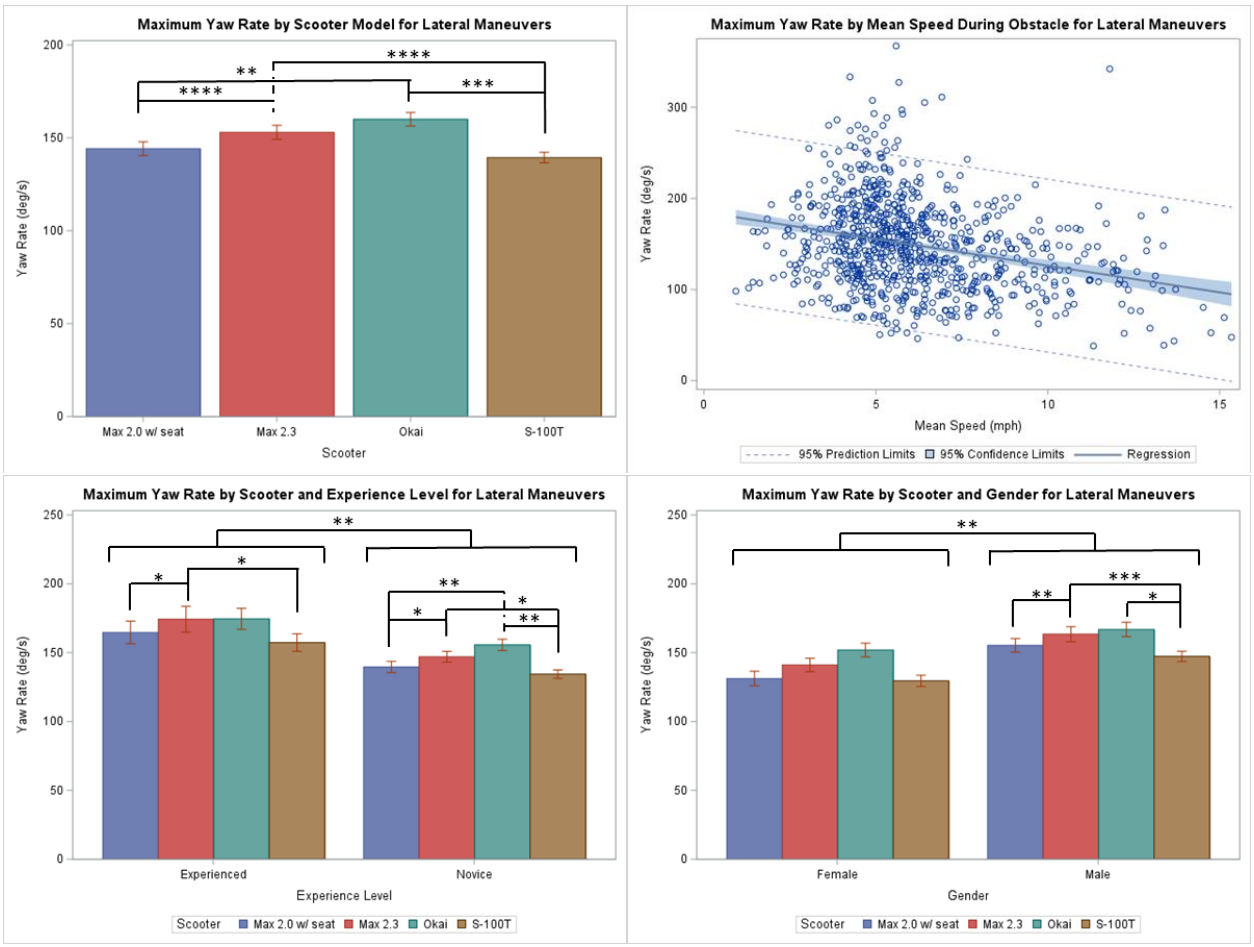

Figure 45. Maximum yaw rate for lateral maneuvers. Top left: yaw rate by scooter. Top right: yaw rate by mean speed during obstacle. Bottom left: yaw rate by scooter and experience level. Bottom right: yaw rate by scooter and gender. (*-p<0.05, **-p<0.01, ***-p<0.001, *-p<0.0001)***

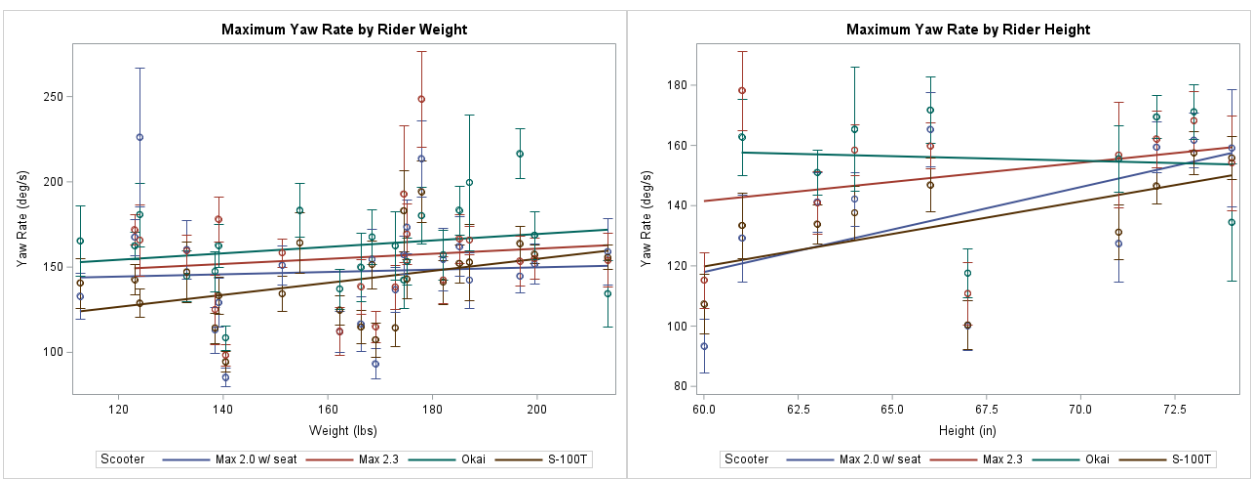

Figure 46. Maximum yaw rate by rider weight (left) and by rider height (right).

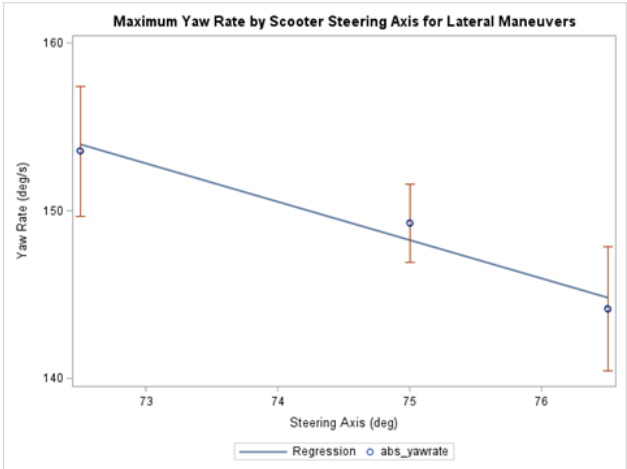

Figure 47. Effect of steering axis on yaw rate.

Riding into Raised Surface Results

The first metric analyzed for obstacles that involved the scooters riding into a raised surface was speed change, or how easily the rider can maintain speed as a function of the scooter while riding over a raised surface. These results can be seen in **Figure 48**. On average, the Max 2.0 decreased speed by 1.32 mph, the Max 2.3 decreased speed by 1.24 mph, the Okai decreased speed by 1.17 mph, and the S-100T decreased speed by 1.55 mph. There was also a significant difference in speed change between the Okai and S-100T (p=0.0075). There were no significant differences in the speed change between experience groups or gender, but it was seen that female riders were able to maintain their speed when riding with the Okai significantly better than when riding with the S-100T (p=0.0114).

Significant trends were also observed with specific scooter features. Scooters with suspension were able to maintain their speed better on average than scooters without suspension (-1.25 mph compared to -1.44 mph, respectively; p=0.0412). A trend was also seen such that scooters with greater ground clearance maintain their speed better (p=0.0251). These trends can be seen in **Figure 49**.

The next metric analyzed was maximum vertical acceleration, and these results can be seen in **Figure 50**. On average, the Max 2.3 experienced 1.11 g of acceleration, the Okai experienced 1.27 g, the S-100T experienced 1.30 g, and the Max 2.0 experienced 1.34 g. There were significant differences in vertical acceleration between Max 2.3 and Okai (p=0.0366), the Max 2.3 and S-100T (p=0.0034), and the Max 2.3 and Max 2.0 (p<0.0001). Speed before the obstacle did have a slight effect on the vertical acceleration experienced by the e-scooters, as higher vertical accelerations were observed at higher speeds (p<0.0001). There were no significant differences in the vertical acceleration between experience groups or gender, but it was seen that experienced riders had higher vertical accelerations on the Max 2.0 than the Max 2.3 (p=0.0147), and the novice riders had lower accelerations on the Max 2.3 compared to the Max 2.0 and S-100T (p=0.0070, p=0.0030, respectively). Male riders also had lower accelerations on the Max 2.3 than the Max 2.0 (p=0.0005).

Smaller vertical accelerations were also experienced by the scooters with suspension systems compared to those without (1.20 g and 1.32 g, respectively; p=0.0011). Rider weight also had a significant effect on vertical acceleration for the Okai (p=0.0092) and the Max 2.0 (p=0.0020). This can be seen in **Figure 51**.

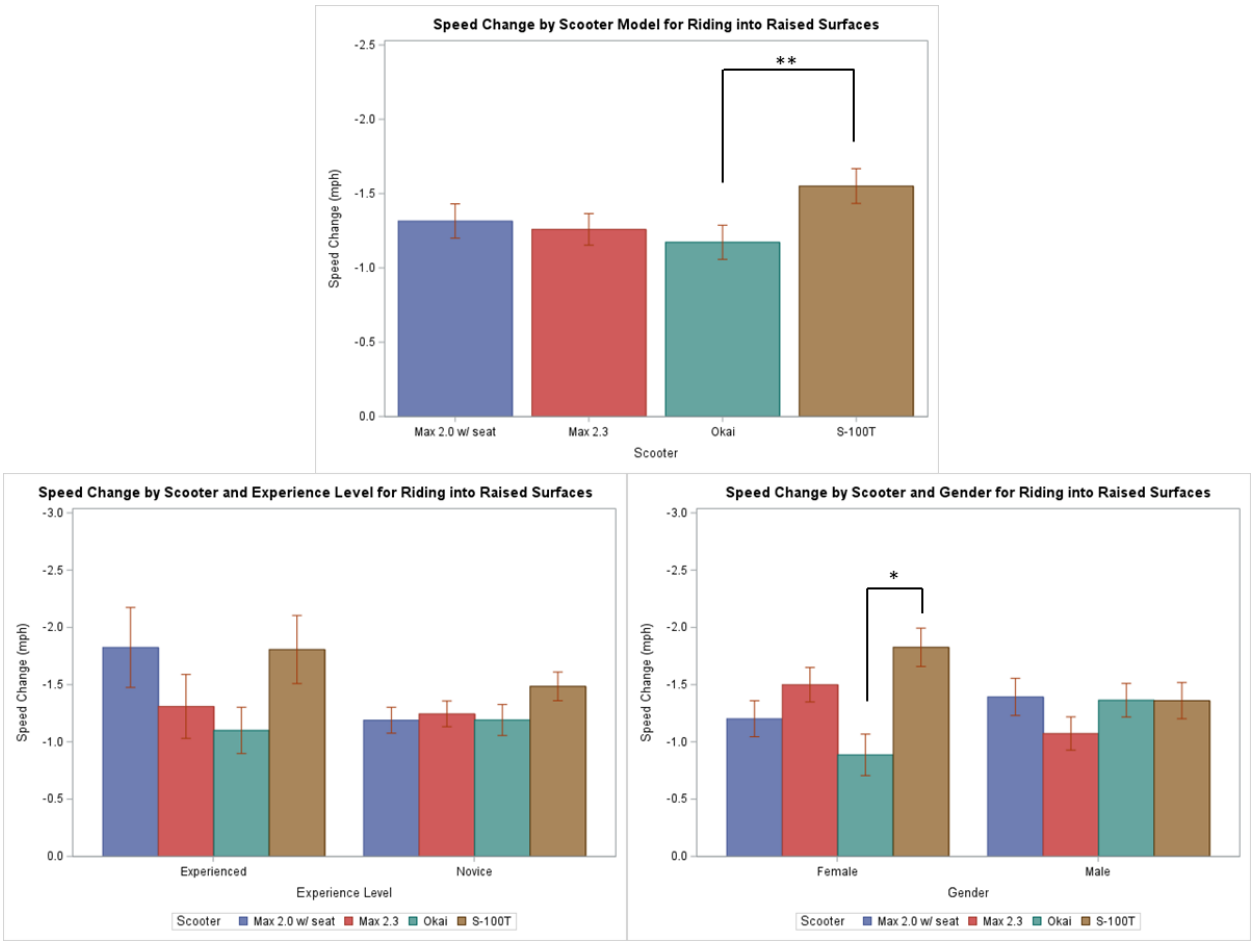

Figure 48. Speed change for riding into raised surfaces. Top: speed change by scooter. Bottom left: speed change by scooter and experience level. Bottom right: speed change by scooter and gender. (*-p<0.05, **-p<0.01)

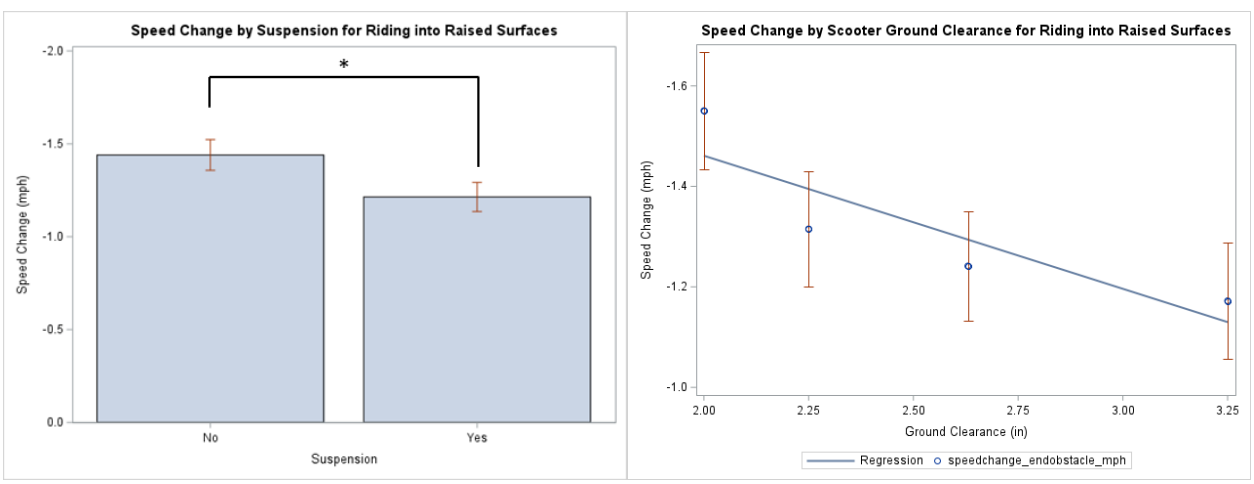

Figure 49. Effect of specific scooter features on speed change. Left: speed change by suspension. Right: speed change by ground clearance.

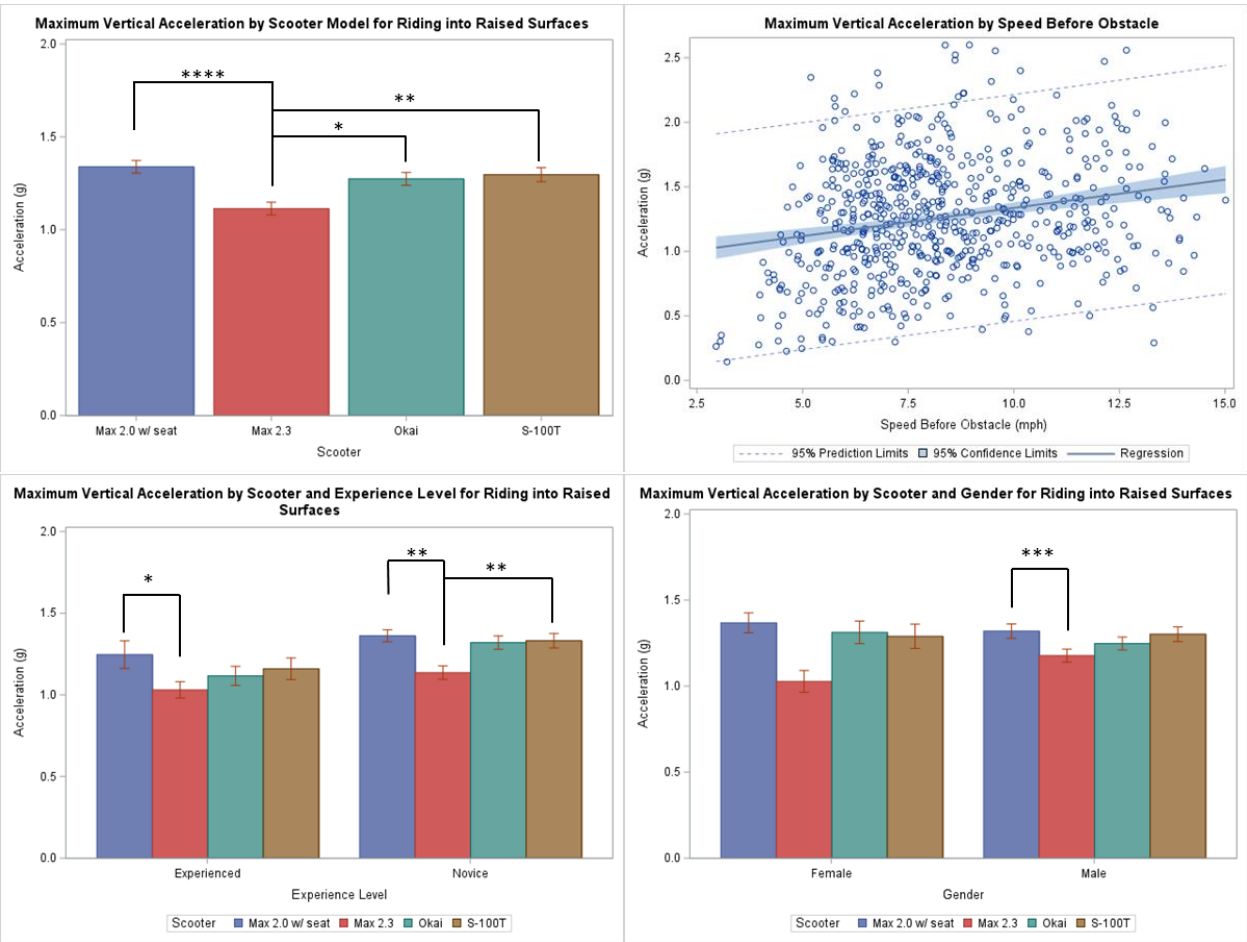

Figure 50. Maximum vertical acceleration for riding into raised surfaces. Top left: vertical acceleration by scooter. Top right: vertical acceleration by speed before obstacle. Bottom left: vertical acceleration by scooter and experience level. Bottom right: vertical acceleration by scooter and gender. (*-p<0.05, **-p<0.01, ***-p<0.001, *-p<0.0001)***

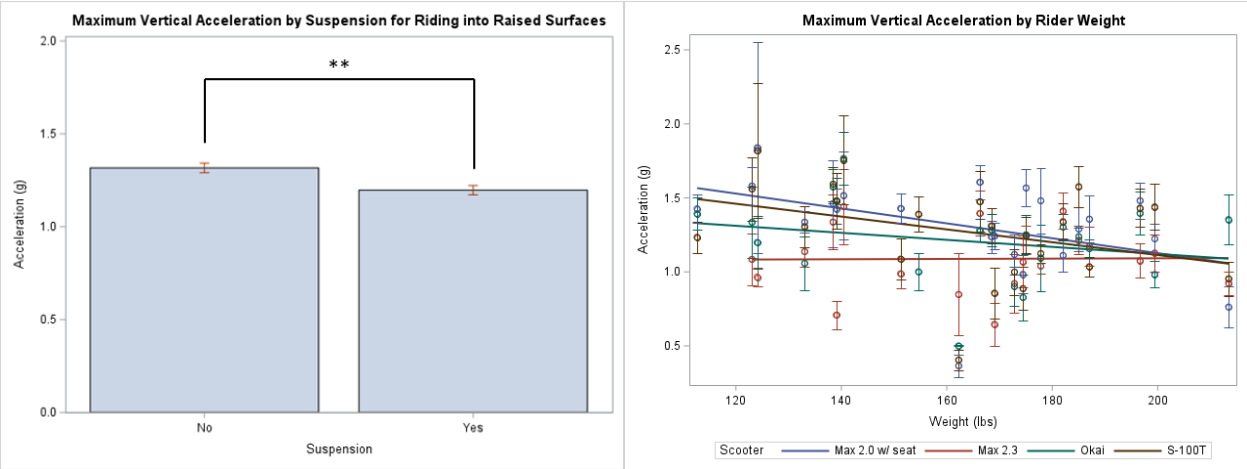

Figure 51. Maximum vertical acceleration by suspension (left) and rider weight (right). (**-p<0.01)

Riding off Raised Surface Results

For obstacles that involved riding off raised surfaces, maximum vertical acceleration and maximum pitch rate were analyzed. There were no differences in vertical acceleration rate between the scooters, and the results for pitch rate can be seen in **Figure 52**. The Max 2.0 had an average pitch rate of -45.4 deg/s, the Max 2.3 had an average of -30.9 deg/s, the Okai had an average of -26.2 deg/s, and the S-100T had an average of -41.1 deg/s. There were no significant differences between scooters, experience groups, or genders.

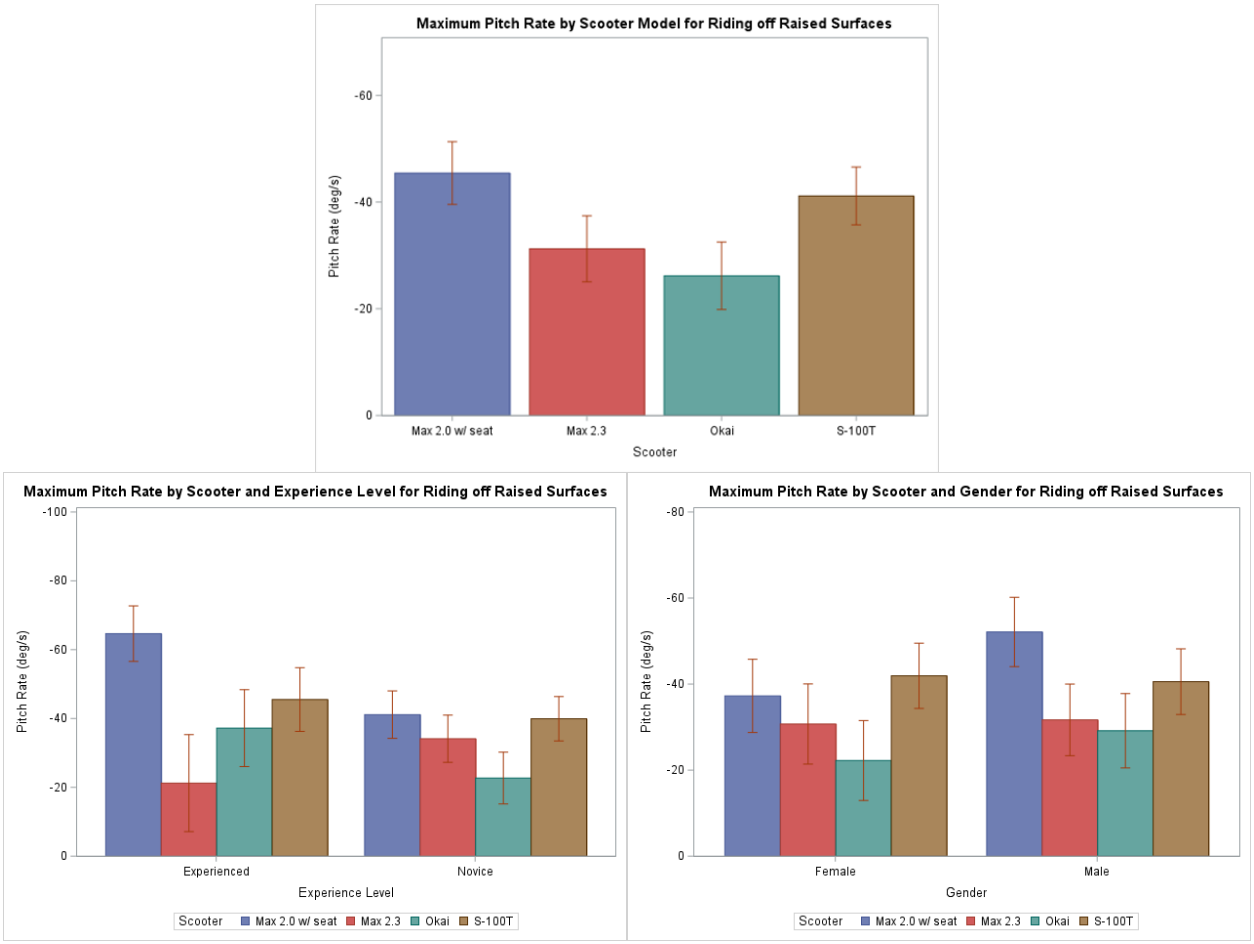

Figure 52. Maximum pitch rate for riding off raised surfaces. Top: pitch rate by scooter. Bottom left: pitch rate by scooter and experience level. Bottom right: pitch rate by scooter and gender.

Significant trends were observed with tire diameter, deck height, and suspension (**Figure 53**), such that increasing tire diameter and deck height resulted in smaller negative pitch rates (p=0.0251 and p=0.0129, respectively). Scooters with suspension systems also experienced smaller negative pitch rates than those without (-28.4 deg/s and -43.2 deg/s, respectively; p=0.0138).

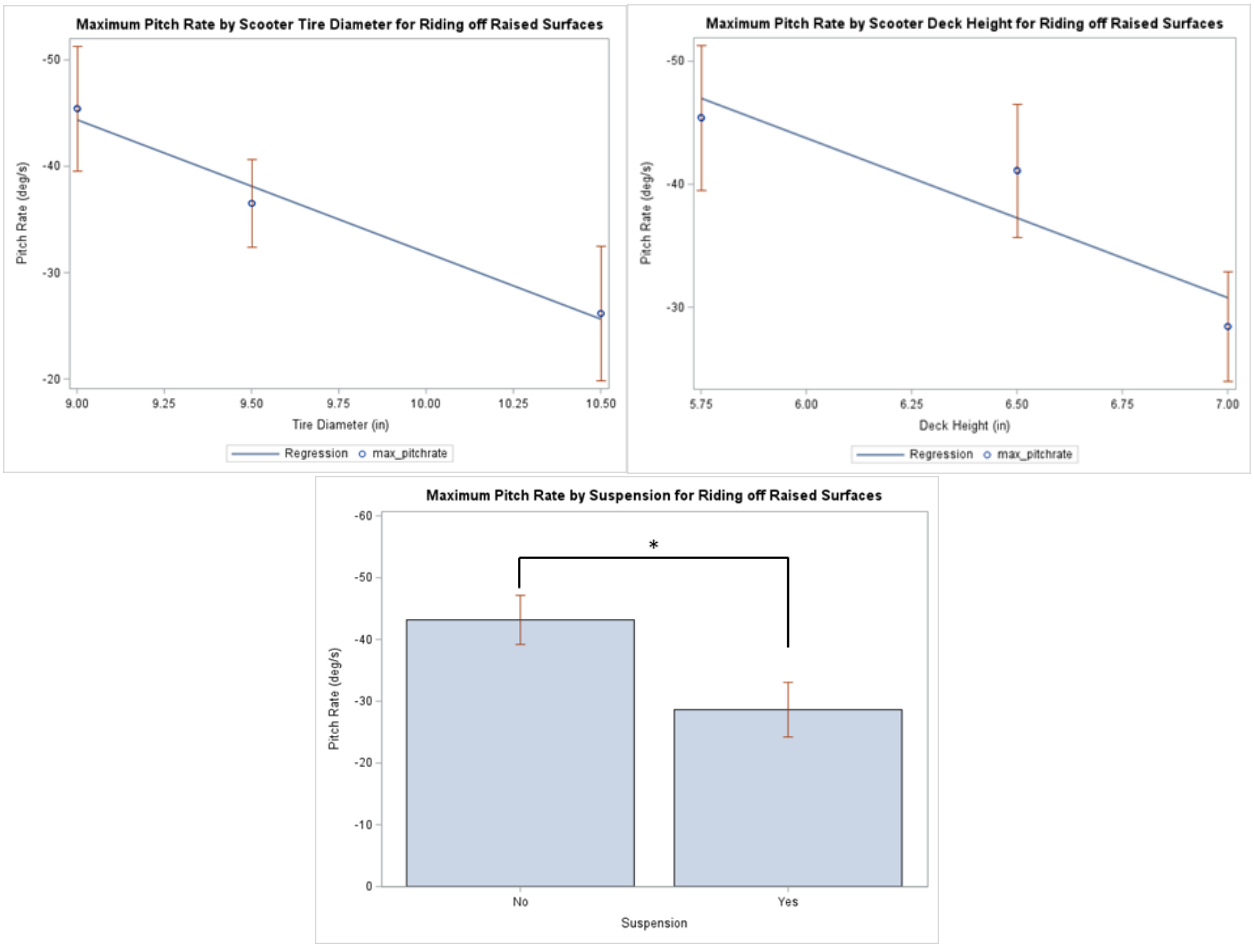

Figure 53. Maximum pitch rate by tire diameter (top left) deck height (top right) and suspension (bottom). (*-p<0.05)

Terrain Transition Results

For terrain transition obstacles, vertical acceleration data was analyzed, which can be seen in **Figure 54**. The Max 2.0 had an average maximum vertical acceleration of 1.37 g, the Max 2.3 had 0.92 g, the Okai had 0.93 g, and the S-100T had 1.11 g. There were significant differences between the Max 2.3 and Max 2.0 ($p<0.0001$), the Okai and Max 2.0 ($p<0.0001$), the S-100T and the Max 2.0 ($p<0.0001$), the Max 2.3 and S-100T ($p=0.0003$), and the Okai and S-100T ($p=0.0001$). While there were not significant differences in vertical acceleration between experience level groups or gender, there were significant differences within each of the groups that were similar to the main effects. Suspension was also seen to influence vertical acceleration experienced during the terrain transitions, as scooters with suspension saw 0.92 g while scooters without saw 1.24 g ($p<0.0001$).

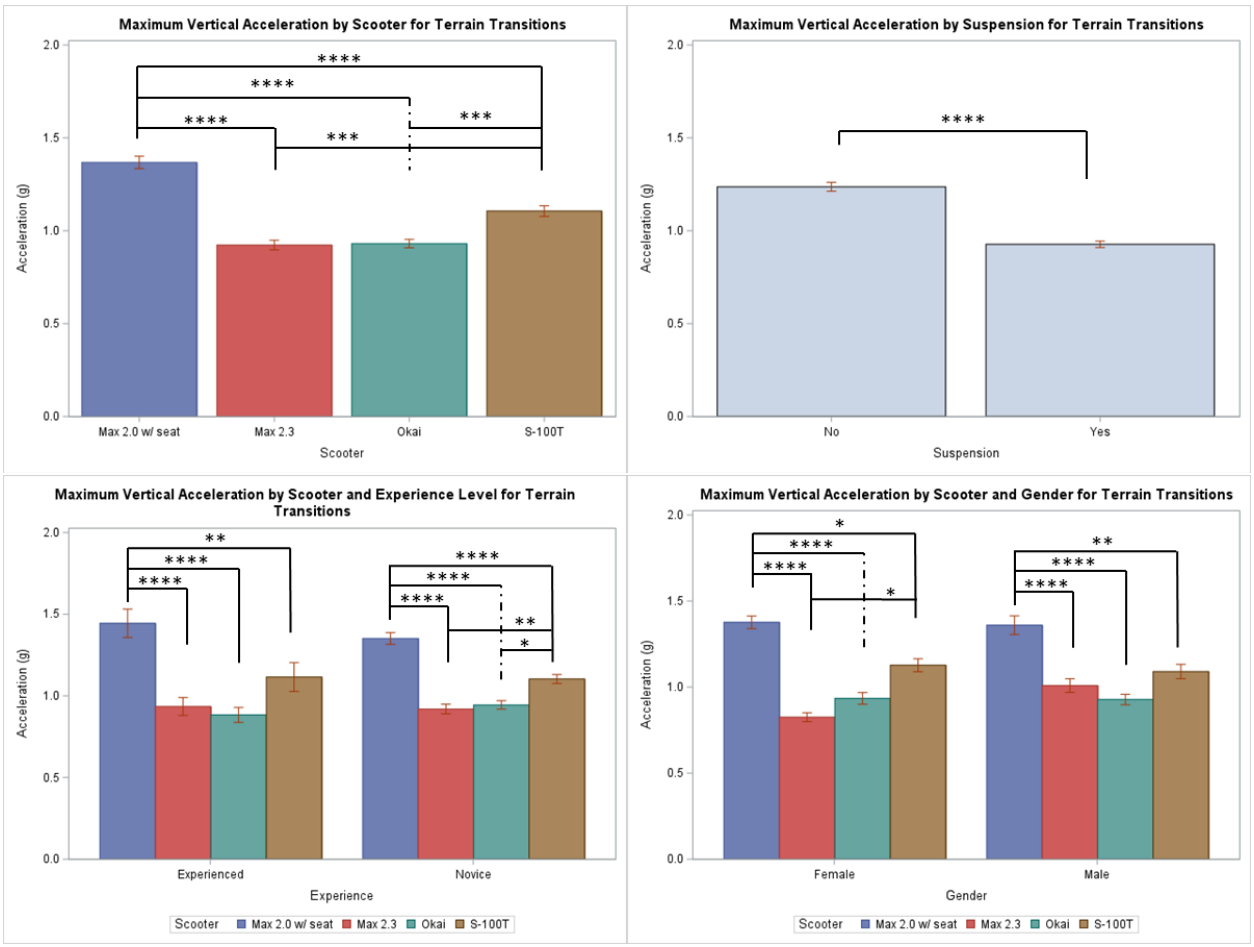

Figure 54. Maximum vertical acceleration for terrain transitions. Top left: vertical acceleration by scooter. Top right: vertical acceleration by suspension. Bottom left: vertical acceleration by scooter and experience level. Bottom right: vertical acceleration by scooter and gender. (*-p<0.05, **-p<0.01, ***-p<0.001, *-p<0.0001)***

Course Time Results

Time to complete the course was also measured and analyzed, the results of which can be seen in **Figure 55** and **Figure 56**. Course time was seen to vary by scooter, with the Max 2.3 completing the course the fastest in an average time of 140 s, followed by the S-100T in 141 s, then the Okai in 143 s, and the Max 2.0 in 150 s. The course times for the Max 2.3, S-100T, and Okai were significantly faster than the Max 2.0 ($p<0.0001$). On average the experienced riders completed the course in 128 s and the novice riders completed the course in 148 s. Male riders also completed the course significantly faster than female riders, with an average time of 126 s compared to 164 s ($p=0.0375$). There were also more significant differences between the scooters in the experienced rider group and the male rider group.

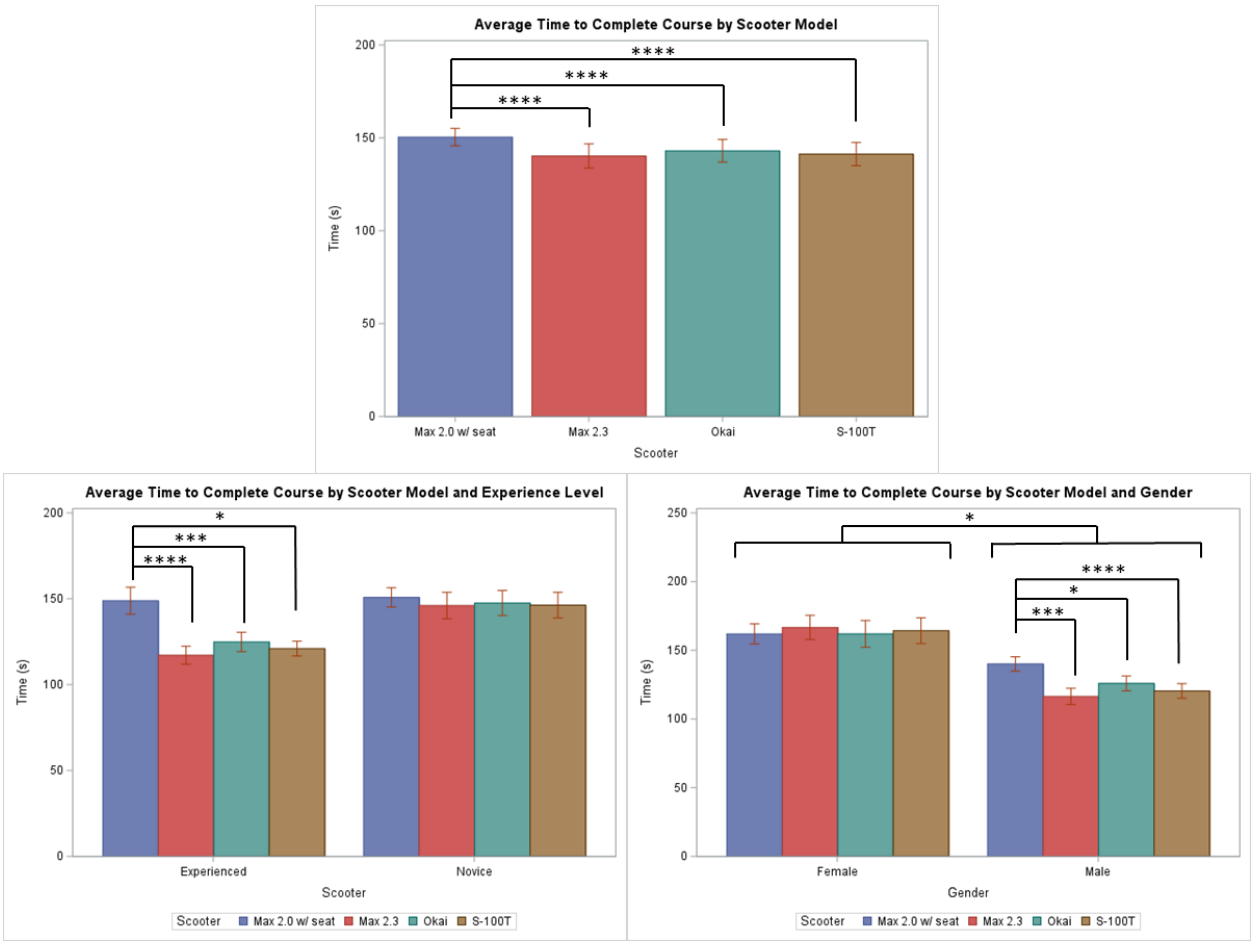

Figure 55. Average time to complete the course. Top: time by scooter. Bottom left: time by scooter and experience level. Bottom right: time by scooter and gender. (*-p<0.05, ***-p<0.001, *-p<0.0001)***

On average, course time was seen to decrease as the trials went on for both the experienced and novice rider groups. The experienced riders had an average first trial time of 139 s and an average fourth trial time of 121 s, and the novice riders had an average first trial time of 176 s and an average eighth trial time of 129 s. Across all trials, the experienced riders had an average time of 128 s, which the novice riders began to approach by their eighth trial. Rider weight was also seen to be a significant factor for the Max 2.3 and S-100T scooters (p=0.0033 and p=0.0280, respectively).

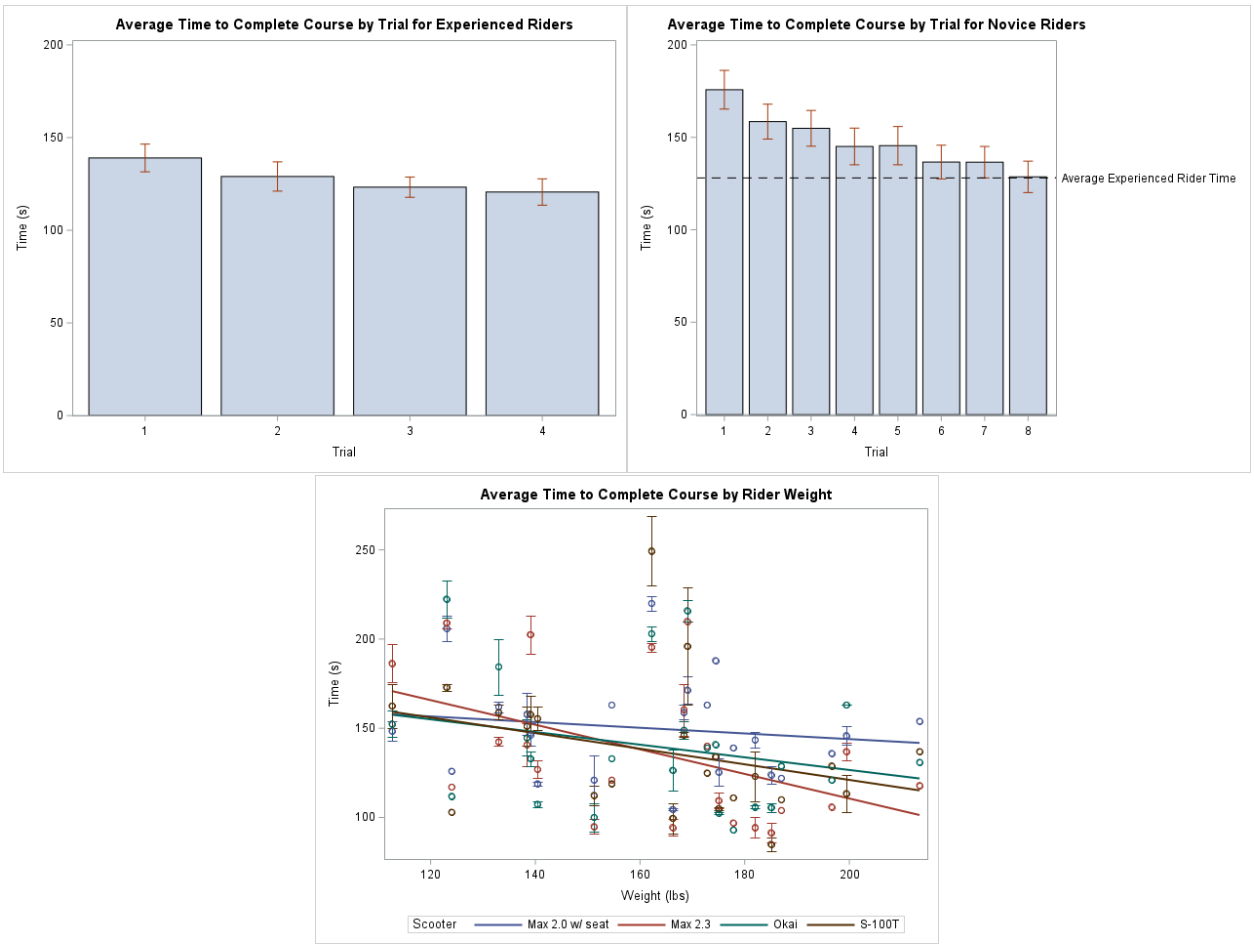

Figure 56. Average time to complete the course. Top left: time by trial for experienced riders. Top right: time by trial for novice riders. Bottom: time by scooter and rider weight.

HSM Survey Results

Average participant ratings on their perceptions of the performance capabilities for each of the scooters after each trial can be seen in **Figure 57**. Both the experienced and novice rider groups rated the turning of the Okai the lowest. Both experience groups also gave the Max 2.3 and the Okai the highest ratings for riding over raised edges and bumps and riding off curbs while the S-100T and Max 2.0 had the lowest ratings. Both groups also felt that the Max 2.0 did not perform as well at riding across sewer grates, tactile paving, potholes, and cracks. The experienced group felt that the Max 2.3 and S-100T did the best at riding across gravel, and that the Max 2.0 did not do well riding across grass or dirt. The novice group thought that the scooters performed similarly well for riding across all types of terrain.

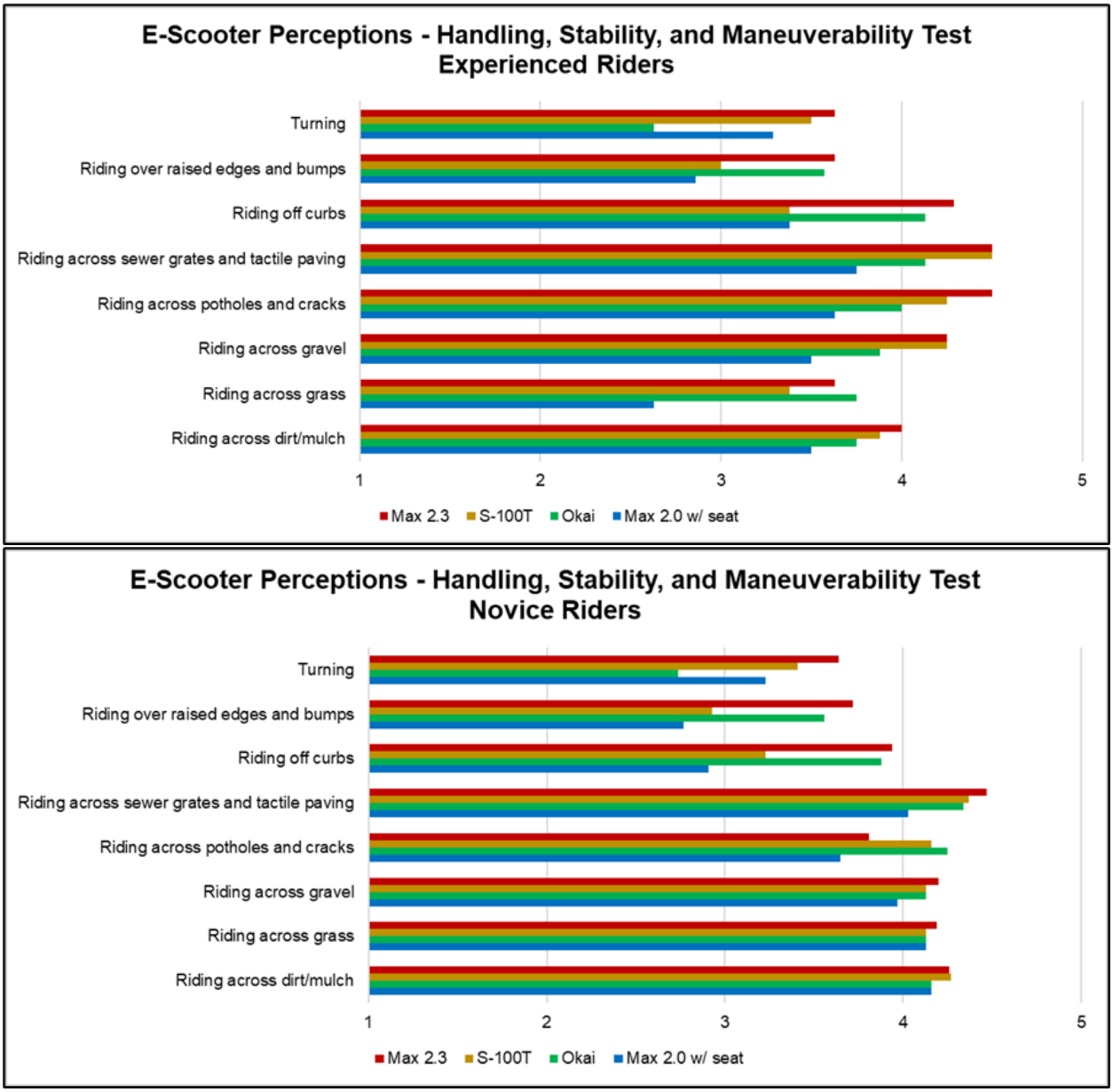

Figure 57. Post-trial survey results. Participants would rate scooters on a scale from 1-5 with 5 being the best rating and 1 being the worst rating. The figure shows the average ratings.

Additional survey results can be found in Appendix B-7.

HSM Fixed Camera Results

The initial posture and posture change and strategies by obstacle type and each of the experience level groups can be seen in **Figure 59** and . Regardless of obstacle type, the initial postures that riders were in to prepare themselves for the obstacle were very similar. There were no major differences in posture between scooters for any obstacle type aside from the Max 2.0 where riders would occasionally use the seat. Novice riders were seen to sit on the Max 2.0 scooter less than experienced riders. Experienced riders tended to prepare themselves more before each obstacle by bending their legs, where novice riders approached the obstacle with their legs straight and bent them while completing the obstacle.

Experienced riders also leaned more with their bodies in preparation of obstacles. Experienced riders used more strategies such as using their feet or lifting the handlebars with their arms than novice riders. Leaning was the most common strategy across all obstacle types, and use of feet was most common for the lateral maneuver obstacles. A combination of lifting the handlebars and using feet was the most common for riding into raised surfaces, and riding into raised surfaces was the most common obstacle not attempted. Novice riders did not attempt a larger percent of obstacles than experienced riders.

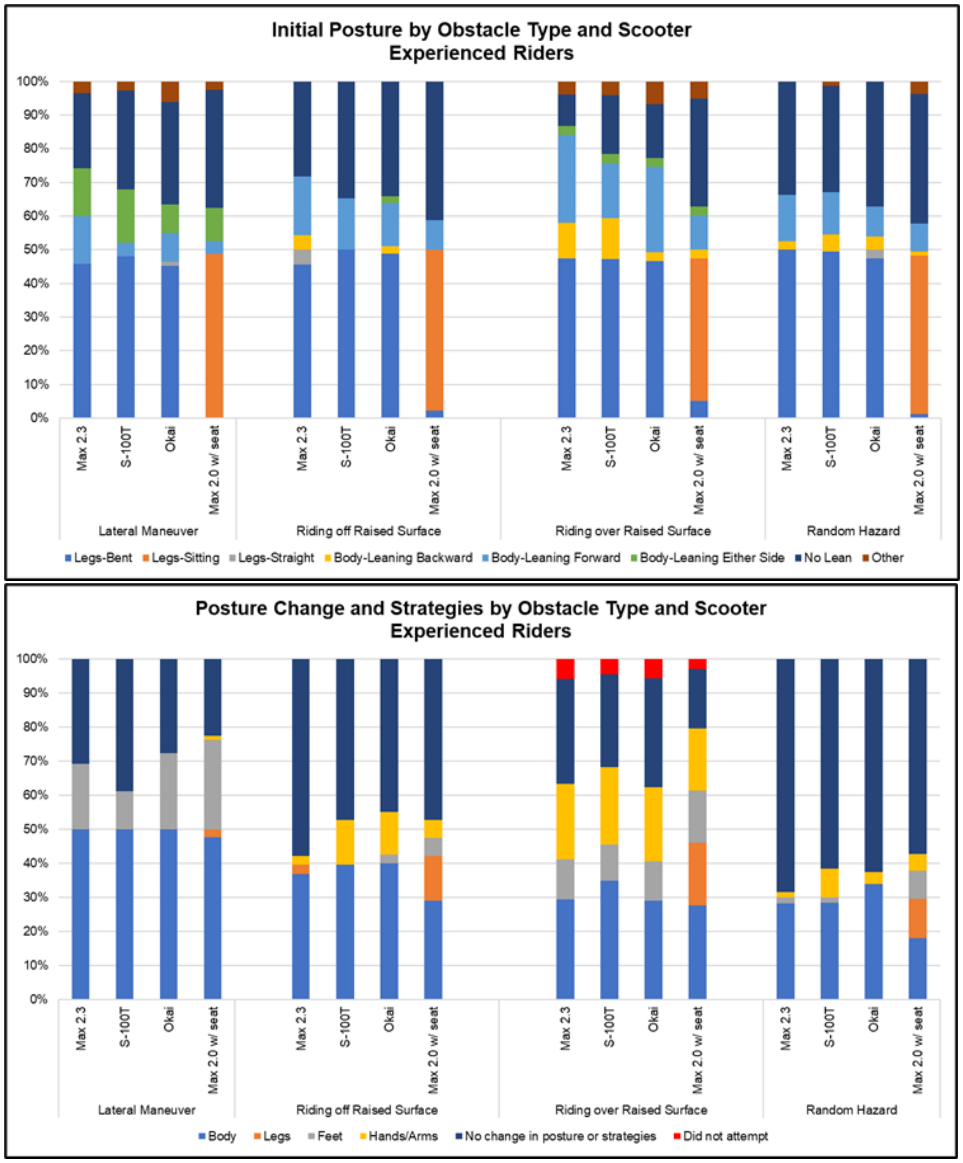

Figure 58. ***Posture and strategies by obstacle type for experienced riders. Top: initial posture. Bottom: posture change and strategies.***

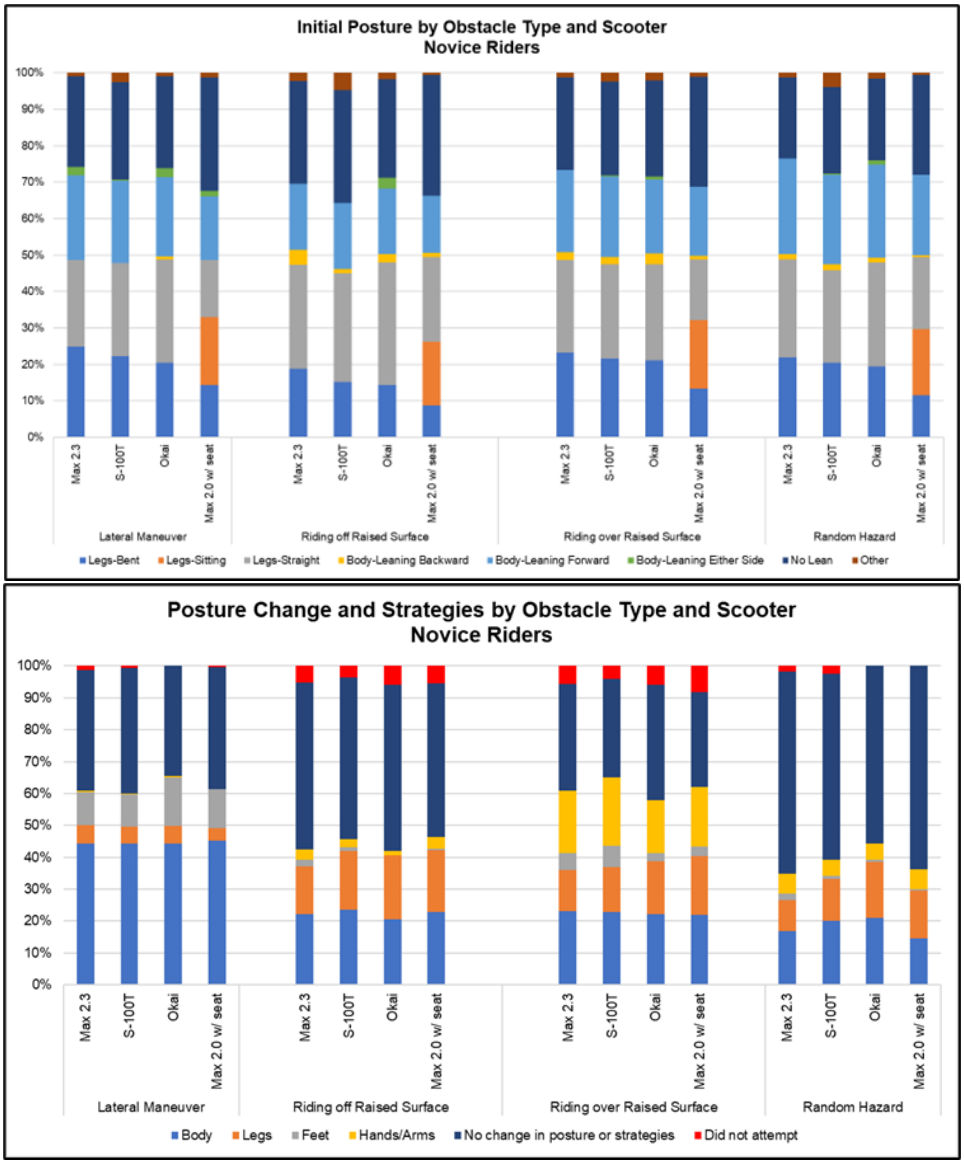

Figure 59. Posture and strategies by obstacle type for novice riders. Top: initial posture. Bottom: posture change and strategies.

For the sideways U-turn obstacle, the Go-Pro videos were also used to understand how often riders could complete it with and without using their feet for assistance. These results can be seen in **Figure 60**. For all scooters, it was seen that riders were less likely to complete the obstacle without using their feet. The Max 2.3 and S-100T had higher percentages of completing the turn without assistance compared to the Okai and Max 2.0.

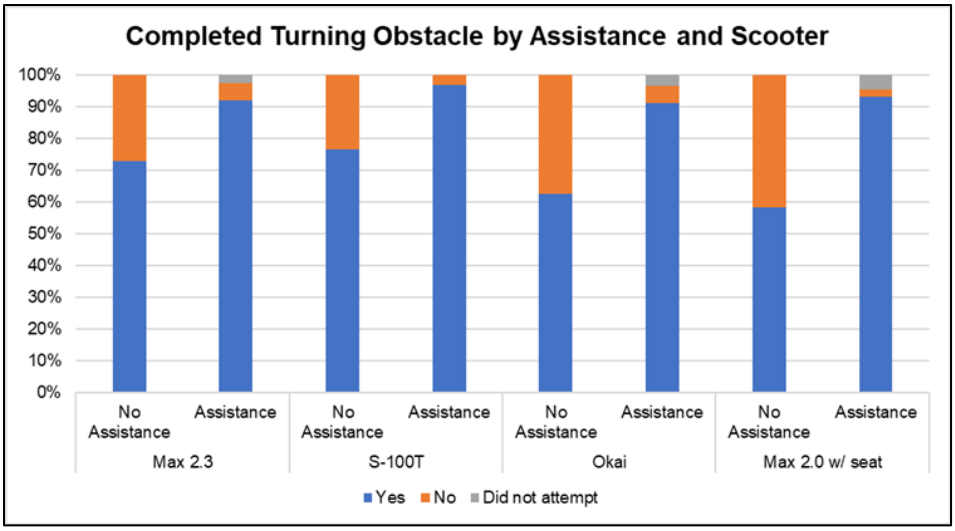

Figure 60. Percentage of attempts where riders were able to complete the sideways U-turn with or without assistance by scooter model.

When only looking at the attempts without assistance and combining the totals for the Max 2.3 and S-100T and the totals for the Okai and the Max 2.0 (**Table 11**), the probability of completing the obstacle using the Max 2.3 or S-100T was 1.97 times greater than completing the obstacle using the Okai or Max 2.0 (95% CI: [0.98, 3.97]). The Max 2.3 and S-100T did have the two shortest handlebar and scooter heights and the longest usable deck lengths when compared to the Okai and Max 2.0. When investigating these factors, a trend was observed with deck length, such that increasing the length of the deck that the rider can stand on increases the probability of being able to complete the obstacle without assistance, which can be seen in **Figure 61**.

Table 11. Attempts without assistance for the sideways U-turn, used to calculate odds ratio.

Without Assistance	Completed	Did not complete	*Total*
Max 2.3 + S-100T	68	23	91
Okai + Max 2.0	36	24	60
Total	36	47	151

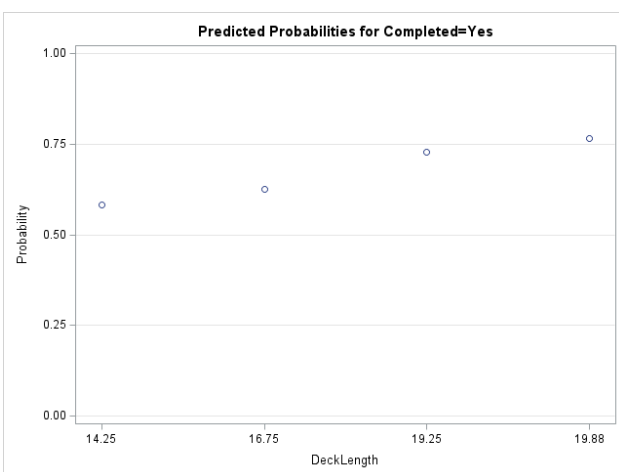

Figure 61. Probability of completing the sideways U-turn obstacle without assistance by deck length.

To understand if experience level or gender also impacted how often riders could complete the turn with and without using their feet for assistance, the results were arranged as shown in **Figure 62**. Novice riders and female riders had lower completion rates of the sideways U-turn when they did not use their feet for assistance when compared to experienced riders and male riders, respectively, although percentages of not completing the obstacle were closer for the Okai for both comparison groups.

