E-Scooter Design: Safety Measures for Next Gen Scooter

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16. 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 e-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.

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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.

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This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program, and Ford Motor Company.

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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 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, e-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 e-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 and will be summarized below (White et al., 2023). 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 1**). 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.

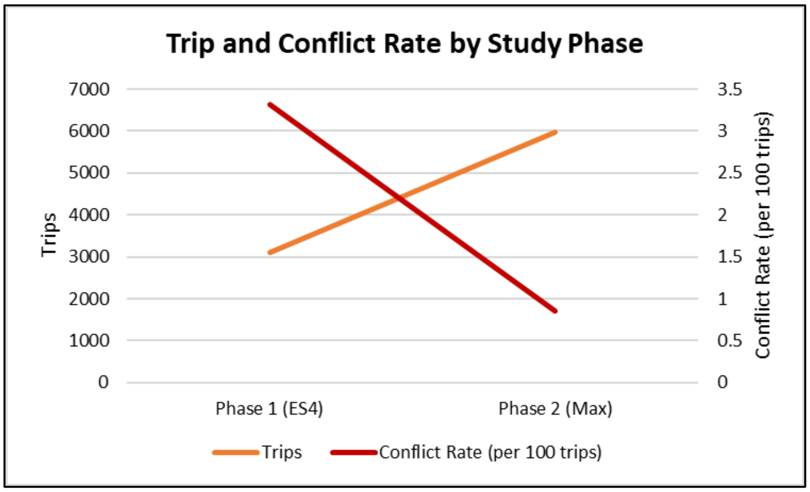

Figure 1. Trip and conflict rate by study phase (White et al., 2023)

During the study, conflict events were also analyzed, and it was observed that the two most common precipitating events were loss of control due to an infrastructure element or conflict with a fixed infrastructure element. A number of infrastructure elements and surface features contributed to the conflict events such as uneven or degraded surfaces, loose surfaces (i.e., grass, gravel, dirt/mulch), terrain transitions, curbs, grates, manholes, stairs, ADA ramps, and tactile paving. This shows that scooter compatibility with infrastructure needs to be studied further.

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.

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 2**. **Table 4** in **Appendix A** compares each of the models and their designs.

Figure 2. 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 selected for testing due to prior use in deployments across the U.S. The Max 2.3, S-100T, and Okai units provided for testing 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 study on Virginia Tech's campus (White et al., 2023) 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.

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 (included in Novotny, 2023). 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 (Novotny, 2023).

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 1**.

Table 1. 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. Fixed cameras were set up alongside the course to capture rider posture and behavior/actions. This setup can be seen in **Figure 3**.

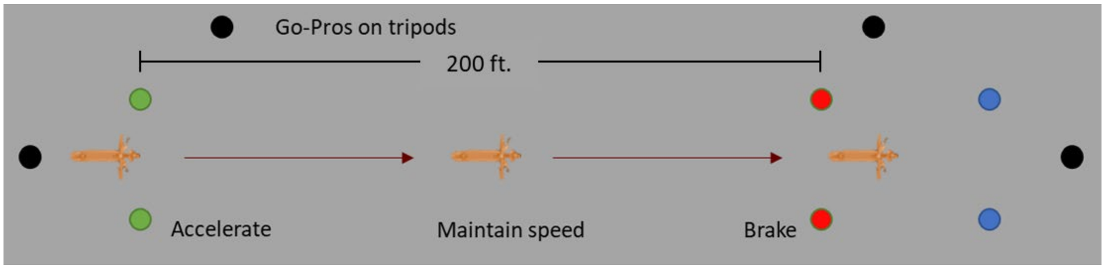

Figure 3. Speed, Acceleration, and Braking test setup.

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 Zero-Crown Road next to 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 (White et al., 2023) as having possibly contributed to the conflicts. In total, there were 22 tasks included in the course, which can be seen in **Figure 4**. Additional images of the obstacles can be found in **Appendix B**.

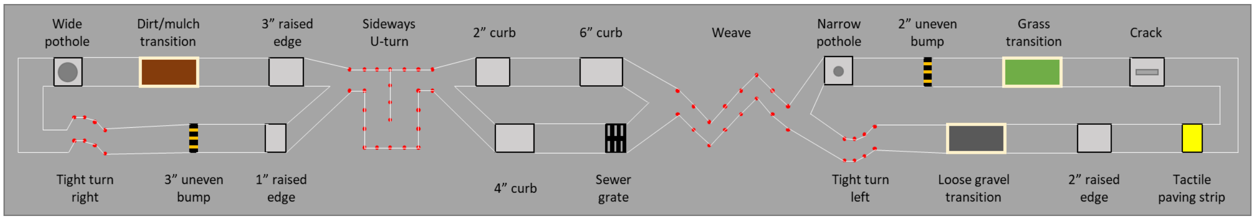

Figure 4. Handling, Stability, and Maneuverability course.

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. Fixed cameras were set up alongside the course to capture rider posture and behavior/actions. 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.

Participants

To understand user perceptions of the various e-scooter models, as well as user performance, 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 Hawes et al. (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 2** shows the breakdown of the participants that were eligible and recruited for the study.

Table 2. Participant Demographic Breakdown.

Experienced Rider Group					Novice Rider Group				
Experience	Criteria: 9 or more previous trips				**Experience**	Criteria: 3 or less previous trips			
	Average trips:					8 – 0 experience, 8 – 1-3 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 5**) with a customized weather-resistant encloser 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 5**. 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 5. 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 6** and **Figure 7**.

Data Reduction and Analysis

Speed, Acceleration, and Braking Test 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 as used for this (**Figure 6**).

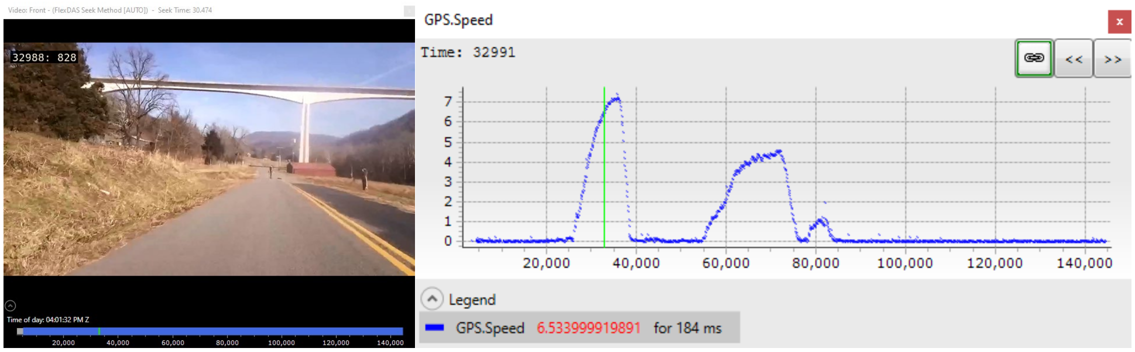

Figure 6. Forward camera view (left) and GPS speed data (right) collected by VTTI's microDAS during SAB test.

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.

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.

Handling, Stability, and Maneuverability Test 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 7**).

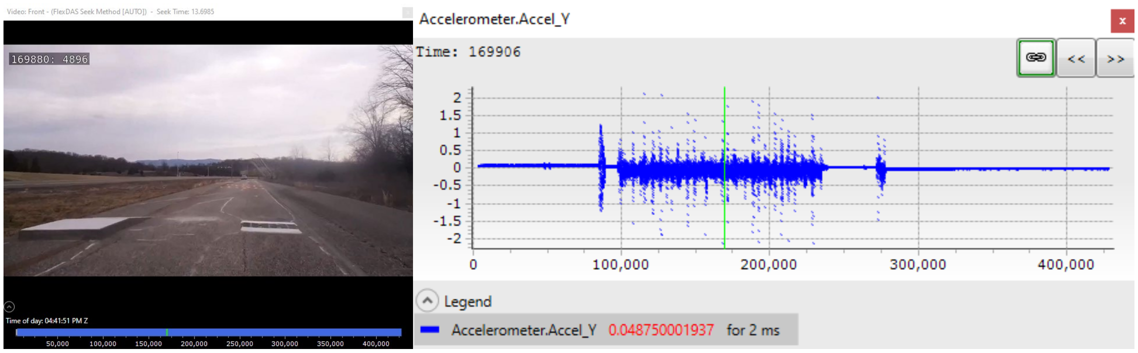

Figure 7. Forward video (left) and accelerometer data (right) collected by VTTI's microDAS during HSM test.

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.

Results

Speed, Acceleration, and Braking Test 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 8**. 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).

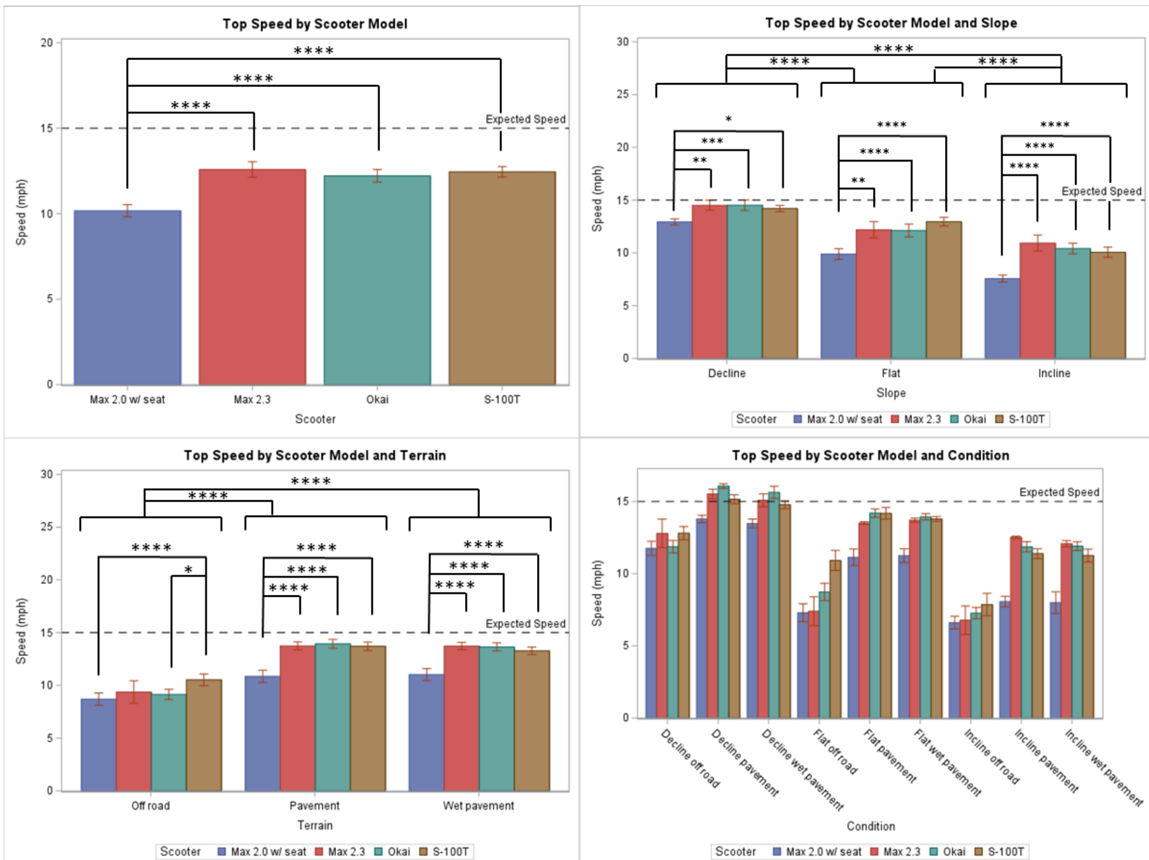

Figure 8. Top speeds from the SAB test. Top left: top speed by scooter model. Top right: top speed by scooter model and slope. Bottom left: top speed by scooter model and terrain. Bottom right: top speed by scooter model and condition. (*-p<0.05, **-p<0.01, *-p<0.001, ****-p<0.0001)**

The 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 ($p<0.0001$).

Acceleration Rate Results

The average 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 9**. 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 ($p<0.0001$).

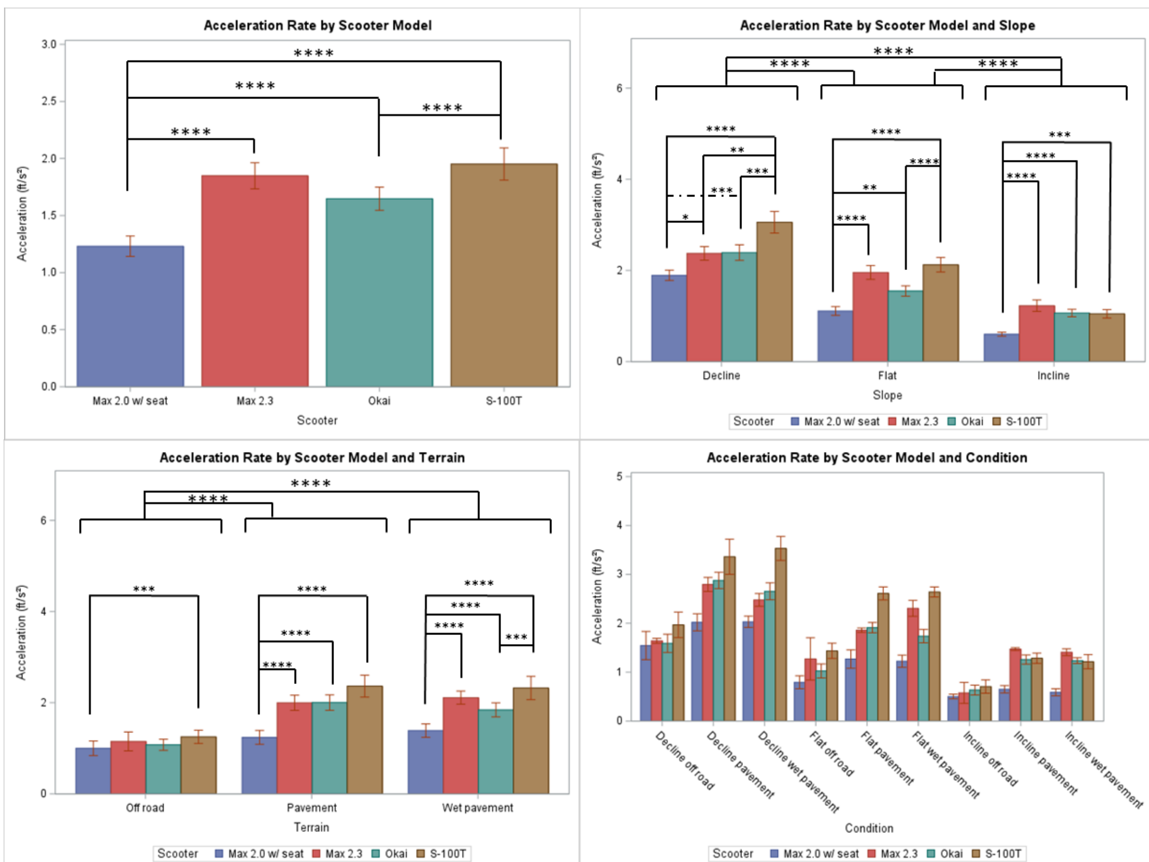

Figure 9. Acceleration rates from the SAB test. Top left: acceleration rate by scooter model. Top right: acceleration rate by scooter model and slope. Bottom left: acceleration rate by scooter model and terrain. Bottom right: acceleration rate by scooter model and condition. (*-p<0.05, **-p<0.01, *-p<0.001, ****-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 ($p=0.0002$).

Braking Distance Results

Braking distances were also calculated for each of the trials. 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 10**. 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, $p=0.0296$).

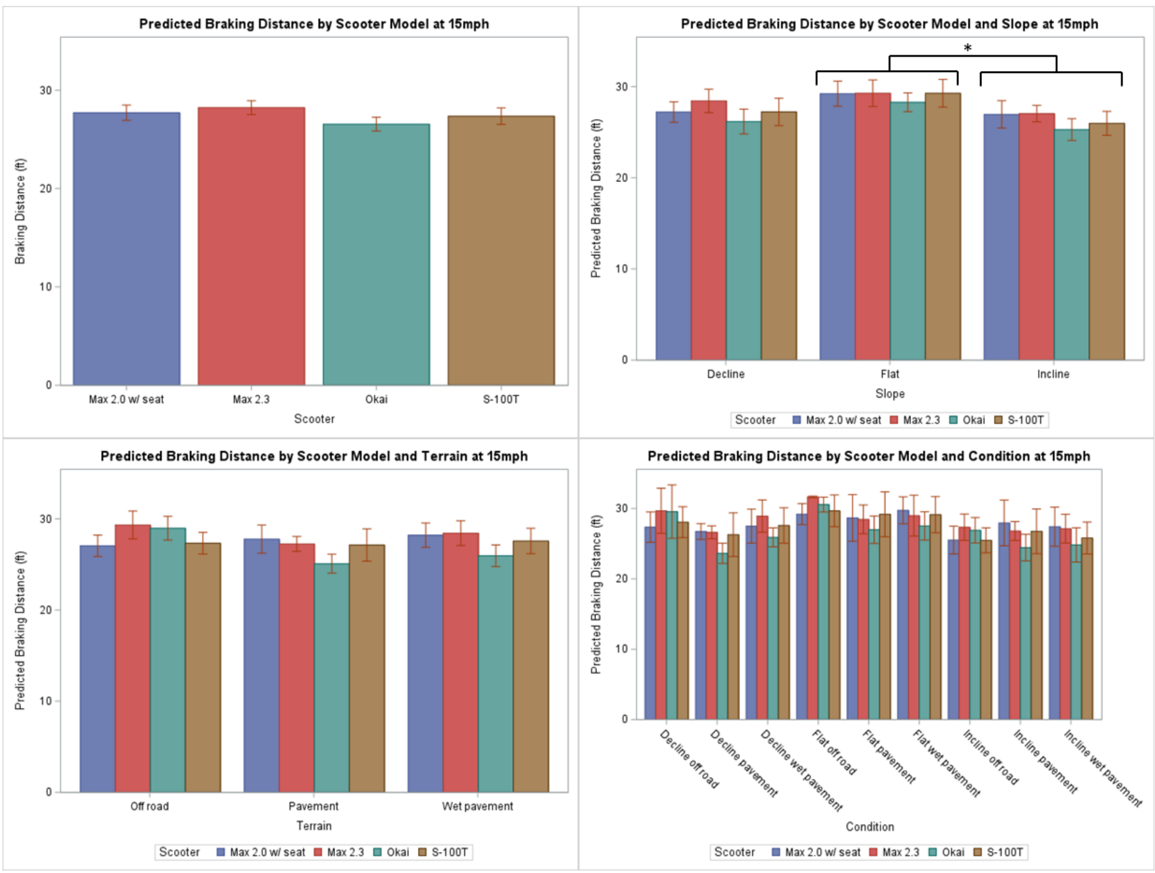

Figure 10. Predicted braking distances for the SAB test. Top left: braking distance by scooter model. Top right: braking distance by scooter model and slope. Bottom left: braking distance by scooter model and terrain. Bottom right: braking distance by scooter model and condition. (*-p<0.05)

Additional results can be seen in **Appendix C** and Novotny, 2023.

Handling, Stability, and Maneuverability Test Results

The Handling, Stability, and Maneuverability test data was analyzed to identify trends between specific scooter features and performance metrics. The following sections summarize those results. See **Appendix A** to reference which features/dimensions correspond to each scooter. For some features, two or more scooters shared the same dimension.

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. Significant trends were observed with specific scooter features. As can be seen in **Figure 11**, increasing scooter weight, deck height, wheelbase, and tire diameter resulted in greater speed decreases ($p<0.0001$).

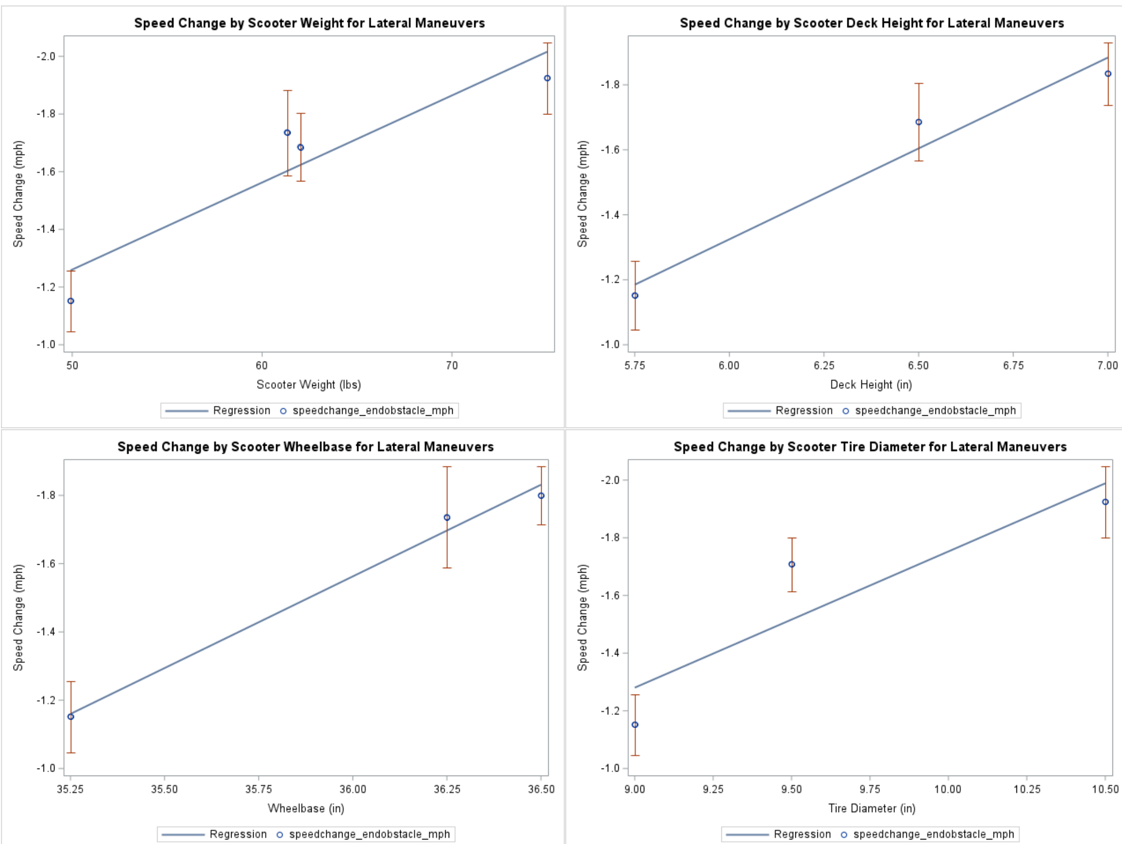

Figure 11. Effect of specific scooter features on speed change. Top left: speed change by scooter weight. Top right: speed change by deck height. Bottom left: speed change by wheelbase. Bottom left: speed change by tire diameter.