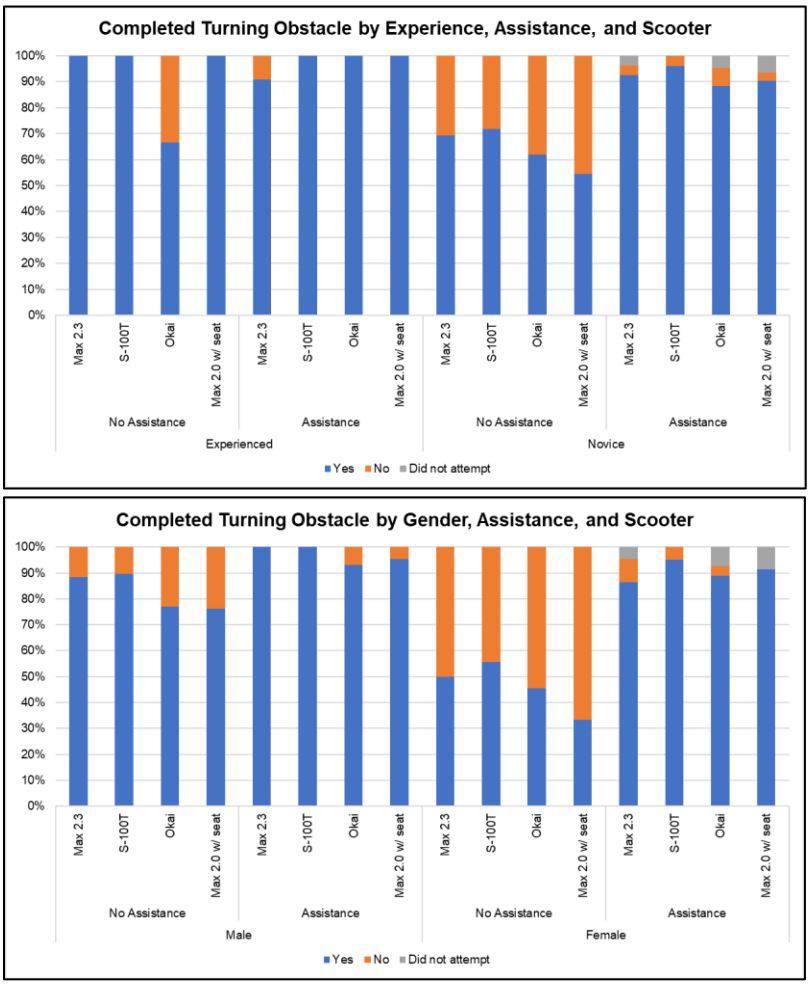

Figure 62. Percentage of attempts where riders were able to complete the sideways U-turn with or without assistance by scooter and experience level (top) or gender (bottom).

For the obstacles that involved riding into a raised surface, the Go-Pro videos were also used to understand how often scooters would get stuck while attempting to ride over them with and without using their feet or arms to lift the front of the scooter for assistance. These results can be seen in **Figure 63**. The S-100T and Max 2.0 were seen to get stuck on the obstacles more frequently than the Max 2.3 and Okai. The scooters were less likely to get stuck on the obstacles if riders used some form of assistance, and scooters were stuck more often on the 3” obstacles.

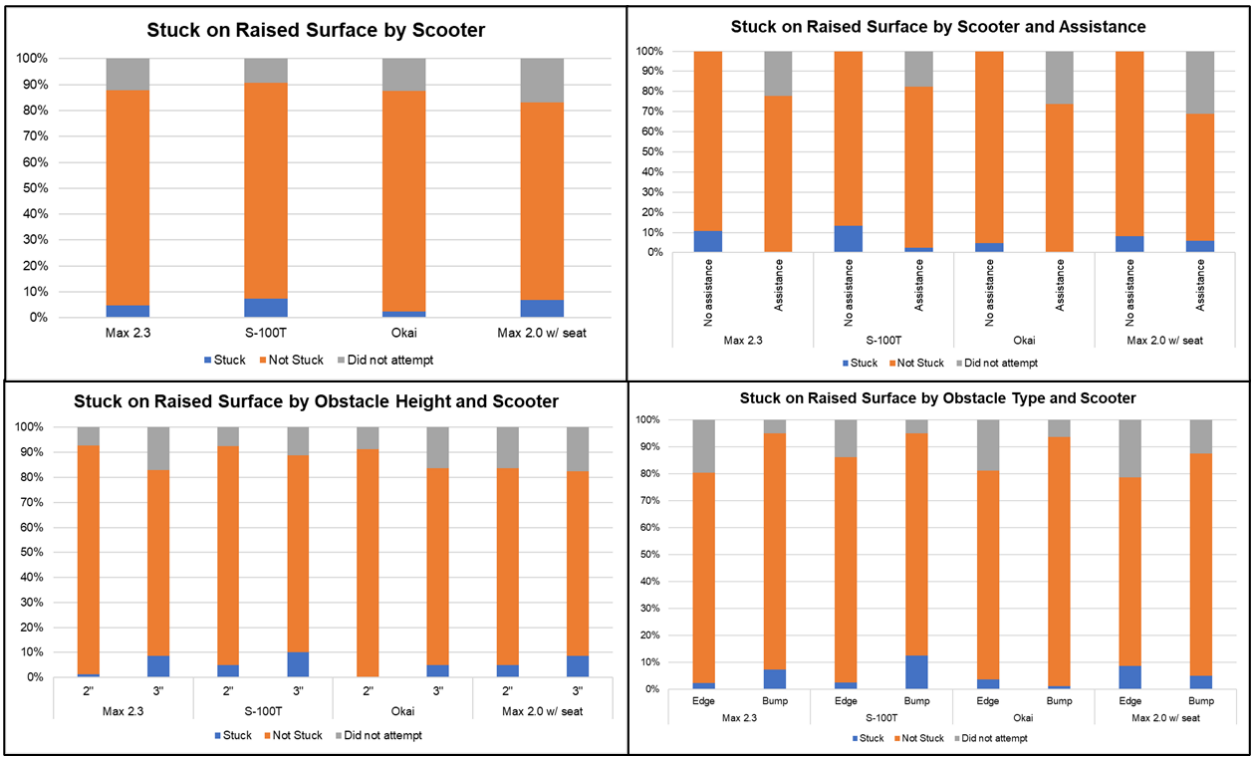

Figure 63. Percentage of attempts where scooters were stuck on raised surfaces. Top left: stuck by scooter. Top right: stuck by scooter and with or without rider assistance. Bottom left: stuck by scooter and obstacle height. Bottom right: stuck by scooter and obstacle type.

When combining the totals for the S-100T and Max 2.0 and the Max 2.3 and Okai (**Table 12**), the probability of the scooter getting stuck on the obstacles using the S-100T or Max 2.0 was 2.04 times greater than getting stuck on the obstacles using the Max 2.3 or Okai (95% CI: [1, 4.19]). The Max 2.3 and Okai scooters did have suspension systems and the greatest ground clearances.

Table 12. Attempts where the scooters were stuck on the raised surface obstacles, used to calculate odds ratio.

Overall	Stuck	Not Stuck	*Total*
S-100T + Max 2.0	23	255	278
Max 2.3 + Okai	12	272	284
Total	35	527	562

When investigating how design features and vehicle speed affected the probability of the scooter getting stuck on a raised surface obstacle, several trends were observed which can be seen in **Figure 64**. The probability of the scooter not getting stuck on a raised surface was higher if a scooter had a suspension system. Probabilities of not getting stuck on a raised surface also increased as the scooter's ground clearance and tire diameter increased. The probability of getting stuck began to increase as obstacle height increased for all design features. Additionally, scooters with suspension systems and greater ground clearances had lower probabilities of getting stuck on the raised surface obstacles at lower speeds.

To understand if experience level or gender also impacted how often scooters were stuck on raised surface obstacles with and without using assistance, the results were arranged as shown in **Figure 65**. There were very few differences in the percentage of attempts where the scooters were stuck on a raised

surface between the experienced and novice rider groups except for the Max 2.0, where a larger percentage of experienced riders were stuck on the obstacle without using assistance, but a larger percentage of novice riders did not attempt the obstacle. The percentages where the scooters were stuck were also similar between male and female riders, but female riders did not attempt the obstacles much more frequently than male riders.

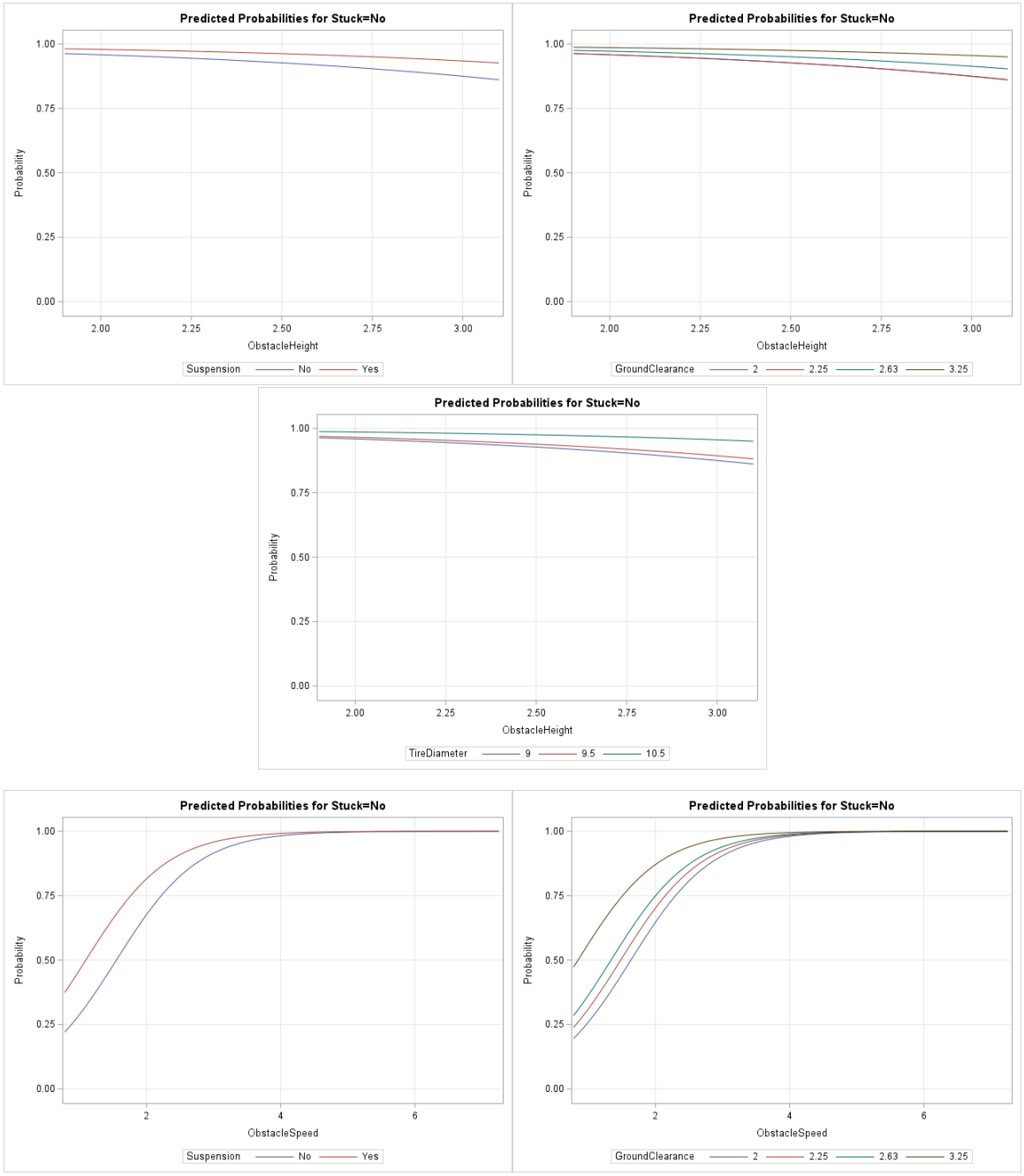

Figure 64. Probability of a scooter getting stuck on the obstacle. Top left: by obstacle height and suspension. Top right: by obstacle height and ground clearance. Center: by obstacle height and tire diameter. Bottom left: by speed at start of the obstacle and suspension. Bottom right: by speed at the start of the obstacle and ground clearance.

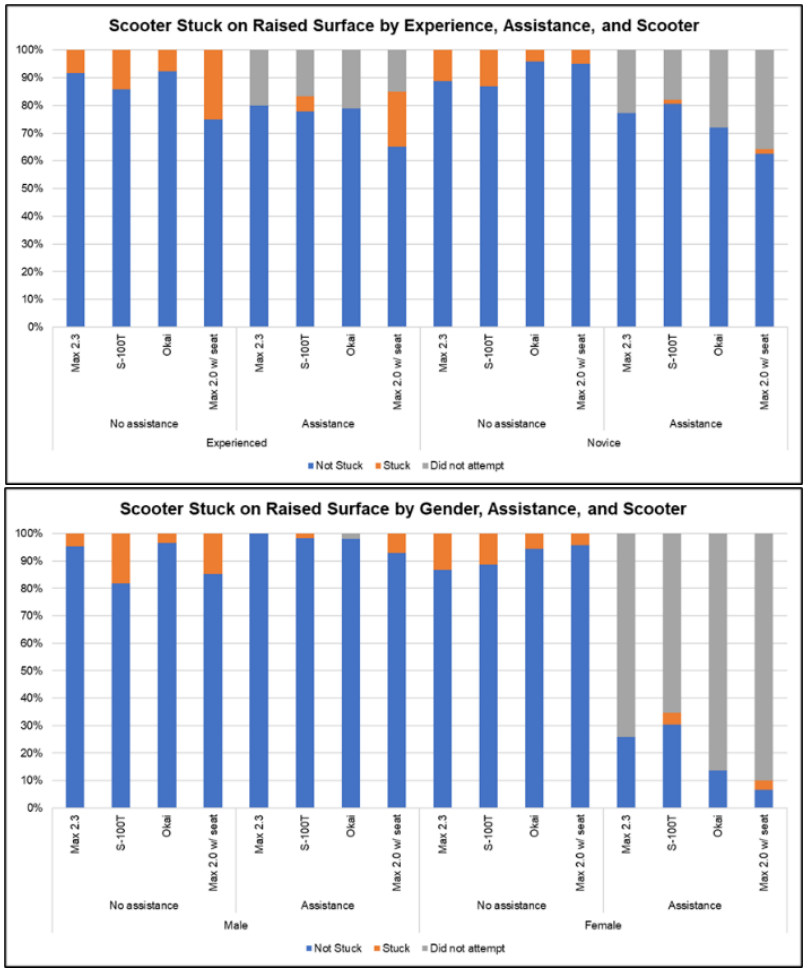

Figure 65. Percentage of attempts where scooters were stuck on raised surfaces with or without assistance by scooter and experience level (top) or gender (bottom).

HSM Safety Critical Event Results

The safety critical events are summarized in **Figure 66** and **Figure 67**. Most SCEs were caused by obstacles where the scooters were riding into raised surfaces, and most SCEs involved either a forward impact with a bailout and no fallover. SCEs decreased as the trials went on. Novice riders had lower rates of SCEs than experienced riders but did have higher rates of bailouts without forward impacts.

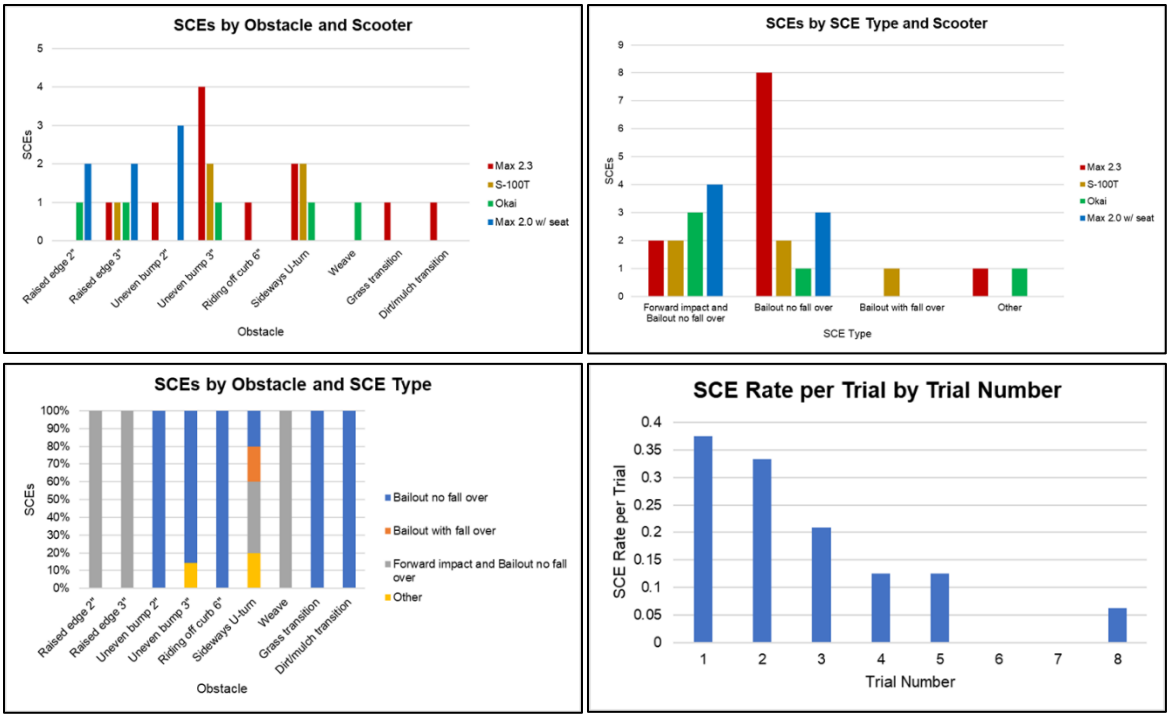

Figure 66. Safety critical event frequency during the HSM test. Top left: SCEs by obstacle and scooter. Top right: SCEs by SCE type and scooter. Bottom left: SCEs by obstacle and SCE type. Bottom right: SCE rate per trial.

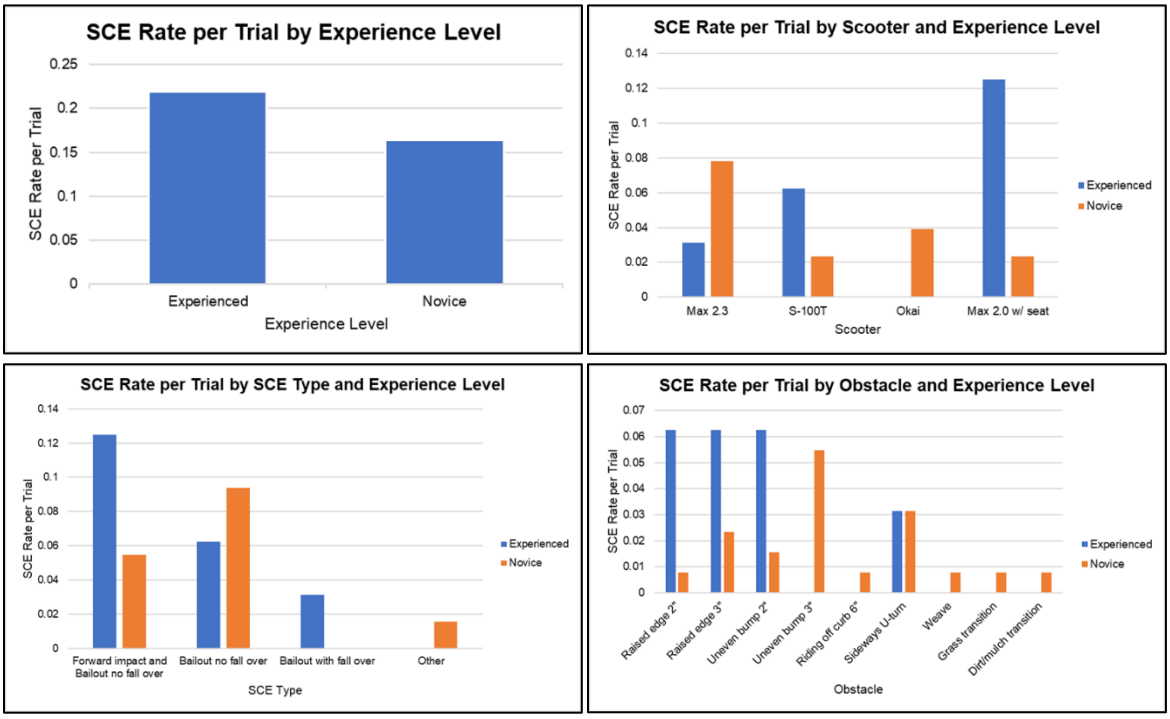

Figure 67. Safety critical event frequency during the HSM test. Top left: SCE rate per trial by experience level. Top right: SCE rate per trial by scooter and experience level. Bottom left: SCE rate per trial by SCE type and experience level. Bottom right: SCE rate per trial by obstacle and experience level.

Geofence Test Results

Geofence MicroDAS Results

The time and distance for the scooters to begin slowing down after entering the slow-zone can be seen in **Figure 68**. The shaded areas on the figure represent the 95% confidence interval, and the lines represent the 95% prediction interval. Speed when entering the slow-zone was a factor that was added to the analysis. It took the Max 2.3 scooter 12.2 s or 63.4 ft to begin to slow down on the incline slope and 14.7 s or 67.8 ft on the decline slope. The Max 2.0 took 6.0 s or 26.1 ft to slow down on the incline slope and 6.0 s or 29.7 ft on the decline slope. There were significant differences in the time and distance that it took for the Max 2.3 and Max 2.0 to respond (p<0.0001). The Max 2.0 responded more consistently to the slow-zone regardless of approach speed, shown by the smaller confidence intervals and limits. Slope and speed when entering the slow-zone were not significant factors in determining response time or distance.

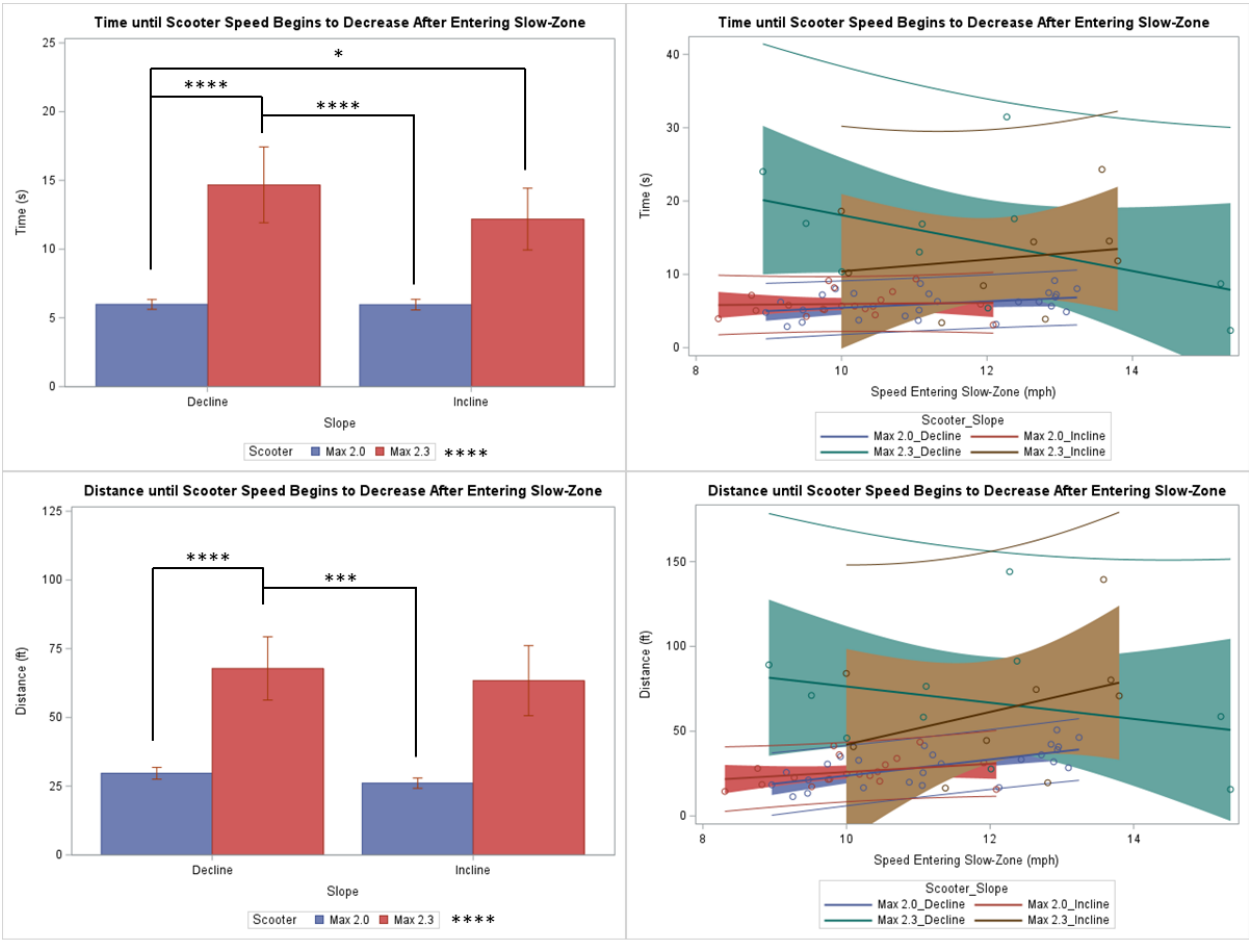

Figure 68. Time and distance until scooter speed begins to decrease after entering slow-zone. Top left: time by scooter and slope. Top right: time by scooter and speed entering slow-zone. Bottom left: distance by scooter and slope. Bottom right: distance by scooter and speed entering slow-zone. (*-p<0.05, ***-p<0.001, *-p<0.0001)***

The time and distance for the scooters to reach the reduced speed of 7 mph after entering the slow-zone can be seen in **Figure 69**. Speed when entering the slow-zone was a factor that was added to the analysis. It took the Max 2.3 scooter 16.8 s or 82.6 ft to reach the reduced speed on the incline slope and 28.7 s or 135.6 ft on the decline slope. The Max 2.0 took 9.7 s or 37.1 ft to reach the reduced speed on the incline

slope and 13.8 s or 60.0 ft on the decline slope. There were significant differences in the time and distance that it took for the Max 2.3 and Max 2.0 to respond (p<0.0001). Additionally, slope was significant factor in the time and distance that it took for the scooters to reach the reduced speed (p<0.0001). The Max 2.0 responded more consistently to the slow-zone regardless of approach speed, shown by the smaller confidence intervals and limits. Speed when entering the slow-zone was a significant factor for determining response distance but not response time.

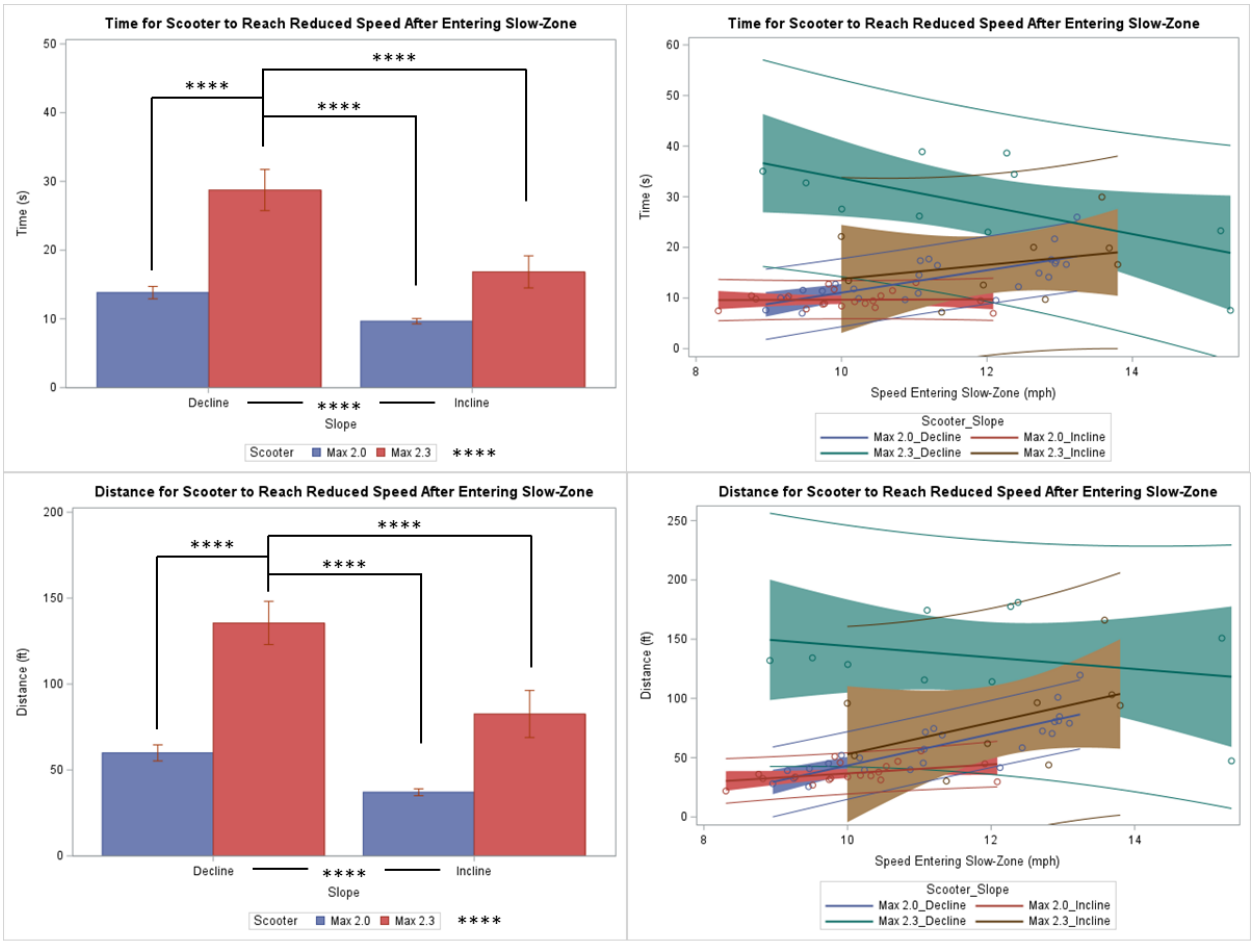

Figure 69. Time and distance for scooter to reach reduced speed after entering slow-zone. Top left: time by scooter and slope. Top right: time by scooter and speed entering slow-zone. Bottom left: distance by scooter and slope. Bottom right: distance by scooter and speed entering slow-zone. (*-p<0.0001)***

The time and distance for the scooters to reach the reduced speed of 7 mph after the speed began to decrease can be seen in **Figure 70**. Speed at the time right before the scooter's speed began to decrease was a factor that was added to the analysis. It took the Max 2.3 scooter 4.6 s or 19.2 ft to reach the reduced speed on the incline slope and 14.0 s or 67.8 ft on the decline slope. The Max 2.0 took 3.7 s or 11.0 ft to reach the reduced speed on the incline slope and 7.8 s or 30.3 ft on the decline slope. There were significant differences in the time and distance that it took for the Max 2.3 and Max 2.0 to respond (p<0.0001). Additionally, slope was significant factor in the time and distance that it took for the scooters to reach the reduced speed (p<0.0001). Both scooters responded more consistently to the slow-zone regardless of approach speed on the incline slope, shown by the smaller confidence intervals and limits. Speed before the speed decrease was a significant factor for determining response time but not distance.

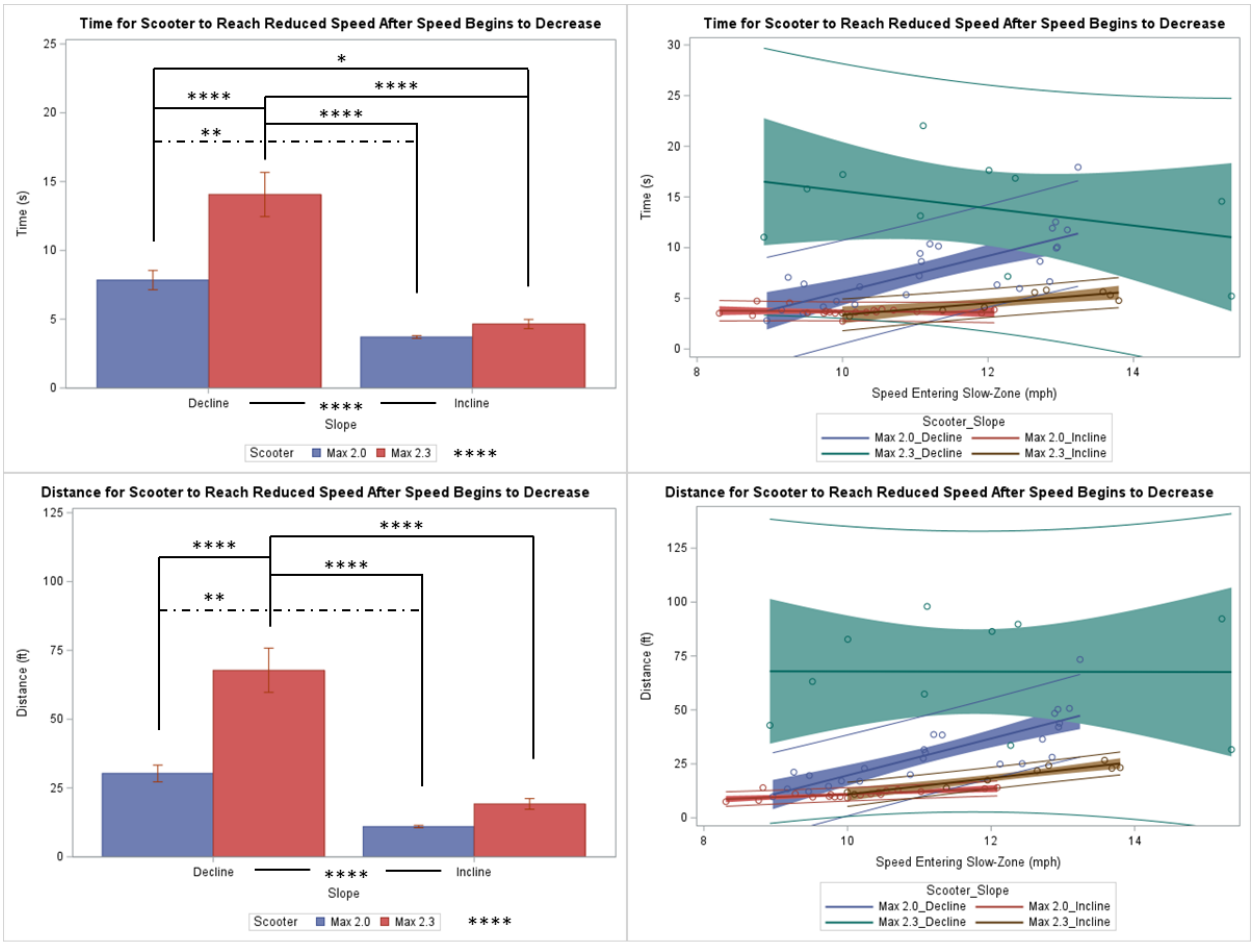

Figure 70. Time and distance for scooter to reach reduced speed after speed began to decrease. Top left: time by scooter and slope. Top right: time by scooter and speed before speed decrease. Bottom left: distance by scooter and slope. Bottom right: distance by scooter and speed before speed decrease. (*-p<0.05, **-p<0.01, *-p<0.0001)***

The difference between the actual reduced speed and expected reduced speed of 7 mph can be seen in **Figure 71**. Speed at the time right before the scooter's speed began to decrease was a factor that was added to the analysis. The Max 2.3 was on average 0.3 mph under the reduced speed on the incline slope and 3.1 mph over on the decline slope. Conversely, the Max 2.0 was 3.0 mph under the reduced speed on the incline slope and 0.5 mph under on the decline slope. There were significant differences in the speed difference for the Max 2.3 and Max 2.0 ($p<0.0001$). Additionally, slope and speed before the speed decrease were significant factors in the speed difference ($p<0.0001$).

The time and distance for the scooters to begin to increase speed after exiting the slow-zone can be seen in **Figure 72**. The reduced speed after exiting the slow-zone was a factor that was added to the analysis. It took the Max 2.3 scooter 8.9 s or 30.4 ft to begin to increase speed on the incline slope and 9.7 s or 46.3 ft on the decline slope. The Max 2.0 took 8.2 s or 19.7 ft to begin to increase speed on the incline slope and 7.4 s or 22.3 ft on the decline slope. The Max 2.0 responded more consistently regardless of approach speed, shown by the smaller confidence intervals and limits.

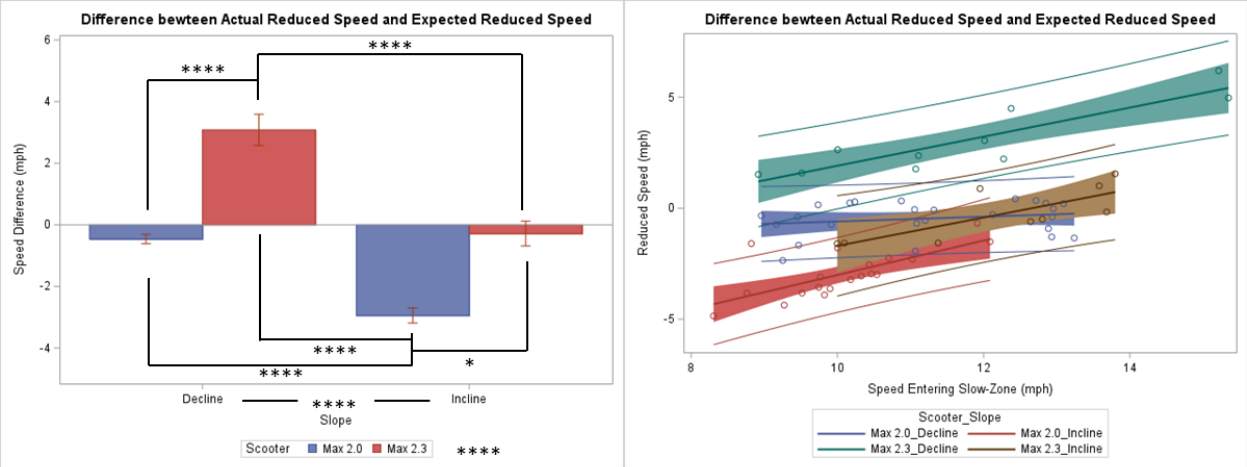

Figure 71. Difference between actual reduced speed and expected reduced speed. Left: speed difference by scooter and slope. Right: speed difference by scooter and speed before speed decrease. (*-p<0.05, **-p<0.01, *-p<0.0001)***

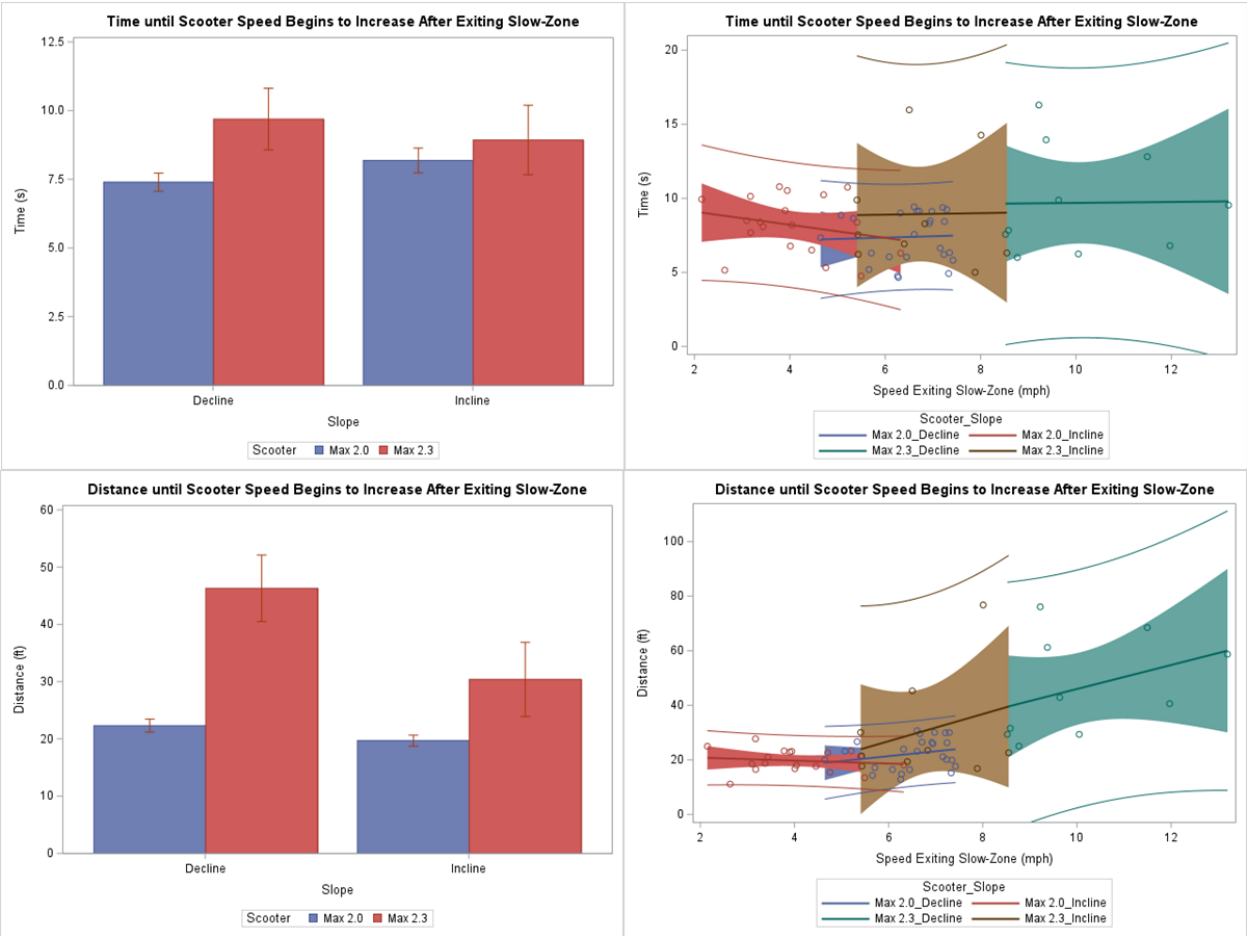

Figure 72. Time and distance for scooter to begin to increase speed after exiting the slow-zone. Top left: time by scooter and slope. Top right: time by scooter and speed exiting slow-zone. Bottom left: distance by scooter and slope. Bottom right: distance by scooter and speed exiting slow-zone.

The time and distance for the scooters to begin slowing down after entering the no-ride zone can be seen in **Figure 73**. Speed when entering the no-ride zone was a factor that was added to the analysis. It took the Max 2.3 scooter 6.7 s or 33.8 ft to begin to slow down on the incline slope and 6.1 s or 30.5 ft on the decline slope. The Max 2.0 took 6.0 s or 30.0 ft to slow down on the incline slope and 5.5 s or 28.5 ft on the decline slope. The Max 2.0 responded more consistently regardless of approach speed, shown by the smaller confidence intervals and limits. Scooter, slope, and speed were not significant factors.

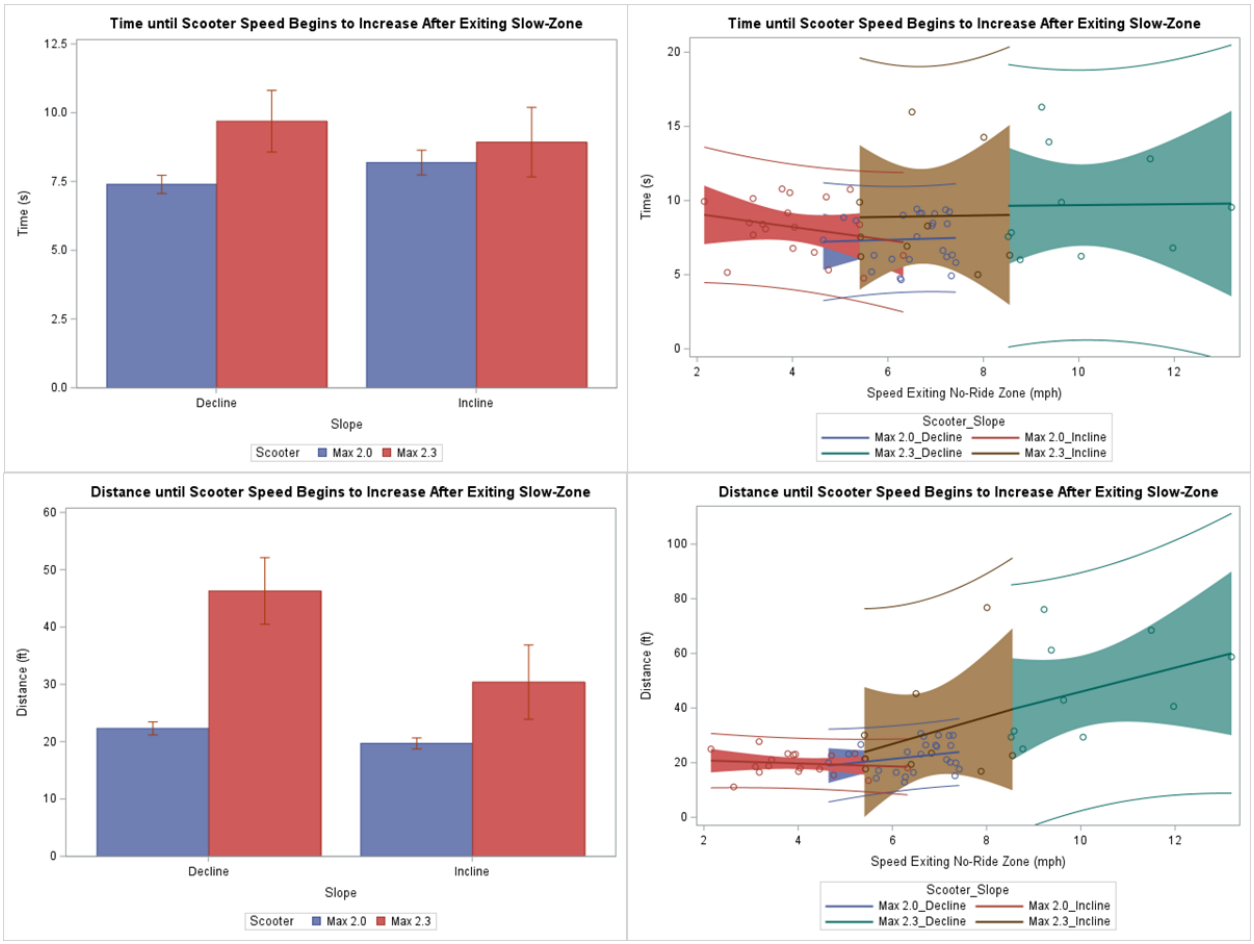

Figure 73. Time and distance until scooter speed begins to decrease after entering no-ride zone. Top left: time by scooter and slope. Top right: time by scooter and speed entering no-ride zone. Bottom left: distance by scooter and slope. Bottom right: distance by scooter and speed entering no-ride zone.

Geofence Survey Results

Participant responses for their perceptions on how the e-scooters responded to the geofences can be seen in **Table 13**. Participants felt that in the slow-zone, the deceleration rate of the scooters was slightly too slow and that the acceleration rate back to full speed was slightly too fast. Similarly, they felt that the scooters stopped at a rate that was too slow in the no-ride zone. The audible notification was slightly too loud for some participants, the tone was neither pleasant nor unpleasant, and it was relatively easy to understand.

Table 13. Participant perceptions on e-scooter response to the geofences.

E-Scooter Handling at Slow Zone	Avg	Std	Min	Max	Definition
Deceleration rate	2.88	0.33	2	3	1 – too slow, 5 – too fast
Acceleration rate back to full speed	3.50	0.71	3	5	1 – too slow, 5 – too fast
E-Scooter Handling at No-Ride Zone	**Avg**	**Std**	**Min**	**Max**	**Definition**
Stopping rate	2.50	0.50	2	3	1 – too slow, 5 – too fast
Audible Notification	**Avg**	**Std**	**Min**	**Max**	**Definition**
Volume level	3.25	0.66	3	5	1 – too quiet, 5 – too loud
Tone	3.00	1.32	1	5	1 – unpleasant, 5 – pleasant
Effectiveness	3.88	1.05	2	5	1 – confusing, 5 – easy to understand

In the survey, participants were also asked if either of the scooters responded better to the slow-zone or the no-ride zone. Half of the participants saw no difference in response to either of the geofences. Three participants thought that the Max 2.0 responded better to the slow-zone, and four participants thought that the Max 2.0 responded better to the no-ride zone (**Figure 74**).

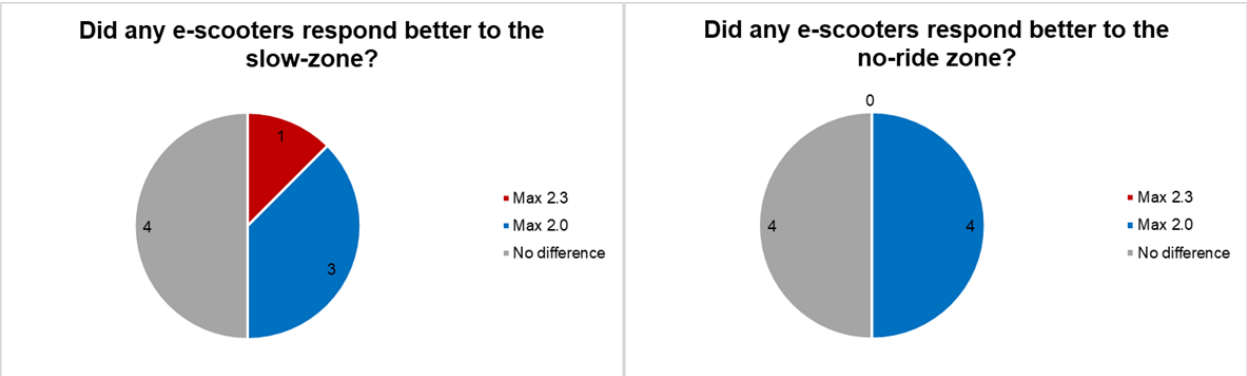

Figure 74. Participant scooter preferences for the slow-zone and no-ride zone geofences.

Discussion

The following sections discuss the results from each of the data sources for each of the three tests.

Speed, Acceleration, and Braking Test Discussion

Top Speed

On average, all four of the e-scooter models reached speeds that were under the expected speed of 15 mph. The speed that the scooters were able to achieve varied highly based upon the scooter, slope, and terrain for the trial, as well as the rider weight, which will be discussed further below.

The Max 2.0 reached significantly lower speeds than the other scooter models across all slopes and conditions. A few reasons for this could be due to the true motor power. The Max 2.0 is an older scooter model and improvements may have been made since its initial release. Additionally, the Max 2.0 scooter that was used in the study had seen more use than the other scooter models, as the other scooters were relatively new and this one had been used during the study on Virginia Tech's campus, and therefore may have been showing signs of degraded motor power. A second contributing factor could be that the Max 2.0 also had a seat attachment. Many riders would often start the trials out by sitting on the scooters while kicking off rather than standing and kicking off, which was seen to generate slower initial accelerations and therefore might have limited the speed that the scooter was able to reach before the

end of the trial. This was one limitation of this test, and if possible, using a stretch of road that is longer than 200 ft could be useful in future studies.

Slope was observed to have a significant effect on speed. As expected, participants were able to reach greater speeds on the decline slope conditions, followed by the flat slope conditions and the incline slope conditions. The decline pavement and decline wet pavement conditions were the only conditions where the scooters had average top speeds above 15 mph. This result might possibly be of concern to e-scooter companies and manufacturers that want to strictly govern the speed of their scooters, indicating that the speed limiting software could use improvements. Differences in speed between the scooters were less on the decline slope.

The scooters reached significantly lower speeds on the off-road terrain than the pavement and wet pavement terrains. This result also comes as no surprise as scooters do not use tires that are designed for off-roading, which tend to be wider for a larger contact patch to better distribute the pressure (Fernando et al., 2006), reducing the amount that the wheels dig into the terrain. The S-100T, which had the widest tires, reached the greatest top speeds. Differences in top speed between the scooters were the least on the off-road terrain. There was not a significant trend with tire width and top speed, which could indicate that there might be a threshold related to the contact patch with parameters of the weight and tire width that affects how easily a scooter can ride on off-road conditions.

Female riders were able to reach slightly higher speeds on the scooters than male riders, which may be because on average they weighed less (the average female rider weight was 150.9 lbs., and the average male rider weight was 189.6 lbs.). Rider weight also appeared to affect the top speed for all the scooters, as heavier riders were seen to reach lower speeds. This result is not surprising as many e-scooter manufacturers provide metrics such as top speed based upon testing with a specific load. For example, for the Max 2.3 and Max 2.0 e-scooters included in this study, the load that was used for their testing was 165 lbs. (Ninebot, 2020), explaining why the heavier, male riders did not reach as high speeds as the lighter, female riders. Rider weight had the greatest effect on the Max 2.0, and this could once again tie back to the Max 2.0 possibly having a weaker motor. When the Max 2.0 was removed from the analysis, scooter weight was observed to have a slight, yet insignificant, effect on speed. Additional testing on the true power output of the motors should be conducted to see if there were differences between the scooters.

Acceleration Rate

Overall, the Max 2.0 had a significantly slower acceleration rate than the other scooter models, and the S-100T also had a significantly faster acceleration rate than the Okai. This result may once again be related to the possible deteriorated motor performance of the Max 2.0 and the strategy which riders used to start the trial while seated. The S-100T had the fastest acceleration rate for all terrain types and all slopes aside from the incline slope, and this may be accounted for by its 500 W motor when compared to the 350 W motors of the other scooters. No trends with scooter features were observed.

Slope was seen to have a significant effect on acceleration, and as expected the fastest acceleration rates were on the decline slope conditions, followed by the flat slope conditions and the incline slope conditions. Differences in acceleration rates between scooters were less drastic on the incline slope, indicating that electric scooter motors may struggle to ride uphill, especially for heavier riders.

The scooters accelerated significantly slower on the off-road terrain than the pavement and wet pavement terrains. It would appear that the scooter tires struggled to gain the traction needed to increase speed on these conditions, and therefore it may be useful to recommend against riding on surfaces other than pavement unless the scooter has appropriate tires. Differences in the acceleration rates between the scooters were minimal on the off-road terrain conditions, as all four scooters appeared to have difficulty with gaining speed.

Increasing rider weight did appear to result in slightly slower acceleration rates for the Max 2.0, which is not a surprising result. There were also greater differences in acceleration rates between the scooters for the male riders, especially for the Max 2.0 and Okai models. This could indicate that these scooters may have diminished performance with heavier riders.

Braking Distance

Braking distance was seen to vary based upon slope and terrain, but this was largely due to the speed before braking. When braking distance was recalculated for each trial using a speed before braking of 15mph with the same braking rate, it was seen that there were no significant differences in the predicted braking distance between scooter models. Further investigation into scooter braking systems by including more diverse designs might provide insight to braking capabilities. No trends with scooter features were observed due to there not being differences in the scooter designs.

There was a difference in the braking distance for the scooters between the flat and incline slopes, such that the braking distances for the flat slope were longer than those for the incline slope. Two possible reasons for this result could be that the scooters had the assistance of gravity to slow them down on the incline slope or that because participants completed the flat slope trials first, they had to get used to and comfortable with the braking capabilities of each of the scooters. This may have resulted in longer braking rates during those first few trials due to a more cautious approach.

Increasing rider weight was also seen to result in slightly increased braking distances, especially for the Max 2.3 model which may have required maintenance on the brakes. This result is expected since if the same braking force was being applied by each of the riders, the acceleration for heavier riders with more mass will be smaller and result in longer braking distances. Male riders were also seen to brake in slightly shorter distances than female riders, which can likely be attributed to them applying greater braking forces resulting in larger braking rates. This could be a behavioral difference relating to comfort, as studies have shown that female riders feel less comfortable on e-scooters than male riders (Campisi et al., 2021).

SAB Surveys

Participants indicated that they preferred the acceleration of the S-100T and Max 2.3 the best. They thought the Okai accelerated too fast, which is not in line with the DAS results since the Okai had the second slowest acceleration rate. However, several participants noted that the accelerator control was delayed in its response which could have caused participants to jolt forward. This may be why the Okai had the lowest rating for acceleration feel. Participants thought the Max 2.0 accelerated too slow, which is in line with the DAS results.

Participants preferred the braking of the S-100T and Max 2.0 the best, and the Max 2.0 had the highest rating for braking feel. Several reasons for this could be that a lower center of gravity from the inclusion of a seat resulted in less weight shift and forward pitch than the other standing scooters which caused the scooter to come to a stop more smoothly, which is a result that has also been found in other studies

(Paudel & Fah Yap, 2021). As noted, during testing the Max 2.3 was braking at about 80% capacity which explains why it was rated and ranked lowest by participants. Participants also did not like the braking feel of the Okai. The Okai did have slightly higher braking rates and shorter braking distances than the other scooters, and while not significant, tire type may contribute to this as the Okai had solid tires and the three other scooters had pneumatic tires. Additional investigation is needed with more diverse scooter designs to understand if tire type did contribute to the braking capabilities.

SAB Rider Posture

Rider posture was very similar for the experienced riders across all scooters except for the seated Max 2.0. The most common initial acceleration posture was with a rider's legs bent and body leaning forward, as riders were typically seen to gain speed by using their feet and legs to push off from the ground, which resulted in a forward lean. When they returned both feet to the scooter deck, their legs would be bent to gain stability on the scooter. After this point, the most common acceleration posture changes were for the rider to return their body to a neutral position, eliminating the forward lean, or to straighten their legs. Aside from the seated Max 2.0, when riders approached the braking zone, the most common initial braking postures for riders were to have their legs either bent or straight, and for their body to either be without a lean or leaning forward. These postures show that riders were anticipating a braking event and preparing to brace themselves for it. Most participants did not change their posture while braking, indicating that they properly prepared themselves for the braking event, and the second most common action was to lean backward, which riders might believe would help to distribute the weight and braking force of the scooter. Studies have shown that shifting weight to the rear of the scooter can decrease stopping distance (Garman et al., 2020). These posture techniques may be useful to novice riders who may not be aware of how to properly brace themselves or stand on an e-scooter for acceleration or braking events.

SAB Safety Critical Events

Most of the safety critical events occurred while braking and on the flat, off-road condition. This condition appeared to give riders the most trouble with riding and may be due to the fine loose gravel that was placed over the grass. The most safety critical events occurred while riding on the S-100T, and therefore it is interesting that participants ranked this scooter at the top overall for both braking rate and braking stability. One possible cause for the large number of safety critical events while braking is that the S-100T is the only scooter model that used a foot brake to slow the rear tire. Many participants reported to only using the hand brake for this scooter, which could have resulted in too much braking force at the front wheel instead of distributing the braking force between the front and rear tires. Braking only the front tire can often result in the scooter pitching forward, which is due to the front wheel being able to exert a higher braking force on the ground due to the dynamic wheel load (Siebert et al., 2021) which did tend to happen often in these events. The experienced riders were successful at bailing out during most of these events. Most crashes occurred on either the first or third trials. It is possible that for the first trial, participants were braking or accelerating at too high of a rate on a new condition, and that for the third trial they accelerated or braked too fast due to overconfidence from previous two trials.

SAB Summary

Overall, differences in top speed and acceleration were observed between the four e-scooter models. Slope and terrain had significant effects on these metrics. Speed before braking was the main factor in braking distance, and when this was accounted for, braking distances were similar across the four e-scooters. Rider weight appeared to have varying effects on each of the scooters in regard to the top speed,

acceleration rate, and braking distance. From the surveys, it was seen that participant preferences were mostly in-line with scooter performance. Riding posture was similar across all scooters and conditions, and these results can be used to inform novice riders on proper techniques. Overall, the results from this test reflect that limited testing by manufacturers (e.g., only testing on flat pavement conditions with riders up to a certain weight) cannot accurately evaluate the true capabilities of an e-scooter.

Handling, Stability, and Maneuverability Test Discussion

Lateral Maneuvers

When looking at the change in speed from the beginning of the obstacle to the end of the obstacle, greater decreases in speed were seen with increasing scooter weight, deck height, wheelbase, and tire diameter. Heavier scooters may be harder to turn, especially through more narrow turning maneuvers, so keeping scooters as lightweight as possible while still including all necessary safety features would help to optimize their performance. However, the use cases that the scooter is being designed for should be considered. While lightweight scooters may be advantageous for low speed turning maneuvers such as those included during this evaluation, riders may benefit from the additional stability of a heavier scooter if they are traveling at higher speeds. Increasing deck height also means a higher center of gravity since most of a scooter's weight is in the deck because of the battery, which reduces the stability of the scooter (Ringer, 2019). It is very likely that larger tires were related to the taller deck height of the scooters, which is also why the similar trend was observed. However, larger tires do also result in greater trail, which requires greater input with steering (Anderson, 1999). A larger wheelbase also means a larger turning radius, making it more difficult to navigate tight turns (Paudel & Fah Yap, 2021).