The maximum roll rate that the scooters experienced during the lateral maneuver obstacles was also analyzed. 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 12**).

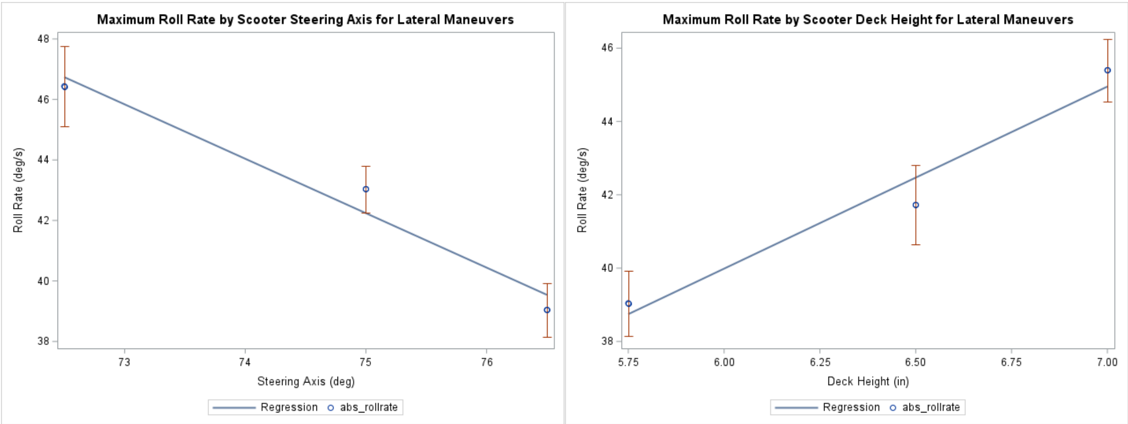

Figure 12. Effect of specific scooter features on roll rate. Left: roll rate by steering axis. Right: roll rate by deck height.

Maximum yaw rate was the final metric investigated during the lateral maneuver obstacles. 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 13**.

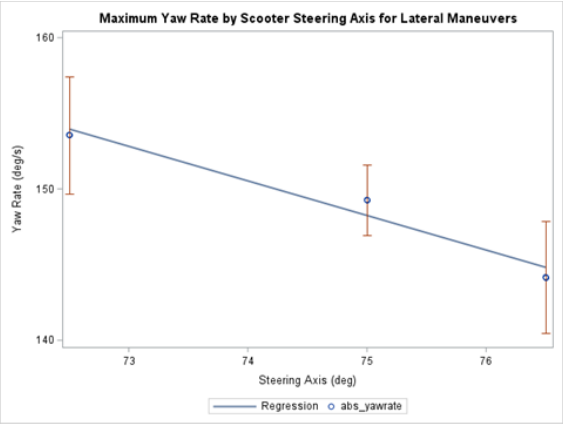

Figure 13. Effect of steering axis on yaw rate.

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. Significant trends were 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 14**.

The next metric analyzed was maximum vertical acceleration. 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). This can be seen in **Figure 15**.

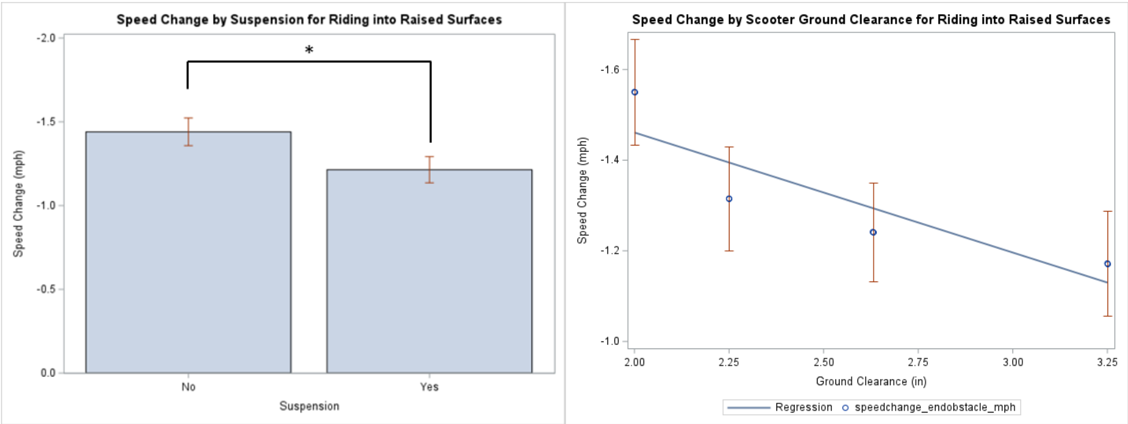

Figure 14. Effect of specific scooter features on speed change. Left: speed change by suspension. Right: speed change by ground clearance.

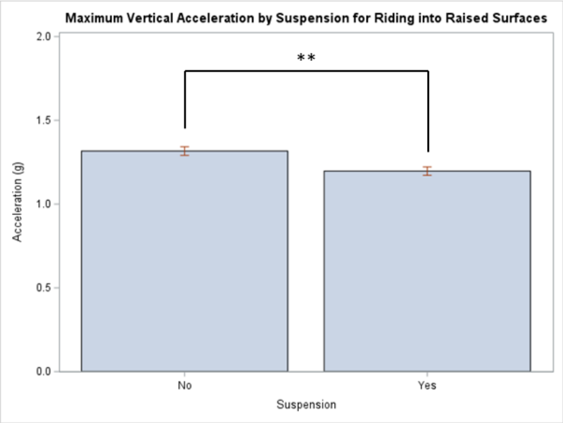

Figure 15. Maximum vertical acceleration by suspension (left) and rider weight (right). (-p<0.01)**

Riding off Raised Surface Results

For obstacles that involved riding off raised surfaces, maximum vertical acceleration and maximum pitch rate were analyzed. Significant trends were observed with tire diameter, deck height, and suspension (**Figure 16**), 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).

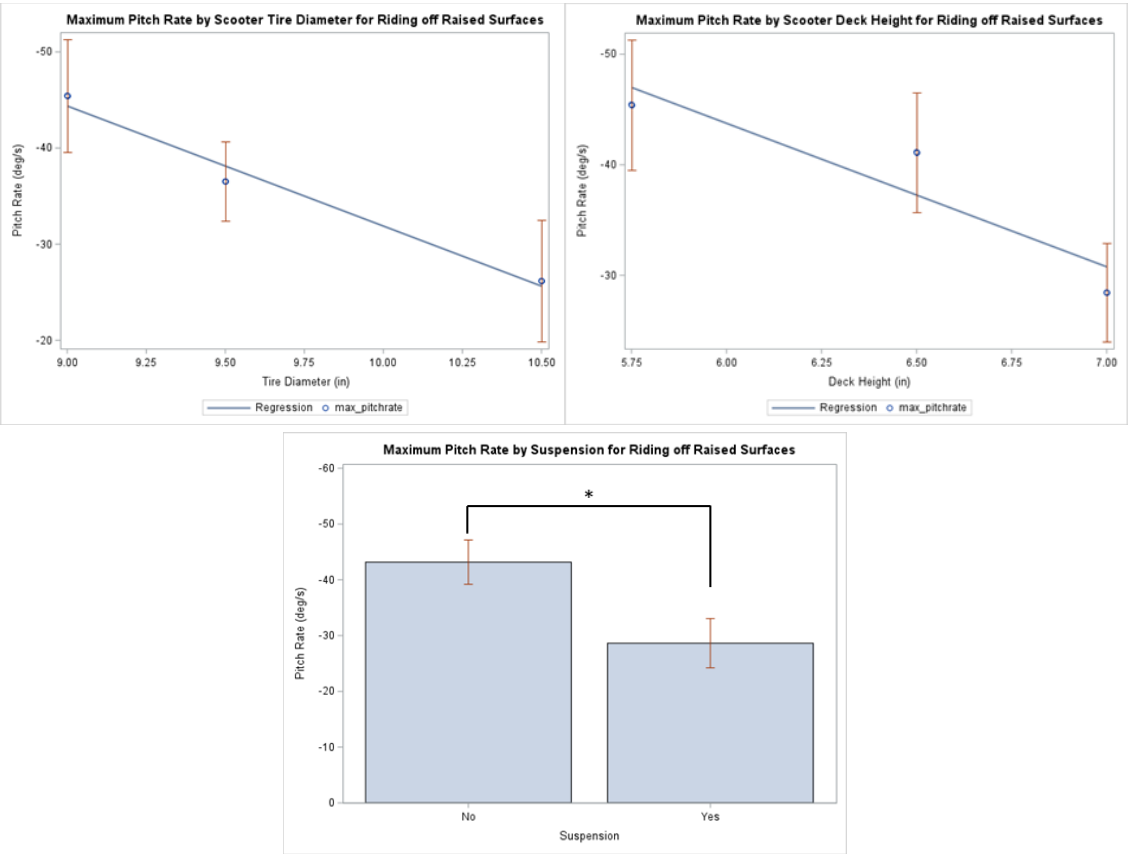

Figure 16. Maximum pitch rate by tire diameter (top left) deck height (top right) and suspension (bottom). (*-p<0.05)

Additional results can be seen in **Appendix D** and Novotny, 2023.

Discussion

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. 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.

Average 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.

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.

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.

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.

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.

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, 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, the following design recommendations are proposed based upon the features that are believed to have the greatest safety benefits (also shown in **Figure 66**), 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.

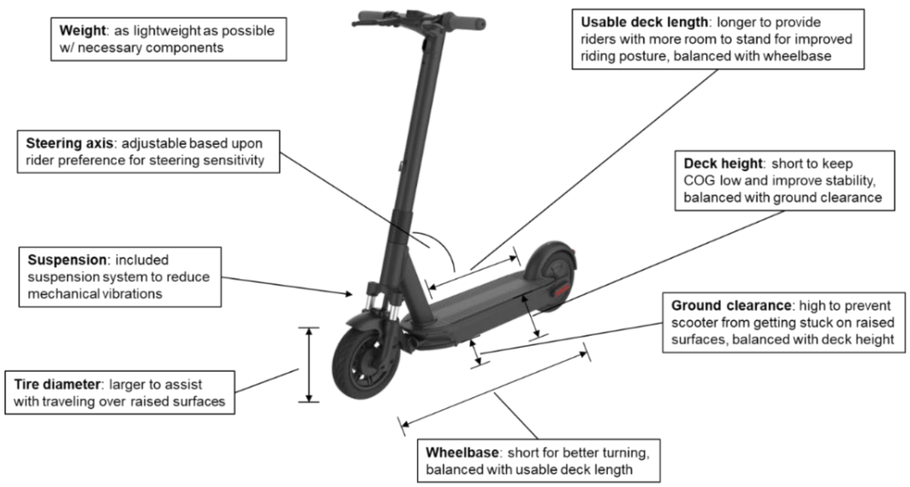

Figure 17. E-scooter design recommendations.

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 3**.

Table 3. 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”

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.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the project page located on the Safe-D website. The datasets for this project are available in the Safe-D Collection of the VTTI Dataverse which is linked on the project site listed below.

https://safed.vtti.vt.edu/projects/e-scooter-design/

Education and Workforce Development Products

A Virginia Tech PhD student, Adam Novotny, was funded under this project and completed this project as part of his dissertation, which he defended in December 2022. His dissertation will be available on Virginia Tech's ETD system: https://vtechworks.lib.vt.edu/handle/10919/5534.

The research team also worked with two senior design teams who assisted with this project, and they completed capstone projects related to the effort.

Technology Transfer Products

The research team interacted on a regular basis with sponsors from Ford as well as Spin. These routine update meetings served to allow the sponsors to select the e-scooter models that were included in testing, weigh in on the design of the testing protocols and test courses, and provide feedback on the results and outputs.

The research team is also planning to submit a subset of the testing and results for a journal publication, journal to be determined.

A webinar will be presented within the Safe-D Webinar series.

Data Products

The kinematic dataset resulting from the HSM Test has been made public. This dataset includes 2,552 observations organized by participant number, trial number, scooter identification number, and a description of the obstacle encountered during each trial by both participant groups (experienced and novice riders).

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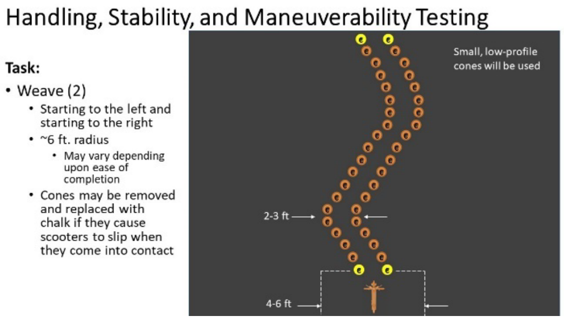
Appendices

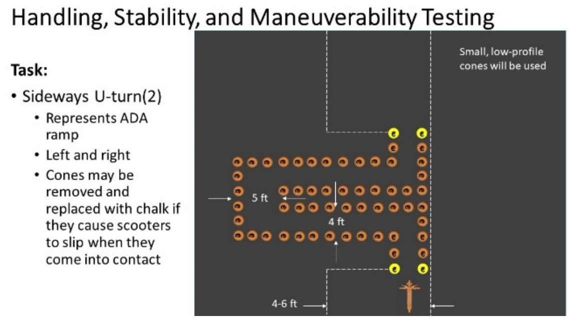
Appendix A – E-Scooter Specifications

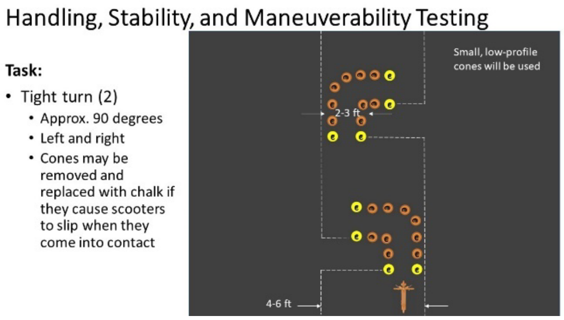
Table 4. E-Scooter Model Specifications.

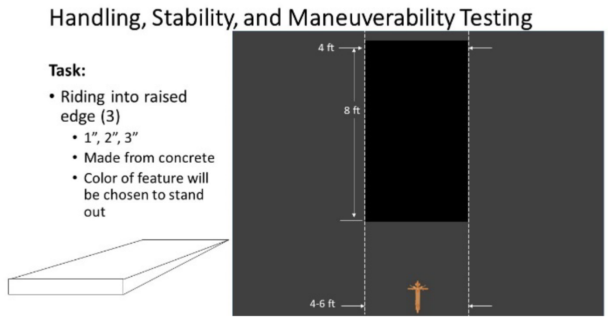
	Segway Ninebot Max 2.3	Spin S-100T	Okai ES400B	Segway Ninebot Max 2.0 w/ Seat Attachment
Previous Use	20 trips	0 trips	0 trips	399 trips
Weight	61.3 lbs.	62.0 lbs.	75.0 lbs.	49.9 lbs.
Dimensions	47.6” x 20.3” x 44.8”	46.0” x 19.0” x 46.0”	47.2” x 20.5” x 48.0”	45.9” x 18.6” x 47.4”
Steering axis angle	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

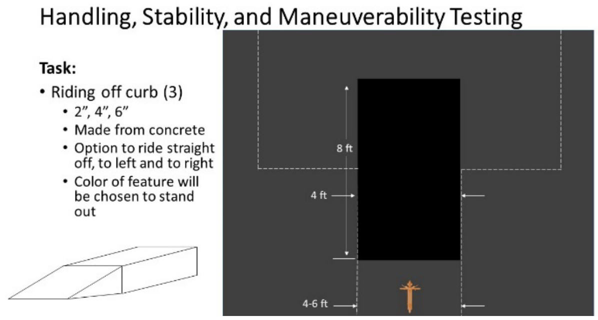
Appendix B – Additional Obstacle Pictures

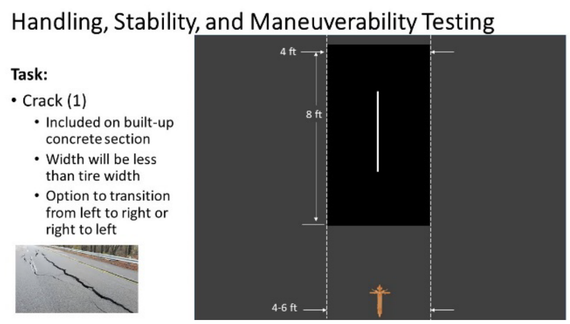


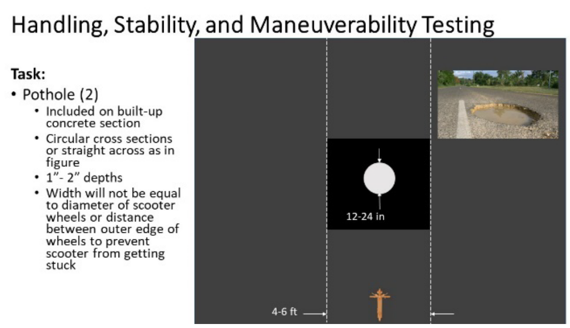


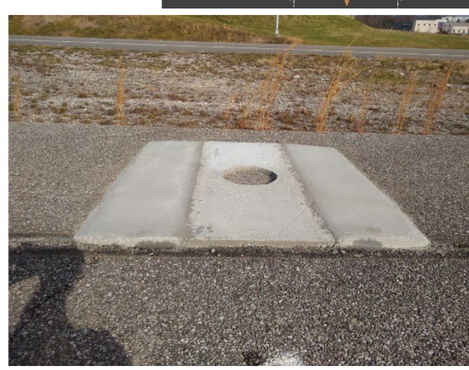


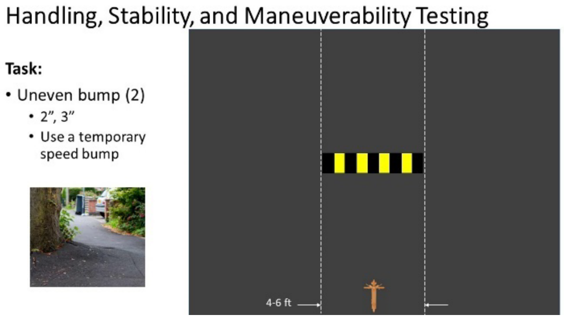


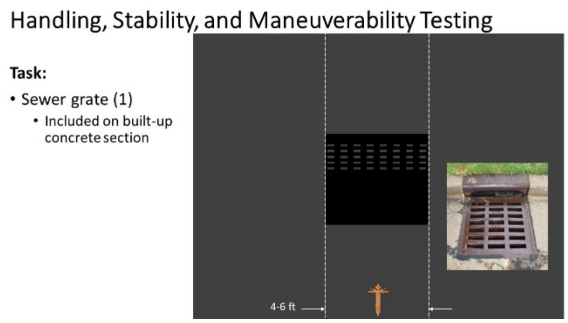


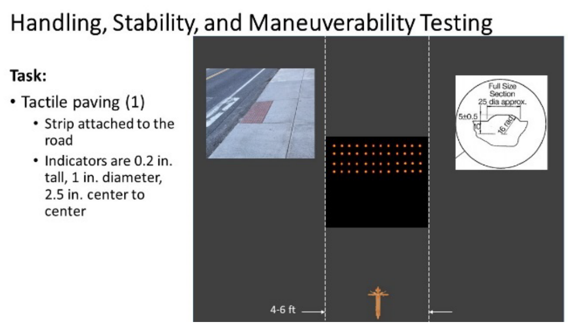

Handling, Stability, and Maneuverability Testing
Task:
• Crack (1)
• Included on built-up concrete section
• Width will be less than tire width
• Option to transition from left to right or right to left
4 ft
8 ft
4-6 ft

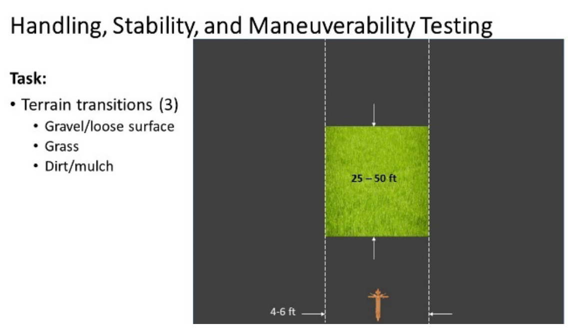

Handling, Stability, and Maneuverability Testing
Task:
• Pothole (2)
• Included on built-up concrete section
• Circular cross sections or straight across as in figure
• 1"- 2" depths
• Width will not be equal to diameter of scooter wheels or distance between outer edge of wheels to prevent scooter from getting stuck
12-24 in
4-6 ft