Scooters with a steeper steering axis experienced less roll and less yaw. Due to steering geometry, having a steeper steering axis requires less input for sharper turns, especially at lower speeds, and reduces the need for a rider to use their body to lean as much (Ringer, 2019). Scooters with higher decks or without a seat experienced more roll, and this is likely due to the higher center of gravity and decreased stability.

Roll and yaw rates were seen to increase with increasing rider weight and height. This is consistent with the trends for the scooter features, indicating that center of gravity is extremely important for stability and that riders need to learn how to control their bodies to ride safely.

All participants had a higher probability of completing the sideways U-turn when they used their feet, and this is a technique that can be passed along to novice riders to help them learn how to properly ride an e-scooter, especially on sidewalks or streets that are busy and may require weaving in between pedestrians or other cyclists. Teaching them to slow down and use their feet may improve safety, not only for themselves, but also for other road users.

Novice riders appeared to maintain their speed better through the turning obstacles than experienced riders, but also started the obstacles with slower speeds. They also had lower rates of roll and yaw than experienced riders. These results possibly indicate that they were either riding more cautiously or did not have proper technique on how to complete these obstacles due to inexperience. Experienced riders did know how to use their bodies to better complete the obstacles, shown by the higher rates of roll and yaw. When looking at obstacle completion rates, novice riders had lower rates of completing the turning obstacles than experienced riders, meaning that they rode outside of the cones while attempting them. If they had slowed down more, they may have been able to turn easier which would have resulted in

higher yaw rates. Additionally, more experience with how to use their bodies to turn the scooter may have improved their probability of completing these tight radius turning obstacles.

Male riders had higher rates of roll and yaw than female riders. Two possible reasons for this could be related to the obstacle completion rate as well as anthropometric and behavioral differences. Female riders had much lower completion rates for the sideways U-turn obstacle than male riders, showing that they may not have been turning the scooter as hard or using their bodies to assist with the turn. The female riders were also shorter in height and lighter in weight than the male riders, and this result is in line by the above finding. Anthropometric differences, such as the relation of the height of the scooter handlebars to the height of the rider, might be worth additional investigation to understand if it is more difficult to turn a scooter based upon that dimensional difference. When female riders attempted the obstacles without using their feet, they had higher rates of not completing the obstacle. Several reports have shown that female riders do not feel comfortable on e-scooters when compared to male riders, which may contribute to confidence with completing tight turning maneuvers (Campisi et al., 2021).

Both the novice riders and female riders had lower completion rates of the sideways U-turn when they did not use their feet for assistance when compared to experienced riders and male riders, respectively.

The scooters with longer deck lengths had a higher probability of completing the sideways U-turn without assistance. A longer deck gives riders more room to stand and get in an athletic posture with their knees bent, which helps with turning. Additionally, the scooters that were shorter in height or had a shorter handlebar height (which is the distance from the deck to the top of handlebars), were also more successful in completing the sideways U-turn without assistance. This may tie back to compatibility with different rider anthropometries, as shorter riders may not have as much mechanical advantage to easily turn the scooter's handlebars than taller riders. Additionally, taller scooters likely also have higher center of gravities, which was a result seen to reduce ease with turning.

Riding into Raised Surfaces

Scooters with a suspension system or larger ground clearance were able to maintain their speed better and were less likely to get stuck while attempting to ride over a raised surface. This is an important finding as these types of impacts typically result in a rider being projected over the handlebars headfirst which could result in serious head injury for the rider (Como et al., 2022). Therefore, it appears that a balance needs to be struck between deck height and ground clearance so that the scooter can easily travel over obstacles but also have as low of a center of gravity as possible. It was also seen that suspension systems decreased the amount of vertical acceleration experienced by the scooter. However, suspension system parameters should be investigated to understand stiffness, as the Max 2.3 had a less stiff suspension system than the Okai which also resulted in lower vertical accelerations. If possible, including a suspension system that adapts to the rider's weight to provide the right amount of stiffness would be beneficial. No significant differences were observed in speed change or vertical acceleration between the experienced and novice rider groups.

Riders were less likely to get stuck while attempting to ride over a raised surface if they used their feet for assistance. There were no differences in the probability of getting stuck between experienced and novice riders. However, female riders were seen to not attempt these raised surface obstacles more frequently than male riders, which could once again tie back to differences in comfort level (Campisi et al., 2021).

Larger tires were seen to help to increase the probability of the scooter successfully riding over a raised surface, and scooters also had an increased probability getting stuck as obstacle height also increased. Therefore, if it is the goal of a scooter manufacturer for the scooter to be able to easily travel over raised surfaces such as uneven sidewalk, small curbs, bumps in the road, and potholes, it might be worthwhile to include these features.

Riding off Raised Surfaces

Three trends observed for the obstacles that involved participants riding off curbs were that increasing the tire diameter and deck height, along with including a suspension system, reduced the forward pitch rate of the scooter. The inclusion of a suspension system should help to reduce pitch rate by damping the response when the front tire contacts the ground (Cano-Moreno, 2021). When looking at the design of these scooters, these three variables were correlated (i.e., scooters with larger tires also had higher deck heights and suspension systems, while scooters with smaller tires had shorter deck heights and did not include a suspension system). However, additional investigation using a parametric analysis with these features should be conducted to understand the individual effect of each of the factors. No significant differences were observed in the pitch rate between the experienced and novice rider groups.

Terrain Transitions

The only trend seen during the terrain transitions was the amount of vertical acceleration experienced by each scooter. The two scooters without suspension systems experienced greater levels of vertical acceleration, so including a suspension system may help to reduce the mechanical vibrations that are transmitted from the contact between the scooter's tire and the ground to the rider's hands on the handlebars. No significant differences were observed in acceleration between the experienced and novice rider groups or between genders.

Course Time

The amount of time that it took to complete the HSM course varied by scooter for experienced riders. The Max 2.3 was seen to complete the course in the shortest amount of time, followed by the S-100T, Okai, and Max 2.0. These results appear to be in-line with the results from the SAB test, as the Max 2.3 did reach the highest top speeds, followed by the S-100T, Okai, and Max 2.0. Given that the Okai was the heaviest e-scooter, riders likely had difficulty maneuvering through some of the turning obstacles despite having an advantage over the S-100T and Max 2.0 for maintaining its speed when riding over the raised surfaces. Time to complete the course did not vary as much by scooter for novice riders.

Male riders completed the course faster than female riders and had more differences in time between the scooters. This result may tie back to male riders having more comfort with riding e-scooters, as well as male riders weighing more on average and certain scooters struggling with heavier riders.

On average, the amount of time to complete the course decreased after each trial for both the experienced and novice rider groups. When averaging the trial times for the experienced riders, it was seen that after 8 trials, the novice riders were completing the course in a very similar amount of time. This shows that the novice riders began to gain experience and confidence with completing the course over time. It also validates the criteria for selecting experienced riders.

HSM Surveys

Both the experienced and novice rider groups rated the Okai the lowest for performing turning maneuvers. The Okai was the heaviest scooter with the largest diameter tires, and it also had one of the

tallest deck heights and longest wheelbases, so these design factors likely did not assist the scooter with completing turning obstacles.

Both the experienced and novice rider groups also preferred the Max 2.3 and Okai for riding over raised edges and bumps and for riding off curbs, and as the Max 2.3 and Okai had suspension systems, larger tires, and the tallest deck heights and ground clearances, it would appear that these are the design features that should be targeted for a goal of riding over these kinds of obstacles.

The experienced rider group rated the Max 2.0 the lowest for terrain transitions, and the Max 2.0 did experience the greatest acceleration during these obstacles.

HSM Rider Posture

Initial postures for all obstacle types were very similar between the scooters. Riders would typically approach the obstacles with their legs bent or sitting if they were using the Max 2.0. Novice riders also chose to sit on the Max 2.0 less than the experienced riders, possibly indicating discomfort using the seat compared to standing.

Experienced riders tended to prepare themselves more before each obstacle by bending their legs, where novice riders approached the obstacle with their legs straight and bent them while completing the obstacle. Experienced riders also leaned more to the left or right with their bodies in preparation of the lateral maneuver obstacles, which may explain why they were able to better complete these obstacles. Experienced riders also used more strategies than novice riders, such as using their feet or lifting the handlebars with their arms to assist the scooters across the raised surfaces. Explaining strategies like these to novice riders may assist them with improving their riding performance and safety.

Leaning was the most common strategy across all obstacle types, as riders were often forced to use their bodies to navigate through the obstacle course, and use of feet was most common for the lateral maneuvers as some of the riders and scooters had difficulty completing these tight turns. A combination of lifting the handlebars and using feet was the most common for riding into raised surfaces, although several participants did show that the scooters could handle getting over them without any kind of assistance. Riding over raised surfaces was the most common obstacle not attempted, most likely due to riders not being comfortable attempting the obstacle or having difficulty completing it on previous trials. Novice riders chose not to attempt a larger percentage of obstacles than experienced riders, once again indicating a lower perceived level of comfort.

HSM Safety Critical Events

Most safety critical events were caused by obstacles where the scooters were riding into raised surfaces, indicating a lack of scooter compatibility with some of these road features. Recommendations to avoid similar obstacles should be provided in safety instructions, tutorials, or training. Most safety critical events involved a bailout without a fall over, as each of the riders were able to maintain control of their bodies when they either lost balance or impacted an obstacle. SCEs decreased as the trials went on, indicating that riders gained experience and comfort performing the maneuvers.

Novice riders had lower rates of safety critical events than experienced riders. This is likely due to experienced riders attempting obstacles that the scooters could not handle, which can be seen by higher rates of forward impacts and higher rates of safety critical events for the S-100T and Max 2.0 which struggled with riding over raised surfaces. Novice riders had higher rates of bailouts without forward

impacts, which is a sign of loss of balance. This may also be correlated to the design of the scooter. Novice riders had higher safety critical rates on the Max 2.3 and Okai, both of which had higher deck heights. The scooters with higher deck heights also had higher centers of gravity, which would reduce the stability and increase the potential for the scooter to roll.

HSM Summary

Several design features were identified during this test to improve performance and comfort with certain types of obstacles. For turning, more compact scooters (e.g., less weight, shorter deck, shorter wheelbase, smaller tires) can maintain speed better. Deck height affects the roll rate while steering axis affects both roll rate and yaw rate, and these parameters affect how much a rider will need to use their body to assist with turning maneuvers which can either make it easier or difficult to perform tight turns. For riding off raised surfaces, suspension systems and a combination of large tires and higher decks can help to reduce the likelihood of the scooter pitching too far forward and causing the rider to crash. For riding into raised surfaces, suspension systems and increased ground clearance can help riders maintain their speed, reduce the amount of vertical acceleration experienced by the scooter, and reduce the probability of the scooter getting stuck on obstacles of increasing height. Increasing tire diameter also helps with getting over taller obstacles. For terrain transitions, suspension systems can help to reduce any vibrations that may be transmitted to the rider.

Rider comfort was also observed to increase with additional experience, shown by the course time decreasing after each trial. The postures and strategies seen during this test that led to successful completion of the obstacles can be advised to novice riders to assist them with learning how to safely ride an e-scooter. From the surveys, participant scooter preferences were in line with scooter metrics.

Geofence Test Discussion

The Max 2.3 took longer to begin to slow and reach the reduced speed after entering the slow-zone than the Max 2.0 on both incline and decline slopes, and the Max 2.0 also responded more consistently than the Max 2.3. Slope did not have a significant effect on the time or distance it took for both scooters to respond and begin to slow in the slow-zone, but it did have a significant effect on the time and distance that it took both scooters to reach the reduced speed, as well as the difference between the actual reduced speed and the expected reduced speed. Approach speed did not have a significant effect on response time or distance for either geofence but did have a significant effect on the difference between the actual reduced speed and the expected reduced speed. There were no significant differences between scooters or slopes for the response time or distance to begin to increase speed after exiting the slow-zone or to begin to decrease speed after entering the no-ride zone. Most participants either felt no difference in the response time of the scooters or thought that the Max 2.0 responded better. The response times and distances collected during this effort can be used by e-scooter companies to continue to improve the interaction between their e-scooters and geofences. It is important that while the scooters respond quickly, they do not react in a manner that is jolting for the rider and contributes to a crash or fall.

Conclusions and Recommendations

These evaluations proved to be successful in identifying performance differences between scooters as well as scooter features, and they also provided information on scooter compatibility with road infrastructure, thus illustrating the importance of conducting testing using real-world riding conditions, tasks, infrastructure, and use cases. E-scooters are often not used in ways that they are designed for, which was observed during the *E-Scooter Safety Assessment and Campus Deployment Planning* study, especially by riders that are either inexperienced or unaware of proper e-scooter riding policies or techniques, and while e-scooter rider education is another area that requires improvement, designing e-scooters to be able to accommodate any kind of improper use may have safety benefits.

Each of the scooters had specific features with performance benefits, and by incorporating the optimal features into a single scooter design, e-scooter safety may be improved. However, manufacturers may want to prioritize certain aspects of e-scooter performance. Therefore, for performing low speed maneuvers such as those included during these evaluations, I am proposing the following design recommendations based upon the features that I believe to have the greatest safety benefits (also shown in **Figure 75)**, which are as follows:

- **Lightweight**: keeping scooters as lightweight as possible with the necessary components allow for riders to more easily complete turning maneuvers.
- **Short wheelbase**: similarly, scooters that have shorter wheelbases are also better at completing tight turning maneuvers. However, this should be balanced with usable deck length.
- **Long usable deck length**: providing riders with more room to stand allows them to get into a more athletic posture that can aid in completing turns.
- **Short deck height**: as scooters currently store batteries in the deck, which make up most of the weight, it is critical to keep the deck lower to the ground for a lower center of gravity which helps to improve the stability of the scooter.
- **Large tire diameter**: if possible, including larger diameter tires while keeping a lower deck height will help the scooters in traveling over raised surfaces.
- **Adjustable steering axis**: a steeper steering axis requires less input for sharp turns but is also more sensitive, and therefore it is important to consider the target audience when selecting a steering axis angle.
- **Suspension**: including a suspension system was observed to allow scooters to maintain their speed better when riding over raised surfaces and terrain and reduced the vertical acceleration, or mechanical vibrations, that is transmitted to the rider.
- **High ground clearance**: scooters with more distance between the ground and the bottom of the scooter deck were able to maintain their speed better while riding over raised surfaces and had a smaller probability of getting stuck or bottoming out on taller obstacles. Consider an arched deck design.

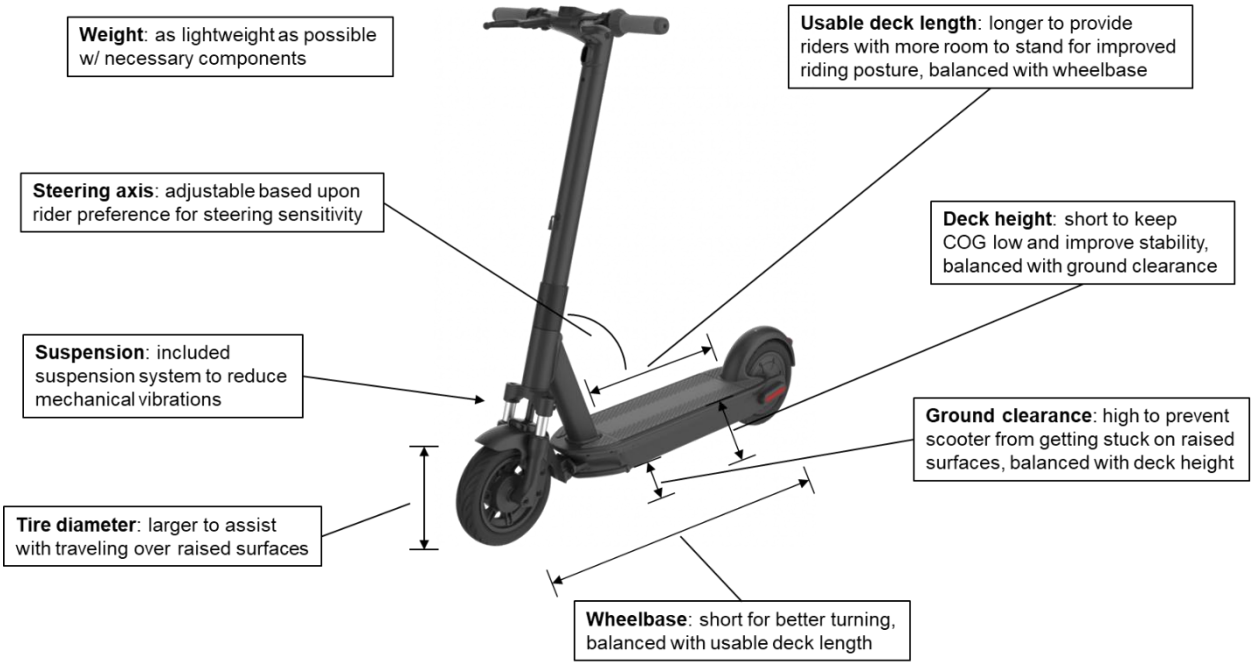

Figure 75. E-scooter design recommendations.

The specifications for each of the above design recommendations, which are based upon the four e-scooter models that were evaluated during this study, are included in **Table 14**.

Table 14. Estimated Scooter Attributes for Improved Safety Based upon Scooters Included in Testing.

Design Feature	Specification
Weight	50 lbs.
Steering axis	72.5 deg (less sensitive) – 76.5 deg (more sensitive)
Suspension	Included
Tire diameter	11.0”
Deck length	19.5”
Deck height	5.75”
Ground clearance	3.25”
Wheelbase	35.25”

Observing experienced rider postures and strategies was also useful and could be used to provide training for less experienced riders. As riding posture did not differ much by scooter, the following general postures can be advised for basic riding:

- **Acceleration**: start with legs bent, one foot on the deck of the scooter and the other on the ground and lean forward while kicking off. Return the second foot to the deck of the scooter.
- **Riding**: ride in a stance that is comfortable but anticipate unexpected events such as hard brakes. Keep legs bent, and either stay leaning slightly forward or in a more neutral position.
- **Braking**: bend legs and try to maintain body posture or lean backwards to reduce the shift of weight to the front of the e-scooter.

Additionally, by comparing experienced rider postures and strategies to those of novice riders also helped to provide insight on rider factors that contribute to performance and safety. The main finding is that experienced riders better understood how to approach obstacles and use their body to assist with completing them. Several techniques for specific types of obstacles are recommended as follows:

- **Turning maneuvers**: bend knees and begin leaning in the direction of the turn.
- **Riding off raised surfaces**: bend knees, slightly lift the front of the scooter using hands or arms so that both wheels of the scooter contact the ground at close to the same time to reduce forward pitch.
- **Riding over raised surfaces**: bend knees, lean back and lift the front of the scooter using hands or arms to raise front tire over the raised surface, or slow and use feet to lift front of the scooter over the raised surface.

While this study did provide a good first step in understanding how e-scooter design is related to performance and safety, additional work is still needed to investigate a much wider sample of e-scooter designs. By fully understanding the interaction of all components of the e-scooter in relation to performance, designs with added safety benefits can be developed which will allow all riders to have improved safety outcomes, even if the e-scooters are misused. Continuing to perform in-depth research on evolving e-scooter designs and the interactions with users and road infrastructure can help to improve safety for all e-scooter riders and other road users.

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Cortney Stancato (Ford) – sponsor project champion

Ted Sweeney (Spin) – sponsor project champion

Sponsors

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Chapter 4: Development of Training for E-Scooter Riders

Abstract

E-scooters have become a common and highly utilized form of transportation for a wide demographic of users. However, due to their accessibility, there is large variation in both knowledge regarding proper e-scooter use and level of operating experience between riders. Novice riders have been observed to contribute to a large proportion of the reported crashes and injuries. In the current scooter share systems, riders are required to review in-app safety instructions prior to renting the device. As this is the only form of training that they will receive, it is critical to ensure that riders are receiving the information that is needed for them to operate an e-scooter safely. It has been hypothesized that the training methods that are currently available could use additional refinement, and therefore this study aims to evaluate two new sets of safety training materials through participant focus group sessions and riding data to understand the optimal method for training riders. The results from this study will be used to inform e-scooter providers on training recommendations for improving e-scooter rider safety.

Introduction

E-scooters are a popular new micromobility solution for short-distance trips. In the current scooter share system found in cities, members of the public can rent an e-scooter if they are the minimum required age and have the corresponding mobile application. Due to their accessibility, knowledge regarding proper e-scooter use and level of operating experience can vary widely, which has been seen to result in many crashes and injuries for e-scooter riders and other road users.

One of the major contributing factors to the crashes and injuries seen during the *E-Scooter Safety Assessment and Campus Deployment Planning* study was user error and misuse. Throughout the course of deployment, several safety critical events were observed. Three concerning characteristics of these events related to rider behavior were identified through this study: (1) fall-overs and bailouts resulting from loss of control due to infrastructure were the most frequent crash type; (2) e-scooter riders were at fault for the majority of crash and near-crash events recorded (Appendix A-6); and (3) there was an increased risk of a safety critical event occurring when the rider behavior was characterized as aggressive riding, trick riding, or excessive speed riding. Rider experience was also analyzed during the third phase of this study where rider trip data was available. As can be seen in **Figure 76**, the greatest number of conflicts occurred for riders who had used an e-scooter 9 times or less (44%), and the number of conflicts began to decrease as rider experience increased.

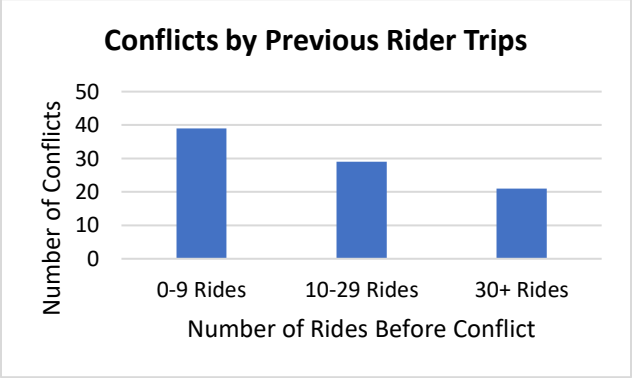

Figure 76. Conflicts by previous rider trips (Source: E-Scooter Safety Assessment and Campus Deployment Planning study).

In addition to these results, a study in Austin, Texas, conducted by the Austin Public Health department found that approximately one-third of injured e-scooter riders were first time users, and around 60% of injured riders had used an e-scooter 9 times or less, very similar to the results observed during the *E-Scooter Safety Assessment and Campus Deployment Planning* study (**Figure 77**, City of Austin, 2019). A second study also found that 23% of incidents occurred during a rider's first ride and 36% of incidents occurred during their first five trips (Murray, 2020), and a study in Washington D.C. also supported these results, showing that 37% of injured riders had incidents during their first ride (Cicchino et al., 2020). Inexperienced riders are contributing to a significant percentage of injuries, showing the need to improve rider training before using an e-scooter for the first time or to draft improved safety instructions. Other notable safety issues arise from having multiple users riding a single scooter, young riders without licenses, and collisions with bicycles (Anderson-Hall et al., 2019).

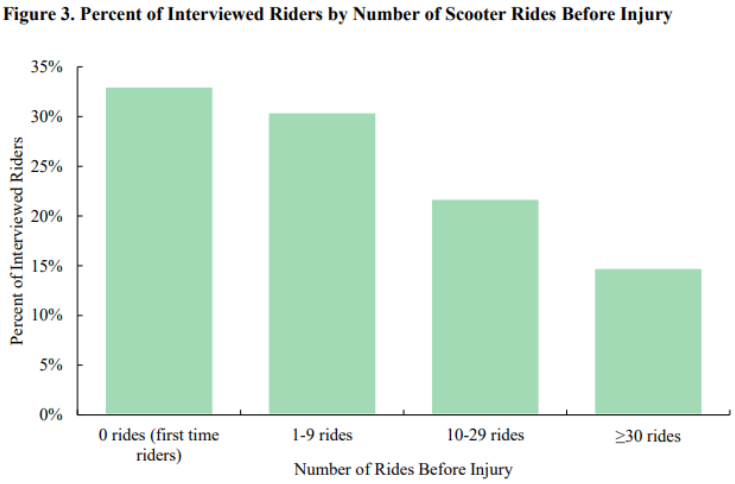

Figure 77. Number of rides before injury. (Source: City of Austin, 2019).

In response to these statistics, many cities are working with e-scooter providers to develop education and rider training or improved app tutorials (Goodman et al., 2019; Ishmael et al., 2020). Some e-scooter companies are also introducing measures that will either limit the top speed that the scooter can reach or limit the speed for new riders during their first ride (Murray, 2020). Lack of helmet use is also a noted issue, and these tutorials could help inform riders about the importance of wearing a helmet in reducing head injuries and establishing higher levels of helmet wearing (Goodman et al., 2019). Information should also be included on where to ride and park e-scooters. Some communities have also begun to include in-person information, such as posters, signage, or other on-street messaging.

Typically, there is a basic tutorial in the application for first-time riders, but no other formal training is required. Given that the purpose of the scooter share system is to provide a convenient transportation option, an official training course may not be practical. Therefore, there is a need to improve the safety instructions that are provided to riders. Experienced riders who operate in a dangerous manner may be less willing to adapt their riding behavior, but inexperienced riders may be unaware that they are causing safety concerns and be open to feedback and guidance. Therefore, novice riders are the target demographic, as I believe that they present a larger opportunity for improvement. The goal of this study is to develop an improved, detailed set of safety training instructions that riders will review before their first ride, as this is the only form of training that they will receive. This study aims to evaluate two new sets of safety instructions.

Literature Review: Training and Novice Rider Detection

To understand the theoretical framework behind training, a basic literature review was conducted. Additionally, a review on a steering entropy paper by Zhang et al. (2021) that is utilized for a novice rider detection algorithm was performed.

Training

At a very fundamental level, training is defined as a systematic effort that provides knowledge, skills, or behaviors that are needed to improve performance with a specific task, and training needs to work to change the knowledge, patterns of cognition, attitude, or motivation of the trainee (Bisbey et al., 2021). In order to do so, the training must be delivered in a way that allows the trainee to learn and apply the learning in a manner in which they receive some degree of feedback (Aguinis & Kraiger, 2009). This important concept is known as transfer.

Many consumer products similar to e-scooters have struggled with training users. For instance, many drivers of vehicles with advanced safety systems (e.g., adaptive cruise control, lane keep assist) have been seen to either misuse or disuse these technologies due to lack of knowledge (Noble, 2020). In a study, consumers were surveyed on the methods that were used to learn how to use their in-vehicle technologies (Abraham et al., 2016). The most common methods found were trial-and-error, reviewing the vehicle's user manual, or being taught by the dealership. There have been several issues with these approaches though, such as inaccurate information (Abraham et al., 2017), incomplete instructions (Leonard, 2001), and inability to self-monitor personal performance (Llaneras, 2006).

Therefore, training must be designed appropriately. A widely accepted model by Thayer and Teachout (1995), while designed for training in the workplace, has aspects that are generalizable to many different fields. In the model, factors that have been identified to support transfer include previous training and education, pretraining self-efficacy, ability, and motivation (Grossman and Salas, 2011). Likability of the training or task, perceived instrumentality of the training, and expectancy that transfer will occur as a result are other important factors (Bisbey et al, 2021). These factors are all important to consider with e-scooter riders as well, as many individuals may have previous experiences with similar devices, a better understanding of safe e-scooter riding practices and techniques, better physical or cognitive capabilities, motivation for using an e-scooter and taking time to thoroughly review the training, and previous perceptions on how useful training may be for riding an e-scooter. Therefore, it is important to keep these in mind when designing training materials in order to reach a wide range of users. The Thayer and Teachout model finishes with an evaluation of if the knowledge translates to behavior that results in desirable results. In the context of this study, the hypothesis is that educating e-scooter riders on techniques and practices for safe riding will improve their riding performance which should theoretically help to reduce the incidence of safety critical events such as crashes and injuries.

In an organizational setting, the first steps that takes place before implementing a training is conducting needs, organizational, task, and person analysis (Goldstein & Ford, 2002; Goldstein, 1993). During this process, the organization identifies where it needs to be trained, what knowledge, skills, or attitudes need to be trained, and who needs to learn them. For e-scooter services, the area for improvement is safety, which has been identified through the literature review and previous two studies to identify safety concerns and contributing factors; the knowledge, skills, and attitudes that need to be trained are proper riding policies, regulations, techniques, and behaviors; and those who need to be trained are the riders, specifically novice riders.

After conducting these analyses, the next step is to analyze the needs of the training. The most important things for this are to develop the objectives of the training, consider any relevant factors, select appropriate training strategies and methods, and develop the content (Bisbey et al., 2021). For training e-scooter riders, improving safety for all road users and reducing the number of crashes and injuries is the objective. One main relevant factor for training is that e-scooters are currently a convenient dockless service. If formal, in-person training is required, use may decrease, and therefore attempting to maintain current training settings (i.e., reviewing training materials in the rideshare app prior to renting) is the goal. Therefore, the training strategies and methods should be compatible with this approach. From Coultas et al. (2012), the four basic guidelines for developing effective training are to present the information or guidelines that need to be learned, demonstrate the necessary knowledge, skills, or attitudes, provide opportunities for practice, and offer feedback. Through results gathered from the *E-Scooter Safety Assessment and Campus Deployment Planning* and the *E-Scooter Design: Performance and Safety Evaluation* studies, guidance for safe e-scooter riding has been developed, and the resulting training methods will demonstrate how to apply them to a real-world setting. The two training formats that are proposed in this study and described in detail below include a more conventional training PowerPoint and a short instructional training video. Instructional training videos have been shown to help with procedural and conceptual learning, especially when there is a mix of viewpoints to assist with engaging in the learning from a trainee's own perspective (Fiorella and Mayer, 2018).

After reviewing the materials, riders will have an opportunity to use an e-scooter and practice applying the training. Several studies have shown that practice serves to improve learning by refining mental models with meaningful context (Murthy et al., 2008), and this holds true for e-scooter riders, as riders with more experience have been observed to have greater safety outcomes, which can be seen from **Figure 76** and **Figure 77**. Feedback is an area for a future study, as it might be useful to track a rider's performance over the course of time. In the current system of scooter sharing services, the main feedback riders will receive is having a safe and enjoyable ride because of effective training instructions.

The final step of training is evaluation of its effectiveness in transferring the training knowledge, skills, and attitudes in a variety of contexts. A commonly used evaluation method is Kirkpatrick's four-level model (1976). There are four criteria to evaluate training: the perceptions of the trainees to the training, what the trainees learned, change in trainee behaviors, and organizational results (Aguinis & Kraiger, 2009). This study for training e-scooter riders aims to evaluate the first three criteria through focus group sessions to gain participant perceptions and understand the acquired knowledge and through collection of riding data to understand how the training was applied and how it affected their riding performance. The organizational results in this context would be understanding how implementing these training materials at a large-scale would impact the resulting safety, and this would be a future study likely run by a city and e-scooter provider. To understand if the training transfers, or if it is commonly used (Baldwin & Ford, 1988), a follow-up naturalistic study in a city with the training would need to be conducted to understand prevalence of the knowledge, skills, and attitudes proposed in the training, and comparisons would need to be made to a different location with an alternative training approach.

Novice Rider Detection

To evaluate if the training transfers, metrics for evaluating riding performance need to be determined. From the *E-Scooter Design: Performance and Safety Evaluation*, it was seen that speed at which a rider operates the e-scooter can be a generally reliable metric for understanding comfort, such that riders who are more comfortable tend to travel at higher speeds. However, it is also possible that this comfort is

overconfidence, and therefore additional metrics for understanding rider stability need to be selected. A recent study by Zhang et al. (2022) described the use of a steering entropy model for predicting degraded driving performance over time that is caused by lack or loss of attention and decreased vigilance. If mental workload is not increased, the performance and control of the vehicle will decrease. The steering entropy model is summarized below.

The method for calculating steering entropy was first proposed by Boer and Nakayama (Nakayama et al., 1999) which utilized the information theory of entropy developed by Claude Shannon (Shannon, 1948). This theory estimates the probability distribution of data, and the Shannon entropy (H_p) is calculated using the below equation:

$$\mathrm{H(X)} = -\sum_i P_x(x_i) \log_b P_x(x_i)$$

With X representing a random variable, x_i representing possible outcomes, and the probability of each outcome being $P_x(x_i)$. The $\log_b$ term is an adjustable parameter for units. When calculated, a higher entropy value indicates less predictable outcomes, and a lower entropy value indicates more predictable outcomes. In the context of driving, or riding an e-scooter in this study, this metric will correlate to the driving, or steering and leaning, control of the vehicle.

To calculate steering or leaning errors or deviations, steering and leaning angle data needs to be collected. A second-order Taylor expansion can then be applied by using data from previous timepoints to predict steering or leaning angle at time *n*, as shown below:

$$a_{p(n)} = a_{(n-1)} + \left(a_{(n-1)} - a_{(n-2)}\right) + 1/2\left(\left(a_{(n-1)} - a_{(n-2)}\right) - \left(a_{(n-2)} - a_{(n-3)}\right)\right)$$

Where *a* is the steering or leaning angle and $a_{p(n)}$ is the predicted steering or leaning angle at time *n*. The error between the predicted steering or leaning angle and the actual steering or leaning angle can be calculated as shown below:

$$e_a = a_{(n)} - a_{p(n)}$$

Based upon the 90th percentile value of the frequency distribution of the prediction errors, the frequency distribution is then divided into a number of bins. The proportion of errors in each bin, p_n, is calculated and the steering entropy value can then be calculated:

$$H(p) = -\sum_1^n p_i \log_n p_i \; (i = 1 \; to \; n)$$

As there are *n* bins, there are *n* possible outcomes for error prediction. By applying this model to e-scooter riding, an idea of the stability and erratic riding of each subject can be determined through calculation of steering and leaning error and entropy. This study will also evaluate if this method is effective or if additional refinement of the algorithm is needed.

Methods

Training Materials

Two new sets of safety training materials were developed for this study based upon findings from literature, the *E-Scooter Safety Assessment and Campus Deployment Planning* study, and the *E-Scooter*

Design: Performance and Safety Evaluation study. The first set of materials was a video, and the second set was a PowerPoint presentation. Each of these training materials included the same information but was presented in a different format to gain perceptions of rider preferences. The different sections in the training included:

- Safety Equipment: proper use of safety equipment and how it can help to prevent injuries.
    - Studies have reported that helmet use for e-scooter riders ranges from 0 to 9% (Trivedi et al., 2019) and only 1% of riders were observed to be wearing helmets during the *E-Scooter Safety Assessment and Campus Deployment Planning* study. Approximately one-third of e-scooter injuries are head injuries (Namiri et al., 2020). Use of helmets or other protective equipment can help to reduce the severity of, or prevent, injuries, and this section will stress this point.
- Getting Ready to Ride: understanding riding policies and traffic laws and getting to know the e-scooter.
    - As e-scooter services are still relatively new, many users are unfamiliar with policies due to either not reviewing resources prior to riding, difficulty finding the policies, or because the regulations differ for each city (Anderson-Hall et al., 2019; DuPuis, Griess, & Klein, 2019). Because of this, many conflicts between e-scooter riders and other road users have been reported, and this has been associated with increased risk from the *E-Scooter Safety Assessment and Campus Deployment Planning* study. Riders will be directed to these resources in this section.
    - New riders may also be unfamiliar with the controls of an e-scooter, which could potentially contribute to the increased number of crashes and injuries for inexperienced riders observed during the *E-Scooter Safety Assessment and Campus Deployment Planning* study and the study conducted by the Austin Public Health Department (City of Austin, 2019). It is also possible that the reported vehicle malfunctions were actually user error (Santacreu et al., 2020; Cicchino et al., 2020). Riders will be shown the features of the e-scooter in this section.
- Starting Your Ride: basic techniques for starting the e-scooter, proper riding stance, and coming to a stop.
    - During the *E-Scooter Safety Assessment and Campus Deployment Planning* study, riders were observed to have improper riding stances such as standing with their center of gravity to the front of the e-scooter instead of towards the center or back and with their feet side by side instead of one in front of the other. The experienced riders from the *E-Scooter Design: Performance and Safety Evaluation* also demonstrated proper stances and techniques while riding, accelerating, and braking, and these postures and techniques will be recommended in this section.
    - Additionally, during the *E-Scooter Design: Performance and Safety Evaluation* study, several safety critical events were observed due to riders accelerating or braking too hard. Riders will be instructed upon the importance of getting a feel for the sensitivity of the e-scooters controls in a safe location.
- Riding: advice for successfully navigating specific types of road infrastructure that might be encountered while riding based upon the design features of the scooter.
    - Experienced riders provided recommendations on obstacles for novice riders to avoid in the *E-Scooter Design: Performance and Safety Evaluation* study. These recommendations

will be included. However, as e-scooters need to be designed to expect misuse, the strategies that experienced riders used to complete these obstacles, such as leaning during turning maneuvers, using their feet, hands, or arms to lift the front of an e-scooter while riding over raised surfaces, and bending their knees while riding off raised surfaces, will be taught here. As these are advanced maneuvers, riders will be encouraged to ride slowly and avoid any obstacles that they are not comfortable with.
    - Additionally, as there were performance differences based upon the design and features of each e-scooter during the *E-Scooter Design: Performance and Safety Evaluation* study, this section will recommend that riders take the time to inspect their e-scooter to understand how compatible it will be with specific road infrastructure, features, and conditions.
    - Aggressive rider and other road user behaviors also increased the risk of conflicts occurring during the *E-Scooter Safety Assessment and Campus Deployment Planning* study, and therefore a point will be included to be respectful and ride slowly around pedestrians and other road users.
- Ending Your Ride: parking the scooter in an appropriate location.
    - Improper parking has been reported to be a nuisance issue and fall hazard for pedestrians (Blomberg et al., 2019; Trivedi et al., 2019), and between 10-20% of rides during the *E-Scooter Safety Assessment and Campus Deployment Planning* study had e-scooters parked improperly at the end of the ride. This section will instruct riders to check the parking locations specified by the city and the e-scooter provider.

The safety advice provided in these instructions are results based upon findings from previous studies conducted by the Virginia Tech Transportation Institute, and the PowerPoint slides can be found in Appendix C-1.

Participants

To understand novice e-scooter user perceptions of the training materials, thirty-four participants (34) were recruited, screened, and invited in groups of five or six to participate in the focus group sessions. Participants were required to have minimal previous experience with e-scooters (less than three rides) and riders with no previous experience were preferred. Additionally, the target group was college-age individuals. **Table 15** shows the breakdown of the participants in this study by the training materials that they received.

Table 15. Participant demographic breakdown.

Training	Gender	Age (yrs.)	Weight (lbs.)	Height (in.)	No Previous Experience	1-3 Previous Rides
Video	8 M, 9 F	21.0 ± 1.9	160.9 ± 23.8	67.1 ± 5.3	7	10
PowerPoint	9 M, 8 F	22.0 ± 2.2	166.1 ± 24.1	68.8 ± 3.8	10	7

Participants were paid $60 for their full participation in the study. This study was approved by Virginia Tech's Institutional Review Board (IRB #22-661).

Focus Group Sessions

Six focus group sessions of 5 to 6 participants were held. During the sessions, participants would review only one of the two assigned training materials, and then would be provided an e-scooter and safety equipment to take two quick rides on paths that were separated from the road around Virginia Tech's Corporate Research Center (Appendix C-2). Two identical e-scooters were used so that multiple participants could ride at a time, but participants would take these rides alone to prevent each other from influencing riding behaviors. All participants in a single session received the same set of training materials. Three of the focus groups received the video training and the other three received the PowerPoint presentation training.

After each participant completed the rides on the e-scooter, a focus group was held to understand perceptions of the training materials. Questions were asked regarding length and practicality of the training, as well as if a quiz at the end would be useful. A five-point Likert scale was also used for participants to indicate how useful they felt each section of the training was, and open discussions were held after each quantitative data point was collected. Participants were then presented with one of the current tutorials that is used by e-scooter companies that a new rider is required to review prior to their first ride. The participants were asked whether they felt that the new training materials that they received at the beginning of the session were an improvement. Finally, participants were shown the second new set of training materials and asked to comment on the different format. The focus groups were recorded using an audio recording device.

Data Collection and Analysis

Surveys

Two surveys were administered throughout the session using QuestionPro. Participants would scan a QR code using their mobile device which would take them to the surveys.

Demographics Survey

An initial survey was administered to participants to collect demographics information as well as information on level of physical activity, previous athletic activity involvement, and perceptions of e-scooter safety. This survey can be seen in Appendix C-3.

Pedestrian Risk Behavior Survey

Participants would also complete a pedestrian risk behavior survey to understand each participant's risk-taking tendencies. This survey was developed by Deb et. al (2017) and slightly modified. Instead of using a scale based upon frequency, a scale on agreement was used. Participants were asked a series of questions on pedestrian behavior and scenarios and asked about their level of agreement for each (1-strongy disagree, 2-disagree, 3-somewhat disagree, 4-no opinion, 5-somewhat agree, 6-agree, 7-strongly agree). There was a total of 20 questions, and 4 questions corresponded to five subscales: violations, errors, lapses, aggressive behaviors, and positive behaviors, which were reverse scaled. A pedestrian behavior metric was then calculated by adding the average of the violations, errors, lapses, and aggressive behaviors and subtracting the positive behaviors. A lower pedestrian behavior score indicated lower risk. This data was paired with the data collected during the ride. These results could also be used to understand any biases from individual participants during the focus group session. This survey can be seen in Appendix C-4.

Riding Data

The two e-scooters were instrumented with VTTI's micro data acquisition system (microDAS). These systems collect forward-facing video along with GPS, acceleration, and gyroscope data. Data was collected during each of the participants' rides to understand riding behaviors related to the kinematic data. As the riding paths did include sections of road where cars would occasionally turn and cause the participants to stop and wait, the paths were divided into 4 segments to remove periods where the scooters might have not been moving. Each trip involved riding to a destination and returning, so in total, there were 8 segments per ride, which can be seen in Appendix C-2. The following metrics were analyzed for each trip segment, as well as across the entire trip:

- Average speed
- Maximum speed
- Mean and standard deviation values of steering angle
  - $\theta = \int G_z \, dt$
- Mean and standard deviation values of leaning angle
  - $\varphi = 0.995 \int G_x dt + 0.005 \, tan^{-1}\left(\frac{a_y}{a_z}\right)$
- Mean and standard deviation values of steering error, $e_\theta = \theta - \theta_{predicted}$
  - Predicted steering angle using 2nd order Taylor expansion with sampling time = 100 ms
    - $\theta_{predicted} = \frac{5}{2}\theta_{(n-1)} - 2\theta_{(n-2)} + \frac{1}{2}\theta_{(n-3)}$
- Mean and standard deviation values of leaning error, $e_\varphi = \varphi - \varphi_{predicted}$
  - Predicted leaning angle using 2nd order Taylor expansion with sampling time = 100 ms
    - $\varphi_{predicted} = \frac{5}{2}\varphi_{(n-1)} - 2\varphi_{(n-2)} + \frac{1}{2}\varphi_{(n-3)}$
- Mean and standard deviation values of steering entropy, H_{e_θ}
  - Steering entropy is calculated for **a** jumping window of 0.5 sec of error (collecting 5 values of error of 0.1s sampling time) of steering angle
- Mean and standard deviation values of leaning entropy, H_{e_φ}
  - Leaning entropy is calculated for a jumping window of 0.5 sec of error (collecting 5 values of error of 0.1s sampling time) of leaning angle

Additional details regarding the calculation of steering error and steering entropy can be seen in Zhang et al. (2022). An analysis of variance was conducted on the resulting data to investigate if there were differences in rider kinematic behavior caused by the training materials that the riders received or by rider specific factors (age, gender, previous experience, risk perception, height, weight, perceptions on the usefulness of the training materials, etc.).

Focus Group Data

Each of the focus groups were recorded using an audio recording device. Following each session, the audio recordings were transcribed and reviewed to look at commonly occurring themes.

During the discussions, participants would raise their hands to indicate if they agreed with statements, and they would also mark down their response on a provided form which was collected at the end of the session. This form also contained the five-point Likert scales that participants would mark to indicate their perceptions of usefulness for each section of the training.

Results

Surveys

The results from the pre-session questionnaire can be seen in **Figure 78-Figure 81**. The top three reasons that participants chose for not using e-scooters were that they do not want to pay to use an e-scooter (26 selections), e-scooters are not easily available (15 selections), and that they prefer to use other modes of transportation (12 selections). When asked about methods for improving perceptions on e-scooter safety, the top three responses were improved safety instructions or tutorials on how to safely ride an e-scooter (21 selections), improved directions on where to ride an e-scooter (18 selections), and better understanding of e-scooter features (16 selections). Participants were also asked where they thought that e-scooters should be ridden, to which 32 participants selected bike lane, 21 selected sidewalk, and 3 selected road. Finally, participants were asked what they thought would make them feel safer regarding e-scooter use. The most common selections were protected lanes for e-scooter riders and cyclists (22), available training (13), restrictions on accounts of unsafe riders (12), wider area to stand (12), and improved safety instructions or tutorials (11).

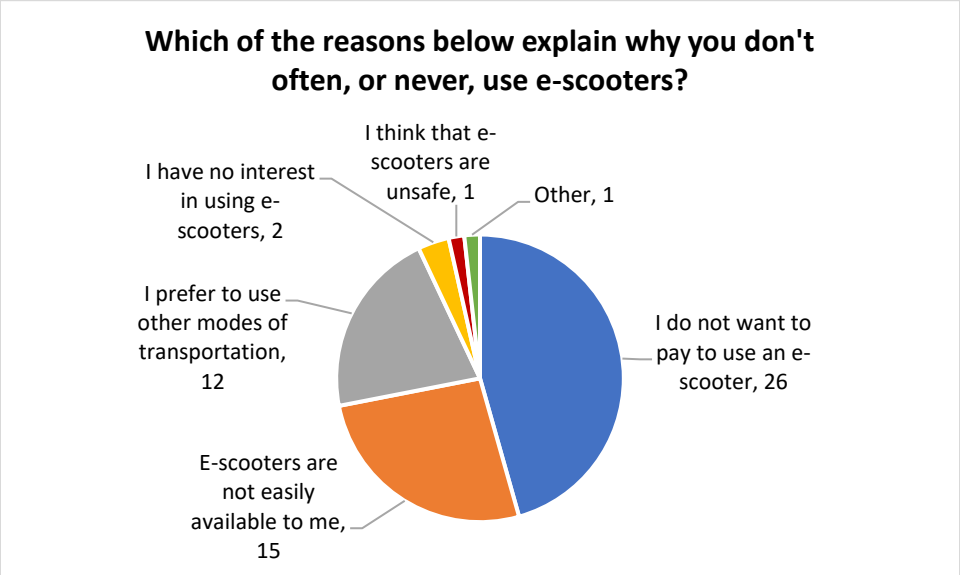

Figure 78. Participant choices for not using e-scooters. (Note: participants could select more than one option for each of the above questions.)

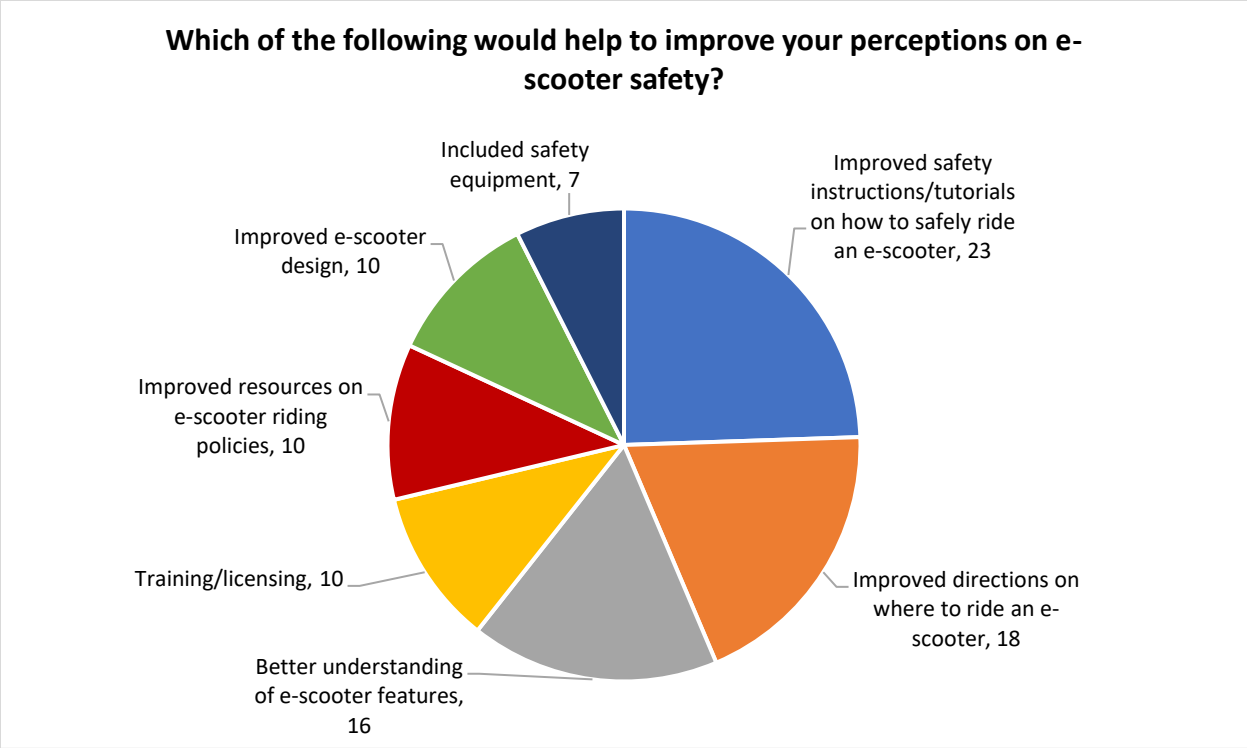

Figure 79. Participant choices on improving perceptions of e-scooter safety. (Note: participants could select more than one option for each of the above questions.)

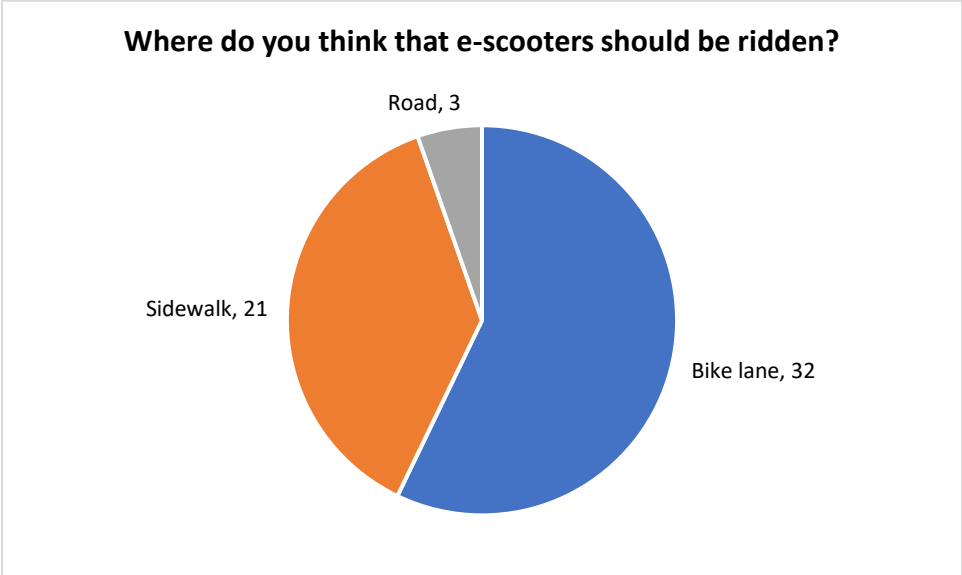

Figure 80. Participant choices for e-scooter riding location. (Note: participants could select more than one option for each of the above questions.)

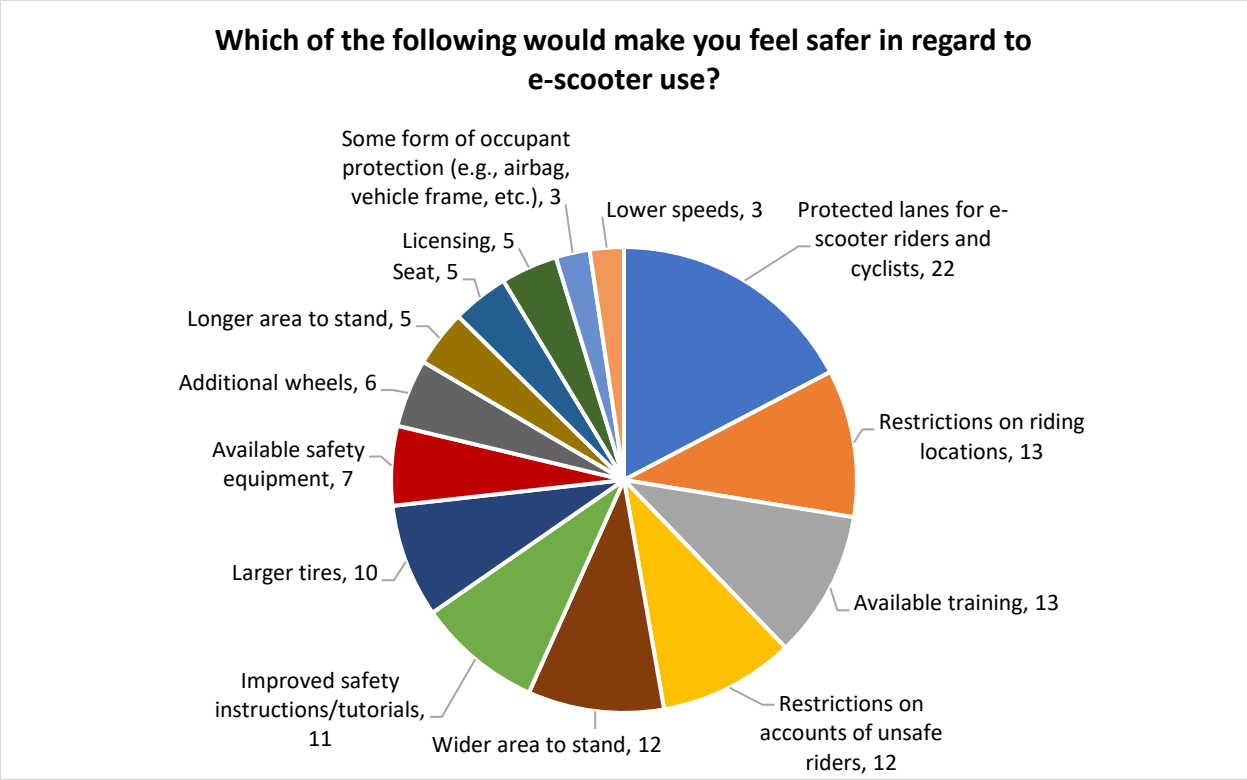

Figure 81. Participant choices for improving e-scooter safety. (Note: participants could select more than one option for each of the above questions).

The average results from the pedestrian risk behavior survey for the participants that received each of the training materials can be seen in **Table 16**. Both groups had very similar levels of risk, and when analyzing the transcribed focus group scripts, there were no correlations in risk between the responses to questions and the individual calculated risk. Additional survey responses can be seen in Appendix C-5.

Table 16. Pedestrian risk behavior survey results. [Average (St. Dev.)]

Training Materials	Violation	Error	Lapse	Aggressive Behavior	Positive Behavior	Pedestrian Behavior
Video	3.32 (1.37)	2.43 (0.89)	1.94 (0.95)	1.82 (0.84)	5.54 (0.87)	3.97 (3.61)
PowerPoint	3.55 (1.53)	2.06 (0.94)	1.81 (0.94)	1.66 (0.75)	5.80 (0.82)	3.28 (3.36)

Riding Data

As a steep learning curve was expected, riding data was analyzed during each of the segments of the first ride, and then the riding metrics were compared across the entire first and second rides. **Figure 82** and **Figure 83** show the mean values for average and maximum speed for each of the segments during the first ride, respectively. As can be seen, both average and maximum speed increased between the first and third segments, was relatively maintained between the fourth and sixth segments, and decreased during the seventh and eighth segments for all groups. Male riders rode at the fastest speeds, followed by riders with 1-3 previous rides of experience, then riders who reviewed the PowerPoint and video training materials, then riders with no experience, and then female riders.

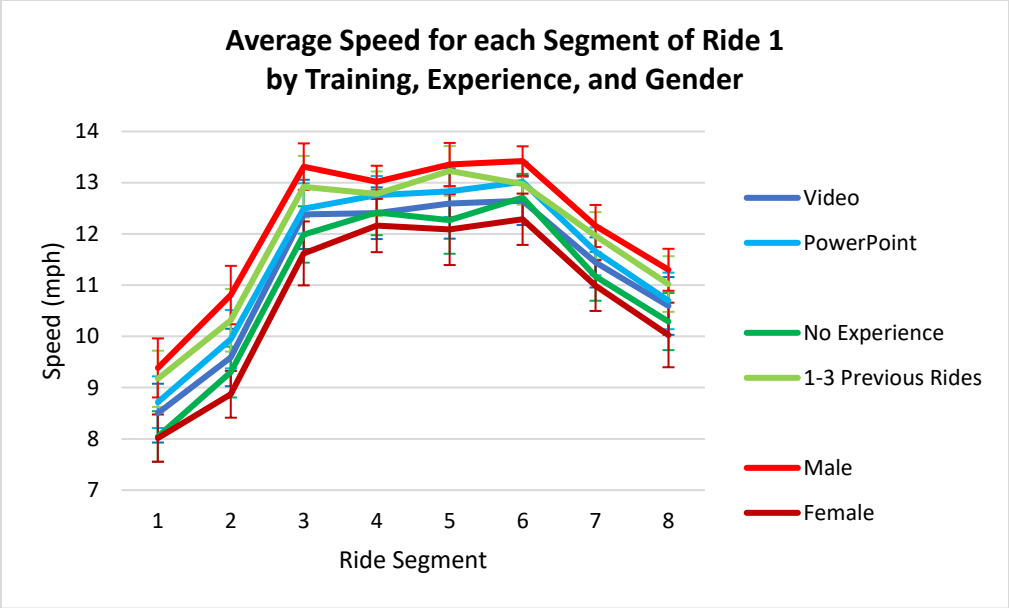

Figure 82. Average speed for each segment of ride 1 by training, experience, and gender. (Note: not all groups are mutually exclusive.)

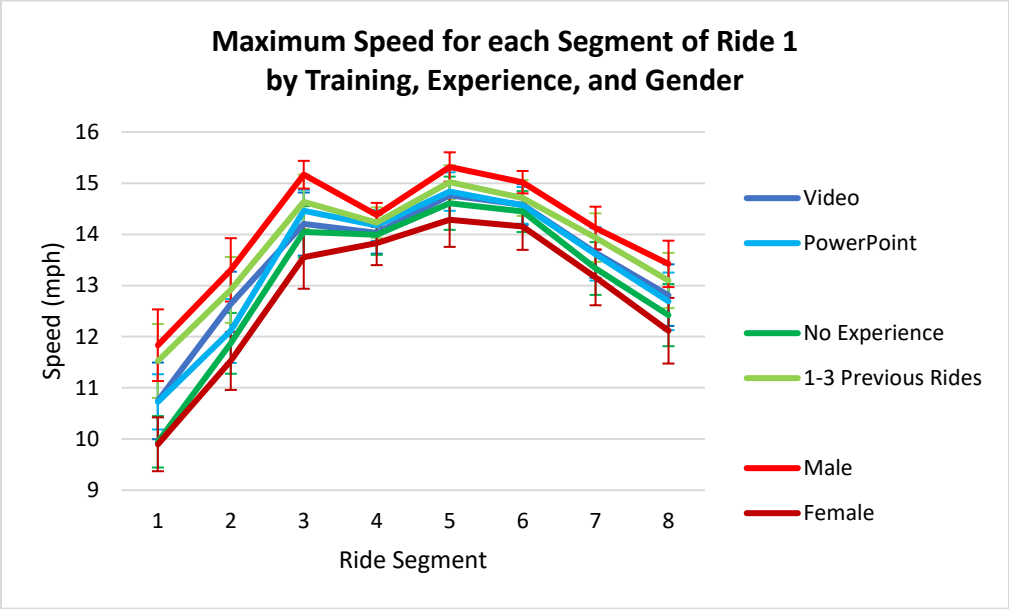

Figure 83. Maximum speed for each segment of ride 1 by training, experience, and gender. (Note: not all groups are mutually exclusive.)

Figure 84 and **Figure 85** show the mean values for steering angle error and leaning angle error for each of the segments during the first ride, respectively. No clear trends were observed, although it appeared that the largest steering angle errors occurred during the first and eighth segments of the ride and the largest leaning angle errors occurred during the eighth segment of the ride. Riders who reviewed the PowerPoint, riders with no previous experience, and male riders started segment 1 with the largest steering angle errors, and riders who reviewed the PowerPoint and with no experience started segment 1 with the largest leaning angle errors.

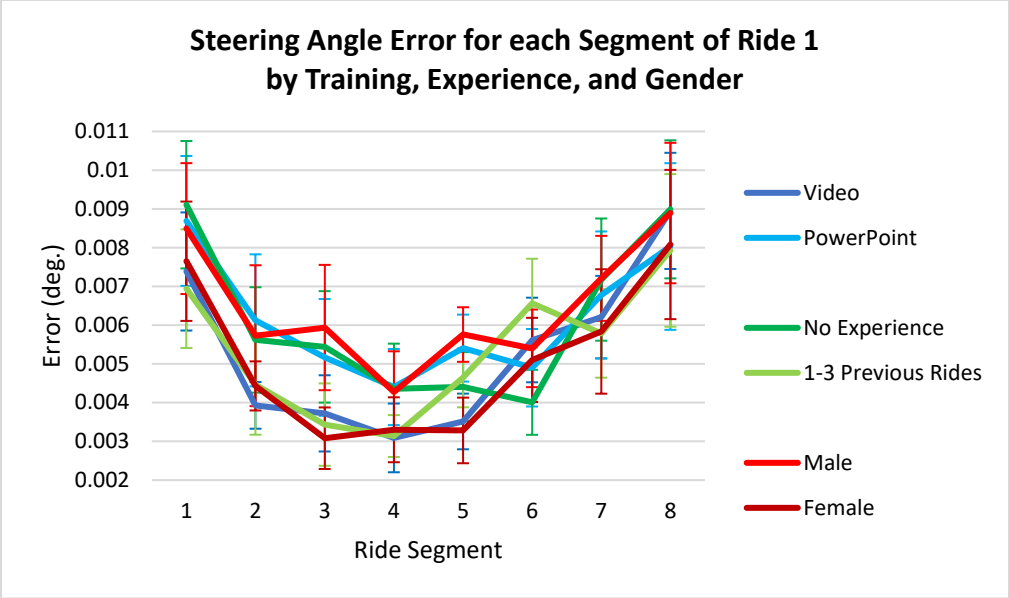

Figure 84. Steering angle error for each segment of ride 1 by training, experience, and gender. (Note: not all groups are mutually exclusive.)

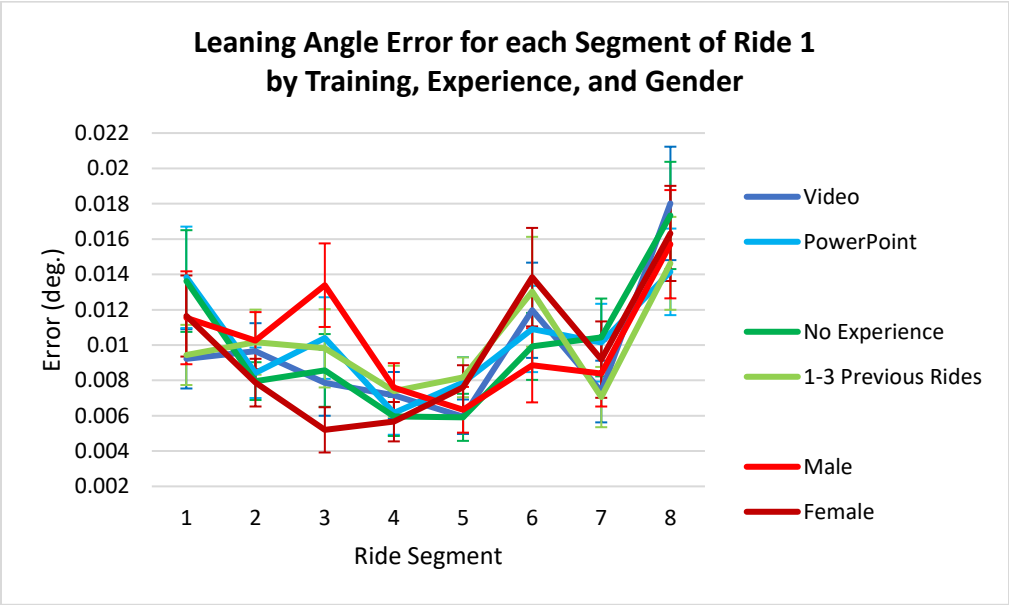

Figure 85. Leaning angle error for each segment of ride 1 by training, experience, and gender. (Note: not all groups are mutually exclusive.)

Figure 86 and **Figure 87** show the mean values for steering entropy and leaning entropy for each of the segments during the first ride, respectively. While there were no clear trends, steering entropy was the greatest during the first segment for riders who reviewed the PowerPoint, riders with no previous experience, and male riders. Leaning entropy was greatest during the eighth segment, especially for riders who reviewed the PowerPoint, riders with 1-3 previous rides of experience, and male riders.

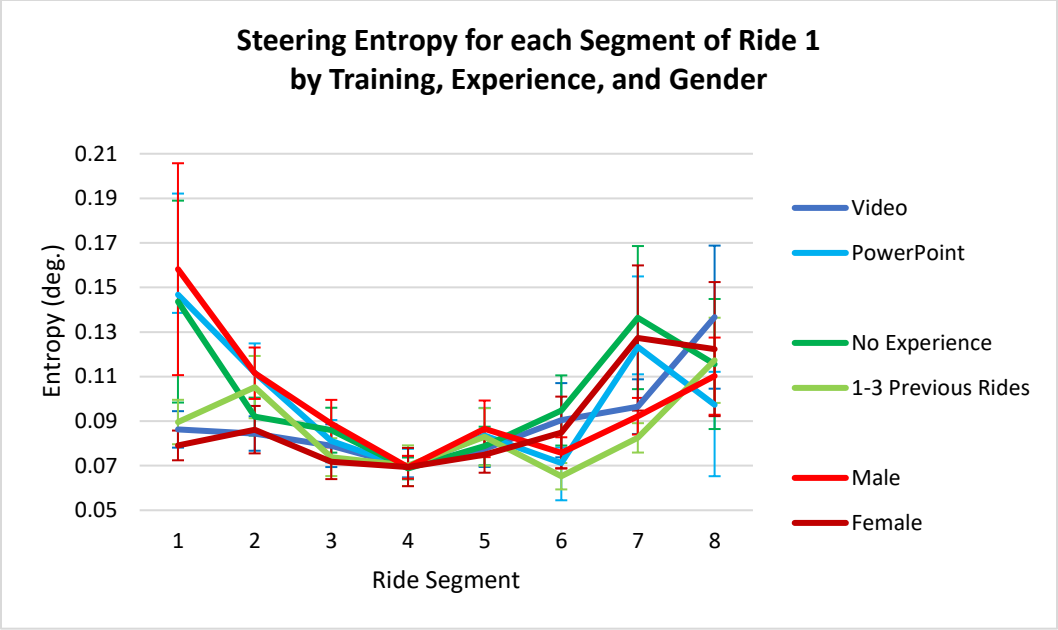

Figure 86. Steering entropy for each segment of ride 1 by training, experience, and gender. (Note: not all groups are mutually exclusive.)

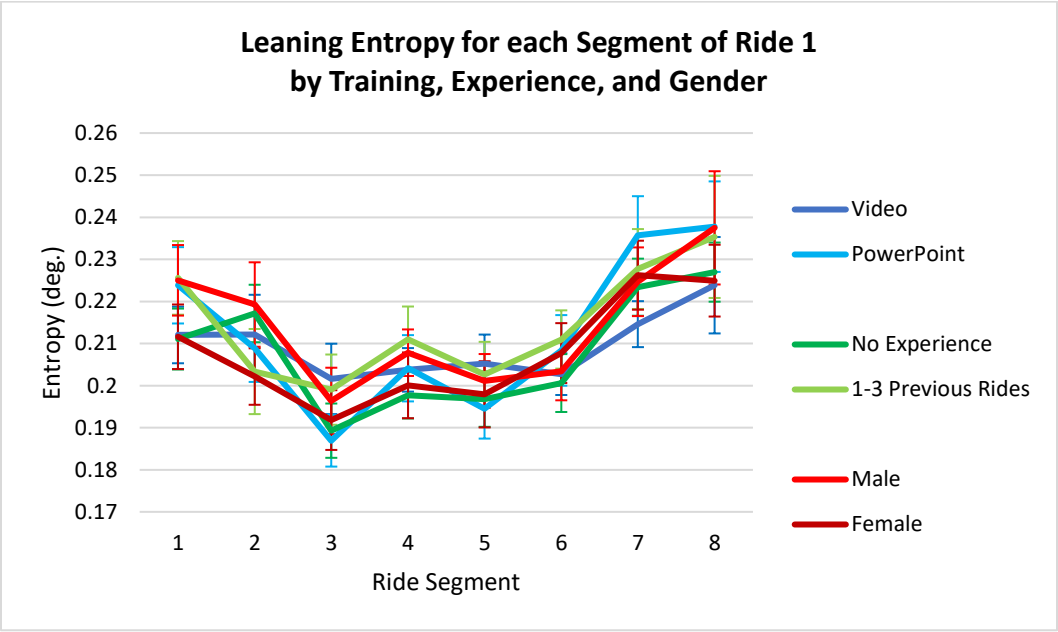

Figure 87. Leaning entropy for each segment of ride 1 by training, experience, and gender. (Note: not all groups are mutually exclusive.)

Table 17 compares the riding metrics for each of the groups across the entire first and second rides. Average speed decreased between the first and second rides for all groups, but maximum speed increased between the first and second ride except for female riders. Steering and leaning angle errors were greatest for male riders and least for female riders during the second ride. Riders with no experience and female riders had the lowest steering and leaning entropies during the first ride, and during the second ride,

riders who reviewed the PowerPoint and riders with no experience had the highest steering and leaning entropies.

Table 17. Comparison of riding metrics between rides 1 and 2 by training, experience, and gender. Color coding is used to easily identify high (red) and low (dark green) values.

Training	Ride	Average Speed (mph)	Max Speed (mph)	Steering Angle Error (deg.)	Leaning Angle Error (deg.)	Steering Entropy (deg.)	Leaning Entropy (deg.)
Video	1	11.51	15.15	0.0022	0.0035	0.0657	0.2083
	2	10.68	15.65	0.0021	0.0031	0.0686	0.2066
PowerPoint	1	11.86	15.16	0.0018	0.0040	0.0643	0.2085
	2	10.13	15.60	0.0020	0.0047	0.0921	0.2188
Experience	**Ride**	**Average Speed (mph)**	**Max Speed (mph)**	**Steering Angle Error (deg.)**	**Leaning Angle Error (deg.)**	**Steering Entropy (deg.)**	**Leaning Entropy (deg.)**
No Experience	1	11.37	14.95	0.0019	0.0042	0.0603	0.2051
	2	10.13	15.29	0.0017	0.0038	0.0888	0.2170
1-3 Previous Rides	1	12.04	15.37	0.0021	0.0034	0.0700	0.2119
	2	10.68	15.94	0.0024	0.0039	0.0717	0.2084
Gender	**Ride**	**Average Speed (mph)**	**Max Speed (mph)**	**Steering Angle Error (deg.)**	**Leaning Angle Error (deg.)**	**Steering Entropy (deg.)**	**Leaning Entropy (deg.)**
Male	1	12.43	15.67	0.0019	0.0033	0.0706	0.2114
	2	11.23	17.12	0.0024	0.0050	0.0859	0.2142
Female	1	11.00	14.67	0.0021	0.0043	0.0597	0.2056
	2	9.55	14.03	0.0017	0.0026	0.0738	0.2108

A final trend that was found related the participants' responses to number of similar devices previously used to average and maximum speed as well as steering entropy. In general, participants that had previously used more similar devices rode at faster speeds and had less steering entropy, indicating more stable steering movements.

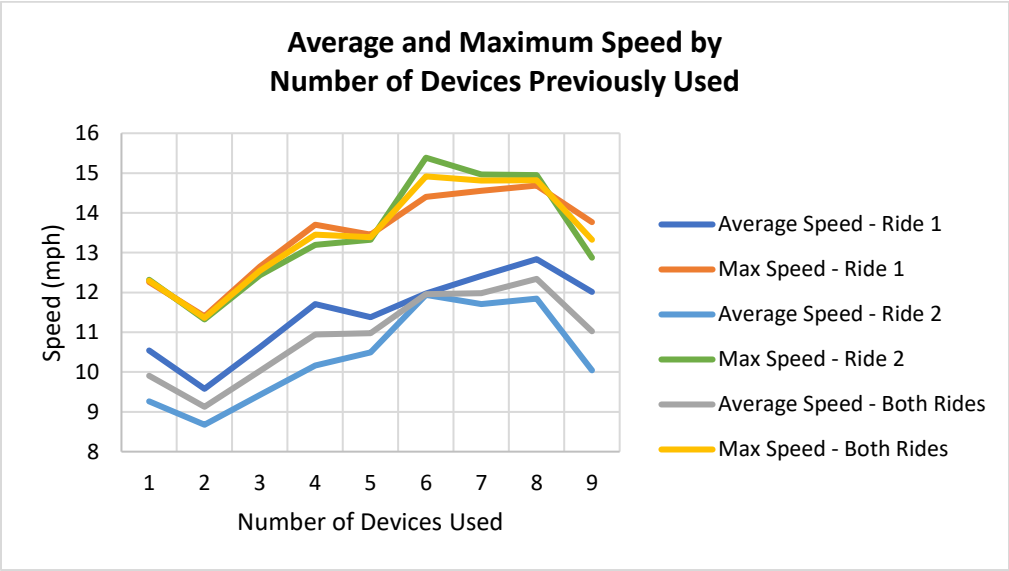

Figure 88. Average and maximum speed by number of devices previously used.

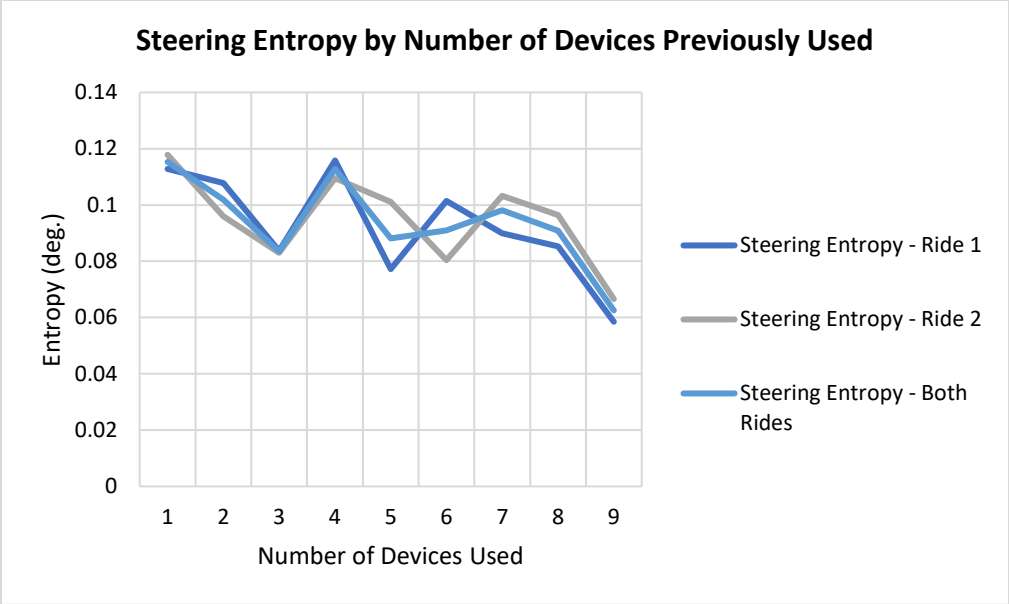

Figure 89. Steering entropy by number of devices previously used.

Unfortunately, there were no significant results from the statistical analysis.

Focus Group Data

The first question that participants were asked was about the length of the training materials that they reviewed prior to riding. Seven participants in the video training groups thought that the training was the right length, while 10 participants felt that it was too long. Similarly, in the PowerPoint training groups, seven participants also felt that the training was the right length while nine participants felt that it was too long, and one participant was unsure. These results can be seen in **Figure 90**.

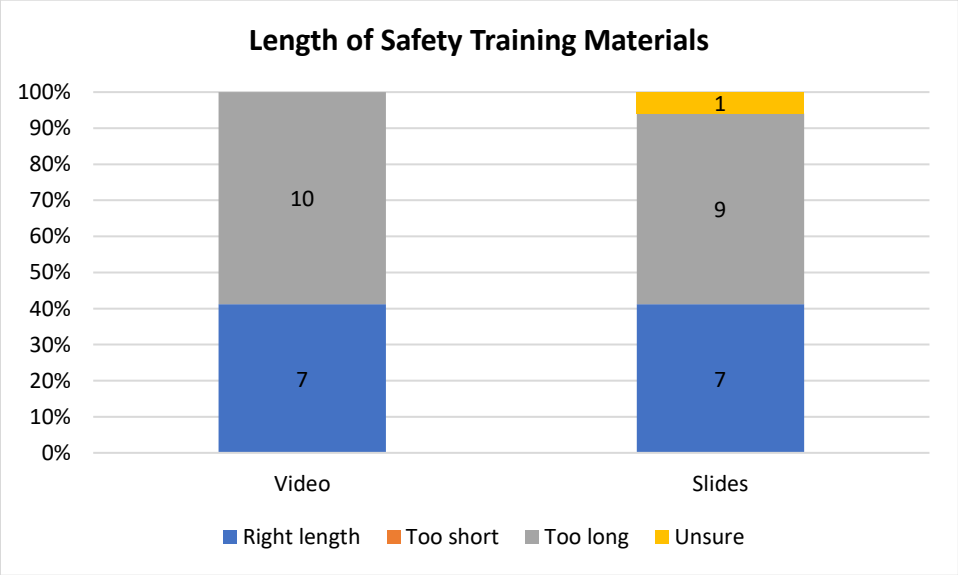

Figure 90. Participant perceptions of training materials length.

Participants were asked to assess the practicality of the training materials and whether it would be something that they would take the time to review if they were renting an e-scooter. In the training video groups, 13 of the 17 participants felt that the training was practical, with 4 feeling that it was not practical. In the PowerPoint training groups, 9 of the participants felt that it would be practical, 6 thought that it would not be practical, and 2 participants were unsure. These results can be seen in **Figure 91**.

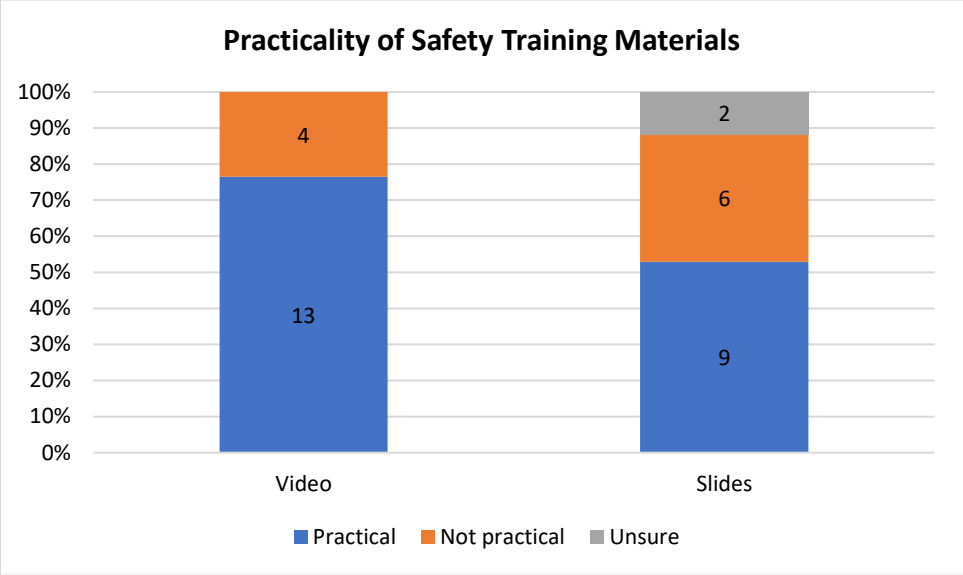

Figure 91. Participant perceptions of training materials practicality.

Participants were asked to rate the usefulness of each section of the training materials. Not at all useful was assigned a value of 0, slightly useful was assigned a value of 1, moderately useful was assigned a value of 2, very useful was assigned a value of 3, and extremely useful was assigned a value of 4. An average rating was calculated for each section of the training materials for each of the different groups. The following ratings were given, which can be seen in **Table 18**. The actual participant responses can be seen in **Figure 92**.

Table 18. Average ratings on usefulness for training materials sections.

Training Materials	Training Section	Avg. Rating	St. Dev.	Value
Video	Safety Equipment	1.76	0.97	Slightly useful – Moderately useful
	Getting Ready to Ride	2.47	0.87	Moderately useful – Very useful
	Starting Your Ride	3.06	0.66	Very useful – Extremely useful
	Riding	3.47	0.62	Very useful – Extremely useful
	Ending Your Ride	2.18	1.07	Moderately useful – Very useful
PowerPoint	Safety Equipment	1.53	0.94	Slightly useful – Moderately useful
	Getting Ready to Ride	2.53	0.94	Moderately useful – Very useful
	Starting Your Ride	3.18	0.95	Very useful – Extremely useful
	Riding	2.88	0.86	Moderately useful – Very useful
	Ending Your Ride	1.82	0.95	Slightly useful – Moderately useful

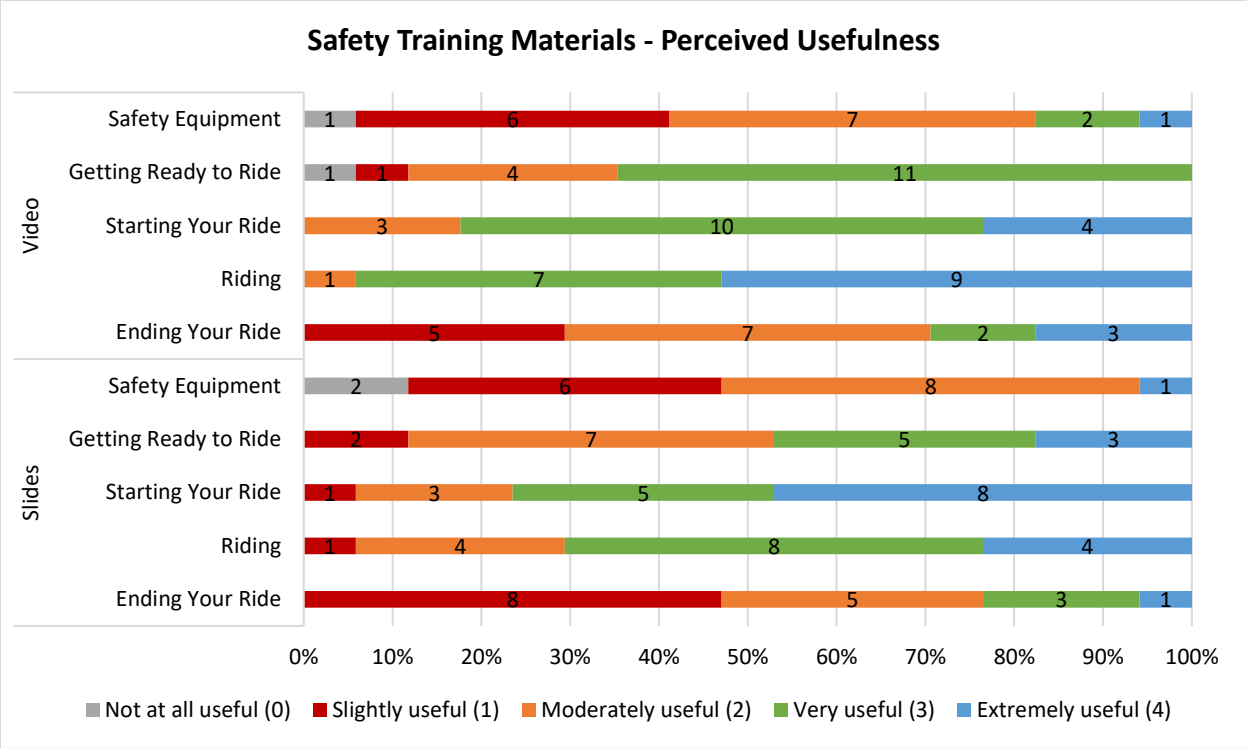

Figure 92. Participant perceptions of training material usefulness by section.

An additional question that participants answered was if they felt that a quiz included with the safety training materials would be useful. For the participants that reviewed the video prior to riding, 14 of the 17 felt that a quiz would be useful, 1 felt that it would not be useful, and 2 participants were unsure. Similarly, 16 of the 17 participants that reviewed the PowerPoint prior to riding felt that a quiz would be useful, and only 1 participant was unsure. These results can be seen in **Figure 93**.

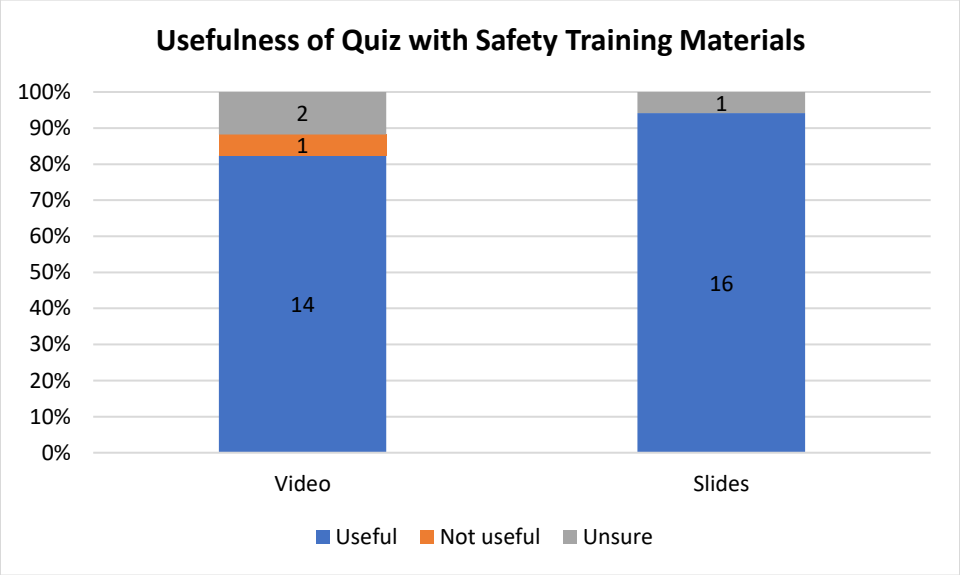

Figure 93. Participant perceptions of usefulness of a quiz included with training materials.

Participants were also asked to compare the safety training materials that they reviewed prior to the ride to a tutorial that is currently used by an e-scooter company. For the participants in the video groups, 8 participants felt that it was an improvement, 5 participants did not think that it was an improvement, and 4 participants were unsure. In the PowerPoint groups, 2 participants felt that it was an improvement, 13 participants felt that it was not an improvement, and 2 participants were unsure. These results can be seen in **Figure 94**.

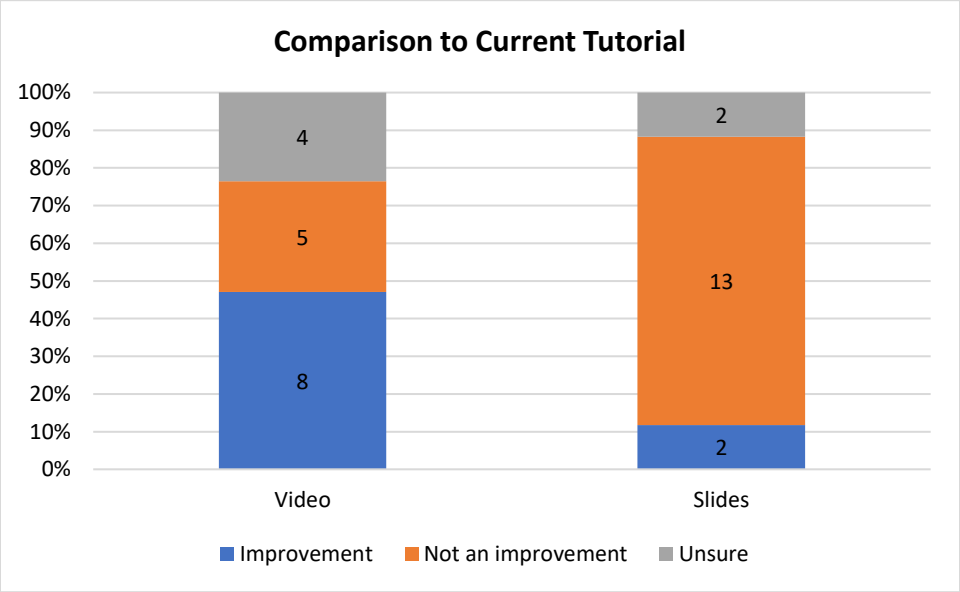

Figure 94. Participant perceptions of safety training materials compared to current tutorial.

Discussion

The following sections discuss the riding metric results, as well as the results from the focus groups and surveys.

Riding Data

While some interesting trends were observed in the riding data, it should be noted that due to the lack of uniformity between the two riding paths, as well as each of the eight segments within the paths, there is a large amount of confounding in the results. Segmentation of the paths did help to reduce any confounding due to participants needing to stop due to yielding to motor vehicles, but it is possible that they encountered pedestrians or cyclists on the paths which may have affected their riding behaviors. These considerations will be discussed further below.

In the beginning of each focus group session, participants were asked if they felt comfortable during the ride. All participants did feel comfortable, but in general, it was agreed that comfort increased over time and that it took about a minute to get used to riding the e-scooter on the first ride to get a feel for the accelerator throttle sensitivity. This riding data was analyzed to see if this trend was captured.

A general trend was observed that average and maximum speed increased during the first three segments of the first ride. This may be due to a steep learning curve, as well as riders gaining confidence and feeling more comfortable operating the e-scooters with added experience; however, it is possible that the actual riding segment may have also affected the speed that the e-scooter was able to reach. As the segments

were mirrored (i.e., segments 1 and 8, 2 and 7, 3 and 6, and 4 and 5 were the same sections of path), similar experience between each pairing should be expected due to each containing the same features and conditions, but slope may have varied slightly. For the first ride, segments 1/8 and 2/7 had additional bumps and were narrower, while segments 3/6 and 4/5 were smoother and wider which may explain why the speeds were fastest on these segments. With this in mind, the main differences seen were between segments 1 and 8 and segments 2 and 7, possibly indicating that riders traveled at higher speeds in the later segments compared to the earlier ones due to additional time riding and experience.

Trends were also seen with average and maximum speed between different groups. Male riders rode at the fastest speeds, followed by riders with 1-3 previous rides of experience, then riders who reviewed the PowerPoint and video training materials, then riders with no experience, and then female riders. Given that these groups are not mutually exclusive, these results are not surprising. In the *E-Scooter Design: Performance and Safety Evaluation* study, it was seen that time to complete the Handling, Stability, and Maneuverability course varied based upon gender, with male riders completing the course significantly faster than female riders, and by experience, with experienced riders completing the course faster than novice riders. Speed may not necessarily indicate comfort or safety though. Excessive speed has been a reported contributing factor to crashes and injuries (City of Austin, 2019) and could possibly explain why male riders are more frequently injured while riding an e-scooter than female riders (Dwyer et al., 2021).

Trends were less consistent with the steering and leaning angle errors. The largest steering angle errors occurred during the first and eighth segments of the ride and the largest leaning angle errors occurred during the eighth segment of the ride. This is very likely due to the individual features and conditions found during each segment of the riding path, and the U-shaped curves on the figures further indicate this since the segments were the same, only ridden in the reverse direction. Riders who reviewed the PowerPoint and riders with no previous experience had the largest steering and leaning angle errors during the first segment of the ride. This could possibly suggest that the video training was more successful in teaching proper riding techniques, such as stability, than the PowerPoint, as videos have been proven to aid with procedural learning (Fiorella and Mayer, 2018). Riders with no experience were also more unstable, especially in the beginning, compared to riders with some previous experience. Similarly, trends were not consistent with steering and leaning entropy. Steering and leaning entropies were the greatest during the first and eighth segments for riders who reviewed the PowerPoint and male riders. As the entropy terms are a function of steering and leaning angle error, it makes sense that participants who reviewed the PowerPoint had large entropy values. Male riders may have also been riding in a more unstable or uncontrolled manner. One additional possible solution for some of the elevated steering and leaning angle errors or entropies could relate to speed. A few of the groups that traveled at higher speeds also had higher entropies, which may be correlated and merits further investigation.

When comparing the two rides, the average speed during ride 2 was slower than the average speed during ride 1. This can very likely be attributed to the riding path, as the second riding path was more challenging compared to the first riding path and was meant to expose participants to more interesting road features and situations. However, when comparing the maximum speed between the two paths, the maximum speed for ride 2 was faster than the maximum speed for ride 2 except for the female riding group, likely indicating improved experience and comfort but more difficulty with the riding path. The steering and leaning angle errors were smallest for females during ride 2 and largest for males during ride 2, possibly indicating that additional caution that females took or lack of caution that males took during the second ride. And for steering and leaning entropies, both riders with no experience and female riders had the

lowest entropies during the first ride, while riders with no experience or who reviewed the PowerPoint had the largest entropies during the second ride. This is likely due to rider attitudes associated with the perceived risk of the first ride, such that riders with no experience or female riders perceived additional risk and decided to take their first ride more cautiously than the other groups. However, the high entropies for the riders with no experience or who reviewed the PowerPoint on the second ride could be attributed to participants either being more nervous or overconfident during the second ride, either of which could result in less stable riding.

Finally, additional previous experience with similar devices was seen to result in riders traveling at faster speeds or having less steering entropy. This result shows that previous experience is an important factor when analyzing novice rider behavior. It also helps to validate that the metrics chosen for this analysis are appropriate but could use additional refinement.

Focus Groups and Surveys

From the pre-session questionnaire results, novice e-scooter riders value available safety training or instructions as well as having safe places to ride, as these were common responses among the multiple questions. Other studies have also shown that including bike lanes also lead to improved perceptions of safety (NATCO, 2020; Sanders, 2020). This theme was also common in the focus group sessions, with many riders indicating their perceptions on the importance of knowing where to safely ride an e-scooter. The large number of selections for improving training materials and making training available for e-scooters was also a very promising result, validating the purpose of this study.

In the focus group sessions, overall, participants found that the training materials were useful and helped to provide valuable feedback for improving its application and designing optimal training materials for e-scooter riders. Length of the training was a very important aspect. Most participants (19/34) found the training to be too long, and approximately equal amounts of participants felt this way for both the video and the PowerPoint. This result was expected as the goal was to provide participants with an extremely thorough and detailed set of training materials for them to review and then ask about which sections that they found the most important or necessary. Participants stated that they would prefer a video that was under 1 minute in length or a shorter set of slides that focused more on the key aspects and that would also allow them to review the materials at their own pace. This is in line with results from previous studies on instructional videos which recommends segmenting, or breaking up a presentation, into meaningful segments and allowing the learner to control when to proceed (Fiorella & Mayer, 2018). They also mentioned that a few of the sections were self-explanatory based upon previous experience and that a few topics went into more depth than what was needed for a first-time rider. However, most participants did note that the longer materials would be useful to include as supplemental resources for riders that were especially interested or concerned about the safe operation of the e-scooter. Participants also stated that appropriate length for the training materials was highly dependent upon the situation. For instance, if they were to purchase an e-scooter or have plans to begin using e-scooters as a frequent mode of transportation, they would prefer longer and more-detailed training materials such as the ones provided during the session. However, if they were just spontaneously renting an e-scooter, they would prefer a shorter set of safety instructions to review. Several participants noted that if they were in a rush to get to their destination, having to review large amounts of material would be inconvenient and irritating. A suggestion was made to ask riders about their previous experience or to provide a table of contents that would allow them to review the sections that they needed. However, many participants responded to this idea saying that it would be an easy way for riders who did not want to take the time to review the

materials to exploit the system. Participants who felt that the training was the right length thought that all the information included was necessary and useful, and especially for the PowerPoint, riders would be able to take as much or as little time to review it.

Most participants felt that the training materials were practical (22/34), and participants who watched the training video felt it was more practical than participants who reviewed the PowerPoint (13/17 and 9/17, respectively). This difference in perceived practicality likely related to the added benefit of the visual demonstrations of riding tasks found in the video. Overall, most perceptions of practicality related to the length of the training. While participants felt that novice riders should be reviewing all the included material to be safe, it was mostly a matter of taking the time to review it all before renting an e-scooter, which could be inconvenient if in a rush. If they were required to review the materials at their current length a day before riding, it might be more practical. Participants believed that a more condensed version of the training would be the best application.

For participants in the training video groups and training PowerPoint groups, the Safety Equipment section was rated as one of the least useful (1.76 and 1.53, respectively or between slightly useful and moderately useful). While most participants agreed that it was a useful reminder and definitely needed to be included, the level of detail in this section could be reduced, as most people will either choose to wear safety equipment or not and the information included would not change their mind. However, several participants did note that the statistic about head injuries would encourage them to want to use safety equipment. Additionally, as most trips are unplanned (Behavioral Traffic Safety Cooperative Research Program, 2022), riders typically do not carry safety equipment with them, and most shared scooter services do not include safety equipment such as a helmet with the scooter. Companies should consider including safety equipment with the scooter that is self-cleaning to reduce sanitary issues and also to help improve the safety for e-scooter riders.

The Getting Ready to Ride section was rated in the middle for usefulness between both groups of participants (2.47 for the video and 2.53 for the PowerPoint, which was between moderately useful and very useful). There were very similar comments across all focus groups, which were that knowing the rules and regulations, especially riding location, was important and something not commonly known by many people. Participants did request that instead of including a resource for the riding policies, it would be more beneficial to have the specifics listed in the training itself. The two training materials were made to be somewhat generic to fit multiple locations, and therefore this information was left more general. While some participants felt that it would be easy to figure out the controls of the scooters, others thought that it was useful to include, specifically understanding the braking system as that can vary widely by scooter.

The Starting Your Ride section was the most useful section for the groups that received the PowerPoint (3.18, or just above very useful) and second most useful section for the groups that received the video (3.06, also just above very useful). Many participants stated that they would not have known that they need to begin kicking off with the scooter before applying the throttle, and some participants who did not pay attention to this portion of the training struggled with it when starting their first ride. Considering that this section included the fundamentals for riding an e-scooter, many participants thought that this was the most important section. For a few participants in the PowerPoint groups, they felt that to fully understand how to apply this portion of the training, they would need to actually do it. Murthy et al. (2008) also found that having an opportunity to practice improves learning by providing meaningful context. Most participants in the video groups did not feel this way, likely due to the added benefit of

being able to see a visual demonstration in the video. Across both groups, it was noted that the level of necessary detail to include may vary based upon previous experience.

The Riding section had the greatest difference between the groups that received the video and the groups that received the PowerPoint. For the groups that received the video, this section was rated the highest (3.47, between very useful and extremely useful) and the second highest for the groups that received the PowerPoint (2.88, just below very useful). This difference was likely attributed to the visual aspect of the training video. Participants felt that they benefitted from watching a demonstration of riding maneuvers and how to approach certain road infrastructure, which is once again in line with the findings from Fiorella and Mayer (2018). Several comments were made that new riders may be nervous about encountering specific obstacles in the roadway, so having this information helped to inspire confidence. For the participants in the PowerPoint groups, while they agreed that having advance knowledge on how to maneuver obstacles was useful, it was still something that they would need to experience to be able to fully understand. Overall, there were mixed opinions about the amount of material included in this section. For instance, some participants felt that providing details about the interaction between the dimensions of the scooter and the road infrastructure was excessive, and that the training should be structured to include only advice related to the specific scooter that is being used but not necessarily the mechanics behind the interactions, while others enjoyed learning about the extra details, indicating different individual preferences. In two of the sessions, comments were made that including information about maneuvering certain obstacles, such as riding off curbs, is something that should not be included in a first-time training for novice riders as this may be encouraging risky behavior. While the intention of this section of the training was to acknowledge that these maneuvers are risky and provide tips for successfully traversing them in case they cannot be avoided, it was agreed that including this information as a supplemental resource would likely be the better option.

The Ending Your Ride section was the part of training that participants found the second least useful (2.18 for video and 1.82 for PowerPoint, right around moderately useful). Similar to the Safety Equipment section, some participants felt that it should be fairly intuitive to know where to leave a scooter so that it is not blocking access for any road users. However, it was also argued that due to the number of reports or first-hand observations of improper scooter parking, it might not be as obvious for some users, and including a brief summary of the parking policies would be necessary, especially if a company has specific procedures or locations for leaving the scooter or if it varies by city. While having specific instructions at the end of the ride are also needed, including them at the beginning for riders to have in the back of their mind could be beneficial.

Across both sets of training materials, participants felt that including a quiz for first time riders would be useful (30/34). It was agreed that knowing that there would be a quiz would ensure that riders would pay attention while reviewing the materials and could be a good reminder of the key safety points. Including an evaluation has been shown to improve the transfer of training (Thayer and Teachout, 1995). A quiz would also prove that riders have some understanding on how to safely operate an e-scooter, regardless of how thoroughly they reviewed the materials, and this would also keep them and other road users safe by not allowing those who fail the quiz to ride until they get the answers correct. Participants who thought that a quiz would not be useful or were unsure mainly felt that some people do not like to take quizzes which could deter potential riders, especially if the training was already long. Slightly more participants in the video group than the PowerPoint group had this opinion, which they attributed to the fact a video would require additional time to listen for the correct response, where as with other formats such as the

PowerPoint, it is easy to return to the information and find the answer. One suggestion was to include a quiz before providing the training materials. This way, any participants who felt that they had enough experience and knowledge to operate an e-scooter safely without reviewing the training materials could do so assuming that they passed the quiz. If they got any questions wrong, they would then be directed to that portion of the training. Additionally, this strategy could allow short quizzes to be administered to users with e-scooter apps that were inactive for a long period of time and need to be refreshed on proper techniques and riding policies, as well as for users in new locations since rules and regulations vary in different cities.

Participants were also asked about anything that they would add or remove from the training. For additional information, suggestions included additional information on proper riding etiquette around pedestrians and other road users, as well as specifics on where the e-scooters can be operated. The most common response for information to be removed was that nothing needed to be removed, but that certain sections, such as the safety equipment and ending your ride sections, could be condensed as this information would likely be common sense to most riders. More detailed information included in the riding section, such as advanced maneuvers and understanding how specific scooter features interact with road infrastructure, could be included as supplemental materials for those who want to learn more in-depth about e-scooter riding. Separating this information would also help to discourage novice riders from performing risky maneuvers.

When participants were asked to review a tutorial currently used by an e-scooter company, responses varied. Most participants who received the PowerPoint to review prior to their ride felt that it was not an improvement over the current tutorial (13/17). There were several reasons for this opinion, such that participants felt that both sets of materials contained similar information, but the current tutorial was shorter, took less time to review, and contained more of the information that they felt was necessary. Participants did agree that the PowerPoint would still be useful for those who wanted to review detailed information and it would also depend on the situation, as having additional resources for long-term and frequent use would be beneficial. Most participants who reviewed the video prior to riding felt that it was an improvement over the current tutorial (8/14) due to the visual aspects such as being able to better understand proper riding stance and how certain maneuvers were performed, which inspired confidence in several riders who were nervous before the session. Participants in this group who did not feel that the video was an improvement mainly had that opinion due to the length of the video and preference for a training that they could review in less time, as well as something that they could more easily refer to.

When participants were shown the new set of training materials that they did not review prior to riding, there were also mixed opinions. Those who had been shown the video first and then the PowerPoint felt that the video was more engaging and allowed them to better visualize riding but did like having the PowerPoint as an option based upon individual preference as well as to easily return to and review. Participants who preferred the PowerPoint liked that they could review the materials at their own pace. For the participants who had been shown the PowerPoint and then the video, most felt that the video was too long and similarly liked the slides due to being able to review them faster but did like the visual demonstrations included in the video.

A few riders mentioned during the focus group that they would consider hands-on training, somewhat similar to the study session, if it was available. While not entirely practical in the current scooter-share

system, companies could look into offering user clinics to provide interested potential riders with safe, hands-on riding practice.

Across all six of the focus group sessions, when asked what they felt were the most important aspects of training, the most common responses were to understand the rules and regulations in the area and where to ride the e-scooter, as well as basic riding techniques such as how to start the e-scooter, proper riding stance, and braking. A few of the groups also included that the more advanced skills for maneuvering specific obstacles were important but including that as an additional resource would likely be the best option for keeping the training materials concise and keeping riders engaged.

Conclusions and Final Recommendations

E-scooters are a unique mode of transportation. Despite containing a motor and traveling at speeds up to 15mph, no formal in-person training or licensing is required such as that required for operating a motor vehicle, motorcycle, or a commercial motor vehicle. Even for bicycles, most individuals are taught by their parents as a form of training. This is likely one of the advantages of the shared scooter system, as e-scooters are an extremely convenient transportation option. However, many e-scooter crashes and injuries have been observed, with novice riders contributing to a significant portion of them, causing companies and policymakers to wonder if formal training should be required. This study attempted to understand novice rider perceptions of training materials to identify the best solution for maintaining the convenience of shared e-scooters while also improving safety outcomes.

Overall, there were not significant differences in riding metrics between the video and PowerPoint training groups. This result was somewhat expected, as from the *E-Scooter Design: Performance and Safety Evaluation*, it was seen that riding performance varied highly between individuals, even within the experienced and novice groups. This can be seen in the course time results in Appendix B-7. Predicting riding performance is complex and needs to account for individual experiences, behaviors, and attitudes, such as physical or athletic ability, past use of similar devices, risk perceptions, etc. This study did attempt to account for this through the survey results, but future studies could include additional tests or surveys for improved correlates. The novice riding algorithm could use additional refinement so that performance is less dependent on the riding surface, and future studies could also include a more uniform riding path. Finally, including a knowledge-based exam might provide a more useful metric on how different training methods impact safety instead of riding due to some of the factors discussed above.

As expected, throughout and within each of the study sessions, participants had different perceptions on the ideal training for e-scooter riders based upon individual preferences. Based upon the input from the participants, a hybrid training that utilizes aspects from both the video and PowerPoint formats is recommended. As length of training was an extremely important factor for participants, especially in the current scooter share service system, presenting the information as concisely as possible will be the most effective approach to ensure that riders are provided with the necessary information for safe e-scooter operation while also remaining engaged and not becoming annoyed while reviewing the training. Therefore, to allow riders to go at their own pace, the information will be presented as a PowerPoint or similar format. Sections that riders may find self-explanatory, such as wearing a helmet or appropriately parking the e-scooter, will be very short and contain only bullets or images. As participants found videos useful for understanding riding techniques, short videos or gifs will be included in the appropriate sections to help riders better visualize riding stance or advice for maneuvers. The following training framework for

e-scooter riders is proposed to optimize safety while also not deterring riders by creating a training that does not fit with the current scooter share system (**Figure 95**).

- Start by asking riders if they have prior e-scooter experience. As this training will be presented to riders through the app before their first ride, it is expected that some individuals will be identified as new users due to it being the first time that they downloaded the app. It is possible that they have experience with personal e-scooters or e-scooters owned by other companies that require a different app. Any individuals who respond that they are experienced will be taken to a short quiz, while the novice individuals will be taken to a page with the training materials.
- The short quiz for experienced e-scooter riders will include basic questions regarding proper and safe e-scooter use. Every user will be required to get every question correct on the quiz to be able to ride. If any questions are answered incorrectly, following the quiz results, individuals will be redirected to the corresponding training resources. After reviewing, they will have the chance to correct their mistakes. This will ensure that every rider has at least a basic understanding of appropriate e-scooter use. The questions will include:
    - Should you wear a helmet while riding?
        - Yes/No (Correct answer: "Yes")
    - Where are e-scooters allowed to be ridden?
        - (Answers will vary based upon local regulations.)
    - In the included picture, where are the accelerator and brake controls located on the scooter, and which brake slows which wheel?
        - (The picture will be based upon the e-scooter model that is about to be used and will vary by model. Generally, the accelerator control will be located on the right side of the handlebars, and the brake controls will be located on either or both sides of the handlebars or as a stomp brake on the rear tire.)
    - How do you start the e-scooter?
        - (Multiple options will be provided. The correct answer will be: “Stand on the deck of the e-scooter with one foot while the other foot is on the ground. Keeping your knees bent and leaning forward slightly, use the foot on the ground to slowly push off until the scooter begins to move at a speed of about 3mph. Return the foot on the ground to the scooter deck and begin to slowly apply the scooter accelerator throttle using your thumb. Return your body to a more neutral, comfortable position.”)
    - Which is the appropriate riding stance?
        - (Multiple options will be provided. The correct answer will be: “Stand towards the center or back of the e-scooter with one foot in front of the other, and keep your knees slightly bent.”)
    - How should you interact with any pedestrians or other road users that you encounter?
        - (Multiple options will be provided. The correct answer will be: “Slow down and alert road users that you are approaching by using your voice or the bell. Give the road users as much space as possible while passing, and if necessary, step off the e-scooter and walk around them.”
    - Which are useful strategies for turning?
        - (Multiple options will be provided. The correct answers will be: “Slow down before the turn. Bend your knees and lean your body in the direction that the e-

scooter will be turning before the turn to assist with the maneuver. If needed, release the accelerator throttle and step off the scooter with one or two feet to assist with the turn.")

    - Should you bend your legs when going over bumps?
        - Yes/No (Correct answer: "Yes")
    - Which of the following are appropriate locations to leave the scooter after your ride?
        - (Multiple options will be provided. The correct answer(s) will vary by location but will generally include areas that are not blocking the right of way for other road users and not causing damage.)
    - Which of the following will happen if you do not follow the rules/policies?
        - (Multiple options will be provided. The correct answer(s) will vary by city and e-scooter provided rules and regulations but may include account restrictions and bans, fines, or other penalties.)

- All individuals will be presented with the training materials, whether they are experienced or novice. The experienced riders who pass the quiz will be asked if they would like to review anything in more detail prior to riding. The experienced riders who answer any questions incorrectly will be redirected to the section that got wrong to fix their answers, and then similarly will be asked if they would like to review any other sections in more detail. The novice riders will be required to go through each section. The training materials will continue to be organized in the same order as previously presented in this study with a table of contents that allows users to look into specific sections more efficiently, but the amount of content will be reduced.
    - Safety equipment: single slide stating that wearing a helmet is recommended with an head injury statistic.
    - Getting ready to ride: two slides, the first of which includes the specific policies for the area so that users do not need to be redirected to another website, and the second of which includes a schematic of the e-scooter with the accelerator, brakes, and scooter deck labeled.
    - Starting your ride: two short videos, no longer than 5 seconds each, showing how to kick off and gently apply the accelerator with proper riding stance, and how to brake with proper riding posture.
    - Riding: short videos, no longer than 10 seconds, on riding techniques for turning maneuvers, riding over raised surfaces, and interactions with other road users.
    - Ending your ride: single slide that includes the policies for the company and the area on where to park the e-scooter, as well as a map of any parking locations if applicable
- After novice riders have reviewed the training materials, they will be required to take the same quiz as the experienced riders and get every question correct, otherwise they will be redirected back to the corresponding section of the training.
- Available for all riders through the app will also be several links to additional resources, such as:
    - Map of riding area with geofences and descriptions (typical in most riding apps)
    - Advanced riding maneuvers, such as riding over or off curbs or across different terrain
    - Information on the scooter and its compatibility with certain obstacles
    - Links to riding policies in the location

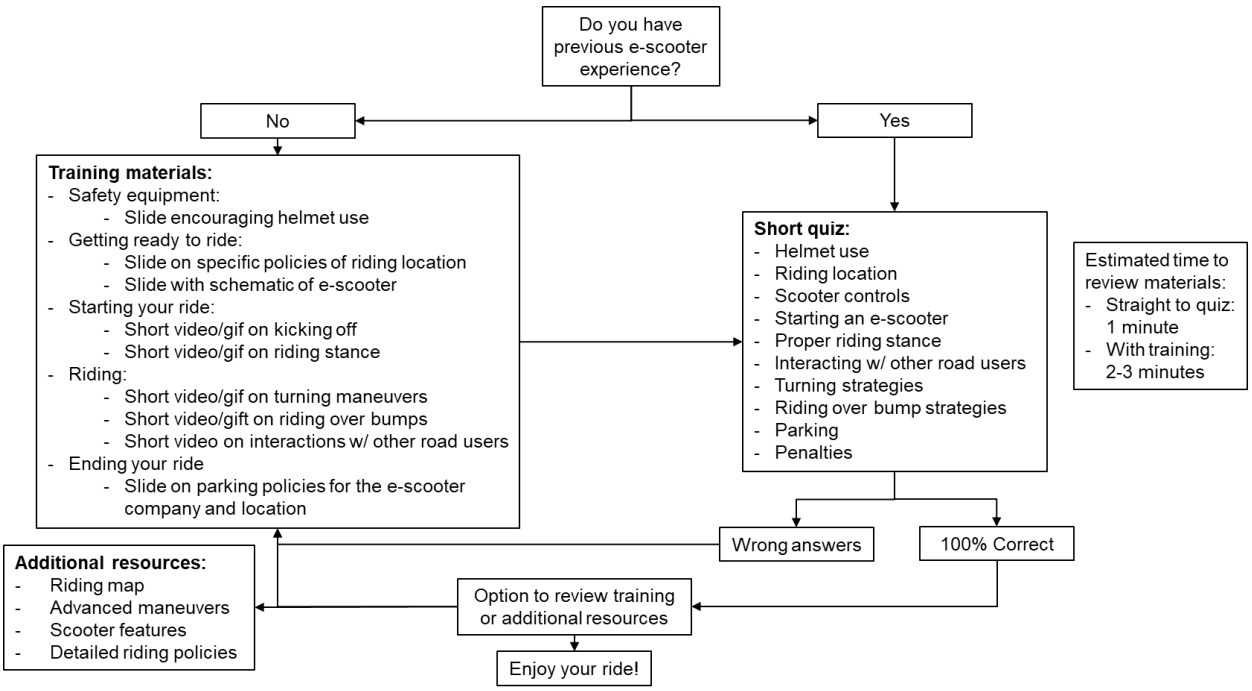

Figure 95. Flowchart for in-app training.

By improving the format and specific information presented to novice riders prior to renting an e-scooter and making additional resources more readily available, it is believed that the knowledge that is obtained will more successfully be transferred to safe real-world riding. As novice riders have been reported to contribute to a large proportion of crashes and injuries, addressing this demographic group should result in significant improvements in safety, not only for the novice riders, but also for the other road users with whom they interact.

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Project Team

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Mike Mollenhauer – primary investigator

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Charlie Klauer – co-investigator

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Chapter 5: Conclusions and Final Recommendations

The introduction of shared e-scooter fleet services to the public has been a complex issue. While e-scooters do have a multitude of benefits, from being a convenient transportation option for a large demographic of users to being environmentally friendly by reducing the number of short distance car trips, there have been a large number of issues associated with their use, mainly related to the safety of e-scooter riders and other road users. These safety concerns started when companies began deploying fleets of e-scooters in cities without their permission. Without any initial research or controlled pilot programs, there were many unanticipated problems that cities and e-scooter companies had to address on the spot and that they are still addressing today.

The results observed from the three studies included in this dissertation point to the main issue: human error and misuse. If used properly, e-scooters are a fantastic micromobility solution. However, issues begin to arise when e-scooters are used inappropriately. From the results observed during the *E-Scooter Safety Assessment and Campus Deployment Planning* study, the naturalistic study that was conducted on Virginia Tech's campus, it was seen that safety relevant conflict events occurred largely due to improper use, such as excessive speed and aggressive riding, unadvisable riding conditions such as non-daylight or riding off-road or on loose surfaces, and unsafe interactions with other road users. Most conflicts were simple fall-over/bailout events which only involved the e-scooter rider, as the most frequent precipitating causes to the conflicts were loss of control due to infrastructure, conflict with a fixed infrastructure element, or loss of control due to an unidentified cause. Unsafe rider behaviors such as multiple riders per scooter, traffic violations, lack of helmet use, and improper parking were also observed. These results point to the e-scooter rider being the problem.

However, user error and misuse should always be expected and accounted for, especially in the design of transportation systems. Therefore, several countermeasures have been identified and proposed to try and reduce the prevalence of these unsafe behaviors. From the *E-Scooter Safety Assessment and Campus Deployment Planning* study, the following deployment policy recommendations were proposed:

- Limiting hours of operation to daylight or improving lighting in the riding environment or on the scooter. It was seen that conflicts were more likely to occur at times with partial light to darkness.
- Improving e-scooter rider education on where e-scooters fit into the current transportation model. Several crashes and near crashes resulted from conflicts with other road users. E-scooter riders need to be instructed on proper riding location and right-of-way regulations.
- Development of methods for training novice e-scooter users or designing e-scooters with added safety benefits. The leading safety critical event that occurred was a simple fall-over or bailout resulting from loss of control without the involvement of another actor, indicating that user error was the cause. Unconventional rider stances observed by the fixed cameras could be a contributing factor. Some form of training or incorporation of a safer model could help to mitigate these events. It was seen that the change from the ES4 to the Max model resulted in lower crash and injury rates due to improvements in the e-scooter design.
- Implementation of software algorithms to flag improper riding behaviors such as aggressive, excessive speed, and trick riding which were seen to contribute to several safety critical events. Placing holds on the accounts of riders who display these behaviors could reduce conflicts.
- Clarification of regulations for e-scooter riders through easy-to-find resources and on-road signage. Many e-scooter riders are either unaware or unclear of the traffic laws regarding proper

e-scooter use due to lack of resources and discrepancies between jurisdictions. It is important to make these rules of operation clear, and incorporation of signs on the road could be an easy way to make riders aware of speed limits and proper riding locations.

- Providing clear instructions on parking, such as the ones provided during this deployment. Parking nuisances can be reduced if riders understand how and where to acceptably park their scooters.
- Stricter enforcement of helmet use. Only 1% of riders were observed to use helmets during the deployment, and several serious head injuries occurred which the use of helmets could have mitigated. E-scooters can reach speeds that become dangerous for the riders given the minimal protection that e-scooters offer riders. Therefore, helmets should be the bare minimum required personal protective equipment.
- Monitoring of item carrying while using e-scooters. Riders were observed to carry items which can affect control of the e-scooter as well as rider balance and dexterity and lead to safety concerns. If conflicts are seen to result from carrying items, regulations should be put into place to ban certain items.

Due to the trend observed from the transition between e-scooter designs during the deployment, the *E-Scooter Design: Performance and Safety Evaluation* study was conducted. This study evaluated several e-scooter designs through benchmark testing that included the observed safety concerns from the deployment to understand design features with the greatest safety benefits. Additionally, by understanding the interaction between the e-scooter and the user, companies can continue to refine their designs so that even if e-scooters are used in ways that they were not intended for or by users with minimal previous experience that they would still be able to perform in a manner that keeps their riders safe. Therefore, from this evaluation, the following design recommendations were proposed:

- **Lightweight**: keeping scooters as lightweight as possible with the necessary components allow for riders to more easily complete turning maneuvers.
- **Short wheelbase**: similarly, scooters that have shorter wheelbases are also better at completing tight turning maneuvers. However, this should be balanced with usable deck length.
- **Long usable deck length**: providing riders with more room to stand allows them to get into a more athletic posture that can aid in completing turns.
- **Short deck height**: as scooters currently store batteries in the deck, which make up most of the weight, it is critical to keep the deck lower to the ground for a lower center of gravity which helps to improve the stability of the scooter.
- **Large tire diameter**: if possible, including larger diameter tires while keeping a lower deck height will help the scooters in traveling over raised surfaces.
- **Adjustable steering axis**: a steeper steering axis requires less input for sharp turns but is also more sensitive, and therefore it is important to consider the target audience when selecting a steering axis angle.
- **Suspension**: including a suspension system was observed to allow scooters to maintain their speed better when riding over raised surfaces and terrain and reduced the vertical acceleration, or mechanical vibrations, that is transmitted to the rider.
- **High ground clearance**: scooters with more distance between the ground and the bottom of the scooter deck were able to maintain their speed better while riding over raised surfaces and had a smaller probability of getting stuck or bottoming out on taller obstacles.

Additionally, observations of experienced rider postures and strategies helped to provide insight on riding techniques that can be recommended for training novice riders during specific riding tasks, such as:

- **Acceleration**: start with legs bent, one foot on the deck of the scooter and the other on the ground and lean forward while kicking off. Return the second foot to the deck of the scooter.
- **Riding**: ride in a stance that is comfortable but anticipate unexpected events such as hard brakes. Keep legs bent, and either stay leaning slightly forward or in a more neutral position.
- **Braking**: bend legs and try to maintain body posture or lean backwards to reduce the shift of weight to the front of the e-scooter.
- **Turning maneuvers**: bend knees and begin leaning in the direction of the turn.
- **Riding off raised surfaces**: bend knees, slightly lift the front of the scooter using hands or arms so that both wheels of the scooter contact the ground at close to the same time to reduce forward pitch.
- **Riding over raised surfaces**: bend knees, lean back and lift the front of the scooter using hands or arms to raise front tire over the raised surface, or slow and use feet to lift front of the scooter over the raised surface.