Handling, Stability, and Maneuverability Testing
Task:
• Uneven bump (2)
• 2", 3"
• Use a temporary speed bump
4-6 ft


Handling, Stability, and Maneuverability Testing
Task:
• Sewer grate (1)
• Included on built-up concrete section
4-6 ft


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
4-6 ft


Handling, Stability, and Maneuverability Testing
Task:
• Terrain transitions (3)
• Gravel/loose surface
• Grass
• Dirt/mulch
25 – 50 ft
4-6 ft

Appendix C – Additional Speed, Acceleration, and Braking Test Results

MicroDAS Results

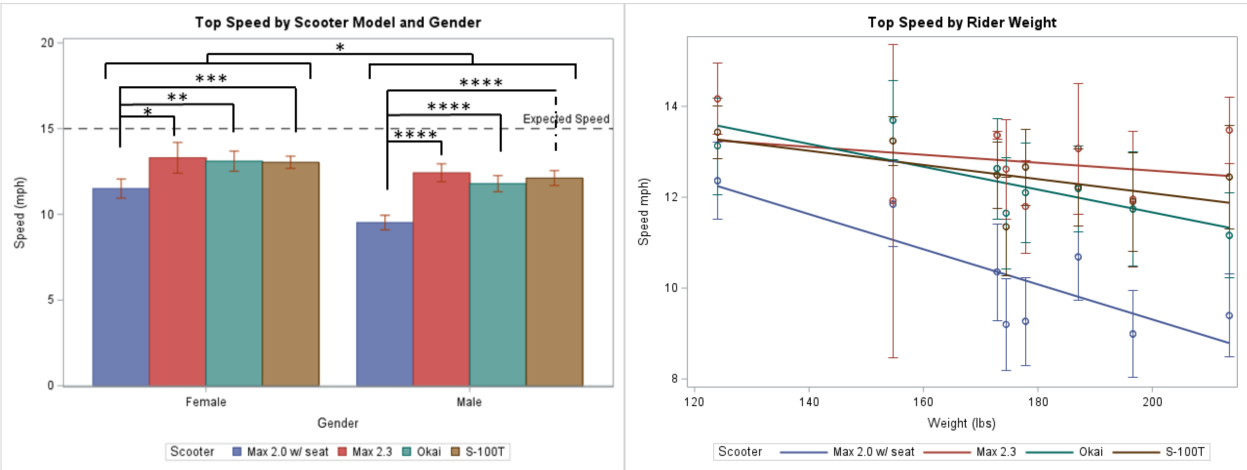


Figure 18. Top speed by scooter model and gender (left) and by scooter model and rider weight (right). (*-p<0.05, **-p<0.01, *-p<0.001, ****-p<0.0001)**

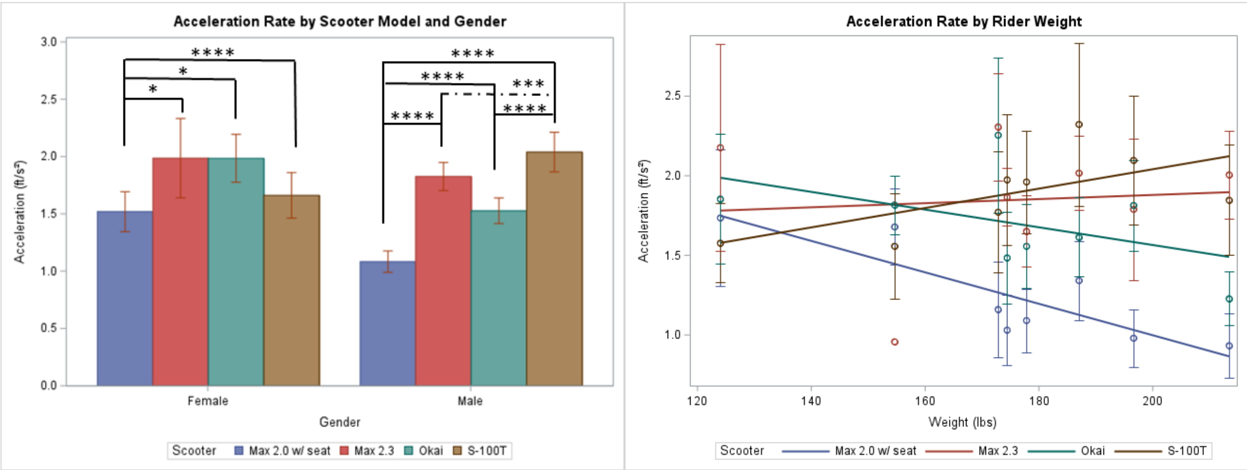


Figure 19. Acceleration rate by scooter model and gender (left) and scooter model and rider weight (right). (*-p<0.05, *-p<0.001, ****-p<0.0001)**

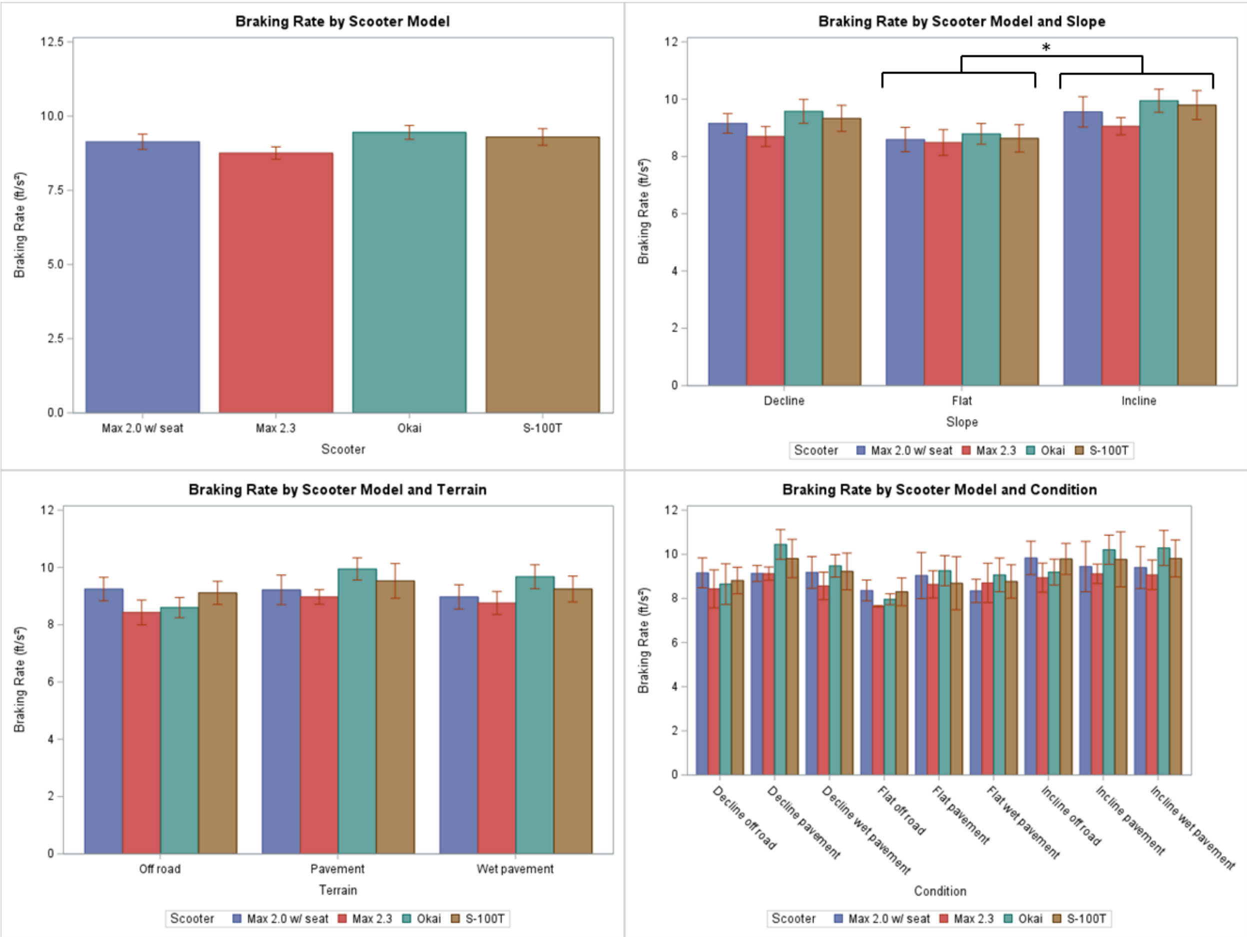


Figure 20. Braking rates from the SAB test. Top left: braking rate by scooter model. Top right: braking rate by scooter model and slope. Bottom left: braking rate by scooter model and terrain. Bottom right: braking rate by scooter model and condition. (*-p<0.05)

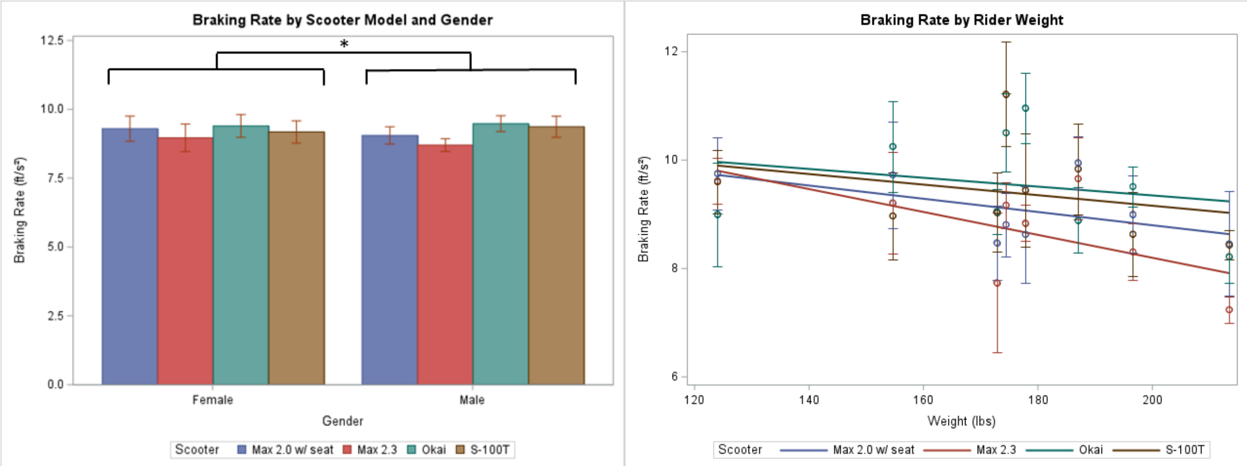


Figure 21. Braking rate by scooter model and gender (left) and scooter model and rider weight (right). (*-p<0.05)