Finally, to address the issue of human error head on, the *Development of E-Scooter Training* study was performed. As shown during the deployment, many safety-related events were caused by improper use, and while some of these events were intentional, others were due to riders not being properly educated. Most e-scooter trips are unplanned, indicating that riders may not typically take the time to review rules and regulations prior to using them. In the current system, it is impractical to require formal education or training courses for e-scooters, but if safety concerns continue to increase, this may be the best solution. However, it is possible that this may deter users from renting e-scooters which could prove to be the end to shared e-scooter services. Instead, the best method for improving rider education is by optimizing the in-app training that they receive prior to renting an e-scooter. From the focus group sessions, it was determined that a hybrid method of training in PowerPoint or similar format that also includes short videos of riding tasks would be optimal, and the following recommendations are proposed:

- Start by asking riders if they have prior e-scooter experience. As this training will be presented to riders through the app before their first ride, it is expected that some individuals will be identified as new users due to it being the first time that they downloaded the app. It is possible that they have experience with personal e-scooters or e-scooters owned by other companies that require a different app. Any individuals who respond that they are experienced will be taken to a short quiz, while the novice individuals will be taken to a page with the training materials.
- The short quiz for experienced e-scooter riders will include basic questions regarding proper and safe e-scooter use. Every user will be required to get every question correct on the quiz to be able to ride. If any questions are answered incorrectly, following the quiz results, individuals will be redirected to the corresponding training resources. After reviewing, they will have the chance to correct their mistakes. This will ensure that every rider has at least a basic understanding of appropriate e-scooter use. The questions will include:
    - Should you wear a helmet while riding?
    - Where are e-scooters allowed to be ridden?
    - In the included picture, where are the accelerator and brake controls located on the scooter, and which brake slows which wheel?

    - How do you start the e-scooter?
    - Which is the appropriate riding stance?
    - How should you interact with any pedestrians or other road users that you encounter while riding?
    - Which are useful strategies for turning?
    - Should you bend your legs when going over bumps?
    - Which of the following are appropriate locations to leave the scooter after you finish your ride?
    - Which of the following will happen if you do not follow the rules/policies?
- All individuals will be presented with the training materials, whether they are experienced or novice. The experienced riders who pass the quiz will be asked if they would like to review anything in more detail prior to riding. The experienced riders who answer any questions incorrectly will be redirected to the section that got wrong to fix their answers, and then similarly will be asked if they would like to review any other sections in more detail. The novice riders will be required to go through each section. The training materials will continue to be organized in the same order as previously presented in this study with a table of contents that allows users to look into specific sections more efficiently, but the amount of content will vary from the materials used during this study.
    - Safety equipment: single slide stating that wearing a helmet is recommended with a head injury statistic.
    - Getting ready to ride: three slides, the first of which includes the specific policies for the area so that users do not need to be redirected to another website, and the second of which includes a schematic of the e-scooter with the accelerator, brakes, and scooter deck labeled.
    - Starting your ride: two short videos, no longer than 5 seconds each, showing how to kick off and gently apply the accelerator with proper riding stance, and how to brake with proper riding posture
    - Riding: short videos on turning maneuvers, postures for bumps, and interactions with other road users
    - Ending your ride: single slide that includes the policies for the company and the area on where to park the e-scooter, as well as a map of any parking locations if applicable
- After novice riders have reviewed the training materials, they will be required to take the same quiz as the experienced riders and get every question correct, otherwise they will be redirected back to the corresponding section of the training.
- Available for all riders through the app will also be several links to additional resources, such as:
    - Map of riding area with geofences and descriptions (typical in most riding apps)
    - Advanced riding maneuvers, such as riding over or off curbs or across different terrain
    - Information on the scooter and its compatibility with certain obstacles
    - Links to riding policies in the location
    - Other useful resources

E-scooters are truly an excellent transportation option, but it is of paramount importance to ensure that they are safe for all demographics of users. Returning to the van Mechelen (1992) model, the above recommendations represent the completion of step 3, which is to introduce preventative measures. These recommendations can be used by policymakers, cities, communities, and e-scooter providers, and

performing future naturalistic studies will complete 4, which is to assess the effectiveness of the solutions by re-establishing the extent of the problem. I believe that if the above recommendations are incorporated into shared e-scooter fleet services, there will be a reduction in the number of crashes, injuries, and safety critical events, which is the ultimate goal and should help to improve the safety of e-scooters for riders and all road users.

Limitations and Future Directions

While the results provided in this dissertation do provide very useful information for e-scooter policymakers and providers, it is important to reflect upon the limitations of this research as well as future studies that can be conducted to further expand upon these outcomes. The following sections will discuss the limitations of the three previous studies and future directions for continuing to improve e-scooter safety.

E-Scooter Safety Assessment and Campus Deployment Planning Study

The main limitation for this study pertains to the design of naturalistic studies. Naturalistic studies, while capturing true riding behaviors and events, do not allow for scientific control. Each event has many factors that contributed to it, and therefore it is impossible to compare individual events. Factors from each event can be aggregated to understand which most frequently contribute to safety critical events, but there may still be confounding factors within each event.

Additionally, results from the analysis do not represent true rates of prevalence or incidence. Given that during naturalistic studies, large amounts of data are captured, not every event can be reduced. This is why sampling plans are created. The results from sampling are intended to provide a general representation of the expected trends for a population, but it is entirely possible that the effects of major contributing factors are missed during these analyses due to the pure random selection of the baseline events. Sampling plans are created with confidence intervals, and therefore the results do have an associated confidence, but the confidence intervals in this study are not 100%, as are all studies, which should be taken into account.

E-Scooter Design: Performance and Safety Evaluation

The first and main limitation of the results from this study is the selection of scooters that were evaluated. The sponsors from this study chose to evaluate four e-scooter models that they had deployed in cities across the country. The selected scooters had very similar designs and there was overlap with several features. The current analysis was able to identify trends with several design features, but there may be some confounding with the results due to the inability to study and change the dimensions of a single feature at a time while keeping the other dimensions constant. Including additional scooter models with more varied features and dimensions may have assisted with this, as it would have allowed for additional data points to be collected for each design feature. Ideally, it would have been optimal to create a full parametric or multivariate model that could predict the performance of any scooter based upon the included features and dimensions. Future studies could work to expand upon this by including additional scooter models in the testing or creating a model with swappable parts to allow for the effects of individual features to be more easily captured and understood.

A second limitation relating to the scooters was the availability of the models and the condition of the units provided. The Max 2.0 unit did have significant prior use from the on-campus deployment, and it is possible that this affected the strength of the motor which resulted in lower acceleration rates and top speeds. It is possible that the Max 2.0 did not perform as well as the other models due to it being an older model and not relating to previous wear, but unfortunately this is something that cannot be determined. Additionally, one of the Max 2.3 units used during the Speed, Acceleration, and Braking test had diminished braking performance despite having little previous use. While this was accounted for in the analysis by including a scaling factor for the braking rate, it does reduce the accuracy of the results. Both

of these issues highlight an important aspect of e-scooter safety though, which is maintenance. If during this controlled study, diminished performance was observed due to scooters with increased wear or mechanical issues, it is concerning to think about the scooters performing similarly in a real-world environment where performance of the scooter may be critical to preventing an incident. Therefore, future studies should investigate wear on scooters to understand the effects on performance, which will provide useful data to e-scooter providers for when to service their scooters.

Due to some equipment issues, there was some data loss during the sessions. This was accounted for in the analysis by using the Tukey-Kramer method to account for uneven sample sizes. Continuing to improve the DAS system will allow for more reliable data collection in future studies.

The maintenance of the test courses is also something that may have contributed to some differences in the results. While the courses were maintained following each session, it is impossible to ensure that the courses were the same for every single participant, and therefore this should also be a slight confounding factor that is considered with the results.

The subjective nature of the Go-Pro data reduction should also be mentioned. While controls were in place for monitoring the quality of the reduction and working to ensure that each of the reductionists was coding the rider postures consistently, it was still a subjective analysis based upon the judgement of each of the reductionists. If possible, future studies could utilize systems where the rider is instrumented with motion capture or sensor technology to collect more quantitative, objective data on rider posture. This may also help to better understand the anthropometric and biomechanical relationship between the rider and the scooter to further improve designs based upon the physical differences of riders.

As with most participant studies, there is some bias in the data due to the volunteer nature of recruitment. Participants are aware that they will be observed during the study, and only those who are comfortable with that choose to participate. Therefore, the resulting dataset is not entirely representative of the population, but it still does provide some insight into the nature of e-scooter safety.

A final limitation involves the study design. As this was a controlled study in which participants performed tasks in front of researchers, it is very likely that their riding behaviors were different than if they had been riding in an unobserved, naturalistic setting. This is a very common drawback of controlled studies, and unfortunately one that cannot be fixed. Future studies could consider providing participants with various e-scooters and allowing them to ride in a real-world environment, and while this would help to better understand a rider's true behavior, it would induce additional confounding that cannot be controlled for.

Development of Training for E-Scooter Riders

One of the limitations of this study, which was addressed while developing the study design, was the previous experience of the participants. The original idea was to have participants review the training materials and then perform a series of tasks which would be evaluated. However, during the *E-Scooter Design: Performance and Safety Evaluation* study, large variability in riding performance was seen in the novice rider group, and much of this variability can be attributed to previous experiences such as use of similar devices like bicycles or just general physical activity levels or athletic ability. Very few differences in performance between the two training groups were detected, which was expected due to this previous observation.

A second limitation for this study relating to the riding performance metrics was the selection of the riding paths. The riding paths were selected to allow riders to experience real-world riding conditions, but unfortunately introduced some confounding factors due to the lack of homogeneity between the paths as well as between segments within a single path. Interactions with pedestrians and cyclists also may have affected the riding data. Future studies could seek to identify or design a path that is more uniform but still includes a variety of road conditions and features to allow for better comparisons to be made when analyzing riding performance over time.

Evaluating the effectiveness of the training materials proved to be difficult during this study. The purpose of collecting the riding data was to understand if riders would operate an e-scooter in a safer and more controlled or stable manner after reviewing the video or PowerPoint training materials. However, there were many confounding factors in the data due to differences in rider factors (previous experience, gender, etc.) as well as conditions that were not controlled for on the riding paths, such as pedestrian or other cyclist encounters. Looking back, it would have been useful to include a quiz on the materials either before or after the riding portion of the study to test the knowledge of the participants and understand which set of training materials was more useful. Including a baseline group could also be useful for making these comparisons. This could be a possible future direction to further evaluate and improve training materials.

This training study also recruited novice riders who were all college age due to younger riders consisting of the largest demographic of e-scooter users, but future studies may wish to include a wider age range to understand the impact of training for older riders.

Finally, as with any focus group study, the sessions and resulting perceptions can be highly subject to bias from participants and individual preferences. Some participants may have strong opinions and be more outspoken than others which result in their perceptions being voiced more and having the potential to influence the opinions of other participants. While several measures were taken during this study to reduce that effect, such as having participants record their responses prior to vocalizing their opinions and allowing each participant to have the opportunity to speak in an order that was randomized, it is still possible that there was bias.

An additional future study that may be useful is to monitor e-scooter rider performance and provide them with close to real-time feedback. Extrinsic feedback has been observed to improve growth by allowing users to understand the difference between their actual behavior and the desired behavior (Patrick, 1992). Several studies that used real-time and post-hoc feedback for training novice drivers has indicated increases in driving safety (Klauer et al., 2017; Peek-Asa et al., 2016). Therefore, using a similar study design with feedback for novice e-scooter riders could have the potential for improving riding safety and promoting safe behaviors and warrants future investigation.

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Fig. 3. Ishmael, C. R., Hsiue, P. P., Zoller, S. D., Wang, P., Hori, K. R., Gatto, J. D., ... & Bernthal, N. M. (2020). An Early Look at Operative Orthopaedic Injuries Associated with Electric Scooter Accidents: Bringing High-Energy Trauma to a Wider Audience. JBJS, 102(5), e18: 2. https://journals.lww.com/jbjsjournal/Fulltext/2020/03040/An_Early_Look_at_Operative_Orthopaedic_Injuries.13.aspx?casa_token=ZZIwp9r9JSAAAAAA:T76iA1CEavGHYtjqLf6SPUFg06td8ByQC5QE9K8yXHkKTFYA5zsN49SFJmEhrzM1bxij4xlanhA9cVSh16N1YAgR. Used with permission from Wolters Kluwer Health, Inc.; license attached.

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Appendix A: E-Scooter Safety Assessment and Campus Deployment Planning Study

Appendix A-1: Video Reduction Data Definitions

Event severity definitions used in the data reduction process are defined below and are listed in order of event severity.

1. Crash - Any contact that the subject scooter has with an object (including curbs), either moving or fixed, at any speed. This also includes any contact between the ground and the scooter (other than tires) or ground and rider (other than foot).
2. Near Crash - Any circumstance that requires an evasive maneuver by the subject vehicle or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. Near Crashes must meet the following four criteria:
    a. Not a Crash. The scooter must not make contact with any object, moving or fixed, and the maneuver must not result in a road departure.
    b. Not pre-meditated. The maneuver performed by the subject must not be pre-meditated. This criterion does not rule out Near Crashes caused by unexpected events experienced during a pre-meditated maneuver (e.g., a premeditated aggressive lane change resulting in a conflict with an unseen vehicle in the adjacent lane that requires a rapid evasive maneuver by one of the vehicles).
    c. Evasion required. An evasive maneuver to avoid a crash was required by either the subject or another vehicle, pedestrian, animal, etc. An evasive maneuver is defined as steering, braking, accelerating, or combination of control inputs that is performed to avoid a potential crash.
    d. Rapidity required. The required evasive maneuver must also require rapidity. Rapidity refers to the swiftness of the response required given the amount of time from the beginning of the subject's reaction and the potential time of impact.
3. Crash relevant - Any circumstance that requires an evasive maneuver on the part of the subject vehicle or any other vehicle, pedestrian, cyclist, or animal that is less urgent than a rapid evasive maneuver (as defined in Near Crash), but greater in urgency than a "normal maneuver" to avoid a crash. A crash avoidance response can include braking, steering, accelerating, or any combination of control inputs. Crash Relevant Conflicts must meet the following four criteria
    a. Not a Crash.
    b. Not pre-meditated.
    c. Evasion required.
    d. Rapidity NOT required. The evasive maneuver must not be required to be rapid.

Existing crash severity definitions:

Vehicle dictionary

A. Most severe
- Results in injury of rider or other actor resulting in doctor's visit; high delta V (for vehicles it's 20mph) or acceleration +/- 2g

B. Police-reportable
- Includes property damage, acceleration on any axis > +/-1.3g

C. Minor crash

D. Low risk tire strike

Motorcycle dictionary

A. Rider-Ground Impact or Object Impact
- Loss of control

B. Rider-Ground Impact (low speed) or Object Impact
- Control maintained

C. Bike-Ground Impact or Road Departure

D. Low Risk Curb or Object Strike

Appendix A-2: DAS Data Reduction Protocols

Spin Data Reduction

MicroDAS on Scooters

(last updated 6/17/2020)

In this document, the term "anchor point" means the point at which a specified variable is to be assessed:

- For conflicts, this is the Conflict Begin timestamp.
- For Baselines, this is the timestamp one second before the end of the event window.

There will be two separate reduction tasks, both of which are covered in this document. Each section may be accessed by clicking on the numbered item below. The tasks are as follows:

I. MicroDAS Baseline reduction (from scooter MicroDAS data)
   a. These will be sampled by the research team, likely stratified by time of day and day of week, and deployment period (time since deployment began).
   b. Baselines will be 4 seconds long, with an anchor point defined as above.
   c. Potential sampling plan: 2,000
II. MicroDAS Conflict reduction (from scooter MicroDAS data)
   a. This will require pre-reduction, separate reduction task to validate the conflict triggers.
   b. Conflict reduction will include all of the baseline variables, plus additional variables to characterize the conflict and its causes/outcomes
   c. Conflict related variables will include:
      i. Some questions about/around the precipitating event
      ii. Reduction will cover ~3 seconds before Conflict Begin through the Conflict End)
   d. Some questions answered about time between the precipitating event and the actual fall or crash

MicroDAS Baseline Reduction

Infrastructure

1. AnchorPoint. Anchor Point Timestamp. The point (timestamp) that is 1 second (1000 ms) prior to the end of the baseline event window. For dynamically coded variables (the 'event window'), the assessment window starts 3 seconds prior to this timestamp and ends 1 second after. For conflicts, this question is replaced by the "Conflict Begin" variable.
   - Timestamp (text box)
2. ConflictSeverity. Conflict Presence/Severity. Continue reduction regardless of response. If event to be coded is a baseline that contains a conflict, additional reduction may be completed later, but the responses provided here would still be useful.
   - No Conflict
   - Crash - If a baseline event, continue reduction and leave a note in log. This event will need to be switched to the conflict type and queued up for a different (longer) annotation set.

- Non-Crash Conflict - If a baseline event, continue reduction and leave a note in log. This event will need to be switched to the conflict type and queued up for a different (longer) annotation set.
- Unable to determine

3. Intersection. What types of intersection(s) did the subject rider cross or traverse during the event window? (Check all that apply)
    - None - no junction present
    - Unpaved path – path not surfaced with a hard, durable material such as asphalt or cement concrete
    - Sidewalk – that portion of a street or highway right-of-way, adjacent to a roadway, beyond the curb or edge of roadway pavement, which is intended for use by pedestrians. Includes stairway if adjacent to a roadway. Sidewalks are, by definition, adjacent to a roadway. If not adjacent to a roadway, consider the "Shared use path" category.
    - Shared use path – a dedicated pathway that is physically separated from motor vehicle traffic by an open space or barrier (i.e., not directly adjacent to a roadway) and either within the highway right-of-way or within an independent right-of-way. Shared use paths may also be used by pedestrians, skaters, wheelchair users, joggers, and other non-motorized users. Most shared use paths are designed for two-way travel. Shared use paths are paved (asphalt or concrete) paths for pedestrians, bikes, etc., without vehicular traffic immediately adjacent. A local example would be the Huckleberry Trail, Duck Pond trail, or paved paths between residence halls and other campus buildings that are not adjacent to a road way.
    - Driveway – entrance or exit to roadway (from non-roadway) for vehicles (includes parking lot entrances)
    - Roadway, Uncontrolled – Crossing, without a traffic control applicable to the subject, a roadway or roadway intersection, including shoulders, intended for vehicular use. May or may not be on a crosswalk (use of crosswalk is included in RidingLocation variable).
    - Roadway, Stop Sign – Crossing, with a stop sign applicable to the subject, a roadway intersection. May or may not be on a crosswalk (use of crosswalk is included in RidingLocation variable).
    - Roadway, Traffic Signal – Crossing, with a traffic signal present applicable to the subject (regardless of signal phase) a roadway intersection. May or may not be on a crosswalk (use of crosswalk is included in RidingLocation variable).
    - Crosswalk - subject is on roadway crossing a crosswalk (not crossing a roadway using a crosswalk) (area for crossing a roadway designated by pavement markings and, if used, signs.)
    - Other – leave a note
    - Unable to determine – leave a note
4. RidingLocation. What roadway designs were encountered (traversed or traveled on) by the subject rider during the event window? (Check all that apply)
    - Roadway – a lane of a traveled way that is open to both bicycle and motor vehicle travel. If crosswalk also present, either crossing over or traveling on, code that as well.
    - Bike lane – a portion of roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs. It is intended for one-way travel, usually in the same direction as the adjacent traffic lane, unless designed as a contra-flow lane.

- Shoulder - the paved or unpaved (e.g., soft) portion of roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use. Shoulders, where paved, are often used by bicyclists but would not be marked as dedicated to bicyclists. Should be separated from dedicated vehicle lane by painted line, crosshatching, or change in surface type (e.g., a soft shoulder).
- Parking lane – in a roadway designated for vehicular traffic, but within a designated parallel or street-side perpendicular parking area (not to be confused with parking lot below)
- Parking lot – within the boundaries of a designated parking lot
- Sidewalk – the portion of a street or highway right-of-way, adjacent to a roadway, beyond the curb or edge of roadway pavement, which is paved and intended for use by pedestrians. Paved (asphalt or concrete). Includes stairway if adjacent to a roadway.
- Crosswalk - area for crossing a roadway designated by pavement markings and, if used, signs. Also code Roadway if crosswalk is on a roadway (either traveling on or crossing over).
- ADA access ramp – wheelchair accessible
- Shared-use path – a dedicated pathway that is physically separated from motor vehicle traffic by an open space or barrier (i.e., not directly adjacent to a roadway) and either within the highway right-of-way or within an independent right-of-way. Shared use paths may also be used by pedestrians, skaters, wheelchair users, joggers, and other non-motorized users. Most shared use paths are designed for two-way travel. Shared use paths are paved (asphalt or concrete) paths for pedestrians, bikes, etc., without vehicular traffic immediately adjacent. A local example would be the Huckleberry Trail, Duck Pond trail, or paved paths between residence halls and other campus buildings that are not adjacent to a road way.
- Unpaved path – A path maintained for use, but not surfaced with a hard, durable material such as asphalt or cement concrete. Includes dirt/gravel trails.
- No designated path (Off-road) – grass, sand, dirt, or artificial turf with no intentionally designated path. Includes paths worn in by use, but not paths maintained for that purpose.
- Other - leave a note (may include trick riding surfaces)

5. SharedLane. If “Roadway” is coded above, describe the relation of other traffic in the roadway to the subject rider at the anchor point. (Check all that apply) If not a roadway, no traffic is ahead, or subject if just crossing a roadway rather than riding on a roadway, use the applicable NA option.
    - Vehicle ahead: Medium/Far - a motor vehicle directly ahead (same direction, same lane), greater than 1 car length ahead longitudinally
    - Vehicle ahead: Short - a motor vehicle directly ahead (same direction, same lane), less than 1 car length ahead longitudinally
    - Vehicle adjacent: Medium/Far – a motor vehicle adjacent ahead (same direction, adjacent lane), greater than 1 car length ahead longitudinally
    - Vehicle adjacent: Short – a motor vehicle adjacent ahead (same direction, adjacent lane), less than 1 car length ahead longitudinally
    - Vehicle passing: unsafe distance - subject rider is passed by a motor vehicle (same direction) with 3 feet or less lateral distance between them based on vehicle’s estimated trajectory when in view of forward camera

- Vehicle passing: safe distance - subject rider is passed by a motor vehicle (same direction) with more than 3 feet lateral distance between them based on vehicle's estimated trajectory when in view of forward camera
- Scooter passing vehicle: unsafe distance - subject rider passes a motor vehicle (same direction) with 3 feet or less lateral distance between them based on vehicle's estimated trajectory when in view of forward camera
- Scooter passing vehicle: safe distance - subject rider passes a motor vehicle (same direction) with more than 3 feet lateral distance between them based on vehicle's estimated trajectory when in view of forward camera
- Oncoming vehicle: unsafe distance - subject rider passes an oncoming motor vehicle (opposite direction) with 3 feet or less lateral distance between them
- Oncoming vehicle: safe distance - subject rider passes an oncoming motor vehicle (opposite direction) with greater than 3 feet lateral distance between them
- Parked vehicle: unsafe distance - subject rider passes a parked motor vehicle on the roadway with 3 feet or less lateral distance between them
- NA – Not a Roadway – Either roadway is not coded above, or roadway is not the riding the riding location at the anchor point.
- NA – No traffic ahead/adjacent - at anchor point
- NA – Just crossing – just crossing the Roadway, not traveling longitudinally in it

6. SurfaceType. What surface types were encountered (traversed or traveled on) by the subject rider during the event window? (Check all that apply)
    - Asphalt
    - Concrete
    - Rough aggregate surface- small pebbles in hard/compact aggregate, rougher than concrete, but still 'paved' (e.g., sidewalks in front of Squires Student Center)
    - Brick/cobblestone – e.g., pavers, large stones set in sand or mortar
    - Loose Gravel
    - Grass
    - Dirt
    - Mulch
    - Wood planks
    - Artificial turf – is seen on many athletic fields, such as Virginia Tech baseball field
    - Sand – may be seen, for example, on volleyball courts
    - Other – leave a note

Surface Features

For this series of questions, indicate which surface features were encountered (traversed, traveled on) by the subject rider during the event window. Include features that are passed within ~3 feet on the right or left. Do not include features that remain ahead and are never reached within the assessment window. (Check all that apply)

Choices for all of the surface feature variables below (Q7-Q18), unless otherwise noted:

- None (includes not present, passed by without ridden on/through, and/or passed by without by trajectory change)
- Ridden through/on (May or may not have altered trajectory to do so)

- Failed avoidance (Rider attempted to avoid the surface feature, but that attempt failed. This option assumes that the failed attempt resulted in some degree of "ridden through/on" as well, no need to check both unless two different encounters of that feature were encountered and dealt with differently.)
- Avoided (Requires deviation from intended/expected trajectory in order to avoid, which may have occurred prior to the event window and requires review of additional lead-up time. If unclear whether trajectory change is a specific response to the coded feature or not, then do not consider as "avoided" (most likely "None").)
- Unable to determine (leave a note)

7. Stairs. Stairs
8. ADARamp. ADA ramp
9. Manhole. Manhole cover
10. Grate. Grate (e.g., storm drain)
11. SteelPlate. Steel Plate
12. TactilePaving. Tactile paving (e.g., textured surface often installed at the ends of sidewalks before crossing into the road)
13. UnevenDegraded. Uneven surface, degraded/needs maintenance (may include potholes, cracked/shifted pavement, etc. on either sidewalks or roadways; does not include simply riding on dirt, grass, gravel unless unexpected holes or similar are encountered. Does not include surfaces that are uneven by design, such as gravel or textured surfaces). 'Avoided' option must include a deviation from intended trajectory rather than a planned turn.
14. PavementToGrass. Transition - pavement to/from unpaved surface (Pavement may be any type of durable surface. Only consider what would potentially be in the rider's path. So, if just riding parallel to grass without risk of going over the edge, code as None.) 'Avoided' option must include a deviation from intended trajectory rather than a planned turn.
15. SidewalkToRoadCutout. Transition - sidewalk to/from road, curb cutout 'Avoided' option must include a deviation from intended trajectory rather than a planned turn.
16. SidewalkToRoadCurb. Transition - sidewalk to/from road, no curb cutout (i.e., jumped the curb) 'Avoided' option must include a deviation from intended trajectory rather than a planned turn.
17. GravelDirtGrass. Transition – between different unpaved surfaces 'Avoided' option must include a deviation from intended trajectory rather than a planned turn.
18. SurfaceFeatureOther. Other surface features - leave a note if not "None"
19. SurfaceCondition. What conditions were encountered (traversed or travelled on) by the subject rider during the event window? (Check all that apply)
    - Dry
    - Wet
    - Snow/Ice
    - Standing water
    - Loose material/debris (e.g., from degraded paving, mulch/rocks/leaves that have been scattered over an otherwise paved sidewalk/road. Do not use this category if Surface Type is already coded as a loose material such as dirt, gravel, grass, sand, etc.; Code as wet/dry/standing water/etc. as appropriate instead.)
    - Other - leave a note
20. ProximateHazards. To what features or hazards does the rider react (i.e., changed trajectory and/or speed in response) during the event window? (Check all that apply) These are in addition to any surface features coded above.)

- None
- Sidewalk furniture - benches, flowerpots/planters, mailboxes, etc. that appear to have been purposefully placed as part of the infrastructure.
- Parked car: doors closed
- Parked car: door(s) not closed – door(s) are already open or in the process of opening/closing as people are loading/unloading, etc.
- Parked bikes
- Handrails - includes the series of chains between posts that line many campus sidewalks
- Bollards/pylons – e.g., concrete, plastic, or metal posts that separate different areas of the road and/or sidewalk to prevent certain types of traffic from passing through.
- Construction – temporary traffic controls (cones, barrels, etc.)
- Landscaping – something planted or installed in the ground (other than typical, mowed grass); does not include bare mulch (which should instead be coded under Surface Type).
- Sign/Sign post
- Parking meter
- Utility pole
- Buildings – includes opening doors
- Vehicle – not parked
- Pedestrian
- Bicyclist
- Scooter rider
- Dog/Animal
- Other - leave a note

Behavior

21. GroupRiding. Does the subject rider appear to be riding with or as part of a group during the event window? If yes, indicate the group size AND the type of group members. (Check all that apply) This does not include being near others in passing or just because all are going in the same direction; this refers to people intentionally travelling together for a defined time period. May need to examine additional video to confirm.
    - None, rider is independent
    - 1 other
    - 2 others
    - 3+ others
    - Other scooters
    - Bicycles
    - Pedestrians
    - Skateboarders
    - Other – leave a note
    - Unsure - leave a note
22. RidingBehavior. What type of behavior do you suspect the subject rider is engaged in during the event window (for baselines) or just prior (within ~3 seconds) to the start of the conflict (for conflicts)?
    - Normal riding

- Trick riding - includes donuts, wheelies, slalom or weaving just for fun (not aggressively with other users)
- Aggressive riding – includes risky/aggressive/dangerous weaving or speeding, intentionally causing close/unsafe proximity to other users, riding in non-traditional situations in a way generally considered non conducive to scooters, etc.
- Excessive speed (>6.7 m/s) – code if the GPS-Speed exceeds 15 mph (6.7 m/s). Do not code if the GPS.Speed seems unrealistic (e.g., due to poor satellite signal). (For reference, 1 m/s = ~2 mph)

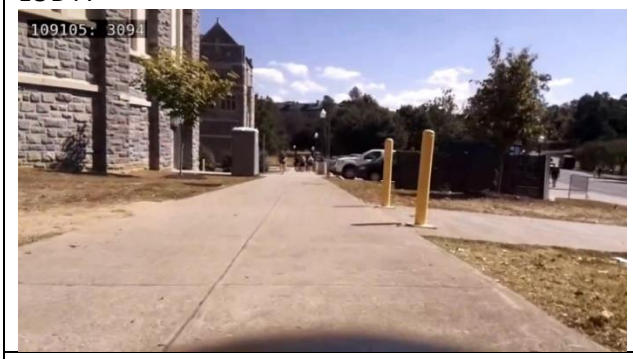
23. OtherActorBehavior. To what type of behaviors from other actors does the subject rider appear to respond? (Check all that apply) Other actors may be other vehicles as well as other scooters, pedestrians, skateboarders, etc. Only code behaviors to which the subject rider appears to respond, whether or not a response is actually needed.
    - None/Normal
    - Vehicle: Aggressive – aggressive motor vehicle behavior. Examples may include (but are not limited to) excessive speed or attempts to inappropriately overtake or cut in front of the subject scooter
    - Vehicle: Possibly Distracted/Inattentive – possibly distracted motor vehicle behavior. Examples may include (but are not limited to) other actors appearing to not look before pulling out of a driveway or turning a corner, failing to stop at a stop sign, encroaching inappropriately into bike lane, or observed texting/talking on phone while driving.
    - Vehicle: Unexpected movements – unexpected motor vehicle movement that do not appear intentionally aggressive. Examples include sudden braking, etc.
    - Other: Aggressive – aggressive behavior by other type of actor (e.g., scooter, pedestrian). Examples may include (but are not limited to) excessive speed or attempts to inappropriately overtake or cut in front of the subject scooter
    - Other: Possibly Distracted/Inattentive – possibly distracted or inattentive behavior by other type of actor (e.g., scooter, pedestrian). Examples may include (but are not limited to) other actors appearing to not look before pulling out of a driveway or turning a corner, failing to stop at a stop sign, encroaching inappropriately into bike lane, or texting/talking on phone while riding/walking.
    - Other: Unexpected movements – unexpected movements by other type of actor (e.g., scooter, pedestrian) that do not appear intentionally aggressive. Examples include pedestrian side-stepping, sudden bicyclist or scooter braking, being cut off by another cyclist, etc.

Trafficway Description

24. LevelOfDemand. What is the level of traffic demand encountered by the subject rider at the anchor point? Assessment of demand should include all actors that are present and relevant to the subject rider's trajectory (e.g., scooters, pedestrians, vehicles, etc.). (Of note, the example images below all show "shared use paths" as defined under the Intersection and Riding Location categories, although the level of traffic demand should be coded in all scenarios using these a guide.)
    - LOD A – No other users or very distance users. Subject rider is likely unaffected by surrounding actors
    - LOD B – One or two other user(s) nearby. Subject rider is required to moderate speed and or steering maneuvers to navigate as a result of other users being present.

- LOD C – Moderate number of other users. Subject rider must maintain close speed and steering control and heightened awareness of numerous users.
- LOD D – Many other users in close proximity. Traffic demand likely exceeds the amount of actors that can be serviced efficiently. Similar to “stop-and-go” conditions found in other types of traffic ways.

LOD A



LOD B

LOD C

LOD D

25. FlowDirection. What is the intended type of traffic at the anchor point, and is the subject rider’s direction and location correct according to regulations/conventions? Location refers to the correct side of the road, sidewalk, or parking lot. Note that this variable does not require the subject rider to match speeds with other traffic.
    - Pedestrian traffic, with flow, slower – sidewalk or other area meant for pedestrians (or similar), subject is going in same direction but going slower than traffic moving in the same direction
    - Pedestrian traffic, with flow, matched speed – sidewalk or other area meant for pedestrians (or similar), subject is going in same direction and matching speed to the other traffic in the same direction
    - Pedestrian traffic, with flow, faster – sidewalk or other area meant for pedestrians (or similar), subject is going in same direction but going faster than traffic moving in the same direction
    - Pedestrian traffic, against flow – sidewalk or other area meant for pedestrians (or similar), subject is going in opposite direction (e.g., likely weaving in/out or requiring pedestrians to give way)
    - Shared vehicle lane, correct direction – same lane used by cars, on the correct side of the road for the direction being traveled

- Shared vehicle lane, incorrect direction – same lane used by cars, on the wrong side of the road for the direction being traveled
- Bike lane, correct direction – designated bike lane, on the correct side of the road for the direction being traveled
- Bike lane, incorrect direction – designated bike lane, on the wrong side of the road for the direction being traveled
- Not Applicable – riding in an area where no flow is expected or (for pedestrian traffic areas) where either no flow exists or flow direction is commingled (not side-of-path specific) or unclear
- Other – leave a note

26. Lighting. Lighting at anchor point.
    - Daylight
    - Partial light (Dawn/Dusk)
    - Darkness, lighted
    - Darkness, not lighted
    - Other
27. PathWidth. Estimate the width of the path on which the subject rider is traveling at the anchor point (sidewalks and shared use paths only).
    - Narrow - 3 feet wide or less (estimating room for no more than 2 side-by-side pedestrians)
    - Moderate - between 3 and 5 feet wide (estimating room for 3 side-by-side pedestrians)
    - Wide - 5 feet wide or more (estimating room for 4 or more side-by-side pedestrians, including wide walking areas and all areas designed for vehicular travel)
    - Unsure – leave a note
    - Not applicable – not a sidewalk or shared use path
28. PathPosition. Location of subject rider on current path at anchor point (sidewalks and shared use paths only).
    - Left side of path
    - Middle of path
    - Right side of path
    - Not applicable – not a sidewalk or shared-use path
29. Notes. Leave notes for any “unknown” or “other” categories or for anything notable not covered under other variables. If a conflict occurs within a baseline, describe it here as well.

MicroDAS Conflict Reduction

For conflicts, all MicroDAS baseline variables are to be coded (those in section I above) in addition to the variables listed in this section.

Incident Description

30. ConflictBegin. Conflict Begin Timestamp. The point (timestamp) in the video when the sequence of events defining the conflict begins. The timestamp at which the Precipitating Event begins. This timestamp is then used as the “anchor point” for all variables that reference the anchor point. For dynamically coded variables, the assessment window starts 3 seconds prior to this timestamp. This question replaces the baseline “Anchor Point” question for conflicts.
    - Timestamp (text box)

31. ConflictEnd. Conflict End Timestamp. The point (timestamp) in the video when the sequence of events defining the conflict ends. The timestamp at which final evasive maneuvers have been completed and all conflict partners have either stopped or resumed normal patterns of travel, whichever occurs first. For dynamically coded variables, the assessment window ends at this timestamp.
    - Timestamp (text box)
32. ConflictMaxSpeed. Max Conflict Scooter Speed (m/s). The maximum speed of the subject scooter starting 3 seconds before Conflict Begin through Conflict End, using GPS.Speed, in m/s. If the GPS.Speed is unavailable or seems unrealistic (e.g., due to poor satellite signal), enter -99. (For reference to determine if realistic, 1 m/s = ~2 mph. The maximum realistic scooter speed can be assumed to be ~7 m/s or ~15mph.)
    - Speed Value rounded to the nearest hundredth (two decimal places) (text box)
33. PrecipitatingEvent. Precipitating Event, if determinable
    - Subject loss of control due to infrastructure – may include causes or a combination of causes due to surface type, surface features, surface conditions coded above; subject loses control due to an infrastructure element (e.g., surface type, surface feature, surface condition) but doesn't actually impact an infrastructure element (other than the ground)
    - Subject loss of control due to excessive speed
    - Subject loss of control, other - leave a note
    - Subject loss of control, unknown- leave a note
    - Conflict with vehicle
    - Conflict with pedestrian
    - Conflict with bicycle
    - Conflict with other scooter
    - Conflict with animal
    - Conflict with non-fixed object – building, trash can, rock, banana peel
    - Conflict with fixed infrastructure element – "conflict with…" entails actually making impact with an infrastructure element (e.g. impacting the edge of the sidewalk/curb when attempting to ride over it)
    - Conflict resulting from carried cargo - if known
    - Other – leave a note
    - Unable to determine - leave a note
34. ConflictType. What type of crash occurred?
    - No impact or fall
    - Simple fall-over/bailout –no other conflict partner or impact present
    - Impact with vehicle
    - Impact with pedestrian – includes pedestrian walking a bicycle
    - Impact with bicycle
    - Impact with other scooter
    - Impact with animal
    - Impact with non-fixed object – e.g., litter, other non-fixed items that are not part of the infrastructural design
    - Impact with infrastructure element – e.g., fixed aspects of the infrastructure such as buildings, sign posts, mailboxes, curb/raised sidewalk, etc.
    - Other – leave a note
35. ConflictRole. What role did the subject rider play in the conflict?

- Struck (or would have struck)
- Struck by (or would have been struck by)
- Non-striking scenario
- Unknown – leave a note

36. ConflictOutcome. How did the scooter fall as a result of the conflict?
    - Fell to the left - making impact with the ground
    - Fell to the right - making impact with the ground
    - Fell forward – rear wheel up or fell over handlebars, making impact with the ground
    - Fell backward – front wheel up or fell over rear wheel, making impact with the ground
    - Combination of above – leave a note
    - Did not fall/remained on scooter
37. ConflictFault. Which conflict partner is at fault? Indicates which conflict partner (scooter, bicycle, pedestrian, vehicle, etc.), if any, committed an error that led to the conflict. Only code a fault if there is observable evidence. Note: Objects and animals cannot be assigned fault; such events are coded as 'subject at fault' or 'no fault'.
    - Subject rider - The rider of the subject scooter committed the error that led to the event. Use this option for loss of control scenarios.
    - Other conflict partner – Another conflict partner (other vehicle, pedestrian, scooter, etc.) committed the error that led to the event.
    - Shared fault - More than one conflict partner committed errors that contributed to the event.
    - No fault - No user errors were committed any errors that led to the event. This is often (but not always) true for animal-related conflicts and objects in the roadway, especially if the conflict cannot be reasonably anticipated or that does not allow for sufficient reaction time given safe riding patterns.
    - Unable to determine - Cannot determine the fault due to limitations in video views, lighting, visual obstructions, or limited perspective, or cannot make a judgment as to whether one user was completely at fault.

Behavior

38. RideStatus. What did the subject rider do just after the conflict ended?
    - Continued riding, no stop – scooter did not fall and did not come to a stop
    - Stopped briefly, resumed – scooter may or may not have fallen, but does come to a stop and resumes riding prior to the end of the video
    - Stopped altogether – video ends
    - Other - leave a note
39. FinalNarrative. Provide a brief description of the conflict, and leave notes for any "unknown" or "other" categories or for anything notable not covered under other variables.

Appendix A-3: Fixed Camera Data Reduction Protocol

Spin Data Reduction

(last updated 7/17/2020)

In this document, the term "anchor point" means the point at which a specified variable is to be assessed:

- For conflicts, this is the Conflict Begin timestamp.
- For Baselines, this is the timestamp one second before the end of the event window.

There will be four separate reduction tasks, all of which are covered in this document. Each section may be accessed by clicking on the numbered item below. The tasks are as follows:

III. Fixed camera Baseline reduction (from stationary cameras affixed at key locations on Virginia Tech campus)
    a. These will be sampled by the research team and imported into a Hawkeye-accessible format by the IT Developer team. Likely stratified by camera and representative of frequency of scooter trips through each camera FOV, time of day, day of week, and deployment period (time since deployment began).
    b. Baselines will be 4 seconds long with an anchor point defined as above. In the case where the referenced rider is not in the fixed camera view for the entire 4s window, then the referenced rider will be assessed for the duration that it is visible within the assessment window (up to 4s maximum)
    c. Potential sampling plan: 1,200

IV. Fixed camera Conflict reduction (from stationary cameras affixed at key locations on Virginia Tech campus)
    a. This will require first that conflicts be identified during the baseline reduction (above). Then, identified conflicts will undergo a separate conflict reduction task.
        i. This will include crashes and non-crash conflicts
        ii. It is unknown how many of these conflicts will be identified, and the number assessed may need to be determined based on how many are identified
    b. Because the baseline reduction codes information for up to 6 riders, the conflict reduction will be performed on a separate event ID, using the conflict bounds to define the conflict assessment window.

Fixed Camera Baseline Reduction

First answer Q1, and then answer questions 2-7 for all scooters in view. (If there are 4 scooters in view during the assessment window, Q1 will be answered once, and Qs 2-7 will each be answered 4 times.)

1. ScooterCount. How many scooters are seen in the video during the 4 second event window? (Enter number, user -99 if unable to determine)

- Integer (text box)

For the questions that follow, number the scooters as defined here: in the first frame of video in the assessment window (i.e., at the start of the 4 seconds), number the visible scooters from a clockwise fashion starting from the 12:00, outermost position. Then, number any additional scooters as they

come into the video view during the event window. Code the first 6 scooters that are numbered using this system.

2. Rider(1-6)Gender. What is the gender of the referenced scooter rider?
    - Male
    - Female
    - Unable to determine
3. Rider(1-6)Age. What is the estimated age of the referenced scooter rider?
    - Typical college student
    - Older – appears to be older than typical college student
    - Younger – appears to be younger than typical college student
    - Unable to determine
4. Rider(1-6)WearingHelmet. Is the referenced scooter rider wearing a helmet?
    - Yes
    - No
    - Unable to determine
5. Rider(1-6)WearingBag. Is the referenced scooter rider wearing a backpack or other type of bag? Includes purse, sidebag, etc., that is hanging on one or more shoulder or in some way strapped to the rider's body (e.g., around waist).
    - Yes
    - No
    - Unable to determine
6. Rider(1-6)HandheldItem. Is the referenced scooter rider carrying a hand held item? Includes phone, grocery bag, water bottle, etc., that is held in hand or similar (e.g,, supported by wrist or lower arm).
    - Yes
    - No
    - Unable to determine
7. Rider(1-6)HandlebarItem. Does the referenced scooter rider have an item hanging from or otherwise supported by the handlebars?
    - Yes, hanging from one handlebar
    - Yes, hanging from both handlebars
    - Yes, balanced on top of handlebars
    - Yes, Other - leave note
    - No
    - Unable to determine
8. Rider(1-6)Hands. How many hands does the referenced scooter rider have on the handlebars at the anchor point?
    - None
    - One
    - Two
    - Unable to determine
9. Rider(1-6)RidingStance. How are the feet and body positioned on the scooter at the anchor point? (check all that apply) Must check at least one center of gravity location (Front vs Center/Back) AND one foot position (fore/aft vs side to side) option, or if one of these is unknown, code the one that is known plus the unable to determine option.

- Front – the rider's center of gravity is towards the front of the scooter (2" of space or less between the rider's hips and the scooter stalk)
- Center/Back - the rider's center of gravity is in the center or rear part of the scooter (more than 2" of space between the rider's hips and the scooter stalk)
- Feet fore/aft – one foot is placed in front and one in back on the scooter footboard
- Feet side to side – both feet are placed next to each other on the scooter footboard
- Unable to determine

10. Rider(1-6)RidingBehavior. Is the referenced scooter rider participating in the following behaviors during the assessment window? (check all that apply)
    - None
    - 2+ riders/scooter – if this is the case, other questions should consider the rider in control only or the lead rider if control is unclear
    - Trick riding - includes donuts, wheelies, slalom or weaving just for fun (not aggressively with other users)
    - Aggressive riding – includes aggressive/dangerous weaving or speeding, intentionally causing close/unsafe proximity to other users, etc.
    - Sign/Signal violation(s) – referenced rider violates at least one stop sign or traffic signal during the assessment window
11. Rider(1-6)RidingLocation. Where is the referenced scooter rider operating the scooter during the assessment window? (check all that apply)
    - Roadway – a lane of a traveled way that is open to both bicycle and motor vehicle travel. If crosswalk also present, either crossing over or traveling on, code that as well.
    - Bike lane – a portion of roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs. It is intended for one-way travel, usually in the same direction as the adjacent traffic lane, unless designed as a contra-flow lane.
    - Shoulder - the portion of roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use. Shoulders, where paved, are often used by bicyclists but would not be marked as dedicated to bicyclists. Should be separated from dedicated vehicle lane by painted line, crosshatching, or change in surface type (e.g., a soft shoulder).
    - Parking lane – in a roadway designated for vehicular traffic, but within a designated parallel or street-side perpendicular parking area (not to be confused with parking lot below)
    - Parking lot – within the boundaries of a designated parking lot
    - Sidewalk – the portion of a street or highway right-of-way, adjacent to a roadway, beyond the curb or edge of roadway pavement, which is paved and intended for use by pedestrians. Paved (asphalt or concrete). Includes stairway if adjacent to a roadway.
    - Crosswalk - area for crossing a roadway designated by pavement markings and, if used, signs. Also code Roadway if crosswalk is on a roadway (either traveling on or crossing over).
    - ADA access ramp – wheelchair accessible
    - Shared-use path – a dedicated pathway that is physically separated from motor vehicle traffic by an open space or barrier (i.e., not directly adjacent to a roadway) and either within the highway right-of-way or within an independent right-of-way. Shared use paths may also be used by pedestrians, skaters, wheelchair users, joggers, and other non-motorized users. Most shared use paths are designed for two-way travel. Shared

use paths are paved (asphalt or concrete) paths for pedestrians, bikes, etc., without vehicular traffic immediately adjacent. A local example would be the Huckleberry Trail, Duck Pond trail, or paved paths between residence halls and other campus buildings that are not adjacent to a road way.
    - Unpaved path – A path maintained for use, but not surfaced with a hard, durable material such as asphalt or cement concrete. Includes dirt/gravel trails.
    - No designated path (Off-road) – grass, sand, dirt, or artificial turf with no intentionally designated path. Includes paths worn in by use, but not paths maintained for that purpose.
    - Other - leave a note (may include trick riding surfaces)
12. Rider(1-6)VehicleInteraction. How is the referenced rider interacting with motorized vehicles in the roadway during the assessment window? (check all that apply) (this question applies only if roadway, bike lane, shoulder, parking lane, or parking lot are coded above.)
    - Scooter passes parked cars – referenced rider is at risk of being hit by vehicle driver opening a car door or pulling out
    - Scooter overtakes vehicle – referenced rider goes around a slow or stopped motorized vehicle (e.g. bus at bus stop, car waiting to park or make a turn, etc)
    - Scooter crosses in front of vehicle – referenced rider crosses in front of a non-parked motorized vehicle, at a crosswalk, at a driveway, while making a turn, or otherwise
    - Vehicle passes moving scooter, different lane initially – a motorized vehicle drives past the referenced rider while the scooter is in motion in the bike lane or parking lane
    - Vehicle overtakes moving scooter, same lane initially – a motorized vehicle goes around the referenced scooter while the scooter is in motion using a shared travel lane (i.e. to go faster)
    - Vehicle passes standing scooter – a motorized vehicle drives past the referenced rider while scooter is standing still (e.g. waiting to cross road, looking at phone, etc)
    - Vehicle crosses in front of scooter – a motorized vehicle crosses in front of the scooter, at a crosswalk, at a driveway, while making a turn, or otherwise
    - Other - leave a note
    - Unable to determine
    - NA – Location type not applicable to motorized vehicles – rider is not riding on a roadway, bike lane, shoulder, parking lane, or parking lot.
13. Rider(1-6)RidingMode. What operating rules is the scooter rider following during the assessment window? (check all that apply) (this question applies only if roadway, bike lane, shoulder, parking lane, parking lot, sidewalk, crosswalk, access ramp, or shared use path are coded above.)
    - Behaving like a car – scooter is in a lane with cars and following the rules of the road like a car driver
    - Behaving like a bike – scooter is using a bike lane, parking lane, or shoulder, and traveling in the same direction as cars, and behaving as one would expect for that location
    - Behaving like a pedestrian – scooter is using the sidewalk, crosswalks, access ramps or shared use path, and behaving as one would expect for that location
    - Behaving unexpectedly or mixed – not following expected behaviors of the mode currently in use (e.g., cutting across lanes of traffic, jumping over curbs, doing U-turn in the middle of the road, etc.) or shifting between behavior modes.
    - Other – leave note

- Unable to determine
- NA – Not subject to specific rules– rider is not riding on a roadway, bike lane, shoulder, parking lane, or parking lot.

14. Rider(1-6)ConflictSeverity. Conflict Presence/Severity (for referenced rider). Was the referenced rider involved in a conflict during the assessment window?
    - No Conflict
    - Crash – includes falling over or making contact with any object, vehicle, or person. This will be further processed and the variables under "Fixed camera Conflict reduction" will be coded accordingly.
    - Non-Crash Conflict – includes nearly falling over, swerving or stopping abruptly to avoid a crash, or causing another vehicle/pedestrian/scooter to swerve or stop abruptly to avoid a crash. This will be further processed and the variables under "Fixed camera Conflict reduction" will be coded accordingly.
    - Unable to determine
15. Rider(1-6)ConflictEvent. If a conflict is coded as present above, then once the conflict is reduced, come back and enter the new Event_ID of the conflict here. (Note, this will be left blank until the new conflict event is created and reduced, but will be populated once the conflict has been fully processed.)
    - Event_ID of conflict (text box), leave null if referenced rider is not involved in a conflict
16. Notes. Leave notes for any "unable to determine" or "other" categories or for anything notable not covered under other variables. If a conflict occurs within a baseline, describe it here as well.

Fixed Camera Conflict Reduction

For conflicts seen in the fixed camera baseline reduction, the variables in this section will also coded during separate conflict reduction task. Because a new Event_ID will be assigned to each conflict, the first couple of variables are used to link the baseline event where the conflict was seen to the conflict event coded here.

Conflicts includes both crashes and near misses (non-crash conflicts). These are incidents where the scooter rider:

- Falls or nearly falls over
- Swerves or stops abruptly to avoid a crash
- Causes another vehicle or pedestrian to swerve or stop abruptly to avoid a crash
- Has contact with any object, vehicle, or person

Incident Description

17. FixedBaselineEvent. Enter the Event_ID of the baseline event where this conflict was coded to a referenced rider.
    - Event_ID of corresponding fixed cam baseline (text box)
18. RiderReference. Enter the Referenced Rider number(s) involved in the conflict. If two riders from the referenced baselines were involved in the conflict, then enter both numbers separated by a comma but not space (e.g., "2,3")
    - Rider reference number(s) (text box)

19. ConflictBegin. Conflict Begin Timestamp. The point (timestamp) in the video when the sequence of events defining the conflict begins. The timestamp at which the Precipitating Event begins. This timestamp is then used as the "anchor point" for all variables that reference the anchor point. For dynamically coded variables, the assessment window starts 3 seconds prior to this timestamp. This question replaces the baseline "Anchor Point" question for conflicts.
    - Timestamp (text box)
20. ConflictEnd. Conflict End Timestamp. The point (timestamp) in the video when the sequence of events defining the conflict ends. The timestamp at which final evasive maneuvers have been completed and all conflict partners have either stopped or resumed normal patterns of travel, whichever occurs first. For dynamically coded variables, the assessment window ends at this timestamp.
    - Timestamp (text box)
21. PrecipitatingEvent. Precipitating Event, if determinable
    - Subject loss of control due to infrastructure – may include causes or a combination of causes due to surface type, surface features, surface conditions coded above
    - Subject loss of control due to excessive speed
    - Subject loss of control, other - leave a note
    - Subject loss of control, unknown- leave a note
    - Conflict with vehicle
    - Conflict with pedestrian
    - Conflict with bicycle
    - Conflict with other scooter
    - Conflict with animal
    - Conflict with non-fixed object - trash can, rock, banana peel
    - Conflict with fixed infrastructure element
    - Conflict resulting from carried cargo - if known
    - Other – leave a note
    - Unable to determine - leave a note
22. ConflictType. What type of crash occurred (or would have occurred if non-crash)?
    - No impact or fall
    - Simple fall-over/bailout –no other conflict partner present
    - Impact with vehicle
    - Impact with pedestrian – includes pedestrian walking a bicycle
    - Impact with bicycle
    - Impact with other scooter
    - Impact with animal
    - Impact with object – e.g., litter, other non-fixed items that are not part of the infrastructural design
    - Impact with infrastructure element – e.g., items listed under the Proximate Hazards variable.
    - Other – leave a note
    - NA – Not a crash
23. ConflictEvasion. Which conflict partner(s) performed evasive maneuvers in attempt to avoid a crash? (check all that apply)?
    - One referenced scooter – select only if only one referenced scooter performed evasive maneuver

- More than one referenced scooter – select if both conflict partners are referenced scooters and both performed evasive maneuvers.
- Non-referenced scooter – select if the other conflict partner is a scooter not referenced in the baseline reduction (or RiderReference variable above) and performed an evasive maneuver
- Pedestrian – select if conflict partner is a pedestrian and performed an evasive maneuver
- Motorized vehicle – select if conflict partner is a motorized vehicle and performed an evasive maneuver
- Non-motorized vehicle – select if conflict partner is a non-motorized vehicle such as a bicycle, skateboard, etc. and performs an evasive maneuver
- NA – Conflict is a crash

24. ConflictRole. What role did the referenced rider(s) play in the conflict?
    - Struck (or would have struck)
    - Struck by (or would have been struck by)
    - Both struck and struck by (or would have been) – only if both conflict partners are riders referenced in the baseline reduction
    - Non-striking scenario
    - Unknown – leave a note
25. ConflictOutcome. How did the referenced scooter(s) fall as a result of the conflict?
    - Fell to the left - making impact with the ground
    - Fell to the right - making impact with the ground
    - Fell forward – rear wheel up or fell over handlebars, making impact with the ground
    - Fell backward – front wheel up or fell over rear wheel, making impact with the ground
    - Combination of above – leave a note, includes when two referenced scooters are involved and have different outcomes.
    - Did not fall/remained on scooter
26. ConflictFault. Which conflict partner is at fault? Indicates which conflict partner (scooter, bicycle, pedestrian, vehicle, etc.), if any, committed an error that led to the conflict. Only code a fault if there is observable evidence. Note: Objects and animals cannot be assigned fault; such events are coded as 'subject at fault' or 'no fault'.
    - Referenced rider - The rider of the subject scooter committed the error that led to the event. (If both conflict partners are riders referenced in the baseline reduction, reference the corresponding rider at fault in the final narrative.)
    - Other conflict partner – Another conflict partner (other vehicle, pedestrian, non-referenced scooter, etc.) committed the error that led to the event.
    - Shared fault - More than one conflict partner committed errors that contributed to the event.
    - No fault - No user errors were committed any errors that led to the event. This is often (but not always) true for animal-related conflicts and objects in the roadway, especially if the conflict cannot be reasonably anticipated or that does not allow for sufficient reaction time given safe riding patterns.
    - Unable to determine - Cannot determine the fault due to limitations in video views, lighting, visual obstructions, or limited perspective, or cannot make a judgment as to whether one user was completely at fault.
27. FinalNarrative. Provide a brief description of the conflict, and leave notes for any "unable to determine" or "other" categories or for anything notable not covered under other variables.

Appendix A-4: Parking Photo Reduction Protocol

The following protocol was incorporated into VTTI's photo reduction tool for assisting with the reduction of Spin scooter parking photos. It consists of a set of questions that will be answered by the reviewer. Multiple responses can be selected for each of the questions.

1. Select the following that describe the quality of the parking photo. Choose all that apply. [If either option is selected, move onto the next photo without answering questions 2-4].
    - The scooter is not in view in the picture
    - There is not enough information in the picture to describe other aspects regarding its location
2. Was the scooter parked according to Virginia Tech policy?
    - Yes (skip to question 4)
    - No
3. Which of the following describe the location of the incorrectly parked scooter? Choose all that apply.
    - Sidewalk – blocking ADA access
    - Sidewalk – NOT blocking ADA access
    - Sidewalk – blocking ADA ramp
    - Sidewalk – blocking stairs
    - Sidewalk – blocking building entrance/exit
    - Sidewalk – blocking other
    - Parking lot – blocking vehicle right of way
    - Parking lot – blocking pedestrian right of way
    - In building
    - Other (roadway, landscaped area, driveway, loading zone, etc.)
        - Text box will be available to leave note
4. Select the following additional notes regarding the parked scooter. Choose all that apply:
    - Laying down
    - Touching vegetation (i.e. leaning on tree or bush, lying on grass)
    - Damaging property (i.e. crushing vegetation, other)
    - Obstructing access to sidewalk furniture (e.g. benches, bus stops, etc.)
    - Obstructing access to fire hydrant or valve
    - Obstructing access to driveway or loading zone

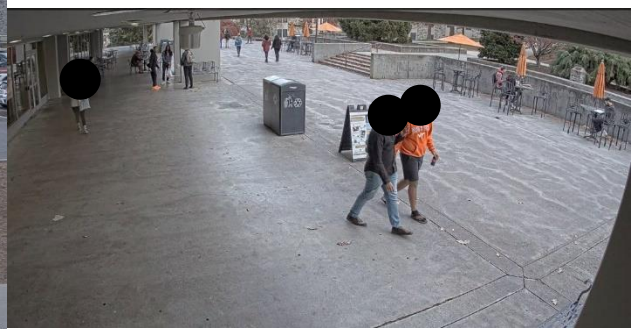
Appendix A-5: Fixed Camera Views

AJ East

Burruss

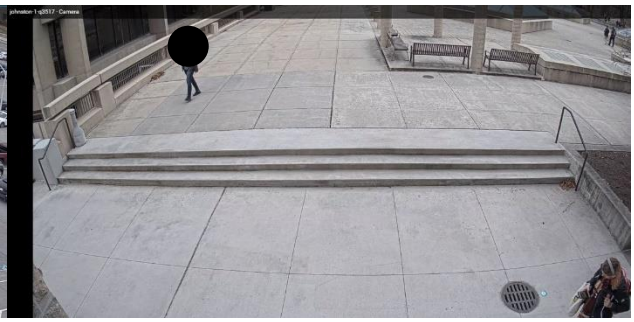
Classroom

Dietrick



Goodwin

Johnston



Kelly

McComas

Newman

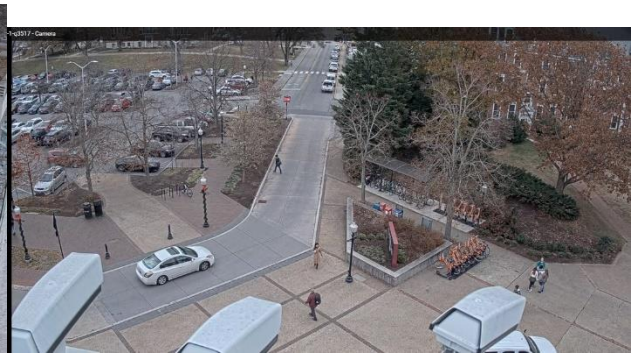
Newman B

Oaklane

Old Security

Owens

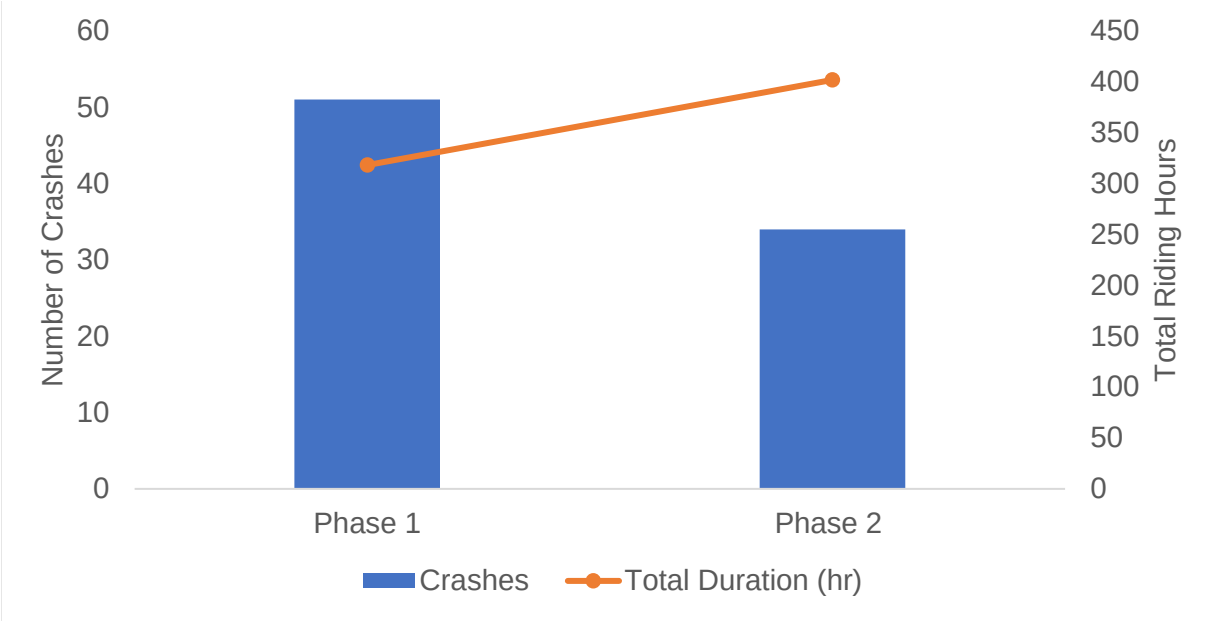
Squires



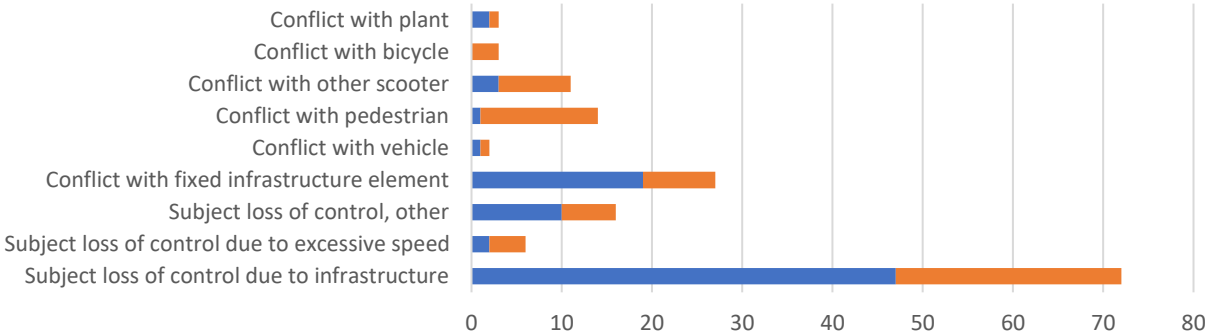
Appendix A-6: On-Scooter MicroDAS Results

Conflict Results

Total Crashes by Phase and Total Riding Hours

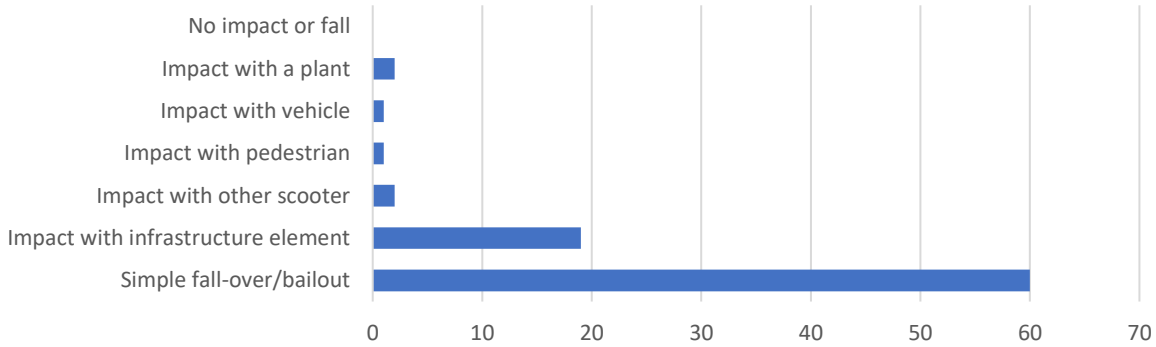


Precipitating Event of Conflicts



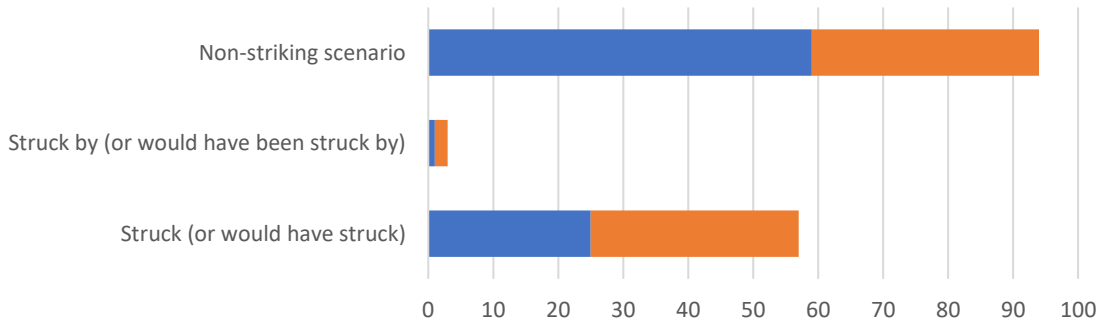
	Subject loss of control due to infrastructure	Subject loss of control due to excessive speed	Subject loss of control, other	Conflict with fixed infrastructure element	Conflict with vehicle	Conflict with pedestrian	Conflict with other scooter	Conflict with bicycle	Conflict with plant
Crash	47	2	10	19	1	1	3	0	2
Non-Crash Conflict	25	4	6	8	1	13	8	3	1

Crash Type



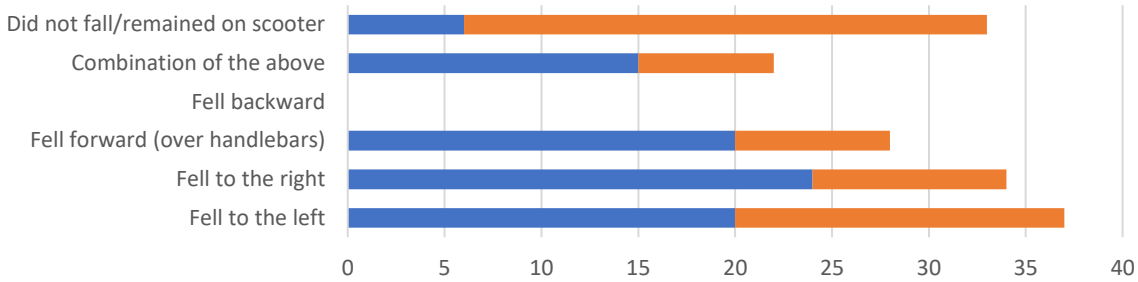
	Simple fall-over/bailout	Impact with infrastructure element	Impact with other scooter	Impact with pedestrian	Impact with vehicle	Impact with a plant	No impact or fall
Crash	60	19	2	1	1	2	0

Conflict Role



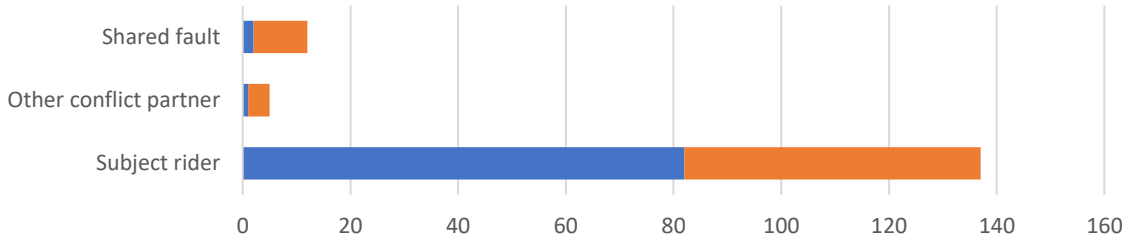
	Struck (or would have struck)	Struck by (or would have been struck by)	Non-striking scenario
Crash	25	1	59
Non-Crash Conflict	32	2	35

Conflict Outcome



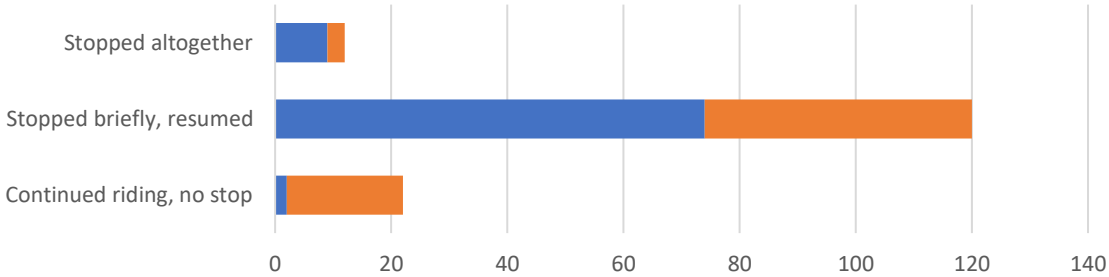
	Fell to the left	Fell to the right	Fell forward (over handlebars)	Fell backward	Combination of the above	Did not fall/remained on scooter
Crash	20	24	20	0	15	6
Non-Crash Conflict	17	10	8	0	7	27

Conflict Fault



	Subject rider	Other conflict partner	Shared fault
Crash	82	1	2
Non-Crash Conflict	55	4	10

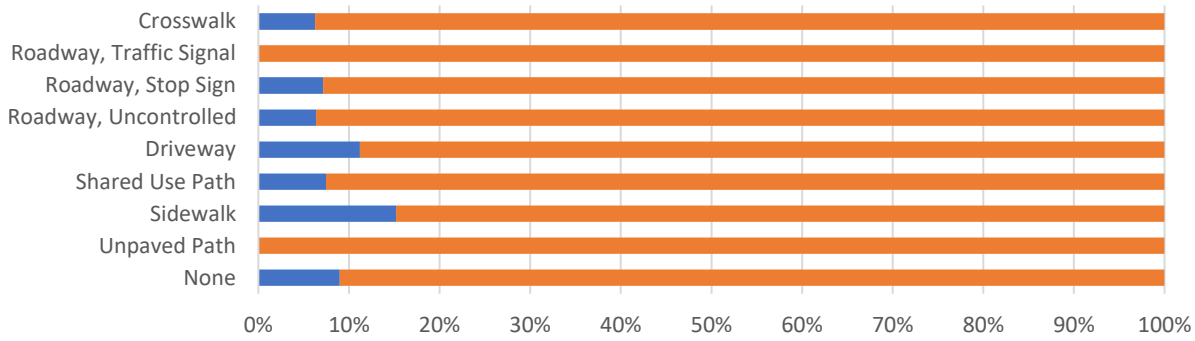
Status of Ride Post-Conflict



	Continued riding, no stop	Stopped briefly, resumed	Stopped altogether
Crash	2	74	9
Non-Crash Conflict	20	46	3

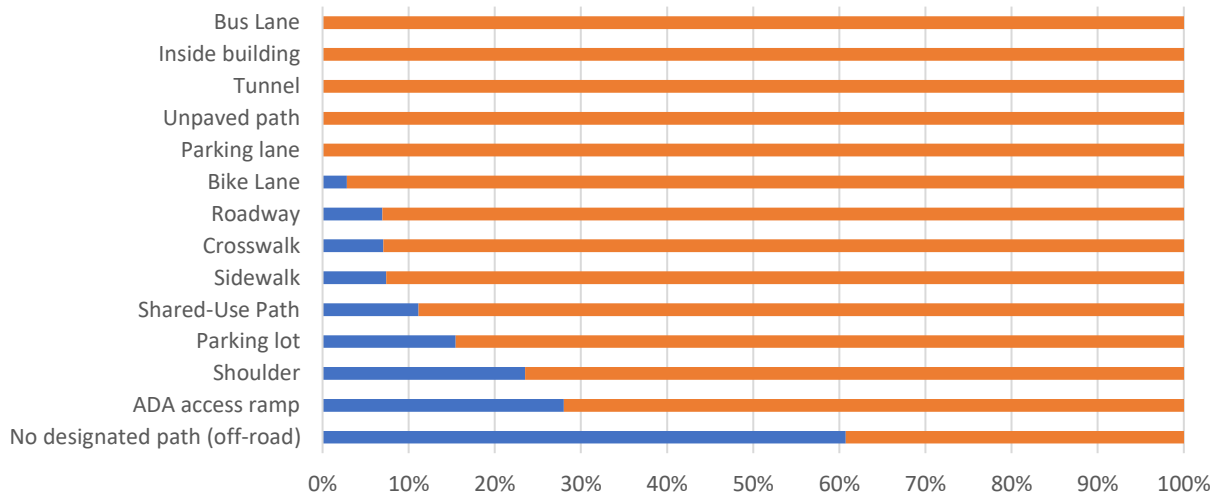
Trafficway/Infrastructure Factor Results

Intersections Traversed during Conflict and Baseline Events



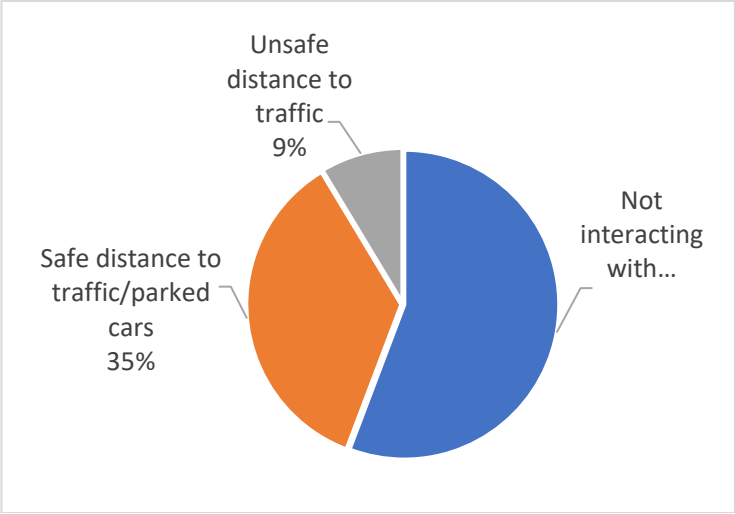
	None	Unpaved Path	Sidewalk	Shared Use Path	Driveway	Roadway, Uncontrolled	Roadway, Stop Sign	Roadway, Traffic Signal	Crosswalk
Conflicts	64	0	19	55	12	11	1	0	6
Baselines	650	6	106	681	95	162	13	1	90

Riding Location during Conflicts and Baselines



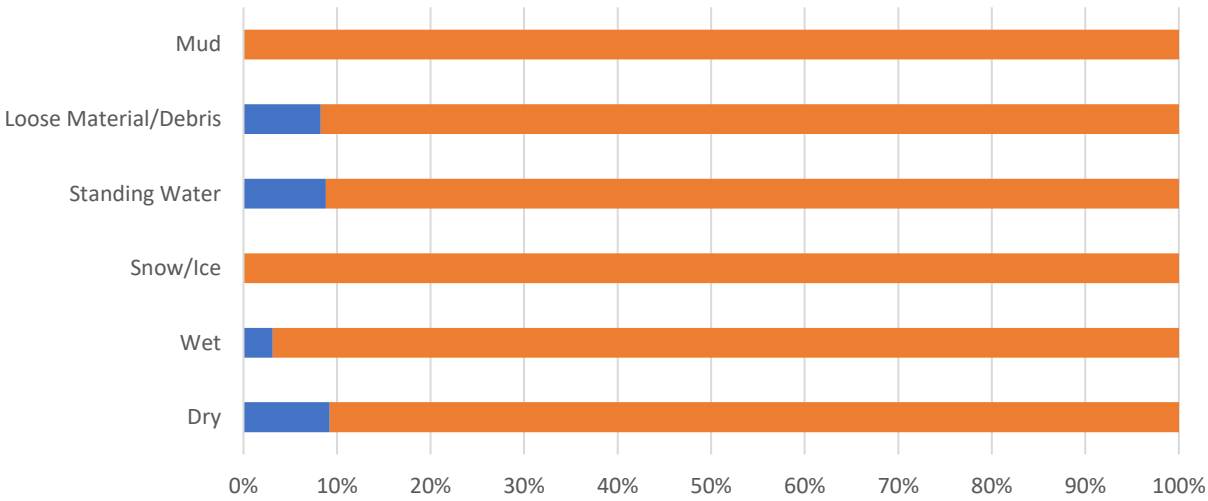
	No designated path (off-road)	ADA access ramp	Shoulder	Parking lot	Shared-Use Path	Sidewalk	Crosswalk	Roadway	Bike Lane	Parking lane	Unpaved path	Tunnel	Inside building	Bus Lane
Conflicts	65	7	4	28	95	41	15	26	3	0	0	0	0	0
Baseline	42	18	13	153	756	513	197	349	103	10	1	4	1	1

Traffic Interaction when Riding in Shared Lane/Roadway



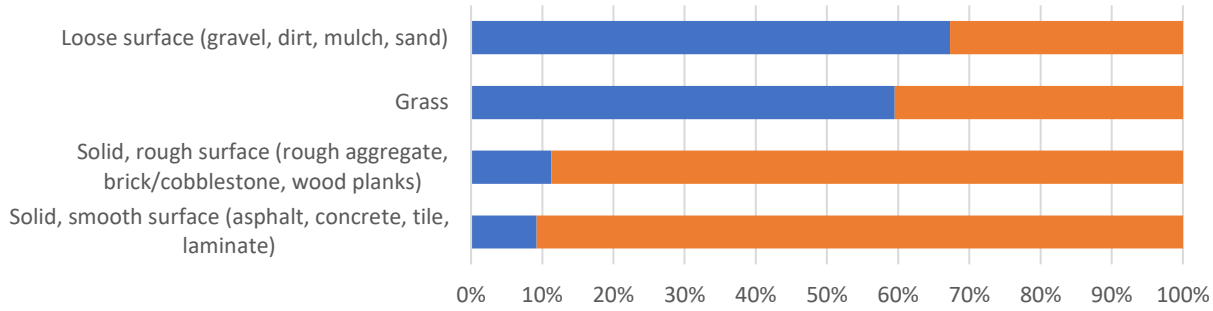
Interaction Characterization	Baseline Event Count
Not interacting with traffic	155
Safe distance to traffic/parked cars	99
Unsafe distance to traffic	24
Total	278

Surface Conditions (all)



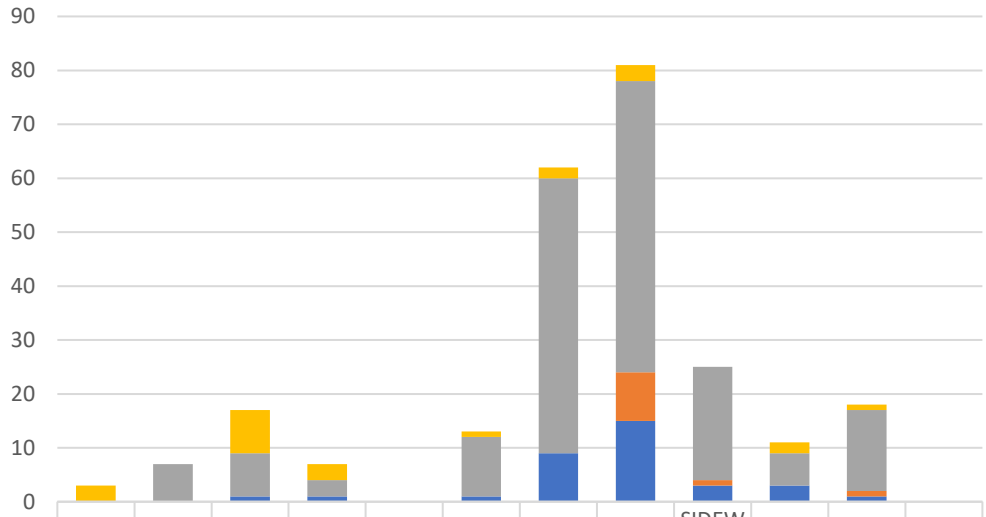
	Dry	Wet	Snow/Ice	Standing Water	Loose Material/Debris	Mud
Conflicts	148	6	0	3	35	0
Baseline	1455	185	10	31	388	4

Surface Conditions (aggregated by type)



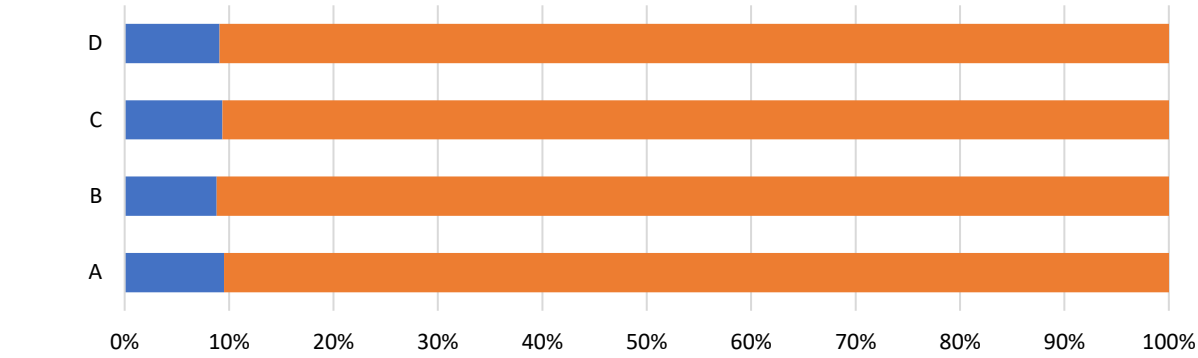
	Solid, smooth surface (asphalt, concrete, tile, laminate)	Solid, rough surface (rough aggregate, brick/cobblestone, wood planks)	Grass	Loose surface (gravel, dirt, mulch, sand)
Conflicts	176	15	50	35
Baseline	1734	118	34	17

Surface Features Encountered During Conflicts



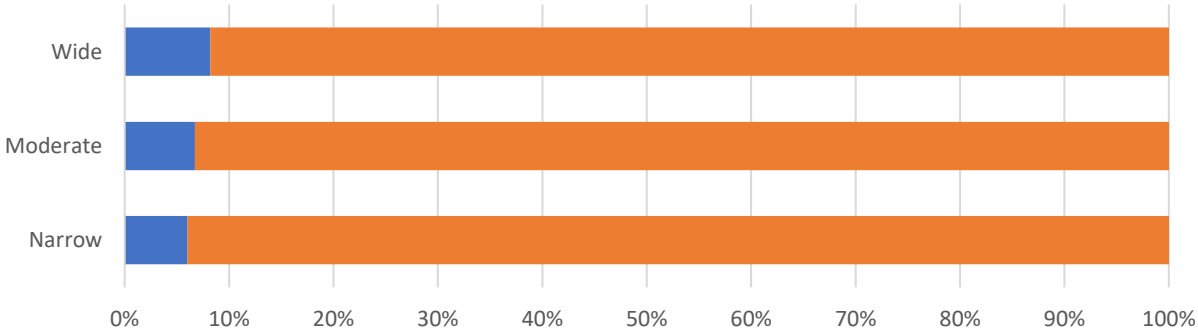
	STAIRS	ADA RAMP	MANHOLE	GRATE	STEEL PLATE	TACTILE PAVING	UNEVEN/DEGRADED	PAVEMENT-GRASS	SIDEWALK-ROAD CUTOUT	SIDEWALK-CURB	GRAVEL-DIRT/GRASS	OTHER
Avoided	3	0	8	3	0	1	2	3	0	2	1	0
Ridden through/on	0	7	8	3	0	11	51	54	21	6	15	0
Failed Avoidance	0	0	0	0	0	0	0	9	1	0	1	0
Ridden Through/On - Failed	0	0	1	1	0	1	9	15	3	3	1	0

Level of Demand of Trafficway



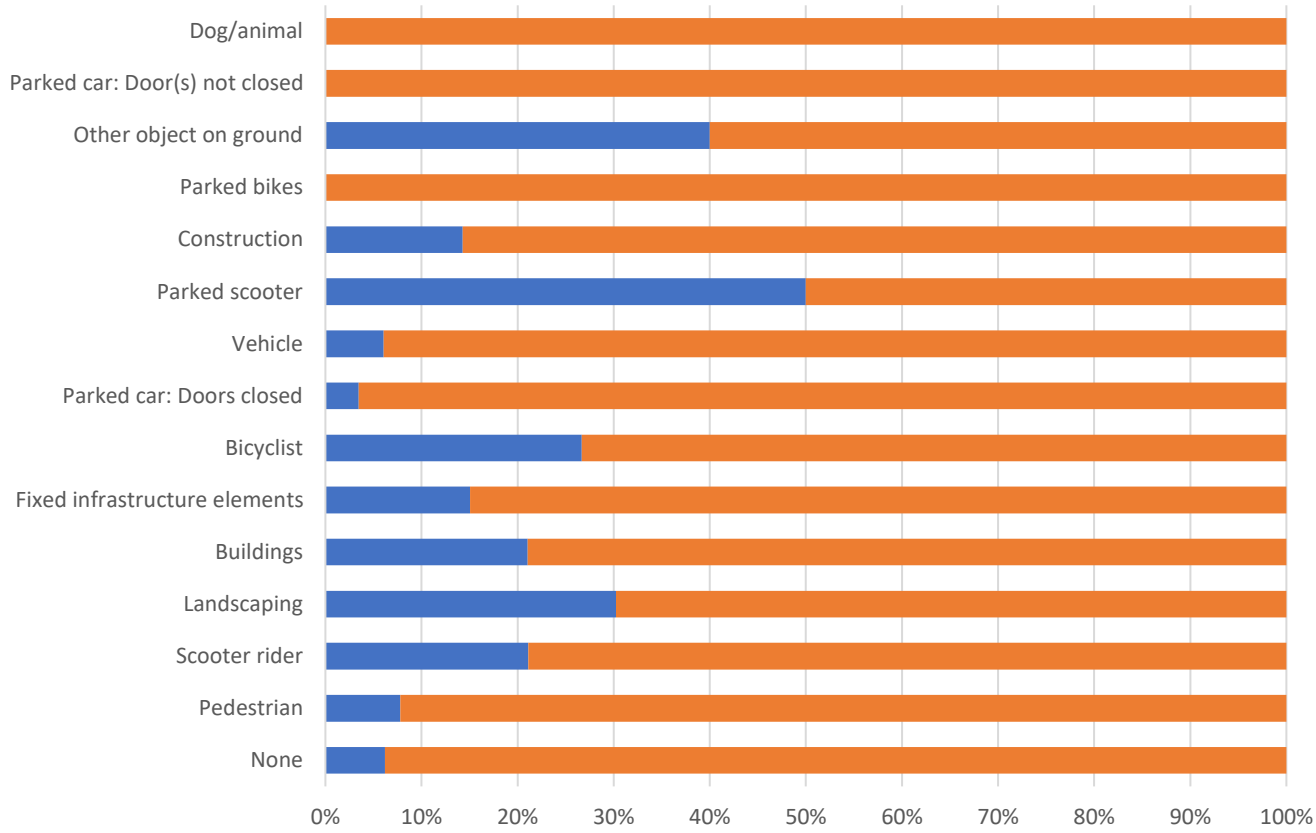
	A	B	C	D
Conflicts	85	59	13	160
Baseline	807	611	126	1602

Width of Path being Traversed by E-Scooter Rider



	Narrow	Moderate	Wide
Conflicts	5	20	68
Baseline	78	277	760

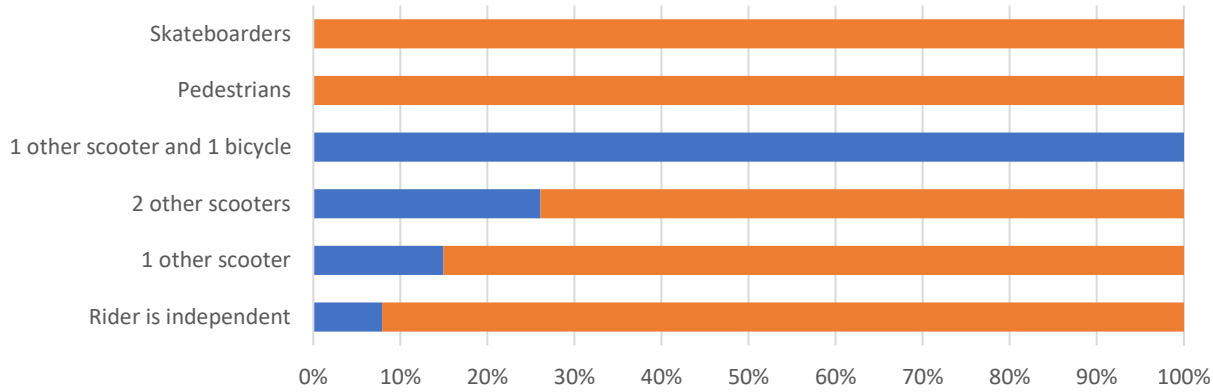
Proximate Hazards to E-Scooter Rider



	None	Pedestrian	Scooter rider	Landscaping	Buildings	Fixed infrastructure elements	Bicyclist	Parked car: Doors closed	Vehicle	Parked scooter	Construction	Parked bikes	Other object on ground	Parked car: Door(s) not closed	Dog/animal
Conflicts	73	26	15	13	4	11	4	2	2	6	1	0	2	0	0
Baseline	1106	308	56	30	15	62	11	56	31	6	6	13	3	2	2

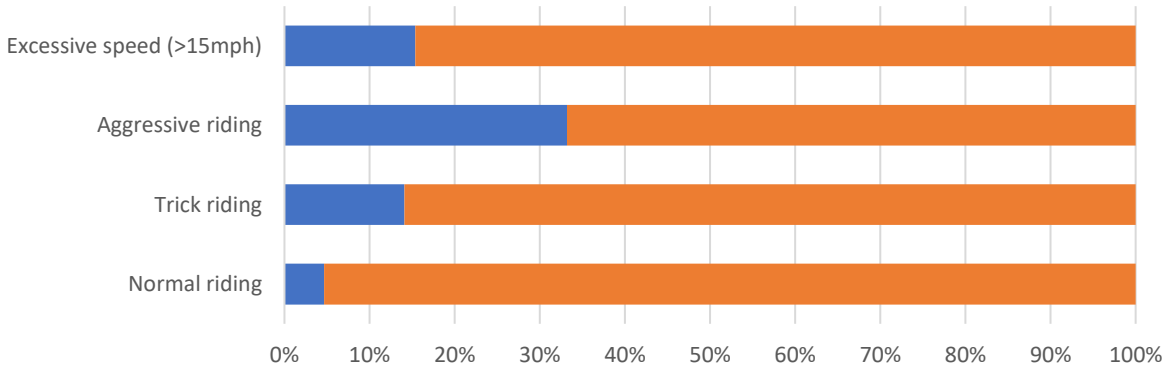
Behavioral Factor Results

Group Riding



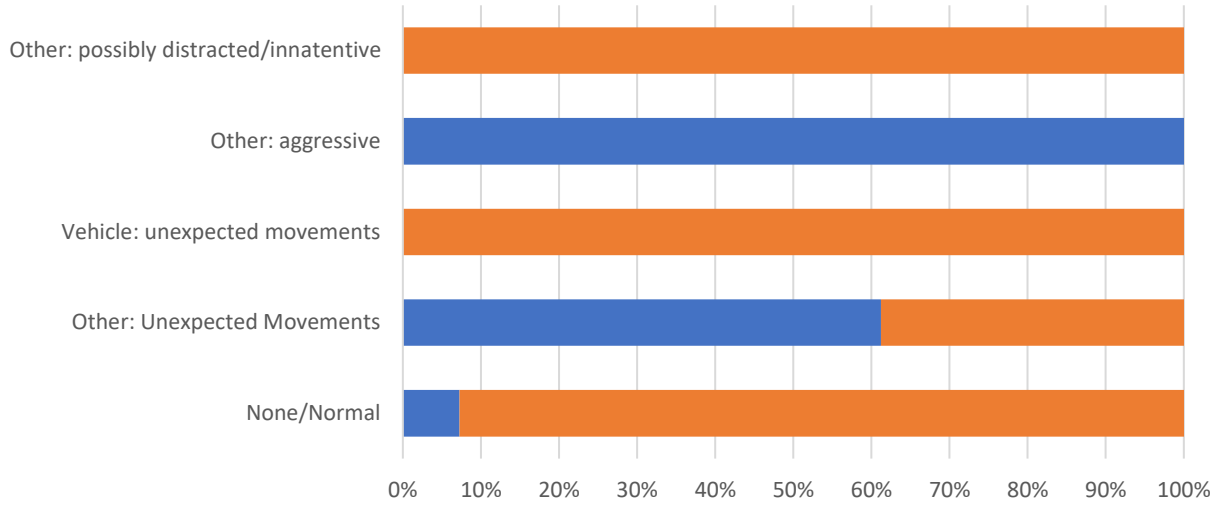
	Rider is independent	1 other scooter	2 other scooters	1 other scooter and 1 bicycle	Pedestrians	Skateboarders
Conflicts	125	22	6	1	0	0
Baseline	1459	125	17	0	2	1

Characterization of E-Scooter Rider Behavior



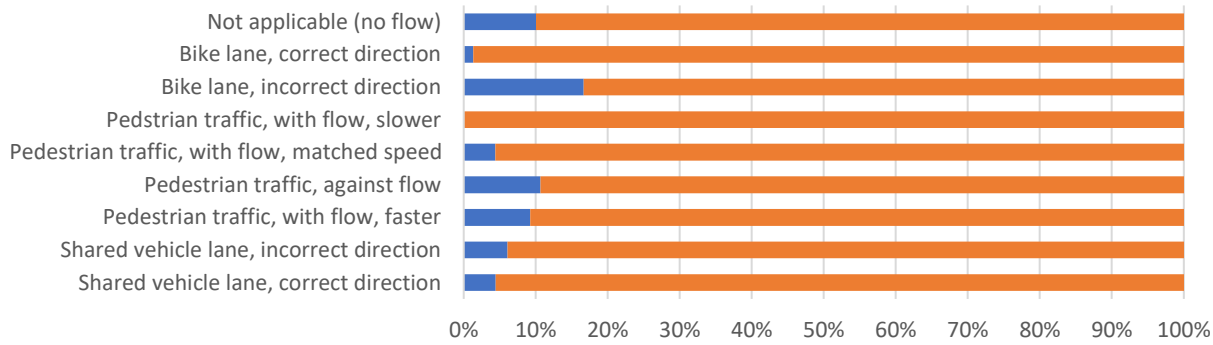
	Normal riding	Trick riding	Aggressive riding	Excessive speed (>15mph)
Conflicts	67	11	74	2
Baseline	1374	67	149	11

Characterization of Behaviors of Other Trafficway Users



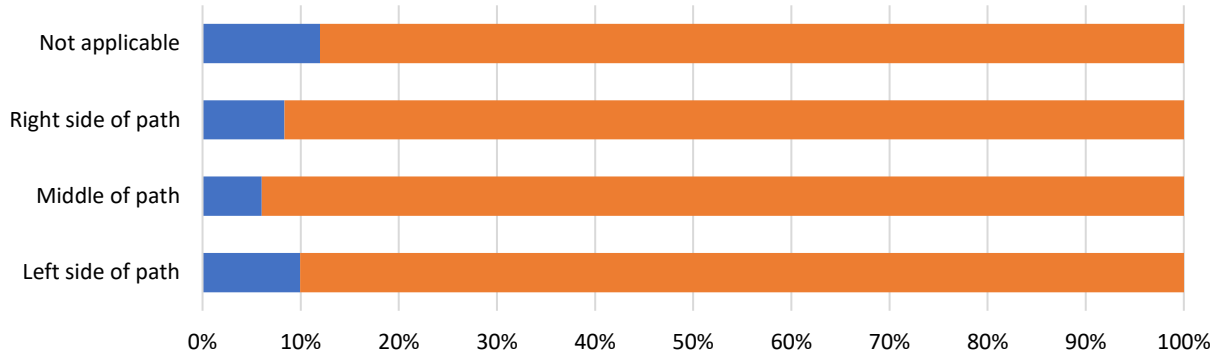
	None/Normal	Other: Unexpected Movements	Vehicle: unexpected movements	Other: aggressive	Other: possibly distracted/innatentive
Conflicts	123	30	0	1	0
Baseline	1571	19	3	0	8

Direction and Speed of Flow Relative to E-scooter Rider



	Shared vehicle lane, correct direction	Shared vehicle lane, incorrect direction	Pedestrian traffic, with flow, faster	Pedestrian traffic, against flow	Pedestrian traffic, with flow, matched speed	Pedstrian traffic, with flow, slower	Bike lane, incorrect direction	Bike lane, correct direction	Not applicable (no flow)
Conflicts	8	2	13	5	3	0	2	1	120
Baseline	172	31	128	42	65	2	10	74	1077

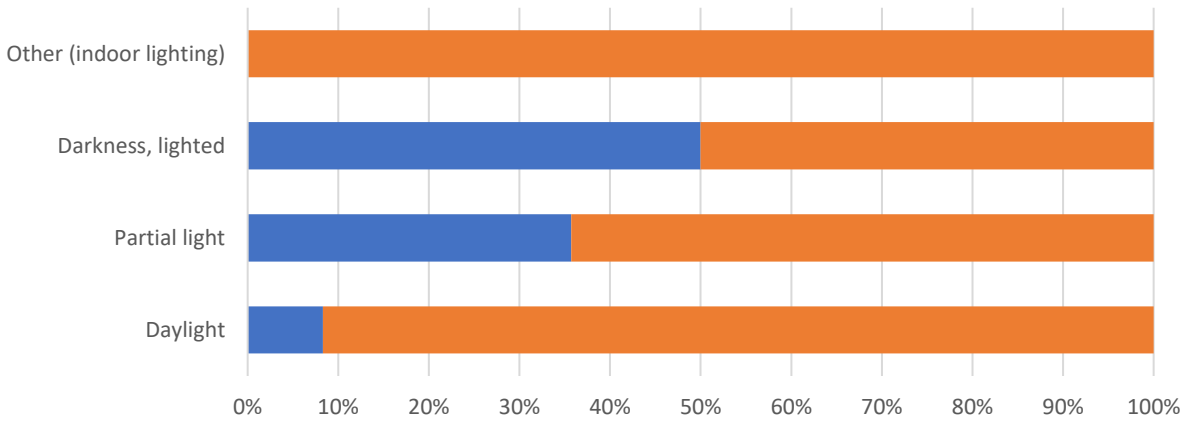
Position of E-Scooter Rider on Path



	Left side of path	Middle of path	Right side of path	Not applicable
Conflicts	27	32	34	66
Baseline	244	498	373	486

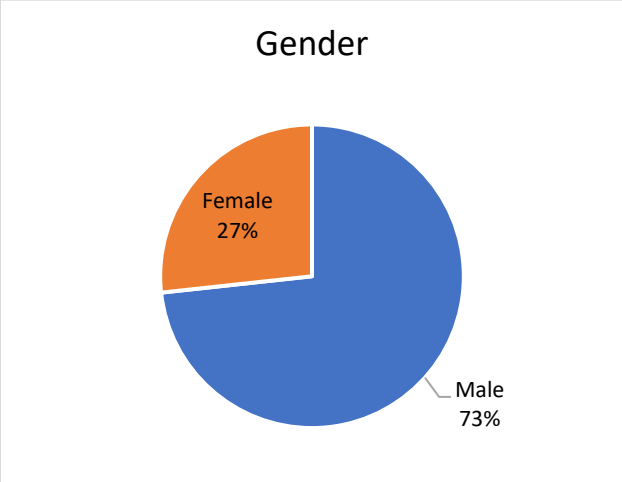
Environmental Factors

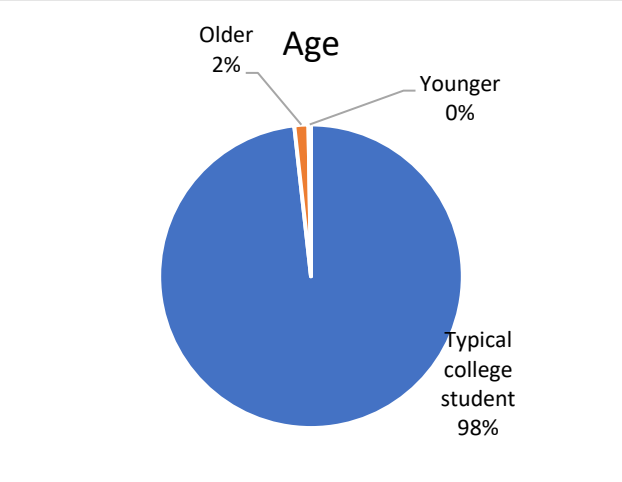
Lighting

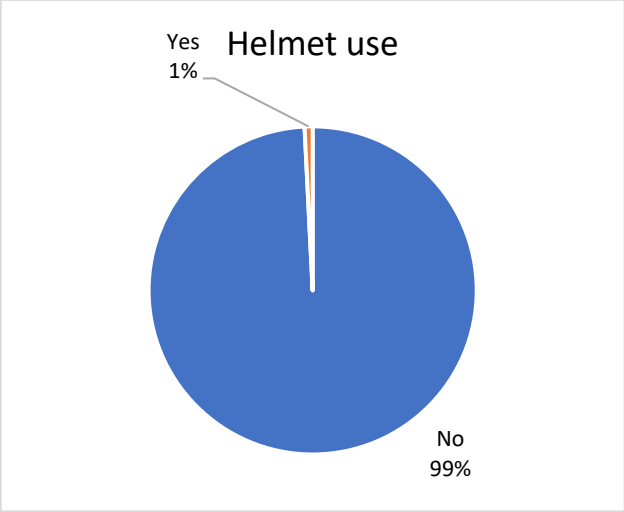


	Daylight	Partial light	Darkness, lighted	Other (indoor lighting)
Conflicts	143	10	1	0
Baseline	1579	18	1	3

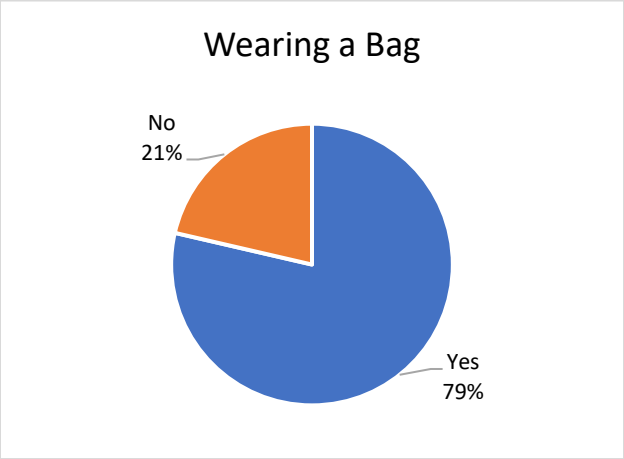
Appendix A-7: Fixed Camera Results

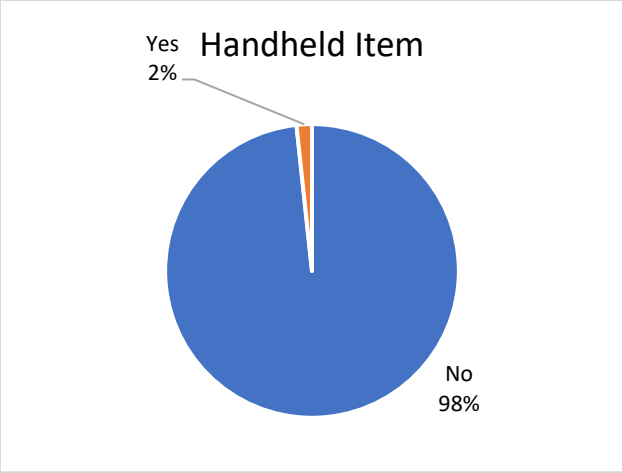


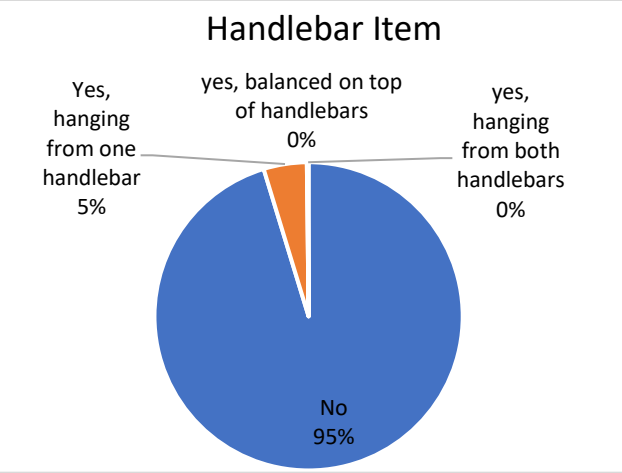


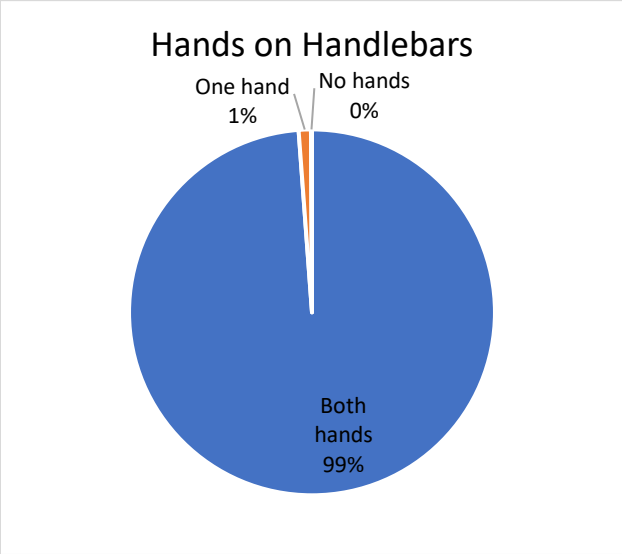


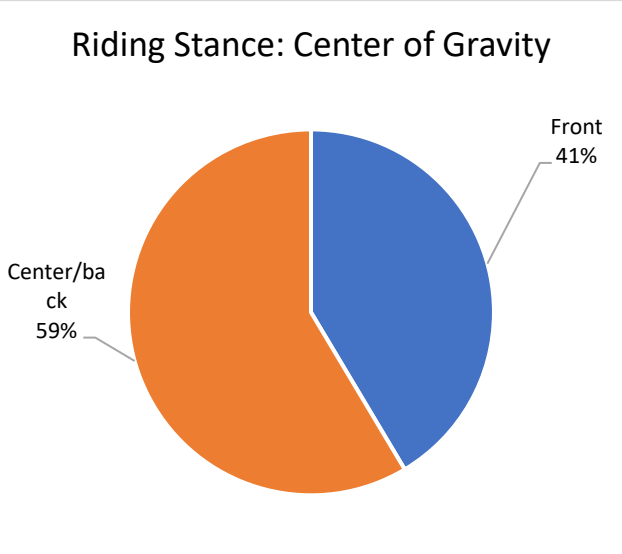
Helmet Use	Count
No	1,128
Yes	9
Unable to Determine	269

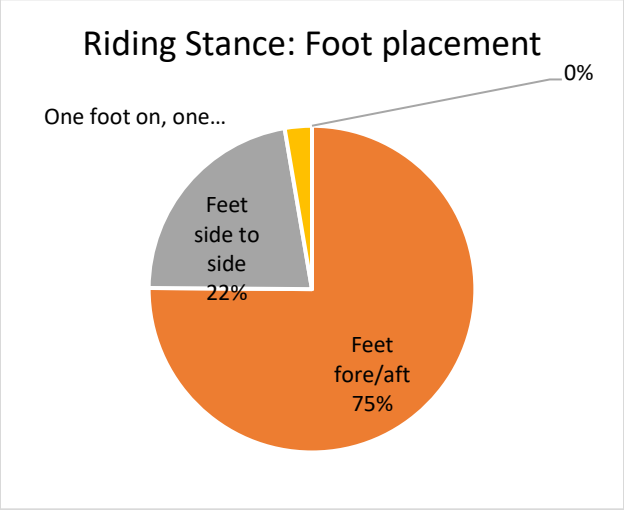


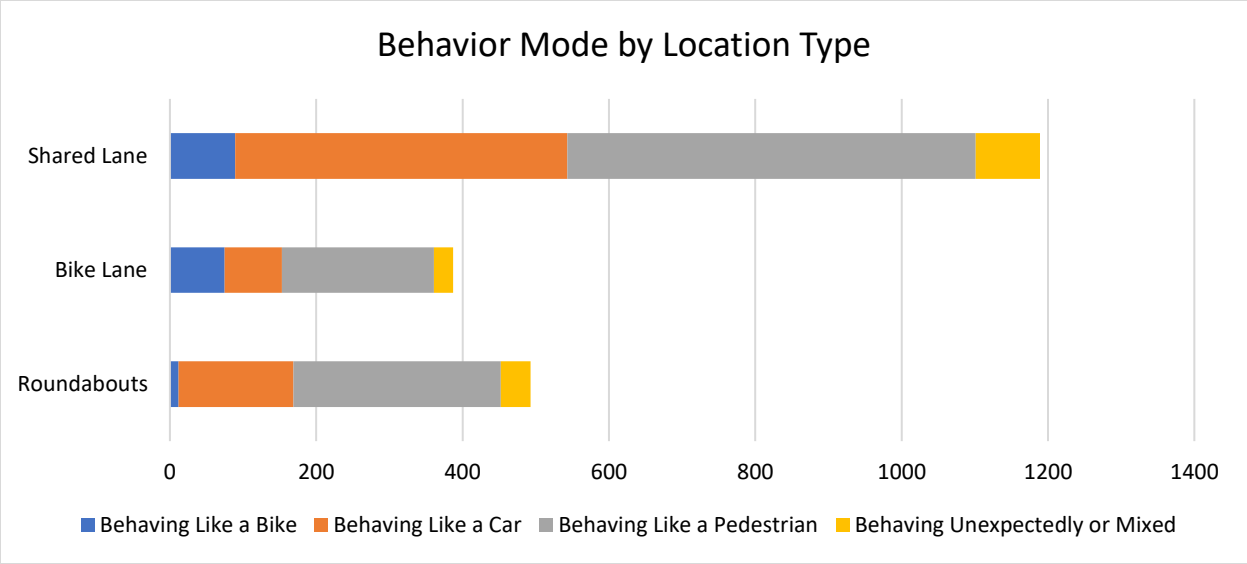

Handheld Item
Yes
2%
No
98%

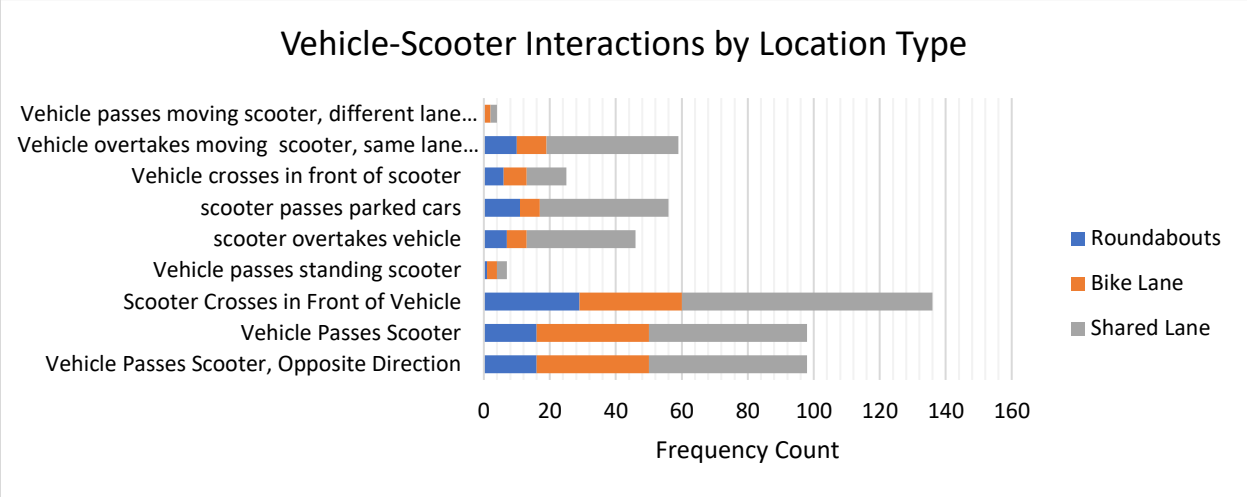

Handlebar Item
Yes, hanging from one handlebar 5%
yes, balanced on top of handlebars 0%
yes, hanging from both handlebars 0%
No
95%


Hands on Handlebars
One hand
1%
No hands
0%
Both hands
99%

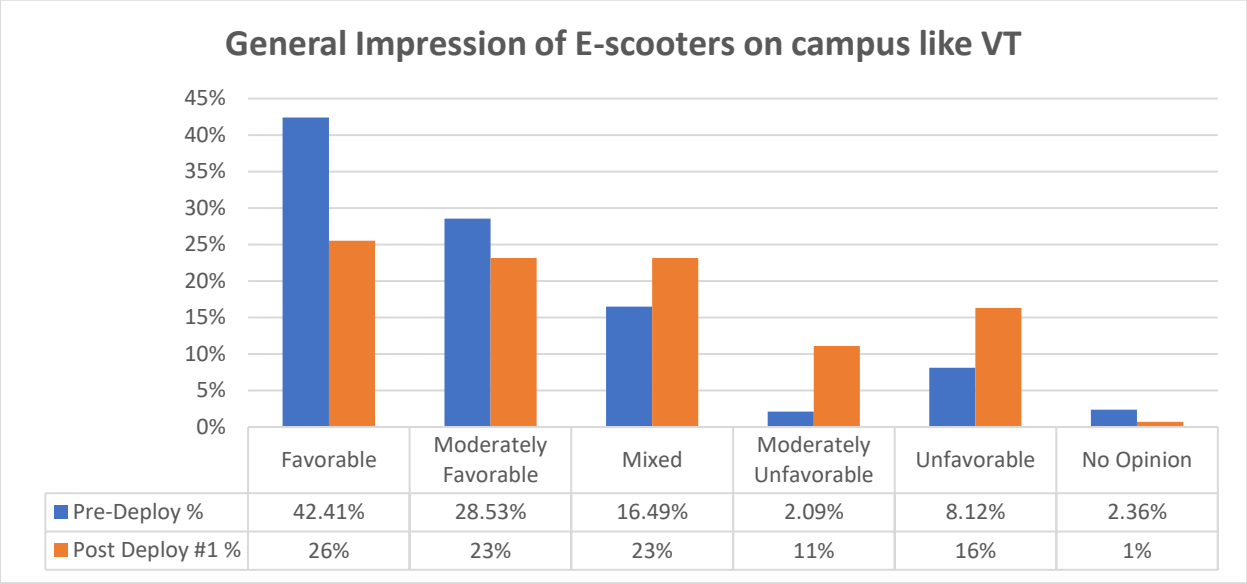

Riding Stance: Center of Gravity
Front
41%
Center/back
59%


Riding Stance: Foot placement
0%
One foot on, one...
Feet side to side
22%
Feet fore/aft
75%


Behavior Mode by Location Type
Shared Lane
Bike Lane
Roundabouts
0
200
400
600
800
1000
1200
1400
Behaving Like a Bike
Behaving Like a Car
Behaving Like a Pedestrian
Behaving Unexpectedly or Mixed

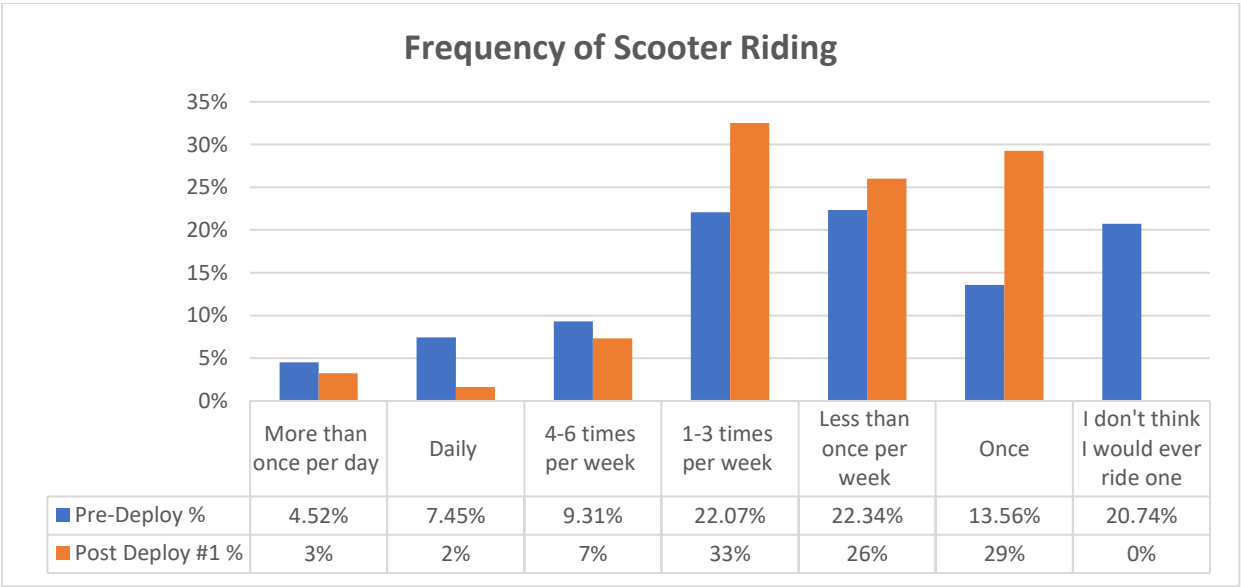

Vehicle-Scooter Interactions by Location Type
Vehicle passes moving scooter, different lane...
Vehicle overtakes moving scooter, same lane...
Vehicle crosses in front of scooter
scooter passes parked cars
scooter overtakes vehicle
Vehicle passes standing scooter
Scooter Crosses in Front of Vehicle
Vehicle Passes Scooter
Vehicle Passes Scooter, Opposite Direction
0
20
40
60
80
100
120
140
160
Frequency Count
Roundabouts
Bike Lane
Shared Lane

Appendix A-8: Long-Form Perception Survey Results



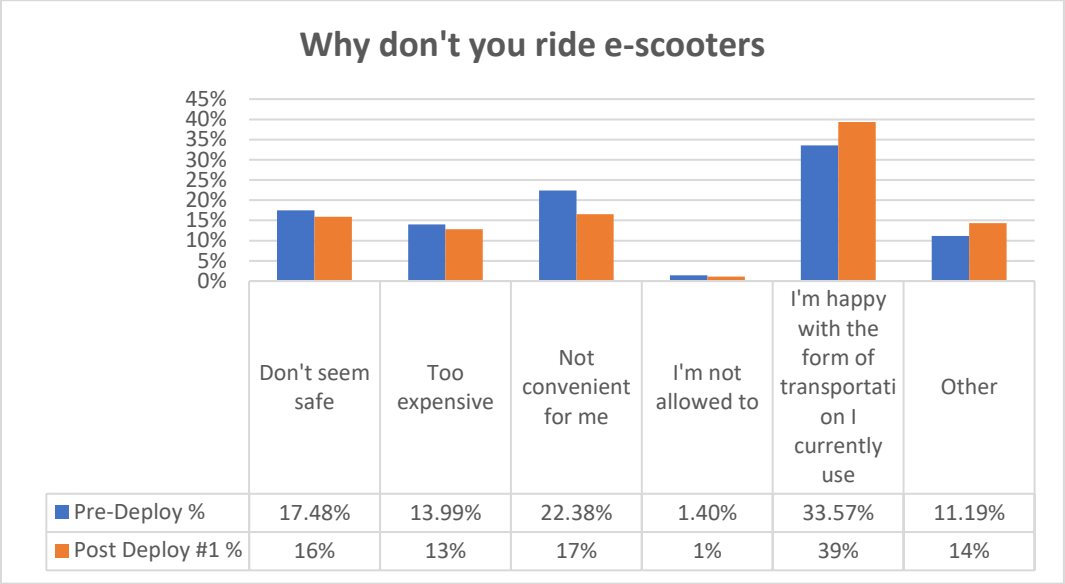
E-Scooter Perceptions (scale of 1 [strongly disagree] to 6 [strongly agree])