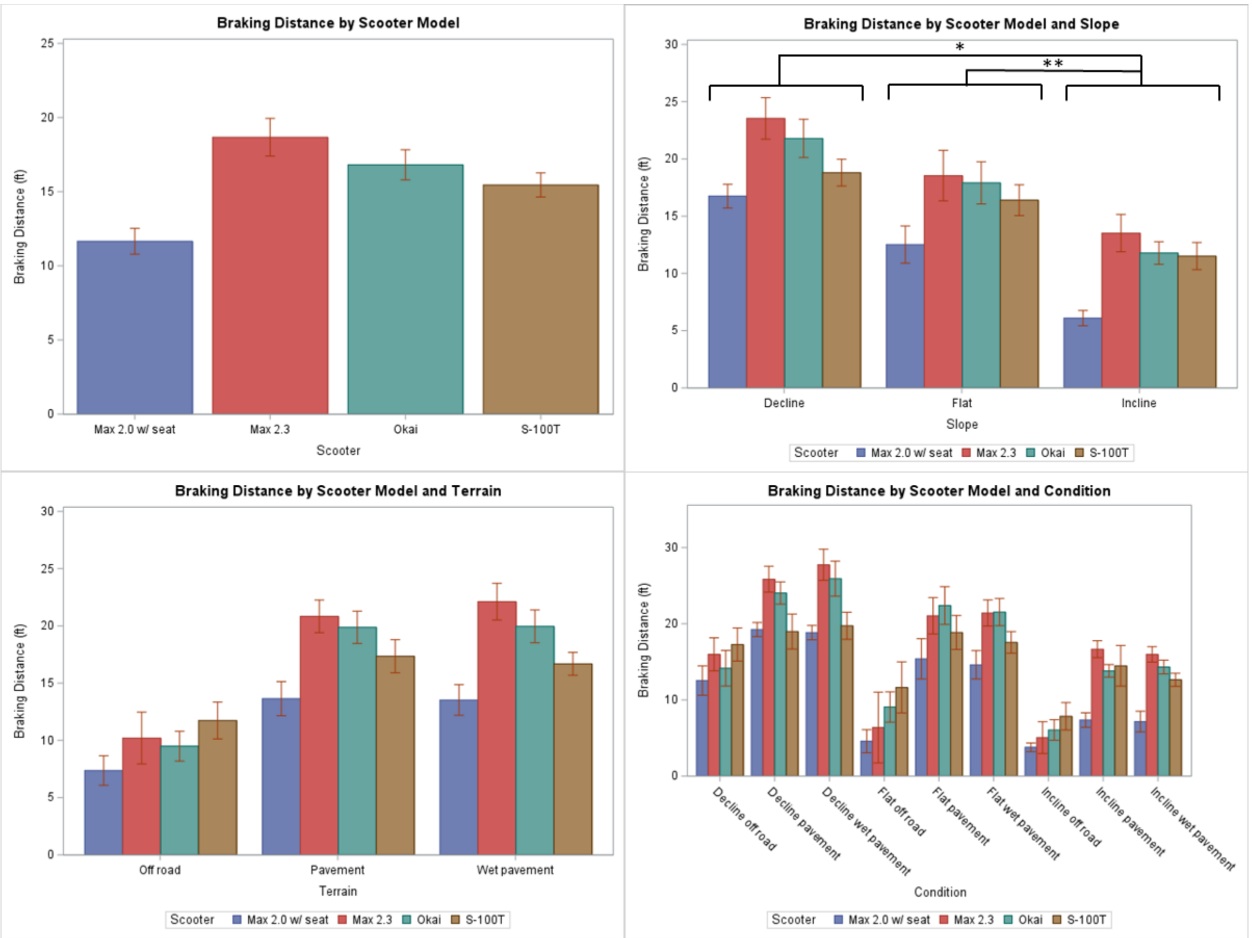


Figure 22. Braking distance from the SAB test. Top left: braking distance by scooter model. Top right: braking distance by scooter model and slope. Bottom left: braking distance by scooter model and terrain. Bottom right: braking distance by scooter model and condition. (*-p<0.05, **-p<0.01)

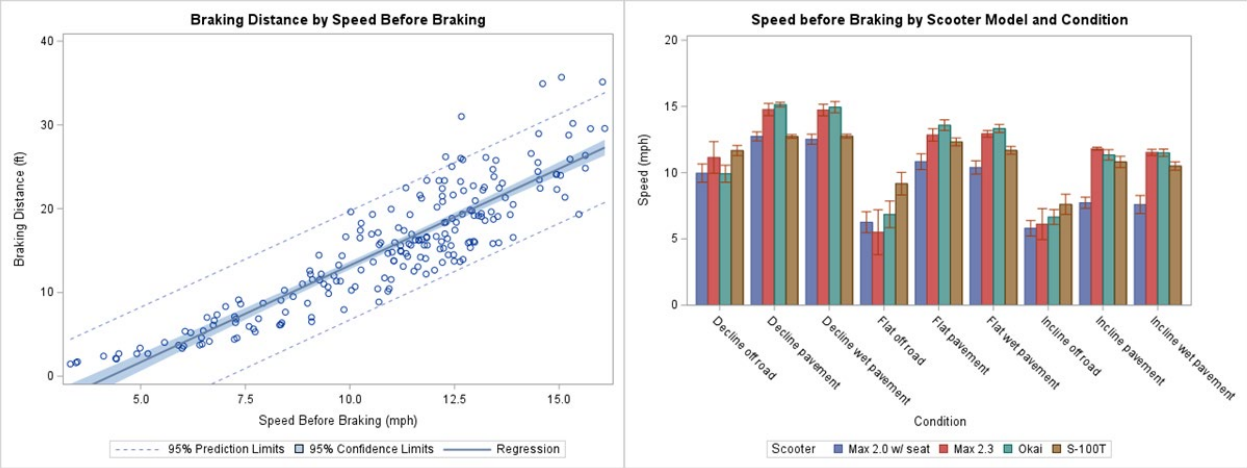


Figure 23. Braking distance by speed before braking (left) and by scooter model and condition (right).

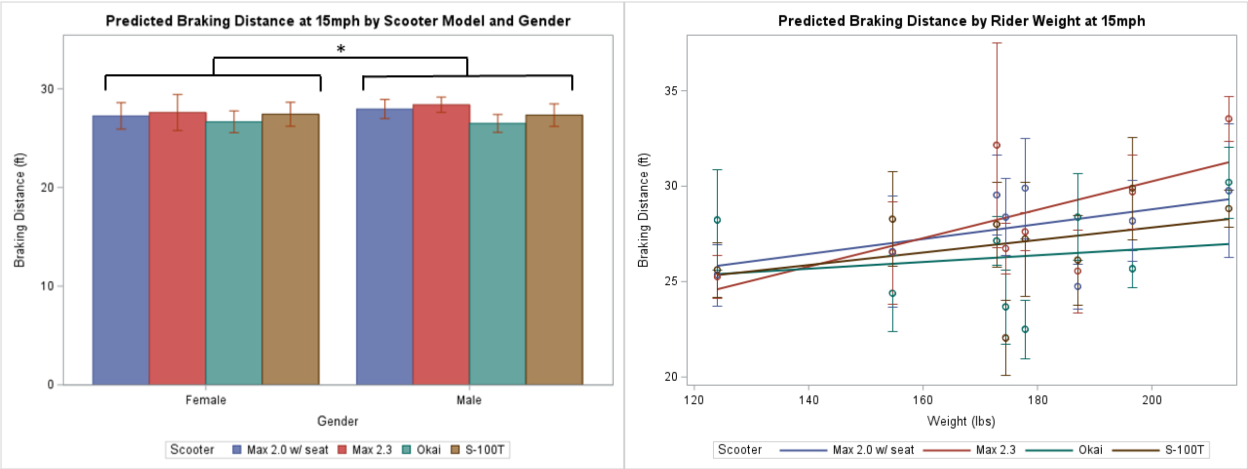


Figure 24. Predicted braking distance by scooter model and gender (left) and scooter model and rider weight (right). (*-p<0.05)

Appendix D – Additional Handling, Stability, and Maneuverability Test Results

MicroDAS Results

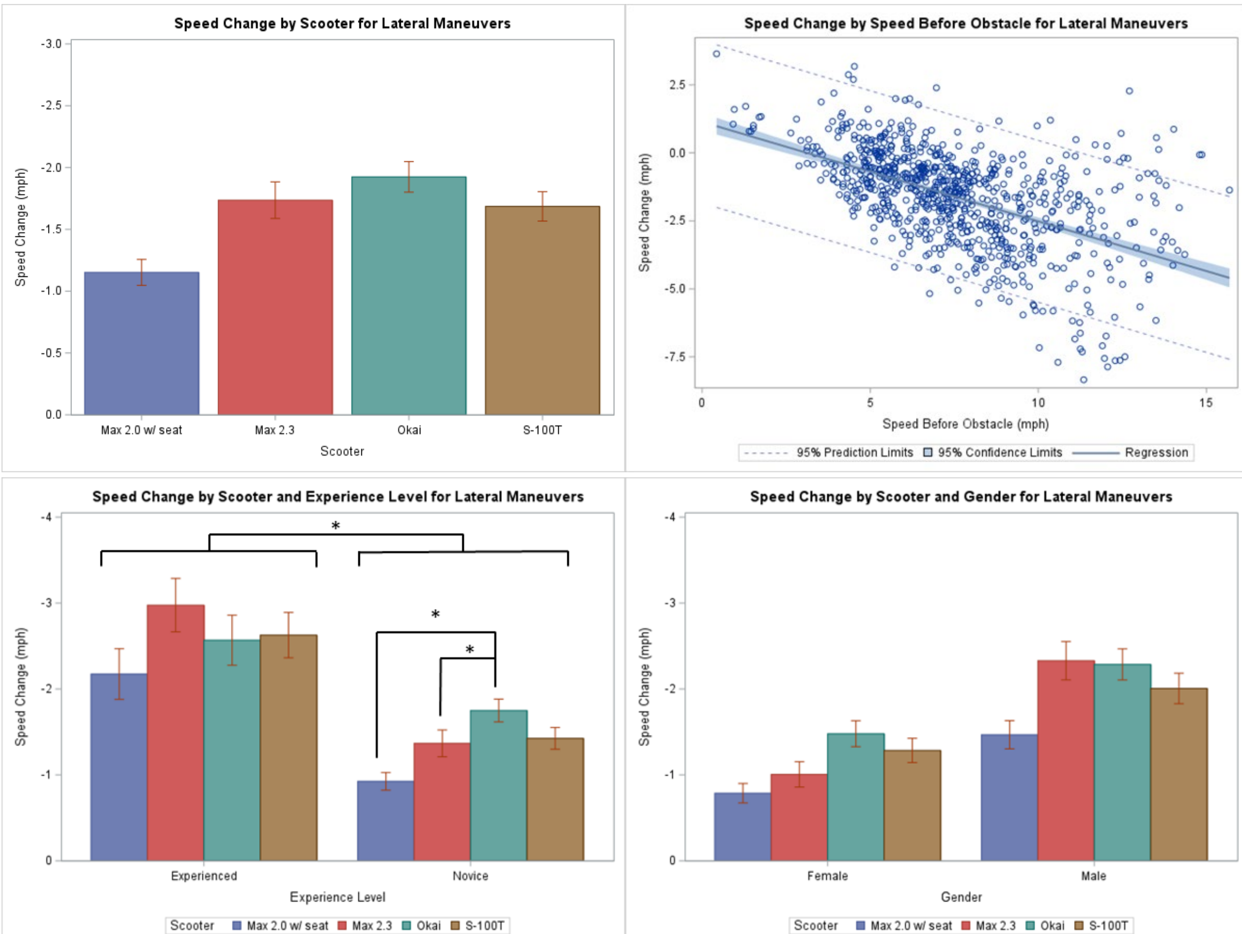


Figure 25. Speed change for lateral maneuvers. Top left: speed change by scooter. Top right: speed change by speed before the obstacle. Bottom left: speed change by scooter and experience level. Bottom right: speed change by scooter and gender. (*-p<0.05)