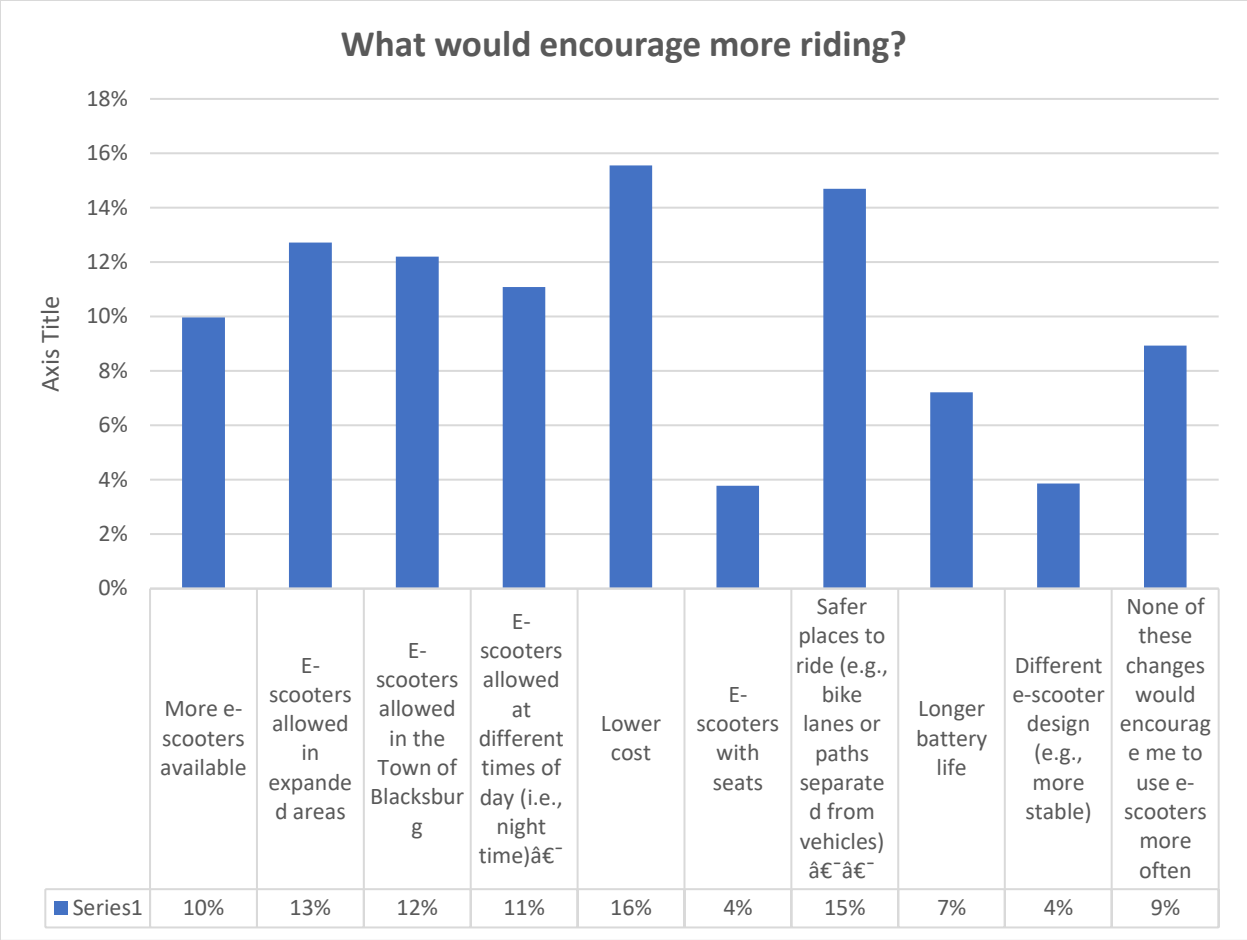
	Pre-Deployment	Post-Deployment
Provide a useful mobility option	4.59	4.43
Make it easier to get around	4.62	4.47
Are generally well-parked and won't block sidewalks or doorways	3.73	3.32
Are ridden in a safe manner	3.56	3.14
I would be more likely to not drive around campus if I know an e-scooter would be available (leave blank if not applicable)	3.61	3.01
I am in favor of e-scooters becoming available for rent in the Town of Blacksburg in addition to Virginia Tech campus	4.38	3.71

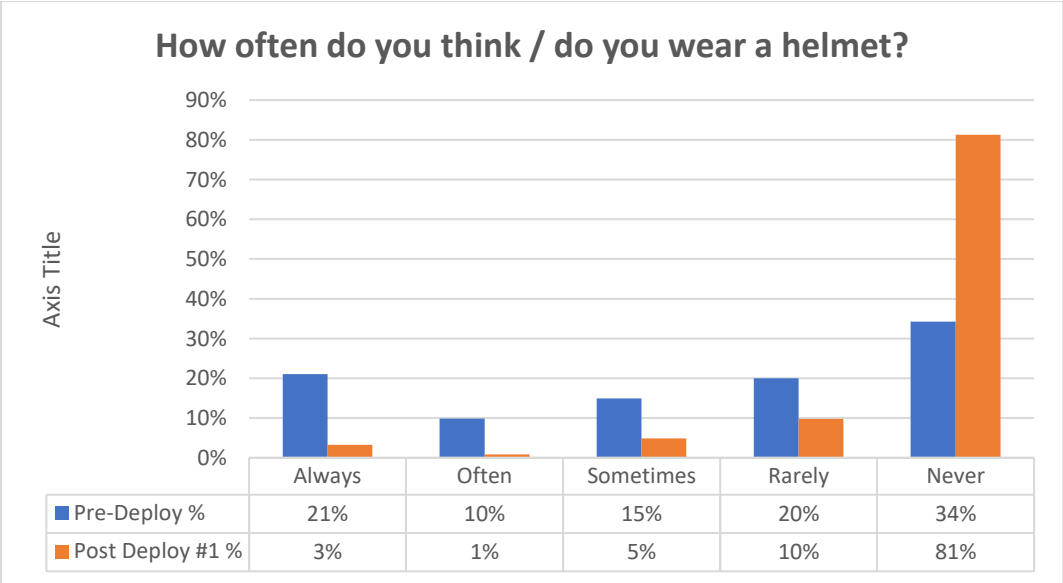


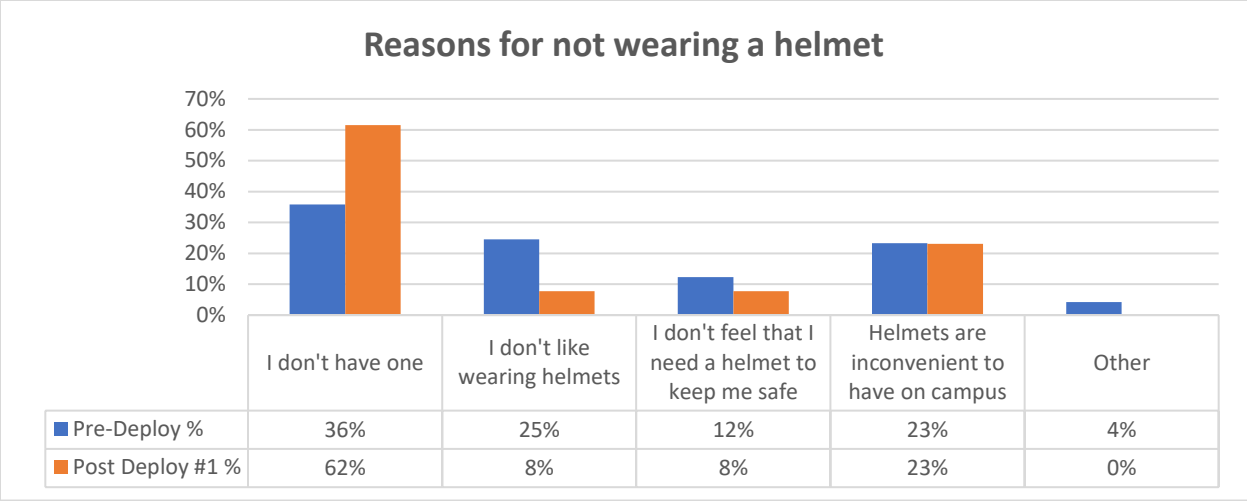
Riding Preference (scale of 1 [strongly disagree] to 4 [strongly agree])

Preferred Riding Location	Pre-Deployment	Post-Deployment
Sidewalk	1.91	1.88
Bike lane in street	2.12	1.94
Shared travel lane	3.4	3.4
Campus trail/footpath	2.57	2.78

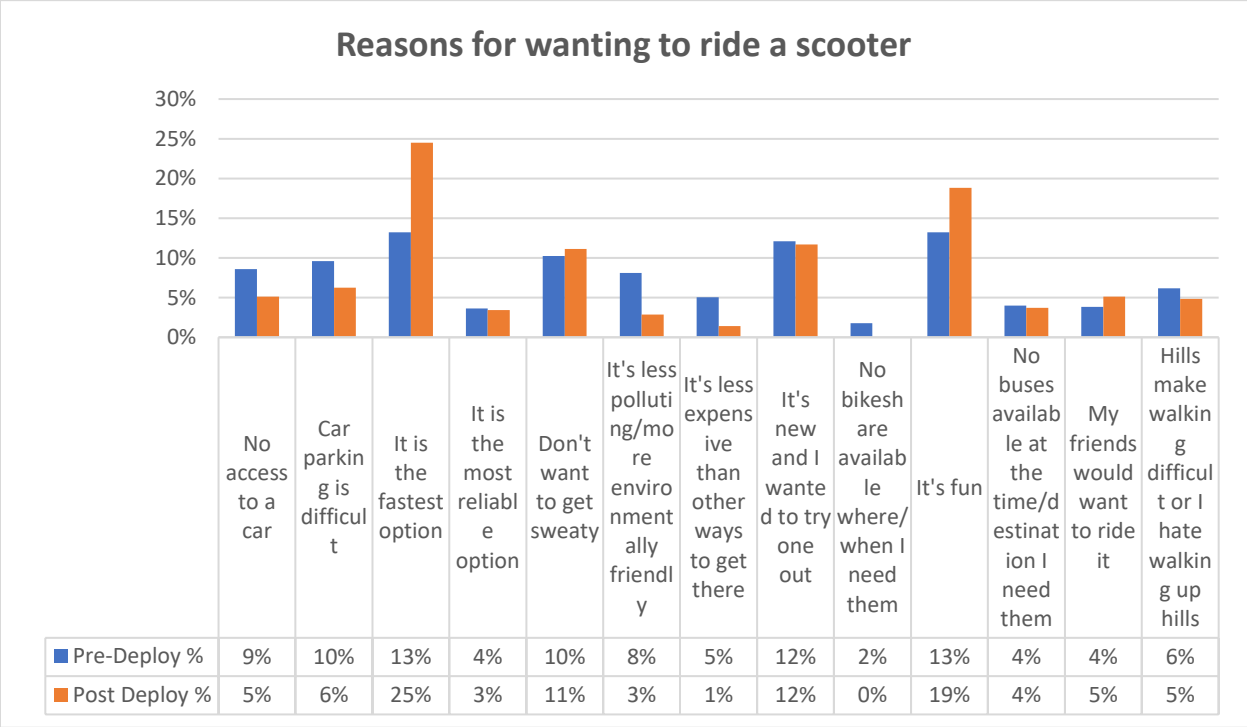



What would encourage more riding?
Axis Title
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
More e-scooters available
E-scooters allowed in expanded areas
E-scooters allowed in the Town of Blacksburg
E-scooters allowed at different times of day (i.e., night time)â€¯
Lower cost
E-scooters with seats
Safer places to ride (e.g., bike lanes or paths separated from vehicles) â€¯â€¯
Longer battery life
Different e-scooter design (e.g., more stable)
None of these changes would encourage me to use e-scooters more often
Series1
10%
13%
12%
11%
16%
4%
15%
7%
4%
9%

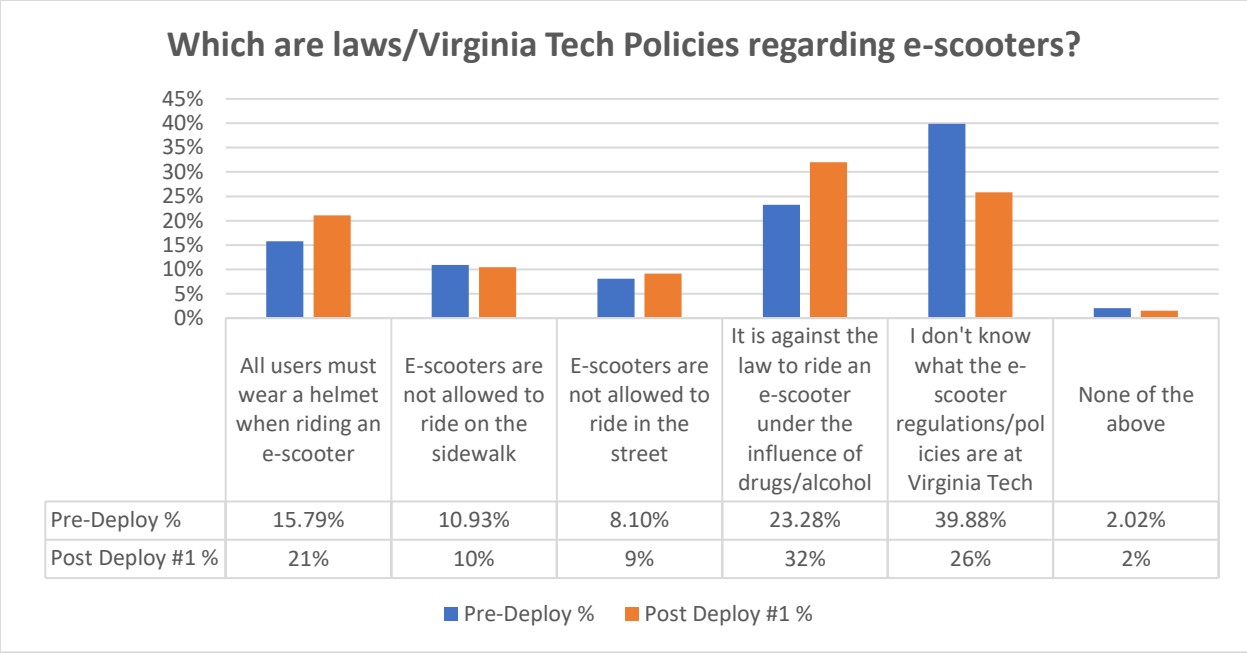

How often do you think / do you wear a helmet?
Axis Title
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Always
Often
Sometimes
Rarely
Never
Pre-Deploy %
21%
10%
15%
20%
34%
Post Deploy #1 %
3%
1%
5%
10%
81%



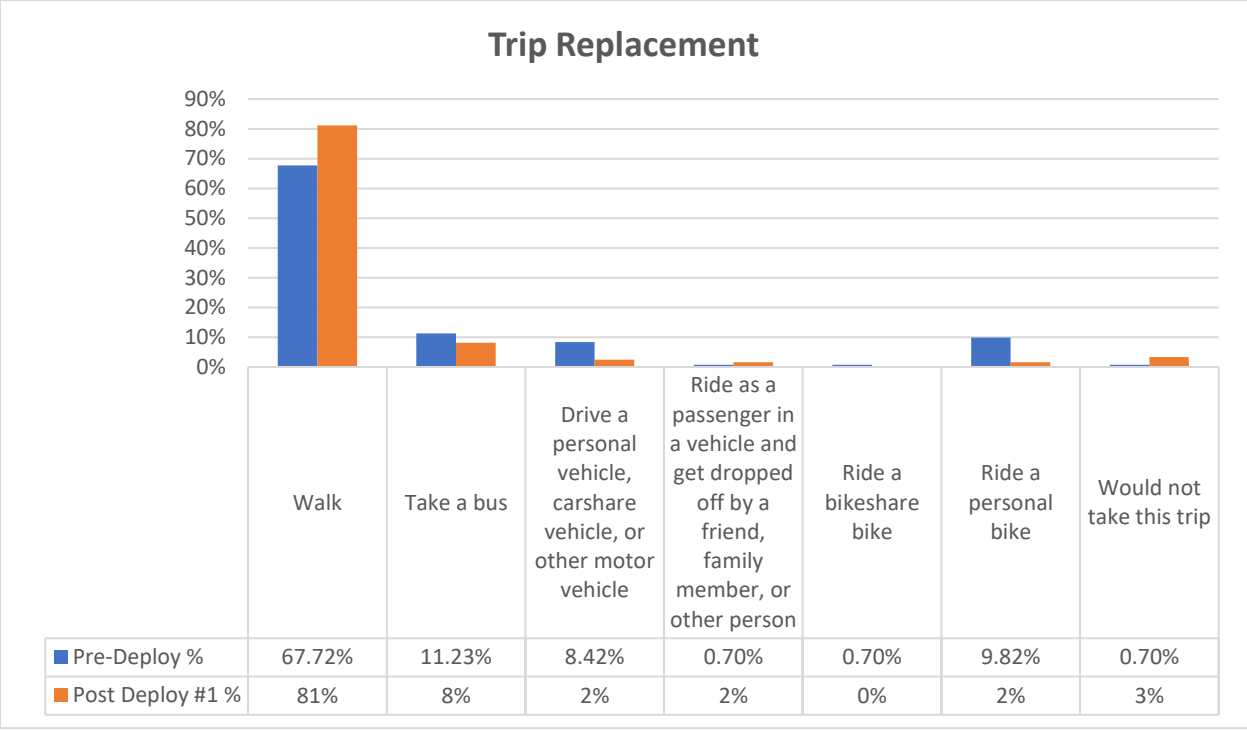
	I don't have one	I don't like wearing helmets	I don't feel that I need a helmet to keep me safe	Helmets are inconvenient to have on campus	Other
Pre-Deploy %	36%	25%	12%	23%	4%
Post Deploy #1 %	62%	8%	8%	23%	0%



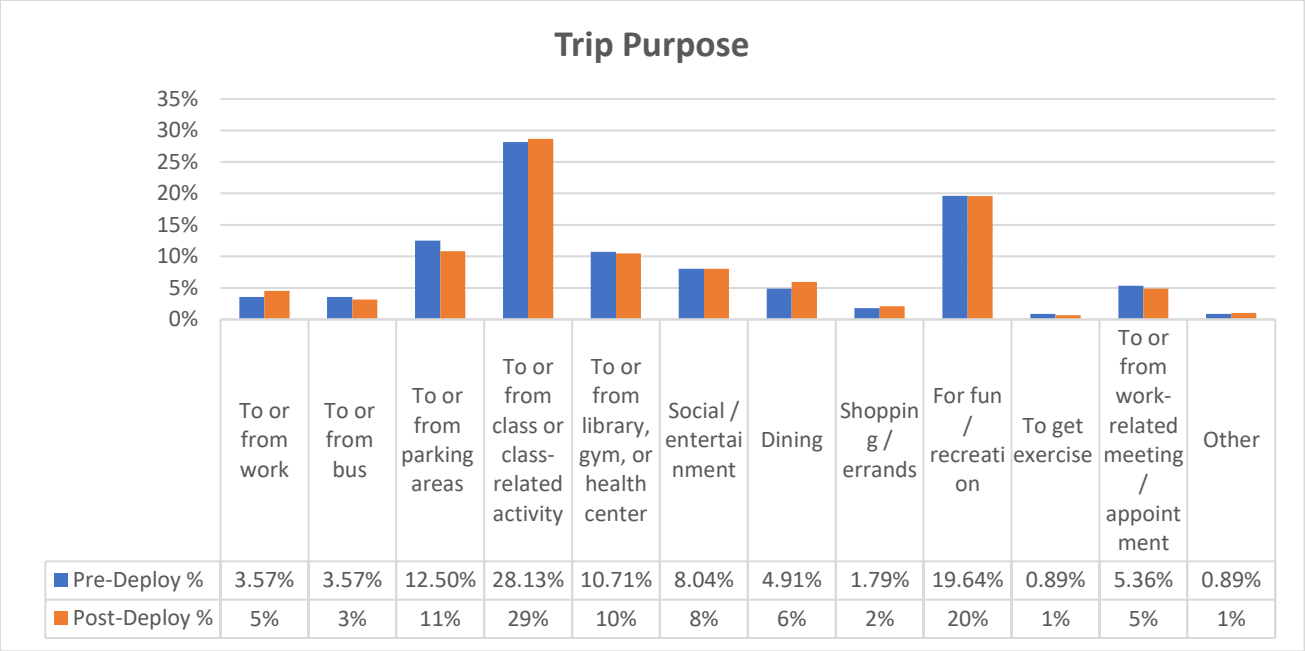
	No access to a car	Car parking is difficult	It is the fastest option	It is the most reliable option	Don't want to get sweaty	It's less polluting/more environmentally friendly	It's less expensive than other ways to get there	It's new and I wanted to try one out	No bikeshare available where/when I need them	It's fun	No buses available at the time/destination I need them	My friends would want to ride it	Hills make walking difficult or I hate walking up hills
Pre-Deploy %	9%	10%	13%	4%	10%	8%	5%	12%	2%	13%	4%	4%	6%
Post Deploy %	5%	6%	25%	3%	11%	3%	1%	12%	0%	19%	4%	5%	5%



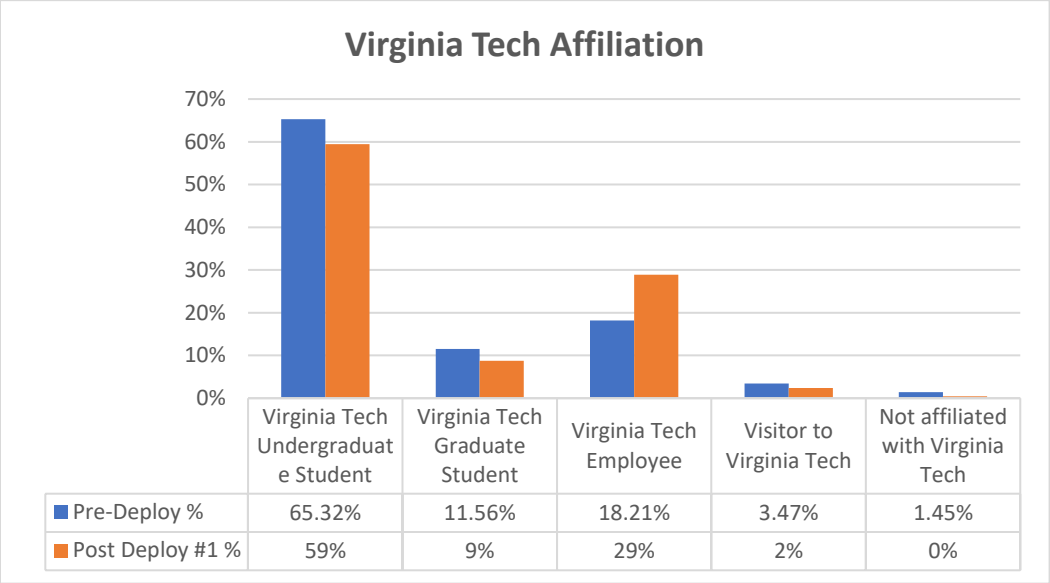
	All users must wear a helmet when riding an e-scooter	E-scooters are not allowed to ride on the sidewalk	E-scooters are not allowed to ride in the street	It is against the law to ride an e-scooter under the influence of drugs/alcohol	I don't know what the e-scooter regulations/policies are at Virginia Tech	None of the above
Pre-Deploy %	15.79%	10.93%	8.10%	23.28%	39.88%	2.02%
Post Deploy #1 %	21%	10%	9%	32%	26%	2%



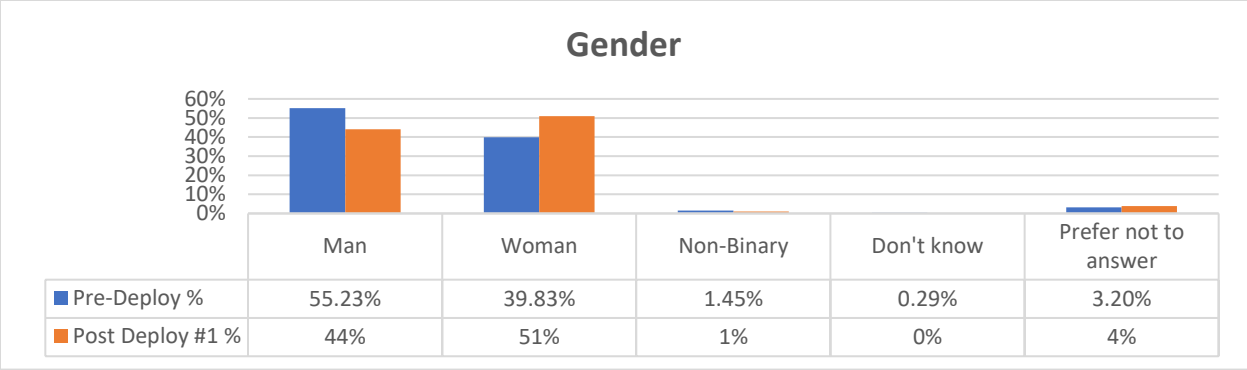
	Walk	Take a bus	Drive a personal vehicle, carshare vehicle, or other motor vehicle	Ride as a passenger in a vehicle and get dropped off by a friend, family member, or other person	Ride a bikeshare bike	Ride a personal bike	Would not take this trip
Pre-Deploy %	67.72%	11.23%	8.42%	0.70%	0.70%	9.82%	0.70%
Post Deploy #1 %	81%	8%	2%	2%	0%	2%	3%



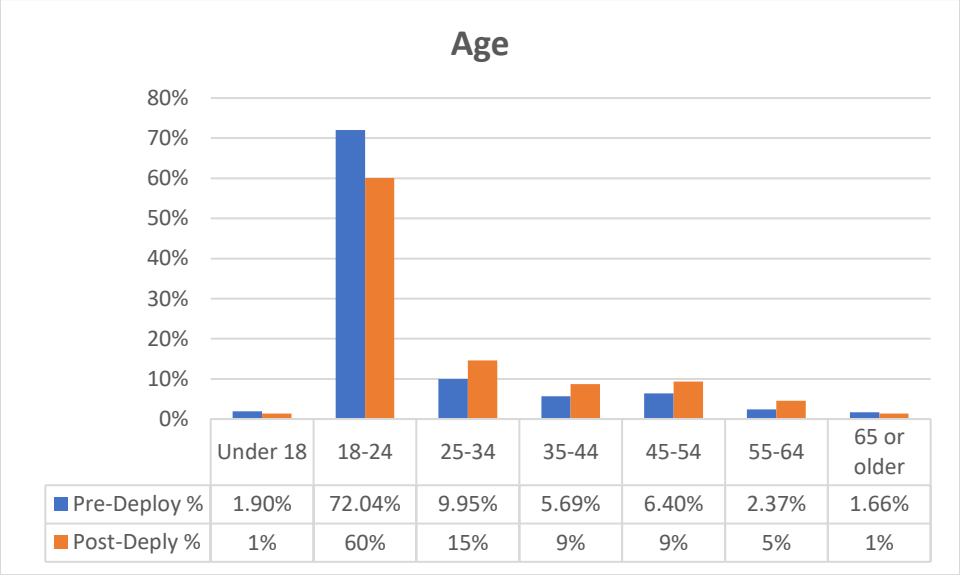
	To or from work	To or from bus	To or from parking areas	To or from class or class-related activity	To or from library, gym, or health center	Social / entertainment	Dining	Shopping / errands	For fun / recreation	To get exercise	To or from work-related meeting / appointment	Other
Pre-Deploy %	3.57%	3.57%	12.50%	28.13%	10.71%	8.04%	4.91%	1.79%	19.64%	0.89%	5.36%	0.89%
Post-Deploy %	5%	3%	11%	29%	10%	8%	6%	2%	20%	1%	5%	1%



	Virginia Tech Undergraduate Student	Virginia Tech Graduate Student	Virginia Tech Employee	Visitor to Virginia Tech	Not affiliated with Virginia Tech
Pre-Deploy %	65.32%	11.56%	18.21%	3.47%	1.45%
Post Deploy #1 %	59%	9%	29%	2%	0%



	Man	Woman	Non-Binary	Don't know	Prefer not to answer
Pre-Deploy %	55.23%	39.83%	1.45%	0.29%	3.20%
Post Deploy #1 %	44%	51%	1%	0%	4%

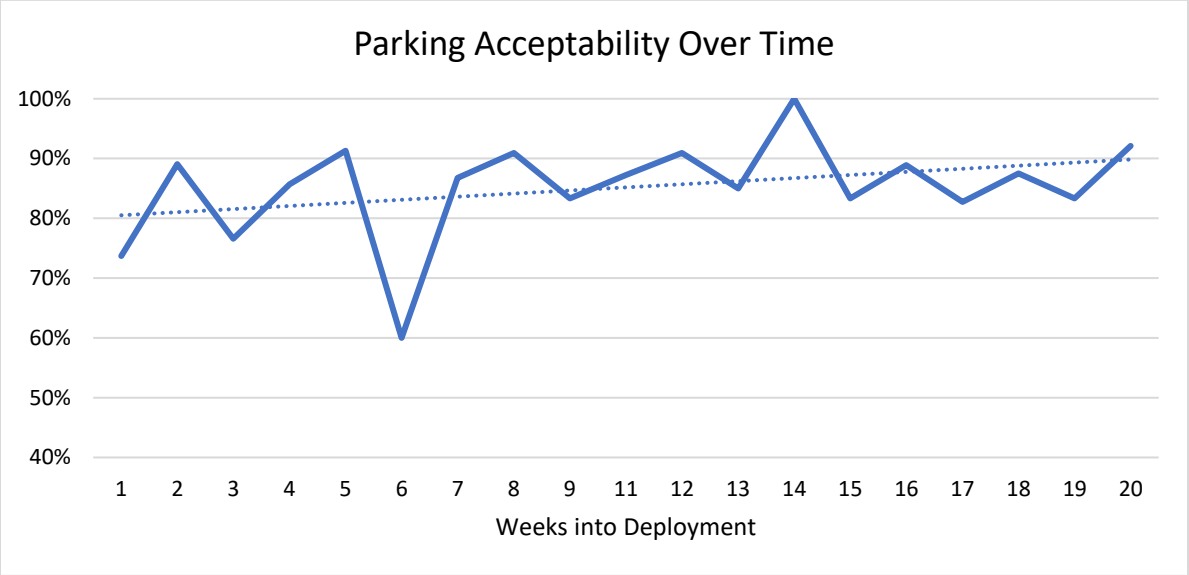


	Under 18	18-24	25-34	35-44	45-54	55-64	65 or older
Pre-Deploy %	1.90%	72.04%	9.95%	5.69%	6.40%	2.37%	1.66%
Post-Deply %	1%	60%	15%	9%	9%	5%	1%

Appendix A-9: Spin Application Data Collection Results

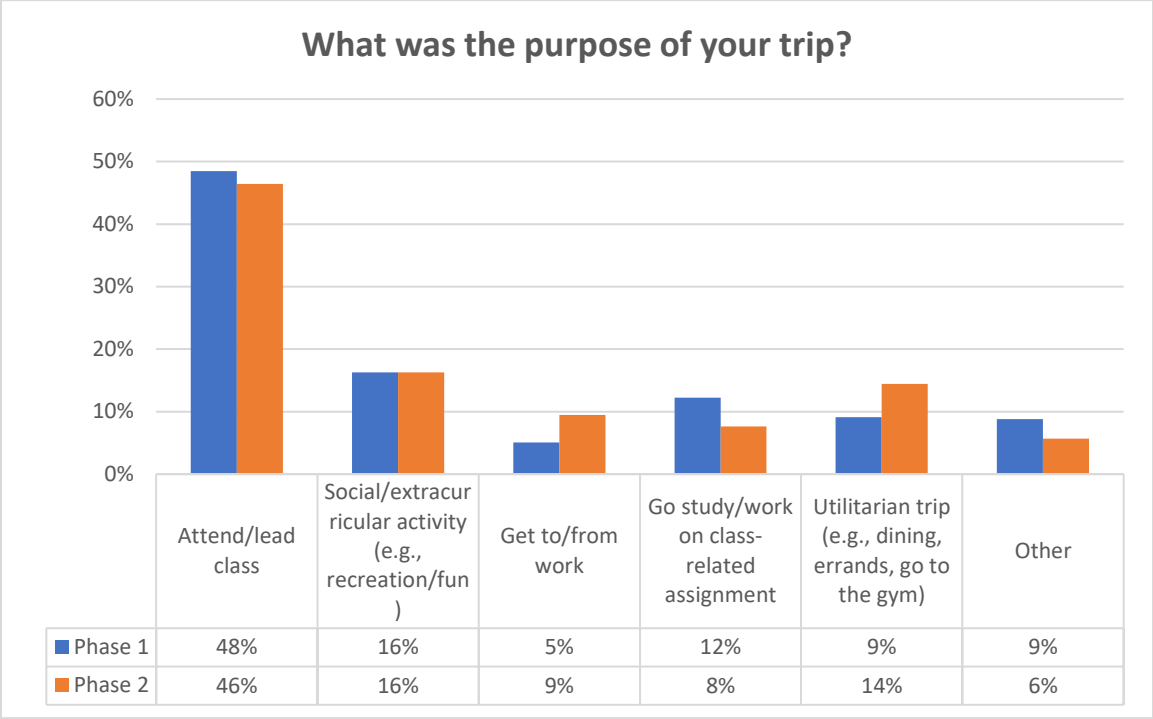
Parking Photo Results

Parking Acceptability	Count	Frequency
Parked according to Virginia Tech Policy	324	86%
Parked acceptably	384	
Not parked acceptably	118	14%
Total	826	100%

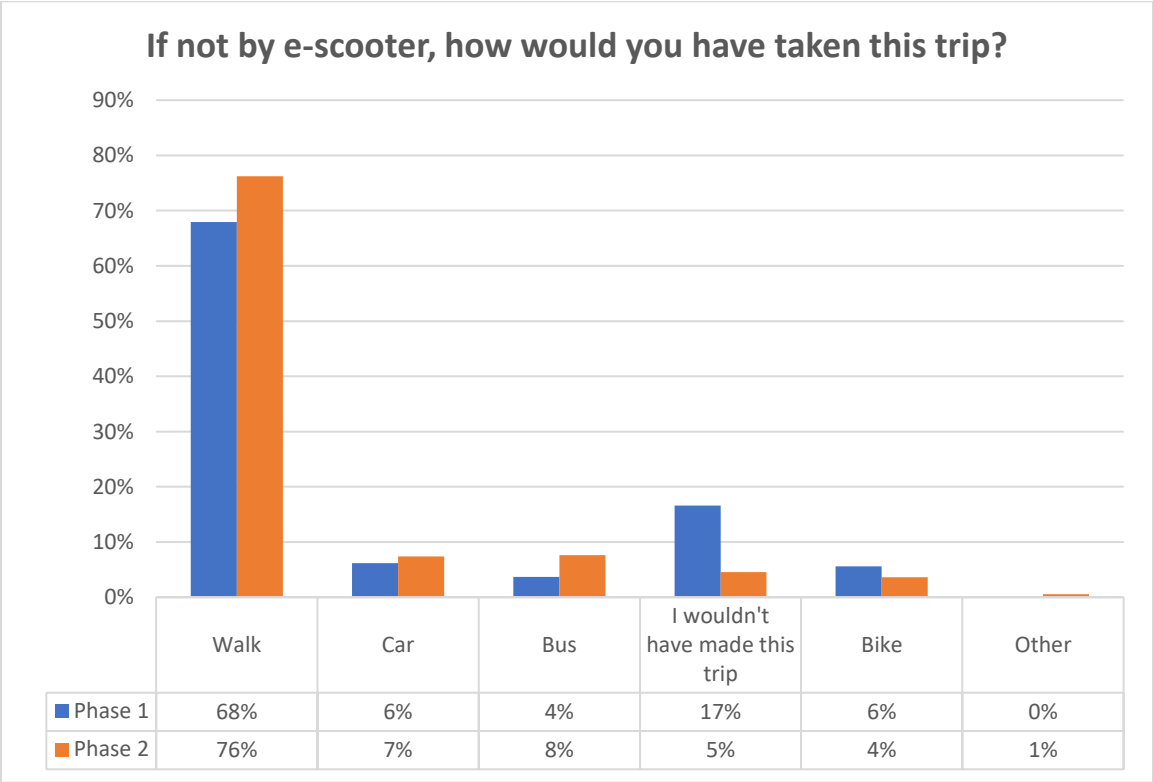


E-Scooter Parking Location	Acceptability	Count	Frequency
Parked correctly (within 5 feet of bike rack)	Acceptable	324	39.2%
Sidewalk - NOT blocking ADA access	Acceptable	348	42.1%
Other - NOT blocking ADA access	Acceptable	36	4.4%
Sidewalk - blocking ADA access	Not Acceptable	64	7.7%
Sidewalk - blocking ADA ramp	Not Acceptable	2	0.2%
Sidewalk - blocking stairs	Not Acceptable	13	1.6%
Sidewalk - blocking building entrance/exit	Not Acceptable	4	0.5%
Sidewalk - blocking other	Not Acceptable	12	1.5%
Parking lot - blocking vehicle and/or pedestrian right of way	Not Acceptable	17	2.1%
Other	Not Acceptable	6	0.7%
Total		826	100%

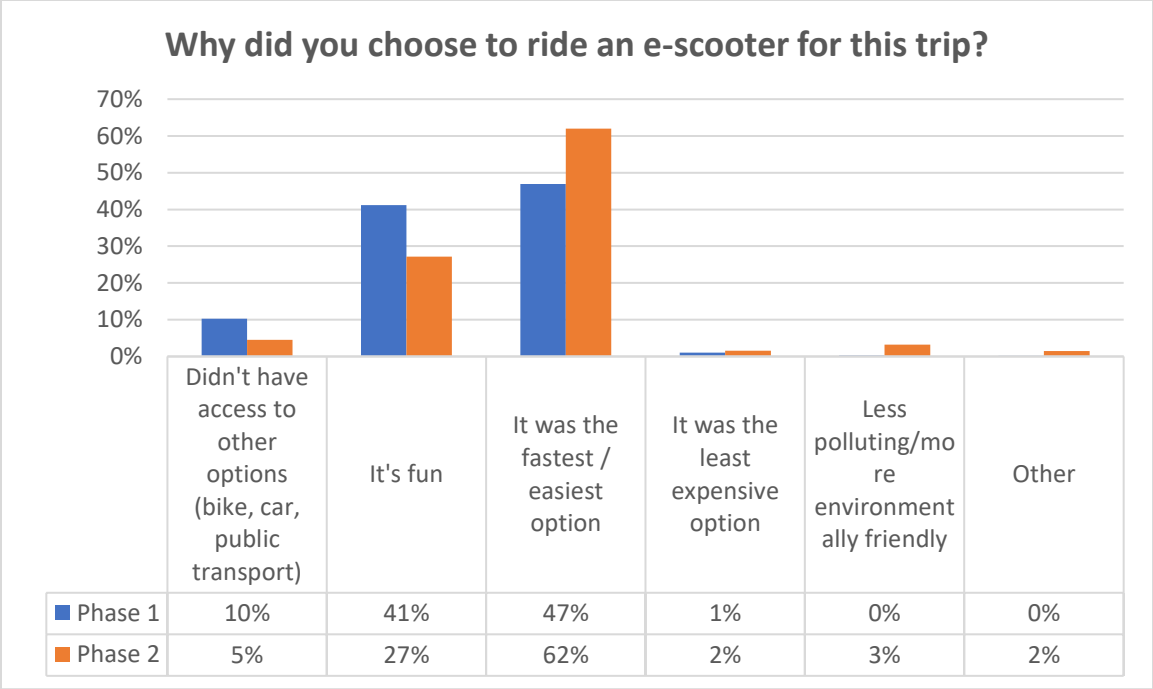
Post-Ride In-App Survey Results



	Attend/lead class	Social/extracurricular activity (e.g., recreation/fun)	Get to/from work	Go study/work on class-related assignment	Utilitarian trip (e.g., dining, errands, go to the gym)	Other
Phase 1	48%	16%	5%	12%	9%	9%
Phase 2	46%	16%	9%	8%	14%	6%



	Walk	Car	Bus	I wouldn't have made this trip	Bike	Other
Phase 1	68%	6%	4%	17%	6%	0%
Phase 2	76%	7%	8%	5%	4%	1%



	Didn't have access to other options (bike, car, public transport)	It's fun	It was the fastest / easiest option	It was the least expensive option	Less polluting/more environmentally friendly	Other
Phase 1	10%	41%	47%	1%	0%	0%
Phase 2	5%	27%	62%	2%	3%	2%

Appendix B: E-Scooter Design: Performance and Safety Evaluation

Appendix B-1: Pre-Testing Evaluation

Pre-Testing Evaluation

- To verify that participants can operate an e-scooter safely before attempting the tests, we will have them complete a pre-testing evaluation
  - Participants will first be allowed a practice ride on the e-scooter of up to 5 minutes
  - After 5 minutes, or once participants are ready, they will be evaluated on their understanding of e-scooter controls, proper riding stance, and ability to perform basic maneuvers

Evaluation Location

- VTTI - parking lot behind main building
  - Flat, pavement surface
  - Area will be blocked off with cones
  - No other road users
  - Cones and chalk markings will be used for evaluation setup

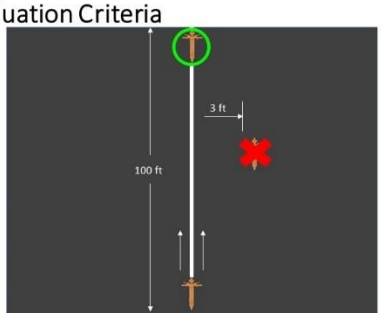
Pre-Testing Evaluation Criteria

- Understanding of e-scooter controls
  - Participant needs to be able to verify that they know where handlebars, accelerator, brakes, and scooter deck are located before riding. As participants are experienced riders, they should know where controls are without instruction.
- Foot placement demonstration
  - Participants need to show researcher proper foot placement (according to manual recommendations) on e-scooter. As participants are experienced riders, they should be aware of proper riding stance without instruction.
- Steering control test
  - Explained on next slides
- Braking test
  - Explained on next slides
- Basic avoidance maneuver test
  - Explained on next slides
- Slalom test
  - Explained on next slides
- Inappropriate behavior
  - Any participants causing trouble during the practice ride will be given a warning. A second offense (during the practice ride or testing) will result in the participant being dismissed from further testing
- *This process will be documented

Pre-Testing Evaluation Criteria

Steering control

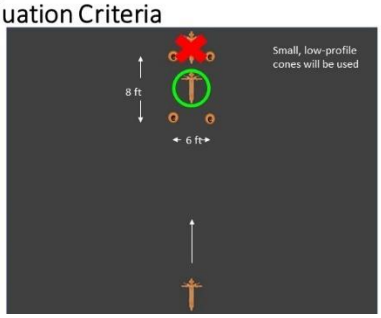
- Participant will travel on a straight marked line of road for 100 ft. at any speed that they are comfortable maintaining
- Researcher will take note of control (ability to stay on the line), balance, scooter wobbling
- 2 attempts will be allowed. Major deviations (>3ft) left or right from centerline, poor balance, or excessive scooter wobbling will result in dismissal from further testing
- Participants going very slow or looking unstable will be dismissed from testing



Pre-Testing Evaluation Criteria

Braking

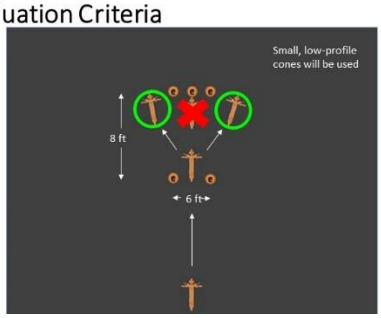
- Participant will approach 4 cones at any speed that they are comfortable maintaining
- Participant will need to brake within the 4 cones
- 2 attempts will be allowed. Failure to brake within the cones will result in dismissal from further testing
- Participants going very slow and looking unstable will be dismissed from testing



Pre-Testing Evaluation Criteria

Basic avoidance maneuver

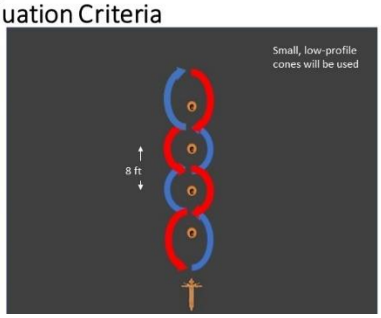
- Participant will approach cones set up across the road straight on at any speed that they are comfortable maintaining
- Participant will need to turn to avoid cones
- 2 attempts to the right side, 2 attempts to the left side. Failure to avoid the cones will result in dismissal from further testing
- Participants going very slow or looking unstable will be dismissed from testing



Pre-Testing Evaluation Criteria

Slalom

- Participant will demonstrate quick-turning abilities
- Participant will weave between cones at any speed that they are comfortable maintaining, then turn around after last cone and weave back through the cones
- 2 attempts will be allowed. Skipping cones or contacting cones with scooter will count as a failed attempt. Failure to complete the trial or demonstration of poor balance or excessive scooter wobbling will result in dismissal from further testing
- Participants going very slow or looking unstable will be dismissed from testing

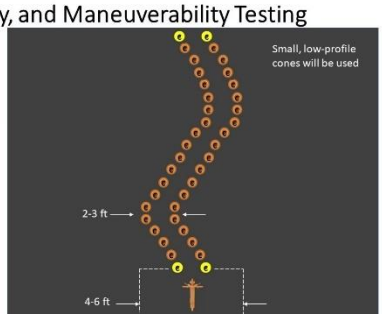


Appendix B-2: Additional Obstacle Pictures

Handling, Stability, and Maneuverability Testing

Task:

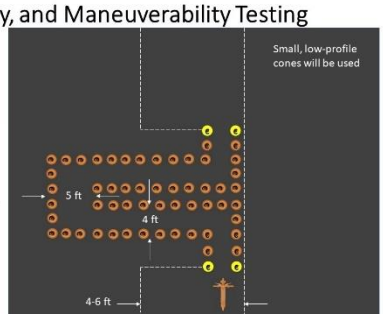
- Weave (2)
  - Starting to the left and starting to the right
  - ~6 ft. radius
    - May vary depending upon ease of completion
  - Cones may be removed and replaced with chalk if they cause scooters to slip when they come into contact



Handling, Stability, and Maneuverability Testing

Task:

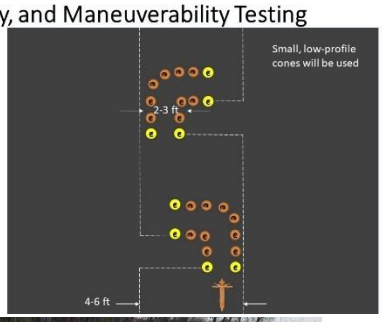
- Sideways U-turn(2)
  - Represents ADA ramp
  - Left and right
  - Cones may be removed and replaced with chalk if they cause scooters to slip when they come into contact



Handling, Stability, and Maneuverability Testing

Task:

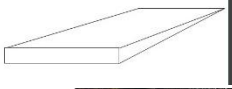
- Tight turn (2)
  - Approx. 90 degrees
  - Left and right
  - Cones may be removed and replaced with chalk if they cause scooters to slip when they come into contact

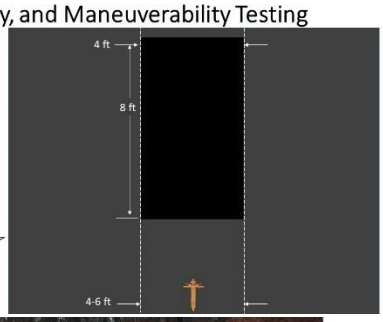


Handling, Stability, and Maneuverability Testing

Task:

- Riding into raised edge (3)
  - 1", 2", 3"
  - Made from concrete
  - Color of feature will be chosen to stand out

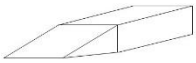


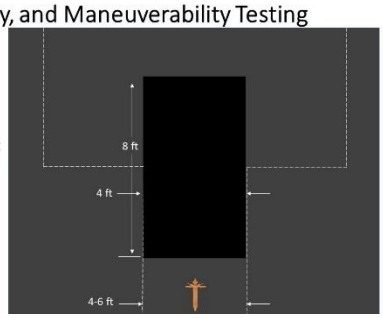


Handling, Stability, and Maneuverability Testing

Task:

- Riding off curb (3)
  - 2", 4", 6"
  - Made from concrete
  - Option to ride straight off, to left and to right
  - Color of feature will be chosen to stand out

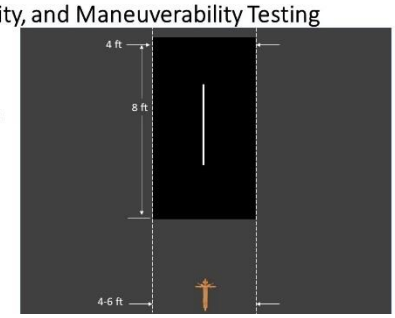




Handling, Stability, and Maneuverability Testing

Task:

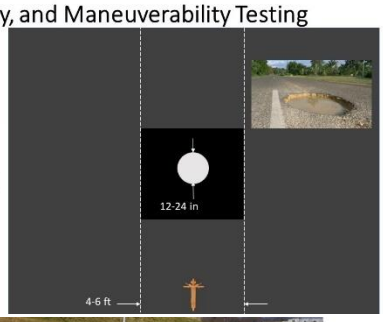
- Crack (1)
  - Included on built-up concrete section
  - Width will be less than tire width
  - Option to transition from left to right or right to left



Handling, Stability, and Maneuverability Testing

Task:

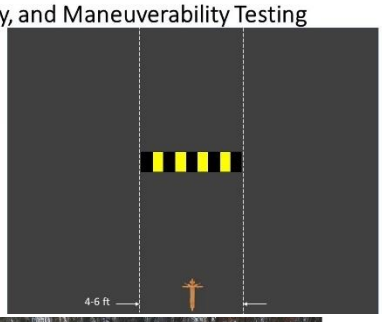
- Pothole (2)
  - Included on built-up concrete section
  - Circular cross sections or straight across as in figure
  - 1"- 2" depths
  - Width will not be equal to diameter of scooter wheels or distance between outer edge of wheels to prevent scooter from getting stuck



Handling, Stability, and Maneuverability Testing

Task:

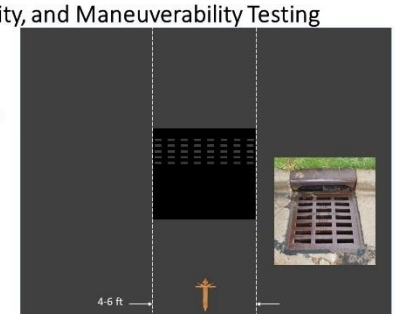
- Uneven bump (2)
  - 2", 3"
  - Use a temporary speed bump



Handling, Stability, and Maneuverability Testing

Task:

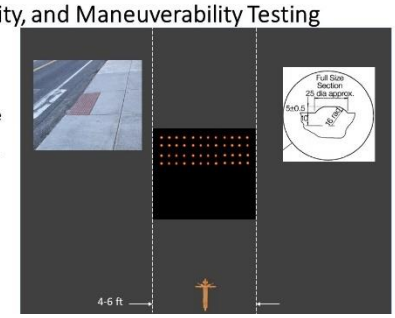
- Sewer grate (1)
  - Included on built-up concrete section



Handling, Stability, and Maneuverability Testing

Task:

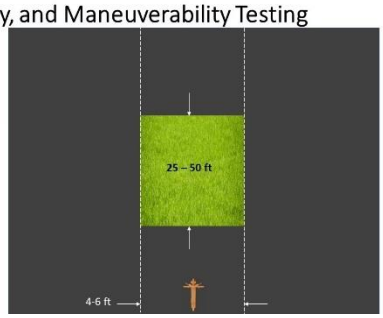
- Tactile paving (1)
  - Strip attached to the road
  - Indicators are 0.2 in. tall, 1 in. diameter, 2.5 in. center to center



Handling, Stability, and Maneuverability Testing

Task:

- Terrain transitions (3)
  - Gravel/loose surface
  - Grass
  - Dirt/mulch



Appendix B-3: Reduction Protocols

Speed, Acceleration, and Braking Test

Fixed Camera Reduction

- **Initial Acceleration Posture:** Select any of the following that describe the rider's INITIAL posture at the start of acceleration? (check 1 option from Legs AND at least 1 option from Body)
    - Legs-Standing straight up
    - Legs-Bending knees
    - Body-No lean
    - Body-Leaning forward
    - Body-Leaning backward
    - Body-Leaning to either side
    - Other (leave a note)
- **Acceleration Posture Change:** Select any of the following that describe the rider's CHANGE in posture while accelerating? (check all the apply)
    - Legs-Stands straight up
    - Legs-Bends knees (other than sitting)
    - Legs-Sits down (Max 2.0 with seat only)
    - Legs-Stands up (Max 2.0 with seat only)
    - Body-Leans forward
    - Body-Leans backward
    - Body-Returns to neutral front/back
    - Body-Leans to either side
    - Body-Returns to neutral side
    - Feet-Changes position (other than adding foot to scooter)
    - Feet-Uses feet to gain speed (after first time with both feet on scooter)
    - No change in posture
    - Other (leave a note)
- **Initial Braking Posture:** Select any of the following that describe the rider's INITIAL posture at the start of braking? (check 1 option from Legs AND at least 1 option from Body)
    - Legs-Standing straight up
    - Legs-Bending knees (other than sitting)
    - Legs-Sitting down (Max 2.0 with seat only)
    - Body-No lean
    - Body-Leaning forward
    - Body-Leaning backward
    - Body-Leaning to either side
    - Other (leave a note)
- **Braking Posture Change:** Select any of the following that describe the rider's CHANGE in posture while braking? (check all the apply)
    - Legs-Stands straight up (from bent knees)
    - Legs-Bends knees
    - Legs-Sits down (Max 2.0 with seat only)
    - Legs-Stands up (Max 2.0 with seat only)
    - Body-Leans forward

- Body-Leans backward
- Body-Returns to neutral front/back
- Body-Leans to either side
- Body-Returns to neutral side
- Feet-Changes position
- Feet-Uses feet to slow down (scooter still moving)
- No change in posture
- Other (leave a note)

Handling, Stability, and Maneuverability Test

Fixed Camera Reduction

- **Select any of the following that describe the rider's INITIAL posture or riding strategies while completing approaching the obstacle? (check 1 option from Legs AND at least 1 option from Bodycheck all that apply)**
    - Legs-Standings straight up
    - Legs-Bendings knees
    - Body-No lean
    - Body-Leanings forward
    - Body-Leanings backward
    - Body-Leanings to side
    - Other (leave a note)
- **Select any of the following that describe the rider's CHANGE in posture or strategies that the rider takes while completing the obstacle? (check all that apply)**
    - Legs-Stands straight up
    - Legs-Bends knees
    - Body-Leans forward
    - Body-Leans backward
    - Body-Leans to left
    - Body-Leans to right
    - No change in posture
    - Feet-Uses one foot for assistance
    - Feet-Uses both feet for assistance
    - Hands/Arms-Lifts handlebars to raise front of vehicle
    - Changes posture (leave a note)
    - No strategies
    - Other (leave a note)

Safety Critical Events

- **Event Type**. Which of the following describes the crash? (check all the apply)
    - Full fall over – involves some part of the scooter contacting the ground (other than wheels) and some part of the rider contacting the ground (other than feet). May also check "Forward impact" if applicable.
    - Bailout with fall over – involves some part of the scooter contacting the ground (other than wheels) but rider's foot catches their fall or rider successfully aborts without falling. May also check "Forward impact" if applicable.

- Bailout no fall over – involves only the rider's feet catching their fall and the rider also keeps scooter from contacting the ground. May also check "Forward impact" if applicable.
- Forward impact – involves the scooter impacting something. May also include a full fall over, bailout with fall over, or bailout no fall over.
- Other – to capture circumstances not fitting into defined categories

- **Post-Event Action**. What is the post-crash action?
  - Rider immediately resumes testing - begins riding scooter within 2-3 seconds after crash
  - Rider pauses and eventually continues testing
  - Rider does not continue - either due to choosing to end trial early or trial complete
  - Other (leave a note)
- **Narrative.** Provide a brief narrative describing the event.

Appendix B-4: Surveys

Pre-Session Questionnaire

Experienced and Novice Riders

Gender:

- Male
- Female
- Non-binary
- Other
- Prefer not to say

Ethnicity (select all that apply):

- White or Caucasian
- Black or African American
- American Indian or Alaska Native
- Asian
- Native Hawaiian or Other Pacific Islander
- Hispanic or Latino
- Other (please specify): _____

Age: _____

Height:

- Feet: _____
- Inches: _____

Weight (lbs.): _____

Dominant hand:

- Left
- Right

Which e-scooter services have you used before? (select all that apply)

- Bird
- Lime
- Spin
- Skip
- Lyft
- Scoot
- Other (please specify): _____

Are there any e-scooter brands that you would never ride? (select all that apply)

- Bird
- Lime

- Spin
- Skip
- Lyft
- Scoot
- Other (please specify): _____

Experienced Riders Only

For approximately how long have you been using an e-scooter?

- Years: _____
- Months: _____

Approximately how many trips do you take a week on an e-scooter? _____

Do you own a personal e-scooter?

- Yes
    - Which brand and model is your e-scooter? _____
- No

Where do you normally ride e-scooters? (select all that apply)

- Campus
- City
- Neighborhood / suburb
- Park
- Other (please specify): _____

Have you ever fallen, crashed, or been injured while riding an e-scooter?

- Yes
- No

Novice Riders Only

About how many days a week do you exercise, and for how many minutes each day?

- Days per week: _____
- Minutes per day: _____

Which type(s) of activities does your exercise typically consist of? (select all that apply)

- Cardio (running, walking, biking, elliptical, etc.)
- Weights/resistance
- Sports
- Other (please specify): _____

Which sports do you currently play or have played in the past 8 years? (select all that apply)

- Baseball/softball
- Football

- Basketball
- Soccer
- Wrestling
- Swimming
- Volleyball
- Tennis
- Golf
- Lacrosse
- Gymnastics
- Cheer
- Boxing
- Ice hockey
- Field hockey
- Bowling
- Cycling
- Motorsports
- Other (please specify): _____

Which of these devices have you used before? (select all that apply)

- E-scooter
- Bicycle
- Non-powered scooter (e.g., Razor scooter)
- Skateboard
- Roller blades
- Ice skates
- Snowboard
- Skis
- Hoverboard
- Segway
- Onewheel
- Other (please specify): _____

Do you have lots of experience using _?

- Yes
    - About how long have you been using _?
        - Years: _____
        - Months: _____
- No
    - About how many times have you used _ before? _____

Which of the reasons below explain why you don't often, or never, use e-scooters? (select all that apply)

- I have no interest in using e-scooters
- I prefer to use other modes of transportation

- I think that e-scooters are unsafe
    - Why do you think that e-scooters are unsafe? (select all that apply)
        - E-scooters are too fast
        - E-scooters offer no protection to riders
        - E-scooters are too unstable
        - E-scooters are difficult to control
        - It is unclear where to safely ride e-scooters
        - Shared e-scooters do not include safety equipment (e.g., helmet)
        - Other (please specify): _____
- I was involved in a fall or crash with an e-scooter (rider, pedestrian, other)
- I was injured as a result of e-scooter use (rider, pedestrian, other)
    - What was your involvement in the fall, crash, or injury? (select all that apply)
        - E-scooter rider
        - Pedestrian
        - Motor vehicle driver or passenger
        - Bicycle rider
        - Other (please specify): _____
- I do not want to pay to use an e-scooter
- E-scooters are not easily available to me
- Other (please specify): _____

Where do you think e-scooters should be ridden? (select all that apply)

- Bike lane
- Sidewalk
- Road
- Other (please specify): _____

Which of the following would help to improve your perceptions on e-scooter safety?

- Improved instructions/tutorials on how to safely ride an e-scooter
- Improved directions on where to ride an e-scooter
- Improved resources on e-scooter riding policies
- Included safety equipment
- Improved e-scooter design
- Other (please specify): _____

Which of the following design aspects of an e-scooter would make you feel safer?

- Lower speeds
- Larger tires
- Additional wheels
- Wider area to stand
- Longer area to stand
- Some form of occupant protection (e.g., airbag, vehicle frame, etc.)
- Restrictions on riding locations

- Restrictions on accounts of unsafe riders
- Protected lanes for e-scooter riders and cyclists
- Other (please specify): _____

Speed, Acceleration, and Braking Test

Post-Trial Survey

Instructions: For the condition that you just performed, please rank each of the e-scooter models on your perception of their acceleration and braking capabilities.

- Acceleration: did the e-scooter accelerate at a comfortable rate, or was it too fast or too slow?
- Acceleration: when the e-scooter accelerated, was it smooth and stable or did the e-scooter wobble?
- Braking: did the e-scooter brake at a comfortable rate, or was it too fast or too slow?
- Braking: when the e-scooter braked, was it stable or unstable?