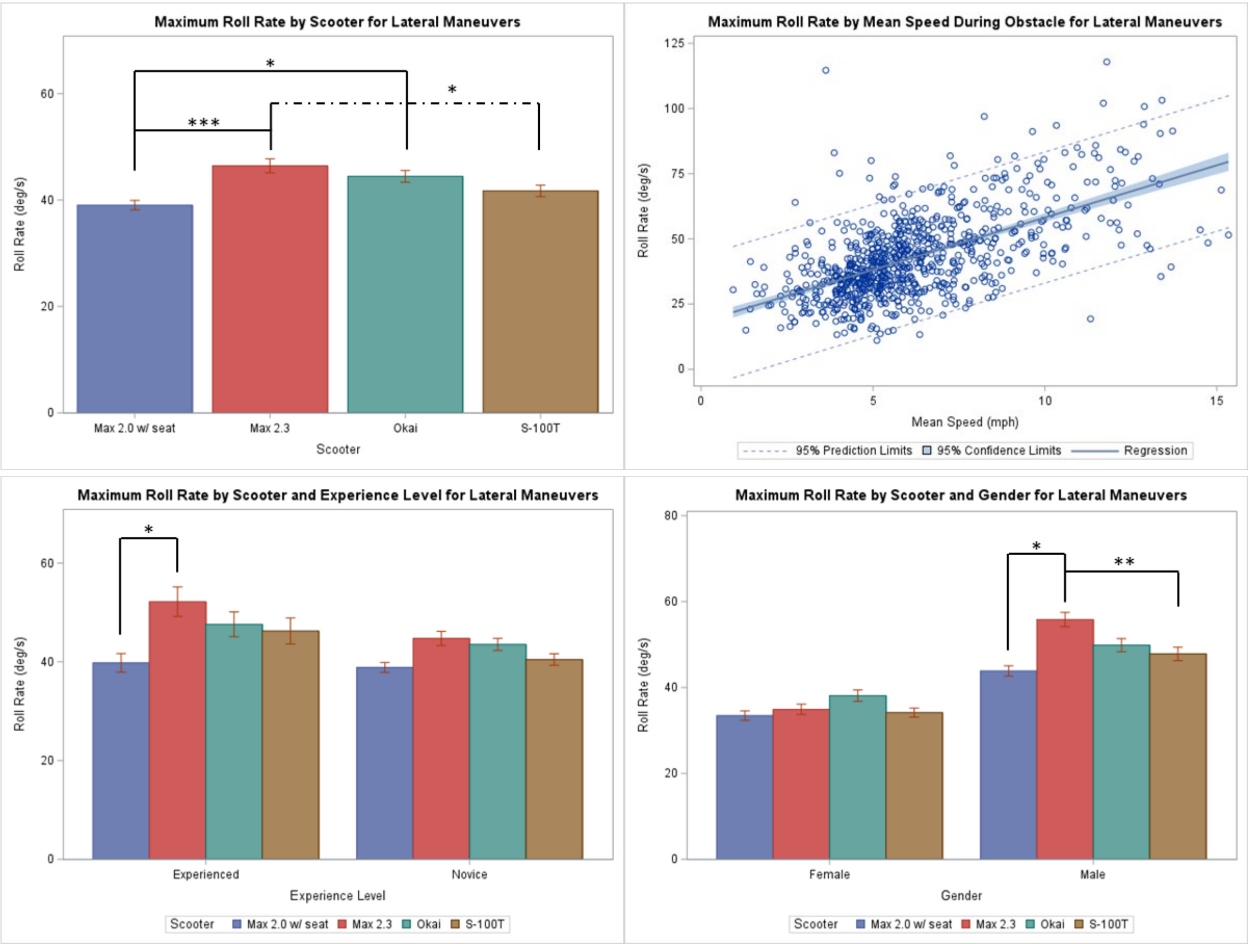


Figure 26. Maximum roll rate for lateral maneuvers. Top left: roll rate by scooter. Top right: roll rate by mean speed during obstacle. Bottom left: roll rate by scooter and experience level. Bottom right: roll rate by scooter and gender. (*-p<0.05, **-p<0.01, *-p<0.001)**

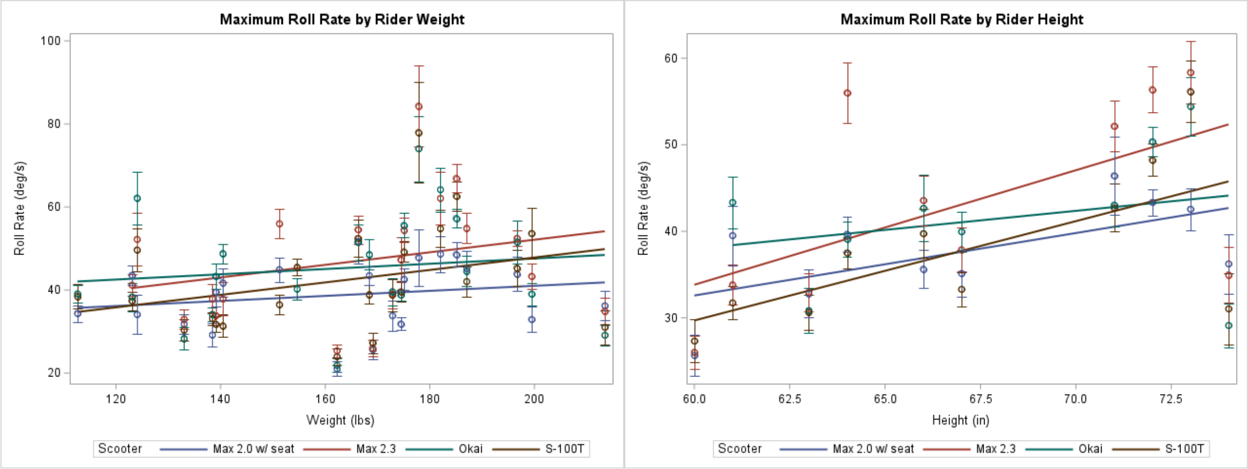


Figure 27. Maximum roll rate by rider weight (left) and by rider height (right).

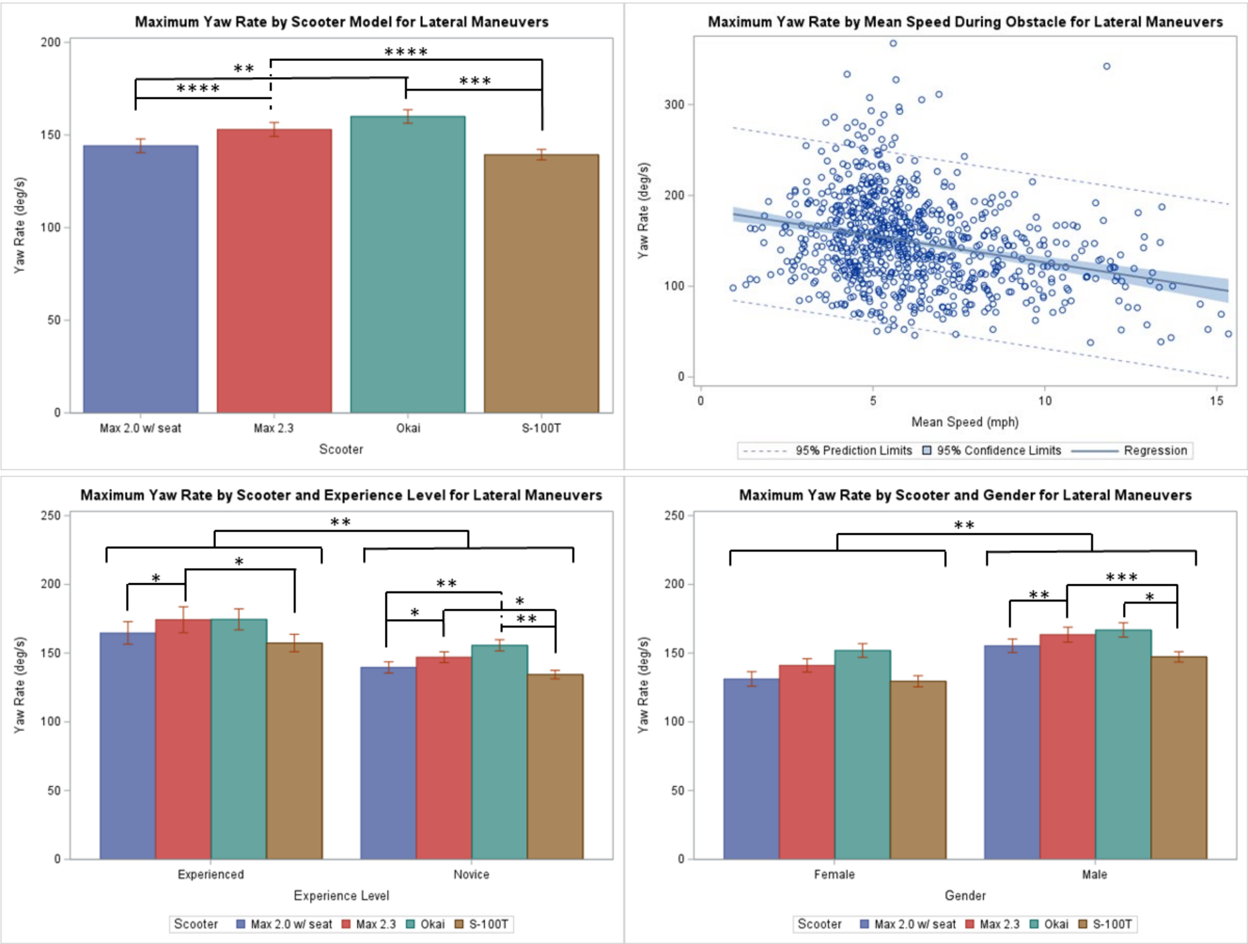


Figure 28. Maximum yaw rate for lateral maneuvers. Top left: yaw rate by scooter. Top right: yaw rate by mean speed during obstacle. Bottom left: yaw rate by scooter and experience level. Bottom right: yaw rate by scooter and gender. (*-p<0.05, **-p<0.01, *-p<0.001, ****-p<0.0001)**