Post-Test Survey

Instructions: For the following questions, please adjust the slider based upon your perceptions of the e-scooter Model _ during the Speed, Acceleration, and Braking test.

- Acceleration rate (1 – too slow, 5 – too fast)
- Acceleration feel (1 – unstable, wobbly; 5 – stable, smooth)
- Accelerator control effectiveness (1 – not effective (hard squeezing to accelerate); 5 – effective (easy squeezing to accelerate)
- Accelerator control placement/location (1 – uncomfortable, 5 – comfortable)
- Braking rate (1 – too slow, 5 – too fast)
- Braking feel (1 – unstable, 5 – stable)
- Brake control effectiveness (1 – not effective (hard squeezing to brake); 5 – effective (easy squeezing to brake)
- Brake control placement/location (1 – uncomfortable, 5 – comfortable)

E-scooter preference for accelerating?

E-scooter preference for braking?

Overall e-scooter preference for the Speed, Acceleration, and Braking test?

Closing Survey

Which conditions do you feel would not be appropriate for less experienced riders to perform?

For which of the following reasons do you find the _ condition inappropriate for less experienced riders?

- The condition caused the e-scooter to travel too fast
- The condition caused the e-scooter to accelerate too fast
- The condition caused the e-scooter to brake too fast or too hard
- The condition made the e-scooter difficult to handle or control
- Other (please specify)

Handling, Stability, and Maneuverability Test

Post-Trial Survey

Experienced and Novice Riders

Instructions: Please adjust the sliders based upon how well you think the e-scooter model that you just used performed each of the listed tasks during the Handling, Stability, and Maneuverability test. If you did not perform a certain task, choose the "Not Applicable" option. (1 – bad, 5 – great)

- Turning
- Riding over raised edges and bumps
- Riding off curbs
- Riding over sewer grates and tactile paving
- Riding across potholes and cracks
- Riding across gravel
- Riding across grass
- Riding across dirt/mulch

Novice Riders Only

Which of the obstacles did you choose not to attempt? (select all that apply)

Why did you choose not to attempt the _? (select all that apply)

- I did not feel comfortable attempting it
    - Why did the _ make you uncomfortable? (select all that apply)
        - I did not think that I would be able to complete it
        - I do not feel like I have enough experience to attempt it
        - I do not feel like I have had enough practice with it
        - I was not prepared for it (e.g., traveling too fast/slow, not in the right position, etc.)
        - Other (please specify): _____
- I attempted it earlier and it made me uncomfortable
- I was not able to complete it earlier
- I did not think that the scooter would be able to handle it
    - Why did you think that this scooter would not have been able to handle the _? (select all that apply)
        - I felt that this scooter traveled too slow
        - I felt that this scooter traveled too fast
        - I felt that this scooter was not stable
        - I felt that this scooter did not have the right size wheels
        - I felt that this scooter did not have the right suspension
        - I felt that this scooter was not good at turning
        - I felt that this scooter did not accelerate at an appropriate rate
        - I felt that this scooter did not brake at an appropriate rate
        - Other (please specify): _____
- It seemed like a better idea not to attempt it
- Other (please specify): _____

Would you attempt the _ if (select all that apply):

- You had more experience riding e-scooters
- You had practice attempting the obstacle
- You saw someone else complete it safely
- You received instructions/tutorials on how to complete it safely
- You were using a scooter with optimal features
    - What features would you want a different scooter to have to complete the _? (select all that apply)
        - Larger tires
        - Wider area to stand
        - Longer area to stand
        - Suspension with less give
        - Suspension with more give
        - More sensitive steering
        - Less sensitive steering
        - Faster acceleration
        - Slower acceleration
        - Faster braking
        - Slower braking
        - More sensitive acceleration controls
        - Less sensitive acceleration controls
        - More sensitive braking controls
        - Less sensitive braking controls
        - Other (please specify): _____
- Other (please specify): _____
- I would never attempt the obstacle

Post-Test Survey

Instructions: For the following questions, you are going to be asked about your perceptions of how the e-scooters performed each task type. You will be asked to rank the e-scooter models. You will also be asked about your overall e-scooter preference for this test. If you chose to opt-out of an entire task type, please do not respond to the corresponding question.

- Weave: was the e-scooter able to maneuver through the weave at a close to constant speed?
- Sideways U-turn: was the e-scooter able to maneuver through the sideways U-turn at a close to constant speed?
- Tight turn: was the e-scooter able to maneuver through the tight turn at a close to constant speed?
- Riding into raised edge: was the e-scooter able to handle riding over the raised edge while also remaining stable?
- Riding into raised edge: was the e-scooter able to handle riding over the raised edge while also remaining stable?
- Riding off curb: was the e-scooter able to handle riding off of the curb while also remaining stable?

- Crack: was the e-scooter able to handle riding across the crack while also remaining stable?
- Pothole: was the e-scooter able to handle riding through the pothole while also remaining stable?
- Uneven bump: was the e-scooter able to handle riding over the uneven bump while also remaining stable?
- Sewer grate: was the e-scooter able to handle riding over the sewer grate while also remaining stable?
- Tactile paving: was the e-scooter able to handle riding over the tactile paving while also remaining stable?
- Grass transition: was the e-scooter able to handle riding across the grass while also remaining stable?
- Gravel transition: was the e-scooter able to handle riding across the gravel while also remaining stable?
- Dirt/mulch transition: was the e-scooter able to handle riding across the dirt/mulch while also remaining stable?

E-scooter preference for turning and maneuvering?

E-scooter preference for riding over or off of obstacles?

E-scooter preference for stability?

E-scooter preference for riding across different surface types?

Overall e-scooter preference for Handling, Stability, and Maneuverability test?

Closing Survey (Experienced Riders only)

Which tasks do you feel would not be appropriate for less experienced riders to perform?

For which of the following reasons do you find the _ task inappropriate for less experienced riders? (select all that apply)

- You were nervous of uncomfortable performing it
- It was difficult to perform
- One or more of the e-scooters could not handle it
- It is normally something you would choose to avoid
- Other (please specify): _____

Geofence Test

Post-Test Survey

Please adjust the slides based upon how you think the e-scooter handled at the slow-zone geofence.

- Deceleration (1 – too slow, 5 – too fast)
- Acceleration back to full speed (1 – too slow, 5 – too fast)

Did any of the e-scooters respond to the slow-zone geofence better than others? _____

Please adjust the sliders based upon how you think the e-scooter handled at the no-ride zone geofence.

- Stopping rate (1 – too slow)

Did any of the e-scooters respond to the slow-zone geofence better than others? _____

Please adjust the sliders based upon your perceptions of the audible notification at the geofences?

- Volume level (1 – too quiet, 5 – too loud)
- Tone (1 – unpleasant, 5 – pleasant)
- Effectiveness (1 – confusing, 5 – easy to understand)

End of Study

E-Scooter Perceptions

For e-scooter Model _ please indicate the extent to which you agree or disagree with the following statements. (1 – strongly disagree, 5 – strongly agree)

- The e-scooter was comfortable to stand/sit on
- The controls were easy to understand
- The controls were easy to use
- The speed of the e-scooter met my needs
- The acceleration of the e-scooter met my needs
- The braking of the e-scooter met my needs
- The e-scooter was easy to turn
- The e-scooter easily rode over road features
- The e-scooter easily rode across terrain other than pavement/asphalt
- The ride was smooth and not bumpy
- I felt safe while riding on the e-scooter
- It was fun riding this e-scooter

Overall Study

Which e-scooter model did you prefer overall?

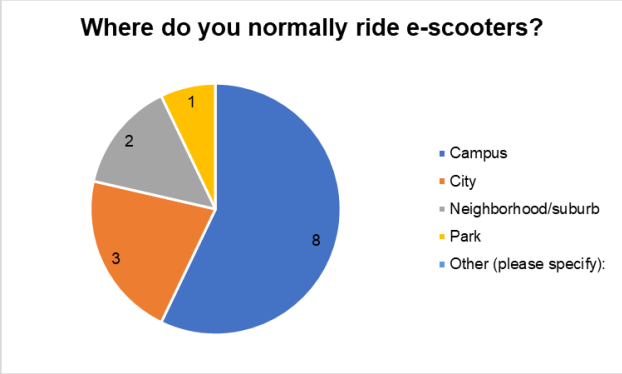
Which of the following factors contributed to you picking the above e-scooter model?

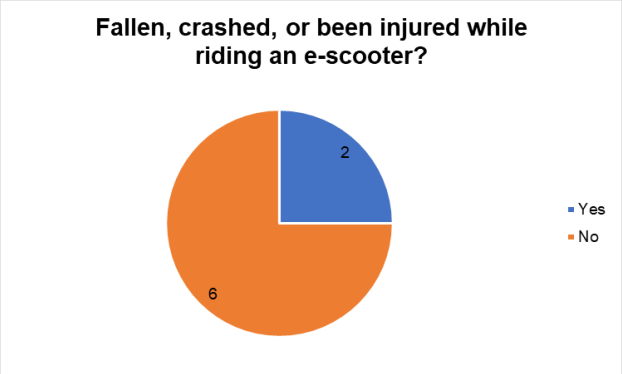
- Design
- Speed
- Acceleration
- Braking
- Suspension
- Turning
- Stability
- Ability to ride across bumps and transitions
- Ability to ride across various terrains
- Other (please specify): _____

Appendix B-5: Pre-Session Questionnaire Results

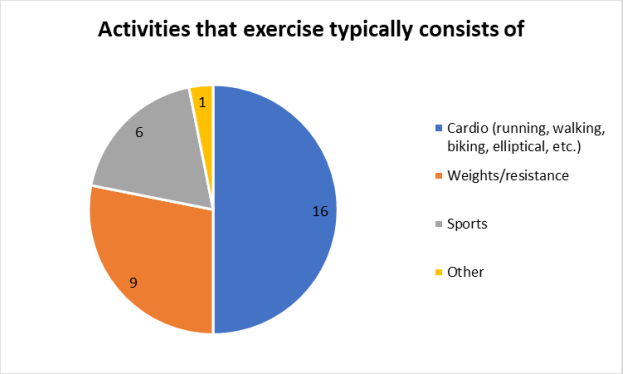
Experienced Riders

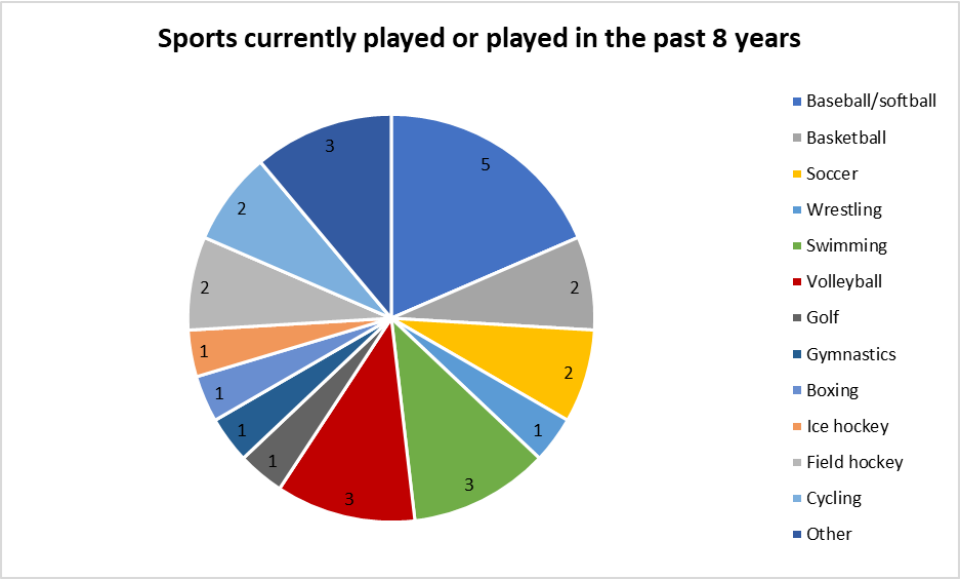
	Avg.	Std.	Min	Max
Time using an e-scooter (months)	33.88	15.67	4	53
Trips on an e-scooter per week	7.88	12.96	2	42

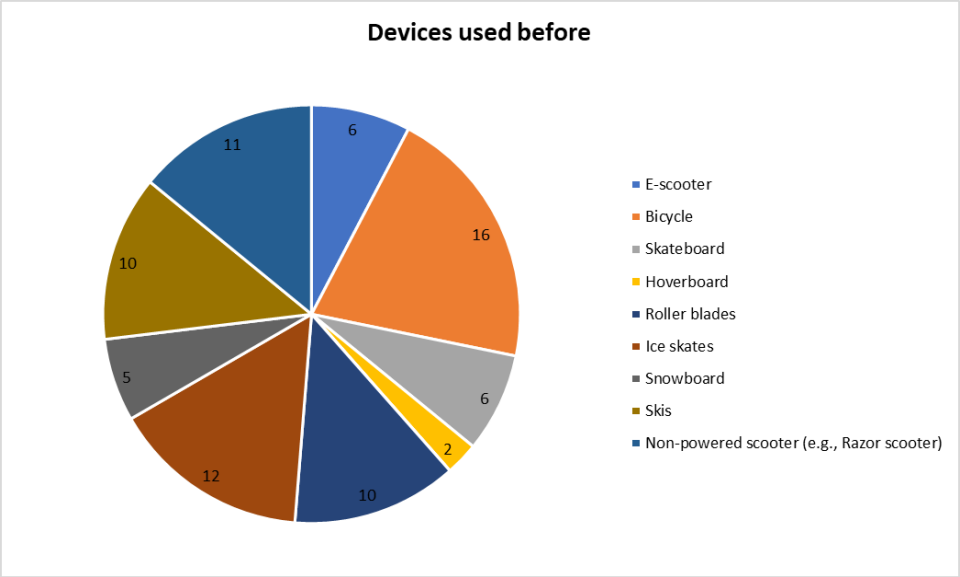


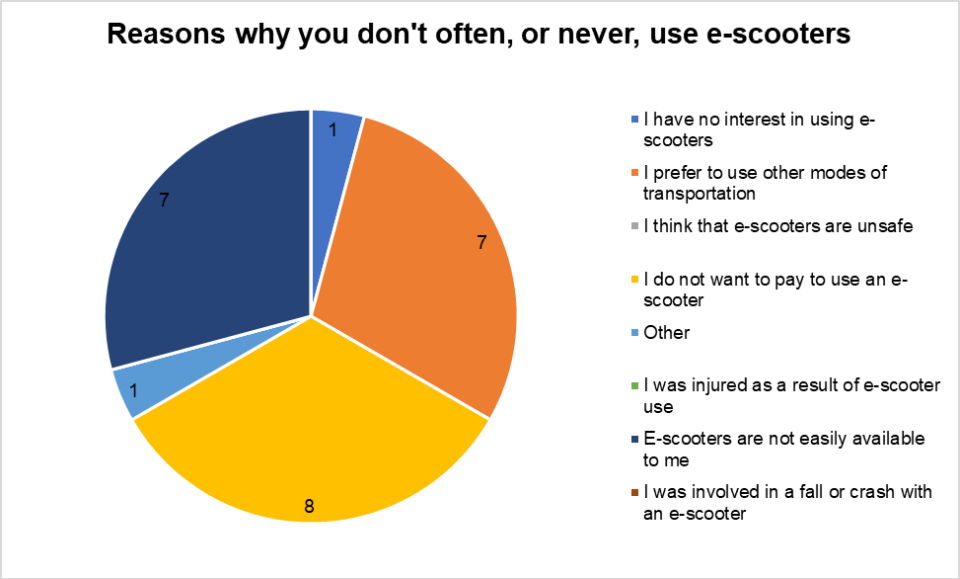


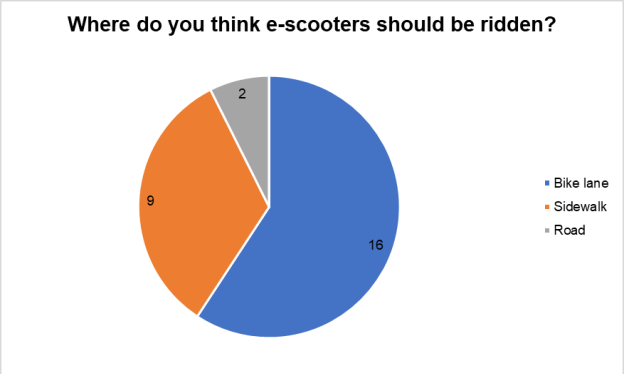
Novice Riders

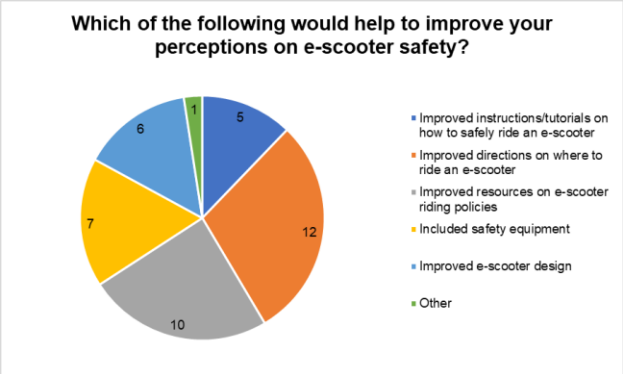


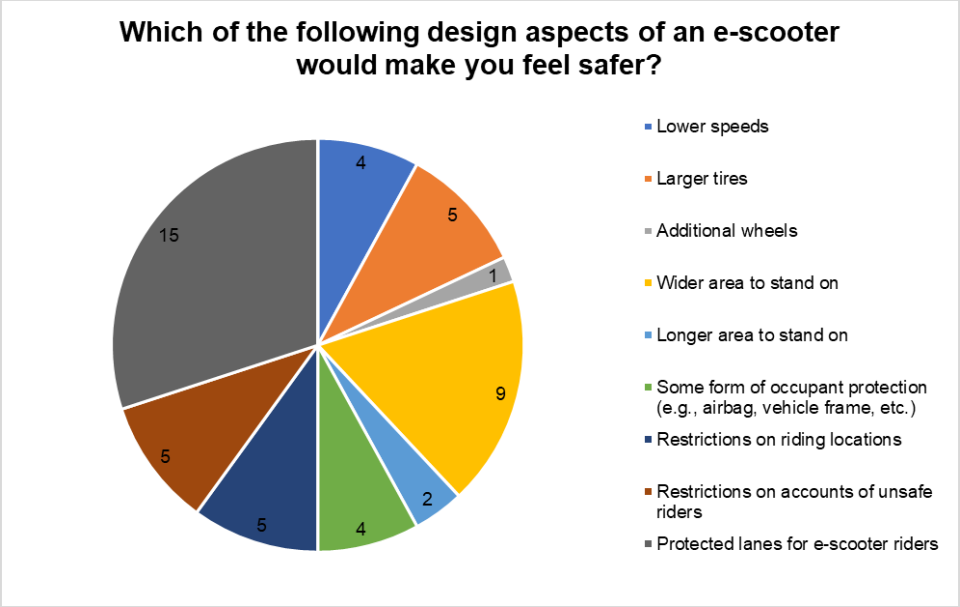

Sports currently played or played in the past 8 years
5
2
2
1
3
3
1
1
1
1
2
2
3
Baseball/softball
Basketball
Soccer
Wrestling
Swimming
Volleyball
Golf
Gymnastics
Boxing
Ice hockey
Field hockey
Cycling
Other


Devices used before
6
16
6
2
10
12
5
10
11
E-scooter
Bicycle
Skateboard
Hoverboard
Roller blades
Ice skates
Snowboard
Skis
Non-powered scooter (e.g., Razor scooter)


Reasons why you don't often, or never, use e-scooters
1
7
8
1
7
I have no interest in using e-scooters
I prefer to use other modes of transportation
I think that e-scooters are unsafe
I do not want to pay to use an e-scooter
Other
I was injured as a result of e-scooter use
E-scooters are not easily available to me
I was involved in a fall or crash with an e-scooter

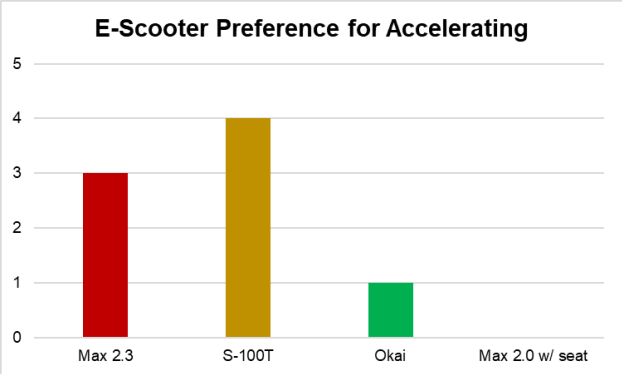

Where do you think e-scooters should be ridden?
16
9
2
Bike lane
Sidewalk
Road

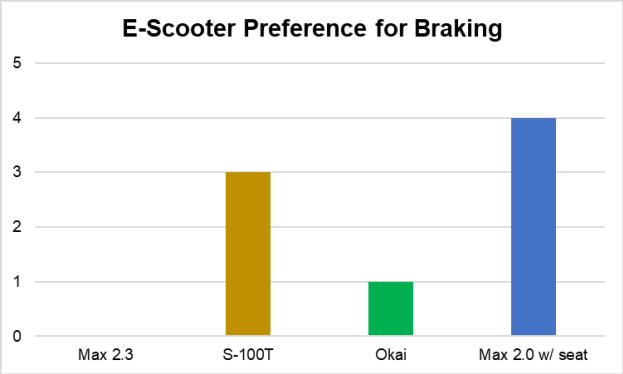

Which of the following would help to improve your perceptions on e-scooter safety?
5
12
10
7
6
1
Improved instructions/tutorials on how to safely ride an e-scooter
Improved directions on where to ride an e-scooter
Improved resources on e-scooter riding policies
Included safety equipment
Improved e-scooter design
Other

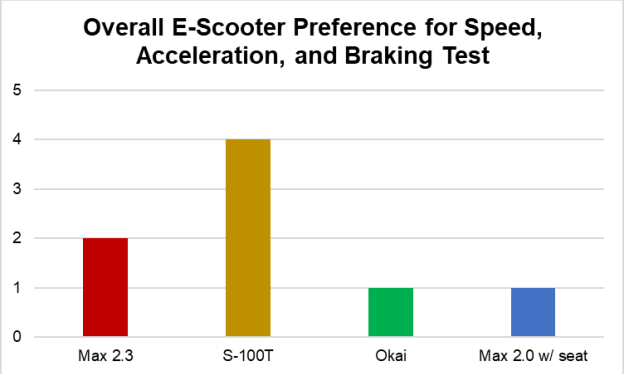

Which of the following design aspects of an e-scooter would make you feel safer?
4
5
1
9
2
4
5
5
15
Lower speeds
Larger tires
Additional wheels
Wider area to stand on
Longer area to stand on
Some form of occupant protection (e.g., airbag, vehicle frame, etc.)
Restrictions on riding locations
Restrictions on accounts of unsafe riders
Protected lanes for e-scooter riders

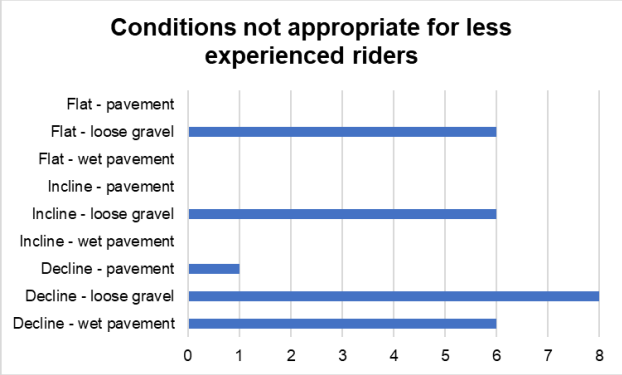
Appendix B-6: Additional Speed, Acceleration, and Braking Results

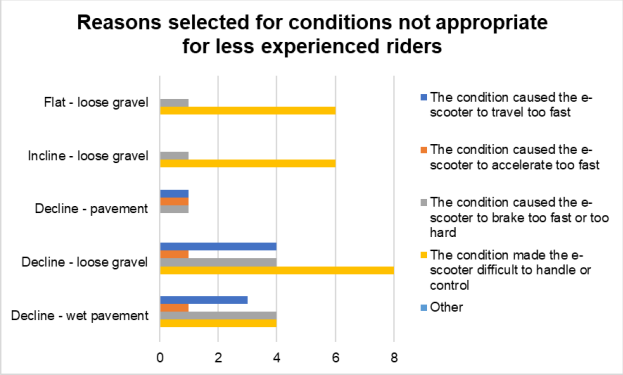
Survey Results





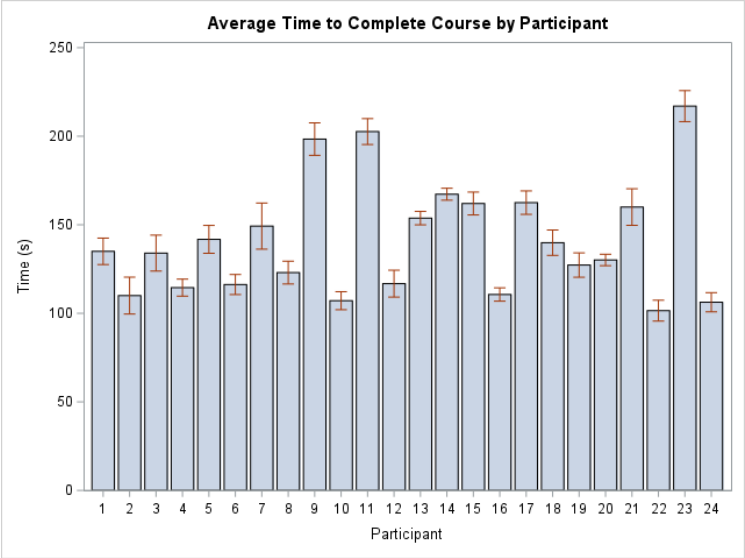






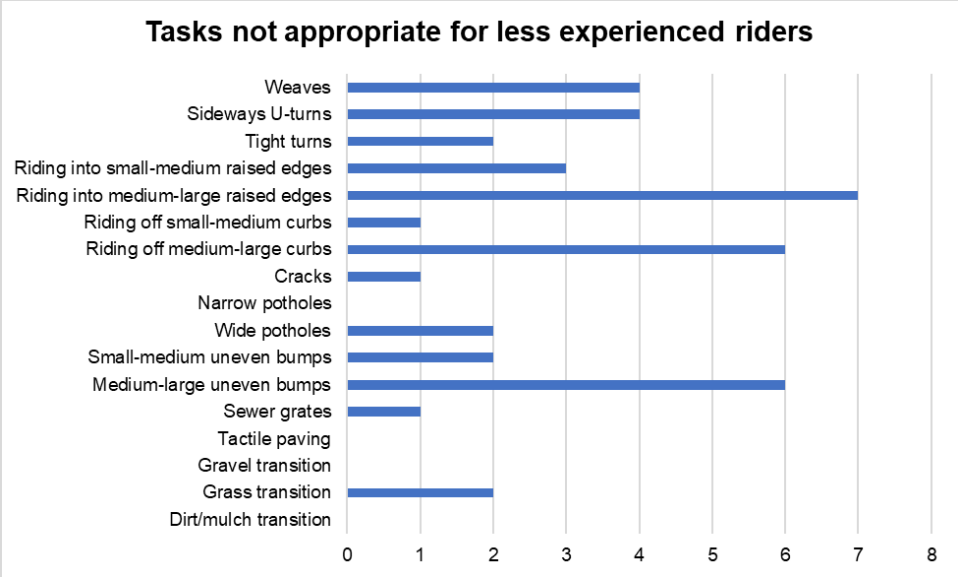
Appendix B-7: Additional Handling, Stability, and Maneuverability Results

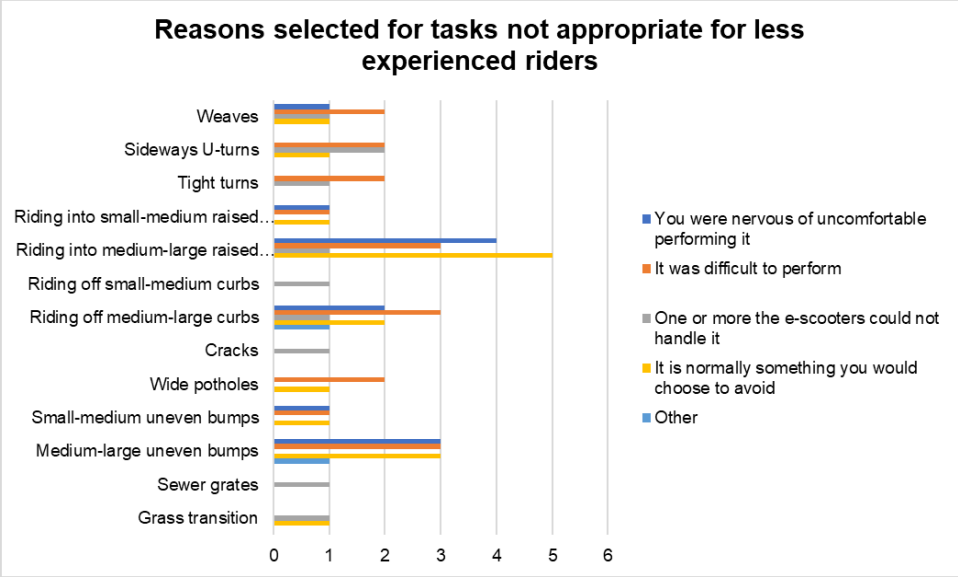
Course Time Results

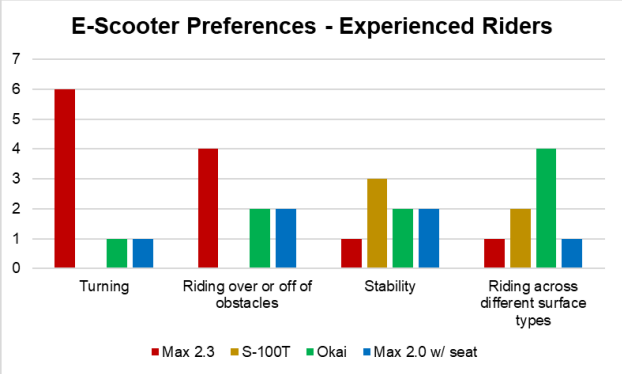


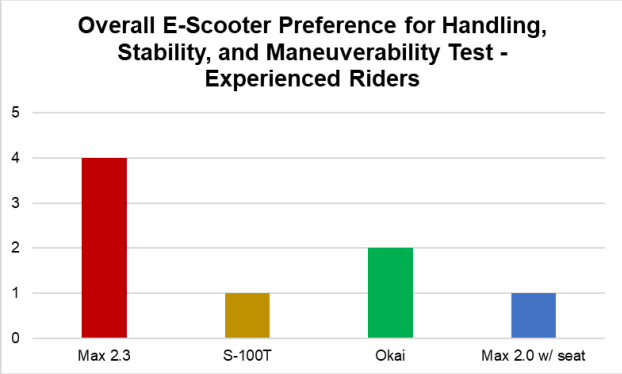
Survey Results

Experienced Riders

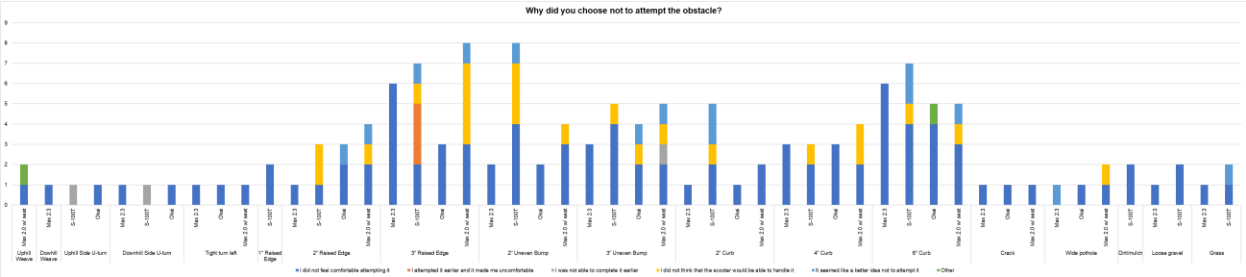


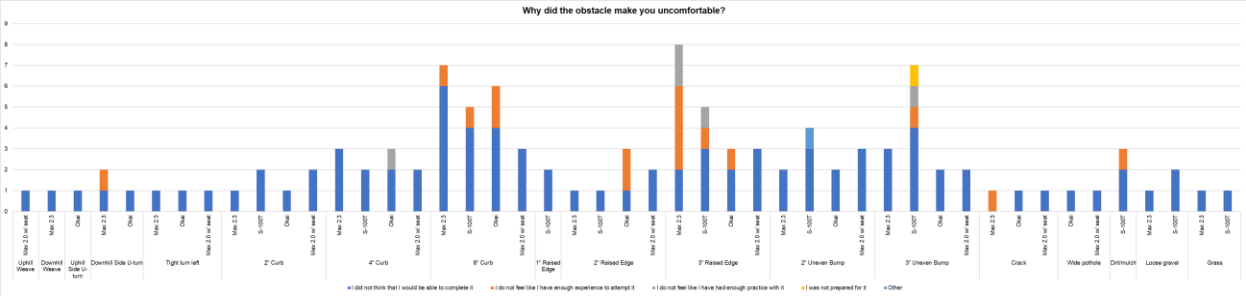


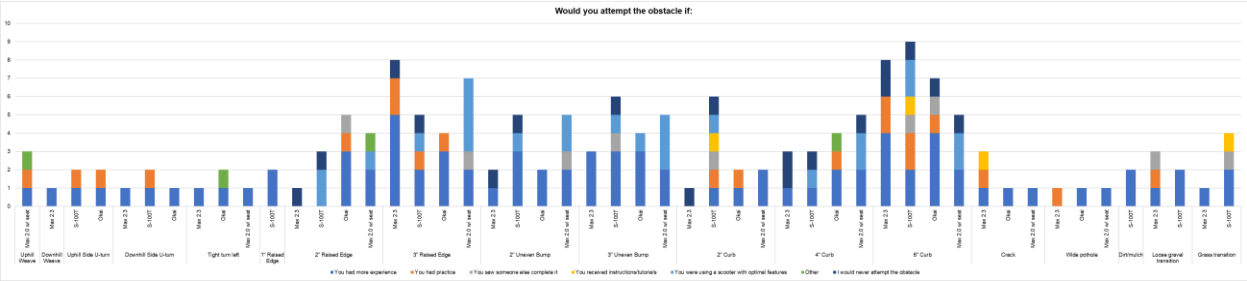


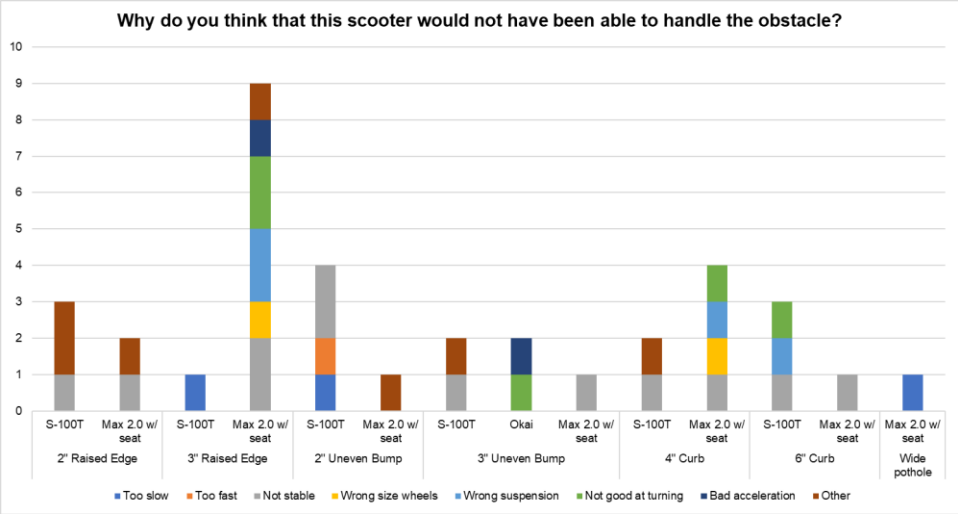


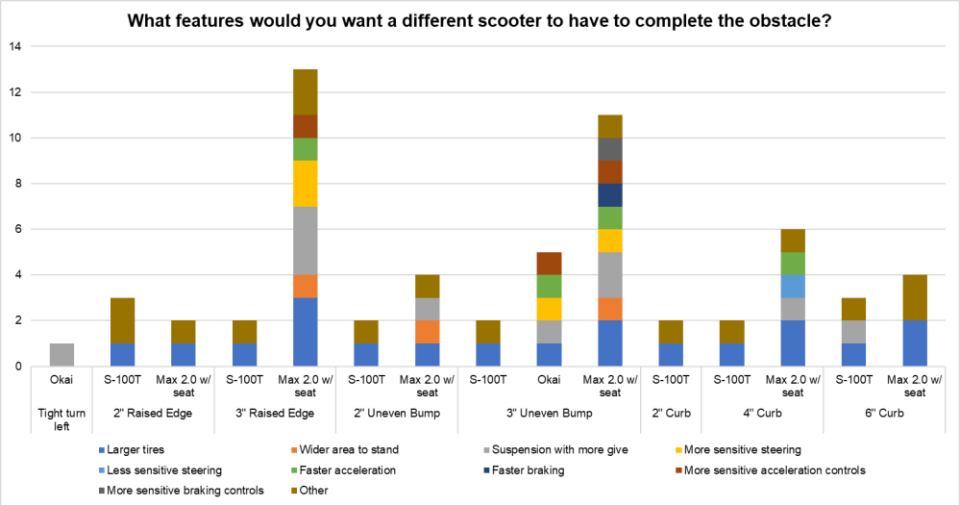
Novice Riders

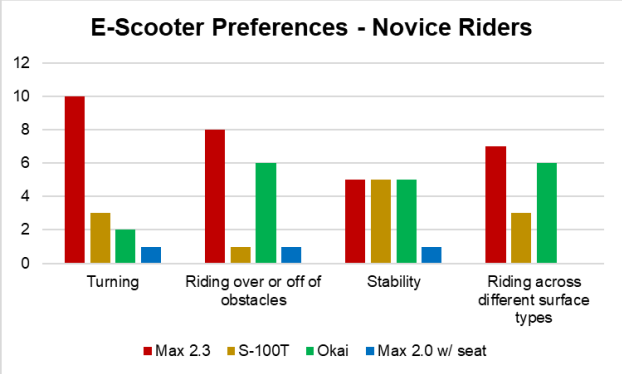


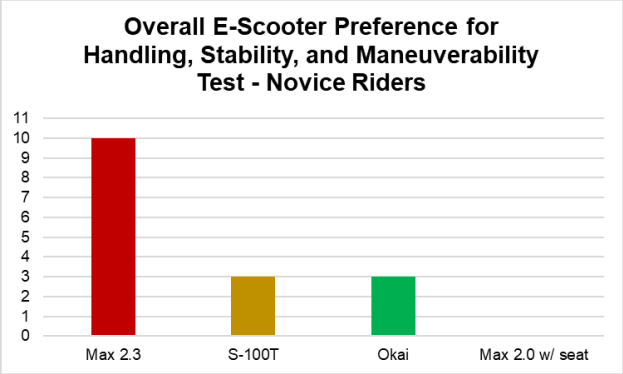



Would you attempt the obstacle if:


Why do you think that this scooter would not have been able to handle the obstacle?
10
9
8
7
6
5
4
3
2
1
0
S-100T
Max 2.0 w/ seat
2" Raised Edge
3" Raised Edge
2" Uneven Bump
Okai
3" Uneven Bump
4" Curb
6" Curb
Wide pothole
Too slow
Too fast
Not stable
Wrong size wheels
Wrong suspension
Not good at turning
Bad acceleration
Other

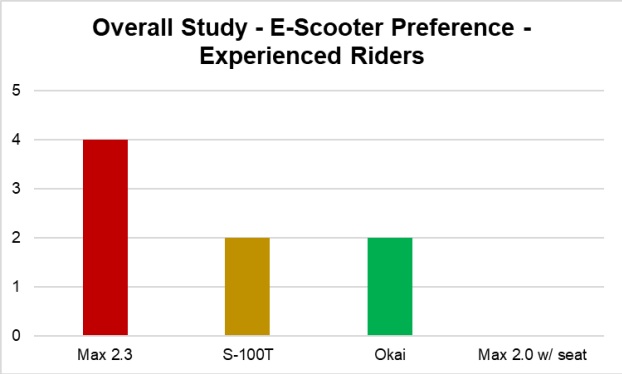

What features would you want a different scooter to have to complete the obstacle?
14
12
10
8
6
4
2
0
Okai
S-100T
Max 2.0 w/ seat
S-100T
Max 2.0 w/ seat
S-100T
Max 2.0 w/ seat
S-100T
Okai
Max 2.0 w/ seat
S-100T
S-100T
Max 2.0 w/ seat
S-100T
Max 2.0 w/ seat
Tight turn left
2" Raised Edge
3" Raised Edge
2" Uneven Bump
3" Uneven Bump
2" Curb
4" Curb
6" Curb
Larger tires
Wider area to stand
Suspension with more give
More sensitive steering
Less sensitive steering
Faster acceleration
Faster braking
More sensitive acceleration controls
More sensitive braking controls
Other

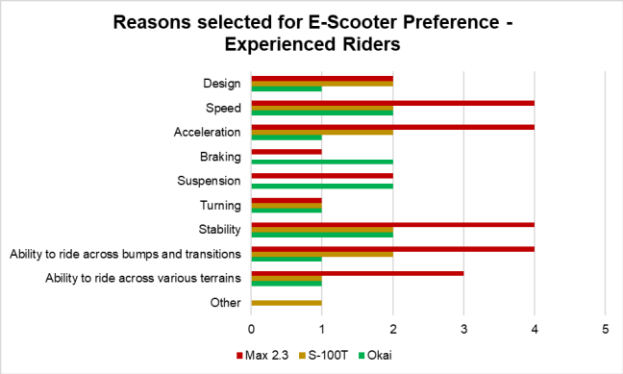

E-Scooter Preferences - Novice Riders
12
10
8
6
4
2
0
Turning
Riding over or off of obstacles
Stability
Riding across different surface types
Max 2.3
S-100T
Okai
Max 2.0 w/ seat


Overall E-Scooter Preference for Handling, Stability, and Maneuverability Test - Novice Riders
11
10
9
8
7
6
5
4
3
2
1
0
Max 2.3
S-100T
Okai
Max 2.0 w/ seat

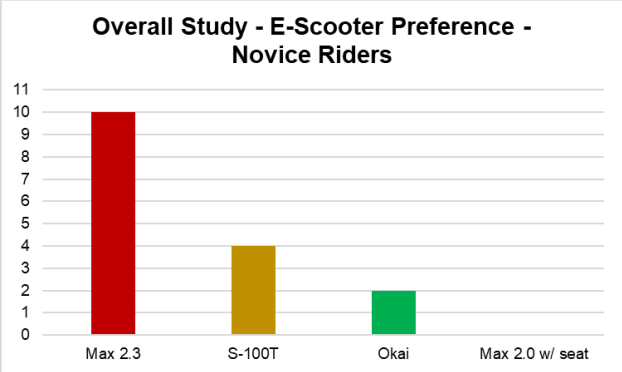
Appendix B-8: Additional Closing Survey Results

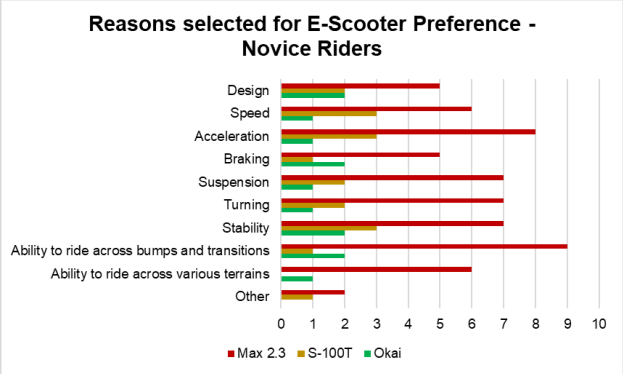
Experienced Riders





Novice Riders





Appendix C: Development of Training for E-Scooter Riders

Appendix C-1: Training Materials

Starting Your Ride

9

Starting Your Ride

- Place both hands on the handlebars
  - Don't place any bags on these → affects the scooter's stability!
- Stand with one foot on the scooter deck and the other foot on the ground
- Lean forward slightly, bend your knees, and push off with the foot on the ground a few times
- Once the scooter begins moving (approximately 3mph) return the foot on the ground to the scooter deck
- **Gently** apply the accelerator and comfortably position your body

10

Riding Stance

- Stand with one foot in front of the other
  - Most room for your feet
- Stand towards the center to back of the scooter
  - Helps to increase stability
  - In the case of a forward impact, reduces chance of an injury to the stomach or chest caused by the handlebars
- Slightly bend your knees
  - Gets you in an athletic posture
  - Helps to increase stability
  - Makes it easier to jump off the scooter if needed

11

Braking

- Bend your knees and lean backwards slightly
  - Braces you and helps to increase stability
- Gently apply the brakes
  - Brake on front wheel is more effective, but if used too rapidly, the scooter can pitch over and send you into the handlebars
  - Use both brakes if available to distribute the braking force
- Try not to brake hard while riding at high speeds

12

Riding

13

Riding

- Take things slow
  - It is easier to jump off the scooter
- Obstacles to avoid
  - Riding off curbs and raised surfaces
  - Riding over bumps or raised edges
  - Performing tight turning maneuvers
  - Riding across degraded surfaces (potholes and cracks)
  - Riding across terrain other than pavement/asphalt (grass, loose gravel, dirt)

14

HOWEVER

- We know that it isn't always possible to avoid these types of obstacles
- It helps to:
  - Understand which design features that your scooter has available to understand how it can handle the obstacles
  - Learn a few strategies for safely maneuvering these obstacles

15

Turning

- Understand the turning radius of your scooter and sensitivity of the handlebars
- Heavy scooters will require greater effort for turning
- Avoid sharp turns at high speeds
- For turns at higher speeds:
  - Bend your knees
  - Rotate the scooter stem
  - Slightly lean your body in the direction of the turn
- You can also slow down and use your feet
- Go slow while maneuvering past pedestrians, cyclists, or other road users

16

Riding Over Bumps and Raised Edges

- Check if your scooter has large diameter tires and sufficient ground clearance
  - Small diameter tires aren't designed to ride over large bumps and edges
  - Less ground clearance may result in the scooter bottoming out and getting stuck
- If you choose to attempt these:
  - Maintain your speed (slowing down may result in you getting stuck)
  - Stand towards the rear of the scooter
  - Bend your knees
  - Lift the front wheel of the scooter by raising the handlebars with your arms (you can also slow down and use one foot to push off from the ground to assist with raising the front wheel)
- Otherwise, slow down, step off the scooter, and walk it over the obstacle

17

Riding Off Raised Surfaces

- Check if your scooter has a suspension system and sufficient ground clearance
  - Suspension system will help to absorb the ground reaction force
  - Less ground clearance may result in the scooter bottoming out and getting stuck
- If you choose to attempt these:
  - Maintain your speed (slowing down may result in you getting stuck)
  - Bend your knees
  - Slightly raise the front wheel when riding off the surface (can help to reduce ground clearance issue)
  - Keep scooter level to assist with the landing
- Otherwise, slow down, step off the scooter, and walk it over the obstacle

18

Riding on Other Terrain

- E-scooters are not designed for off-roading
- If you still choose to do so, check your scooter's tire width
  - Wider tires will traverse across other terrain better
- When transitioning between different types of terrain, slow down and bend your knees in case there is any instability
- Avoid hard braking → the front tire can dig in and the scooter may pitch over
- Otherwise, step off the scooter and walk it across

19

Ending Your Ride

20

Ending Your Ride

- Make sure that you leave your scooter in a location specified by the rental company
  - The app should have instructions, and there may be marked locations
  - Otherwise, leave it towards the side of the sidewalk so that it isn't in the way for other road users
  - Make sure it isn't blocking the street, bike lanes, access to buildings, stairs, or ADA access ramps
  - Don't damage any trees, plants or grass with where you park it
- You may also need to take a picture in the app to prove that you left it in an appropriate location

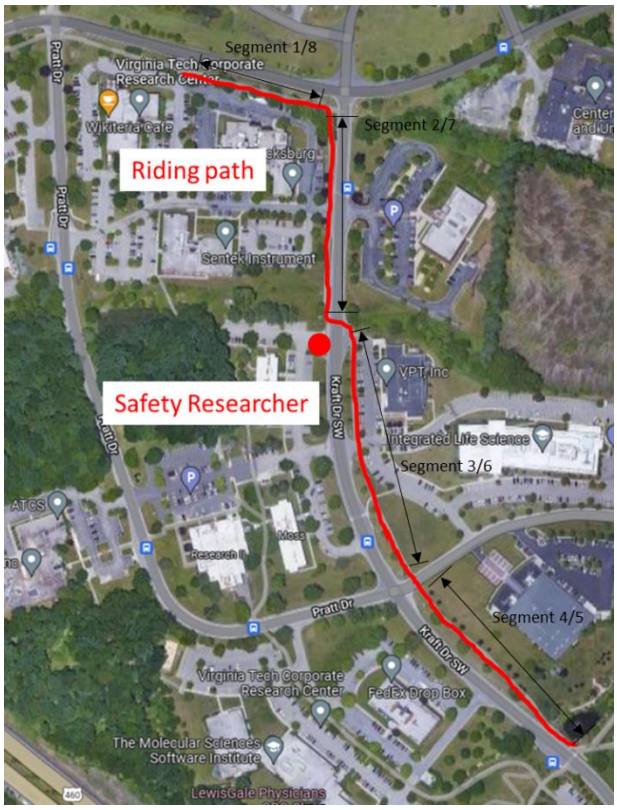
21

Well, that's it!

- Overall, we hope that you found this training useful and that you have a safe and fun ride!

22

Appendix C-2: Riding Paths



Appendix C-3: Pre-Session Questionnaire

Gender:

- Male
- Female
- Non-binary
- Other
- Prefer not to say

Ethnicity (select all that apply):

- White or Caucasian
- Black or African American
- American Indian or Alaska Native
- Asian
- Native Hawaiian or Other Pacific Islander
- Hispanic or Latino
- Other (please specify): _____

Age: _____

Height:

- Feet: _____
- Inches: _____

Weight (lbs.): _____

Dominant hand:

- Left
- Right

About how many days a week do you exercise, and for how many minutes each day?

- Days per week: _____
- Minutes per day: _____

Which type(s) of activities does your exercise typically consist of? (select all that apply)

- Cardio (running, walking, biking, elliptical, etc.)
- Yoga
- Weights/resistance
- Sports
- Other (please specify): _____

Which sports do you currently play or have played in the past 8 years? (select all that apply)

- Baseball/softball
- Football

- Basketball
- Soccer
- Wrestling
- Swimming
- Volleyball
- Tennis
- Golf
- Lacrosse
- Gymnastics
- Cheer
- Boxing
- Ice hockey
- Field hockey
- Bowling
- Cycling
- Motorsports
- Other (please specify): _____

Which of these devices have you used before? (select all that apply)

- E-scooter
- Bicycle
- Non-powered scooter (e.g., Razor scooter)
- Skateboard
- Roller blades
- Ice skates
- Snowboard
- Skis
- Hoverboard
- Segway
- Onewheel
- Other (please specify): _____
- None of the above

Please indicate either how many times you have used or how long you have been using the below device(s). (only selected options will appear)

- Times Used: _____
- Years Used: _____
- Months Used: _____
- Frequency Used (times/week): _____

Which of the reasons below explain why you don't often, or never, use e-scooters? (select all that apply)

- I have no interest in using e-scooters
- I prefer to use other modes of transportation

- I think that e-scooters are unsafe
    - Why do you think that e-scooters are unsafe? (select all that apply)
        - E-scooters are too fast
        - E-scooters offer no protection to riders
        - E-scooters are too unstable
        - E-scooters are difficult to control
        - It is unclear where to safely ride e-scooters
        - Shared e-scooters do not include safety equipment (e.g., helmet)
        - E-scooter riders don't need any form of training or licensing
        - Other (please specify): _____
- I was involved in a fall or crash with an e-scooter (rider, pedestrian, other)
- I was injured as a result of e-scooter use (rider, pedestrian, other)
    - What was your involvement in the fall, crash, or injury? (select all that apply)
        - E-scooter rider
        - Pedestrian
        - Motor vehicle driver
        - Motor vehicle passenger
        - Bicycle rider
        - Other (please specify): _____
- I do not want to pay to use an e-scooter
- E-scooters are not easily available to me
- Other (please specify): _____

Where do you think e-scooters should be ridden? (select all that apply)

- Bike lane
- Sidewalk
- Road
- Other (please specify): _____

Which of the following would help to improve your perceptions on e-scooter safety?

- Improved safety instructions/tutorials on how to safely ride an e-scooter
- Training/licensing
- Improved directions on where to ride an e-scooter
- Better understanding of e-scooter features
- Improved resources on e-scooter riding policies
- Included safety equipment
- Improved e-scooter design
- Other (please specify): _____

Which of the following design aspects of an e-scooter would make you feel safer?

- Lower speeds
- Larger tires
- Additional wheels

- Wider area to stand
- Longer area to stand
- Seat
- Some form of occupant protection (e.g., airbag, vehicle frame, etc.)
- Restrictions on riding locations
- Restrictions on accounts of unsafe riders
- Protected lanes for e-scooter riders and cyclists
- Improved safety instructions/tutorials
- Available training
- Licensing
- Other (please specify): _____

Appendix C-4: Risky Pedestrian Behavior Survey

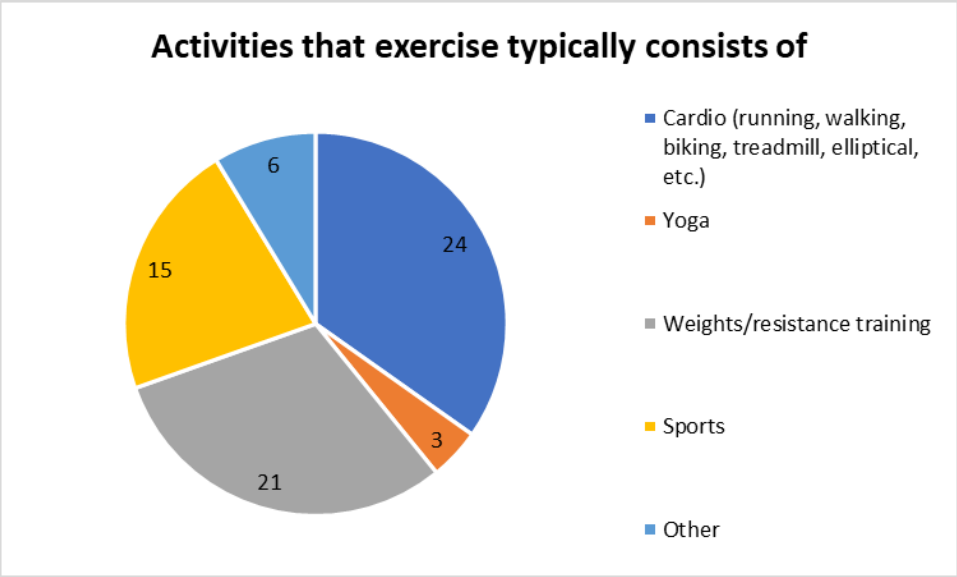
The following statements will be rated on a standard 7-point Likert type scale (see below).

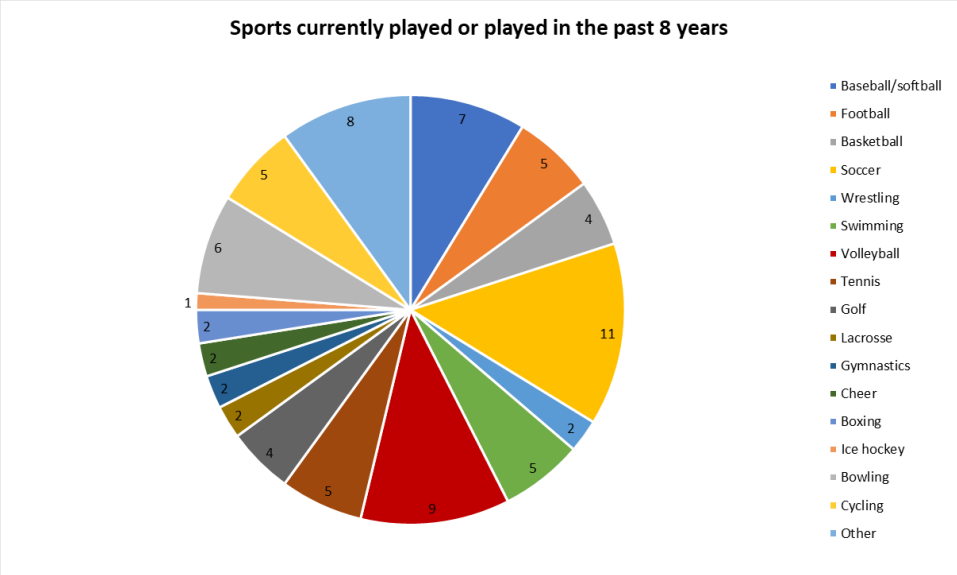
- ○ Strongly Disagree (1)
- ○ Disagree (2)
- ○ Somewhat Disagree (3)
- ○ No Opinion (4)
- ○ Somewhat Agree (5)
- ○ Agree (6)
- ○ Strongly Agree (7)

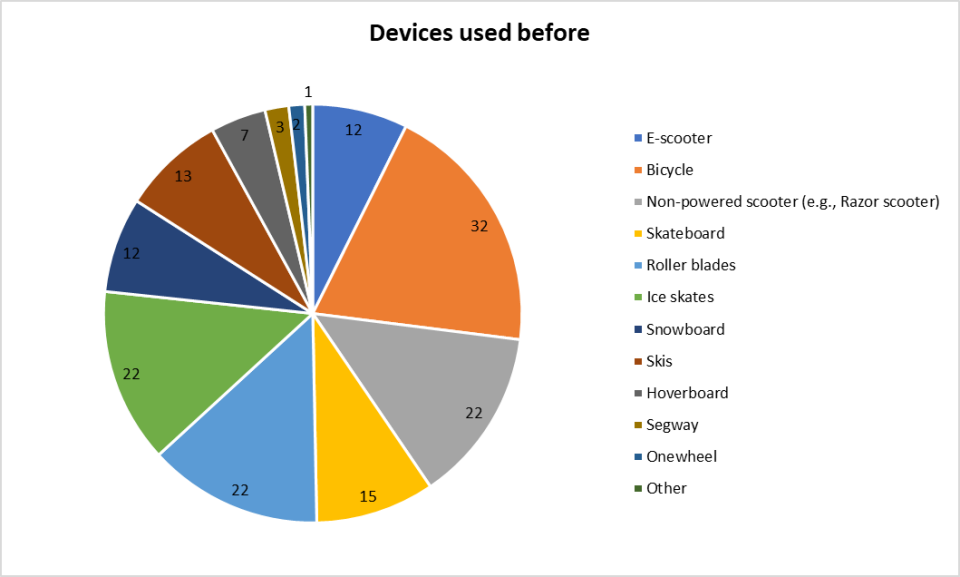
1. V1 I cross the street even though the pedestrian light is red.
2. V2 I cross diagonally to save time.
3. V3 I cross outside the pedestrian crossing even if there is one (crosswalk) less than 50 m away.
4. V10 I take passageways forbidden to pedestrians to save time.
5. E2 I cross between vehicles stopped on the roadway in traffic jams.
6. E7 I cross even if vehicles are coming because I think they will stop for me.
7. E8 I walk on cycling paths when I could walk on the sidewalk.
8. E9 I run across the street without looking because I am in a hurry.
9. L5 I realize that I have crossed several streets and intersections without paying attention to traffic.
10. L6 I forget to look before crossing because I am thinking about something else.
11. L7 I cross without looking because I am talking with someone.
12. L8 I forget to look before crossing because I want to join someone on the sidewalk on the other side.
13. A1 I get angry with another road user (pedestrian, driver, cyclist, etc.), and I yell at him.
14. A3 I cross very slowly to annoy a driver.
15. A4 I get angry with another road user (pedestrian, driver, cyclist, etc.), and I make a hand gesture.
16. A6 I have gotten angry with a driver and hit their vehicle.
17. P1 I thank a driver who stops to let me cross.
18. P3 When I am accompanied by other pedestrians, I walk in single file on narrow sidewalks so as not to bother the pedestrians I meet.
19. P4 I walk on the right-hand side of the sidewalk so as not to bother the pedestrians I meet.
20. P5 I let a car go by, even if I have the right-of-way, if there is no other vehicle behind it.

Appendix C-5: Additional Survey Results

Pre-Session Questionnaire







Pedestrian Risky Behavior Survey