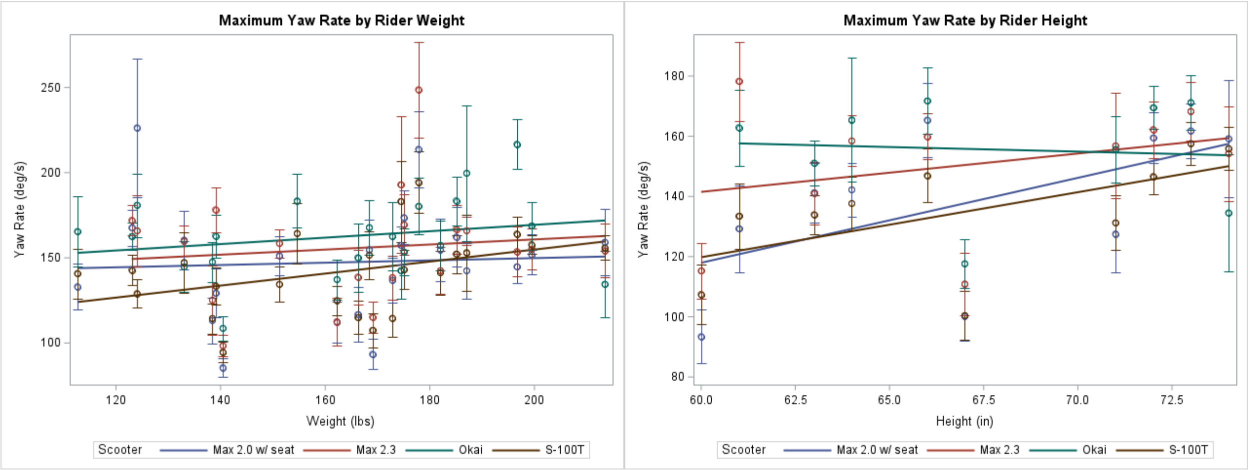


Figure 29. Maximum yaw rate by rider weight (left) and by rider height (right).

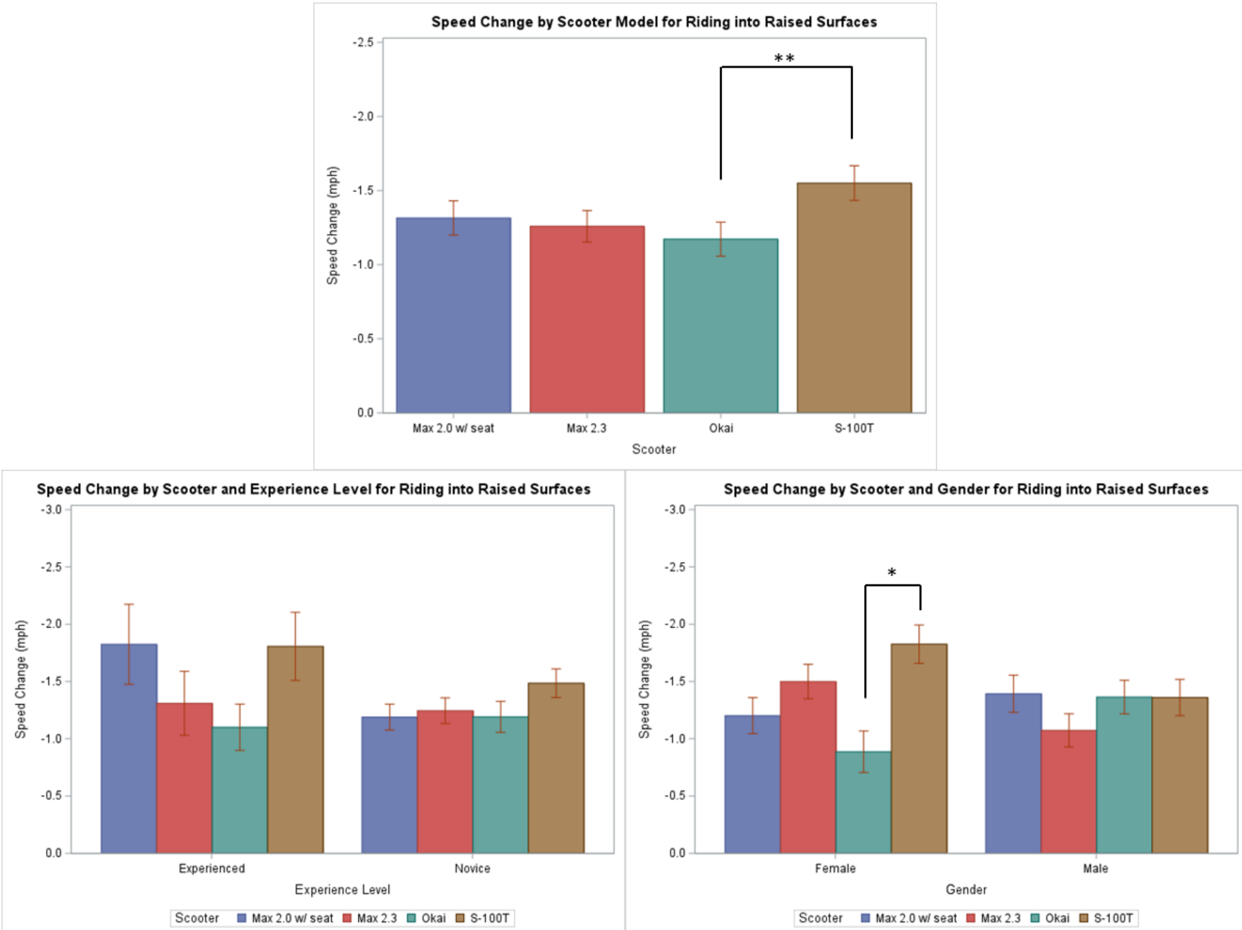


Figure 30. Speed change for riding into raised surfaces. Top: speed change by scooter. Bottom left: speed change by scooter and experience level. Bottom right: speed change by scooter and gender. (*-p<0.05, **-p<0.01)

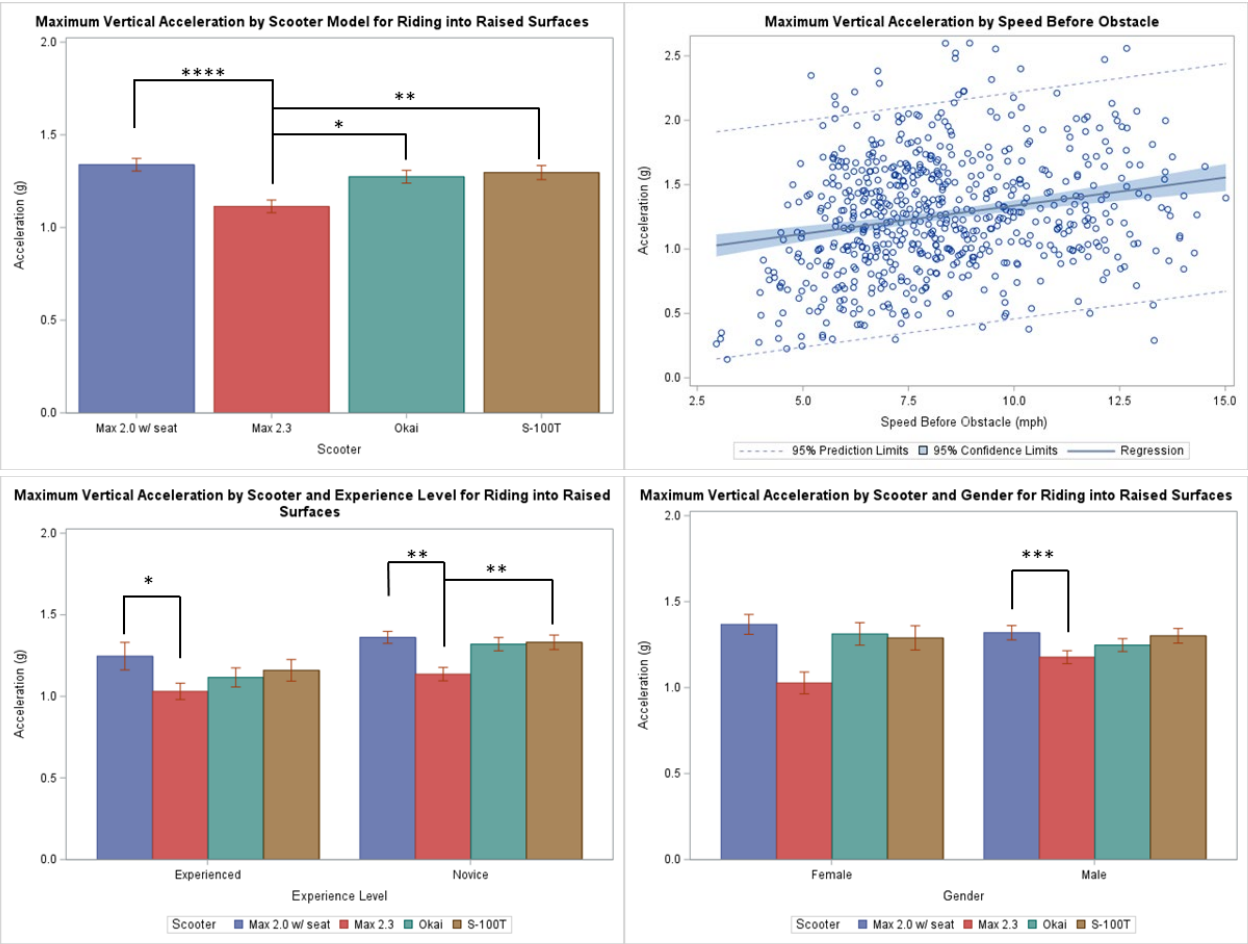


Figure 31. Maximum vertical acceleration for riding into raised surfaces. Top left: vertical acceleration by scooter. Top right: vertical acceleration by speed before obstacle. Bottom left: vertical acceleration by scooter and experience level. Bottom right: vertical acceleration by scooter and gender. (*-p<0.05, **-p<0.01, *-p<0.001, ****-p<0.0001)**

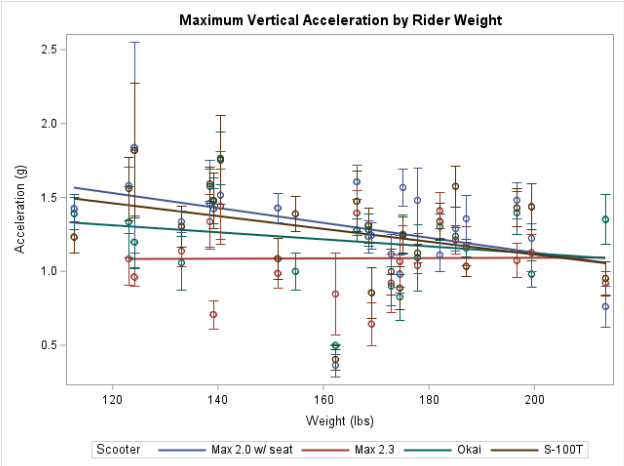


Figure 32. Maximum vertical acceleration by rider weight.

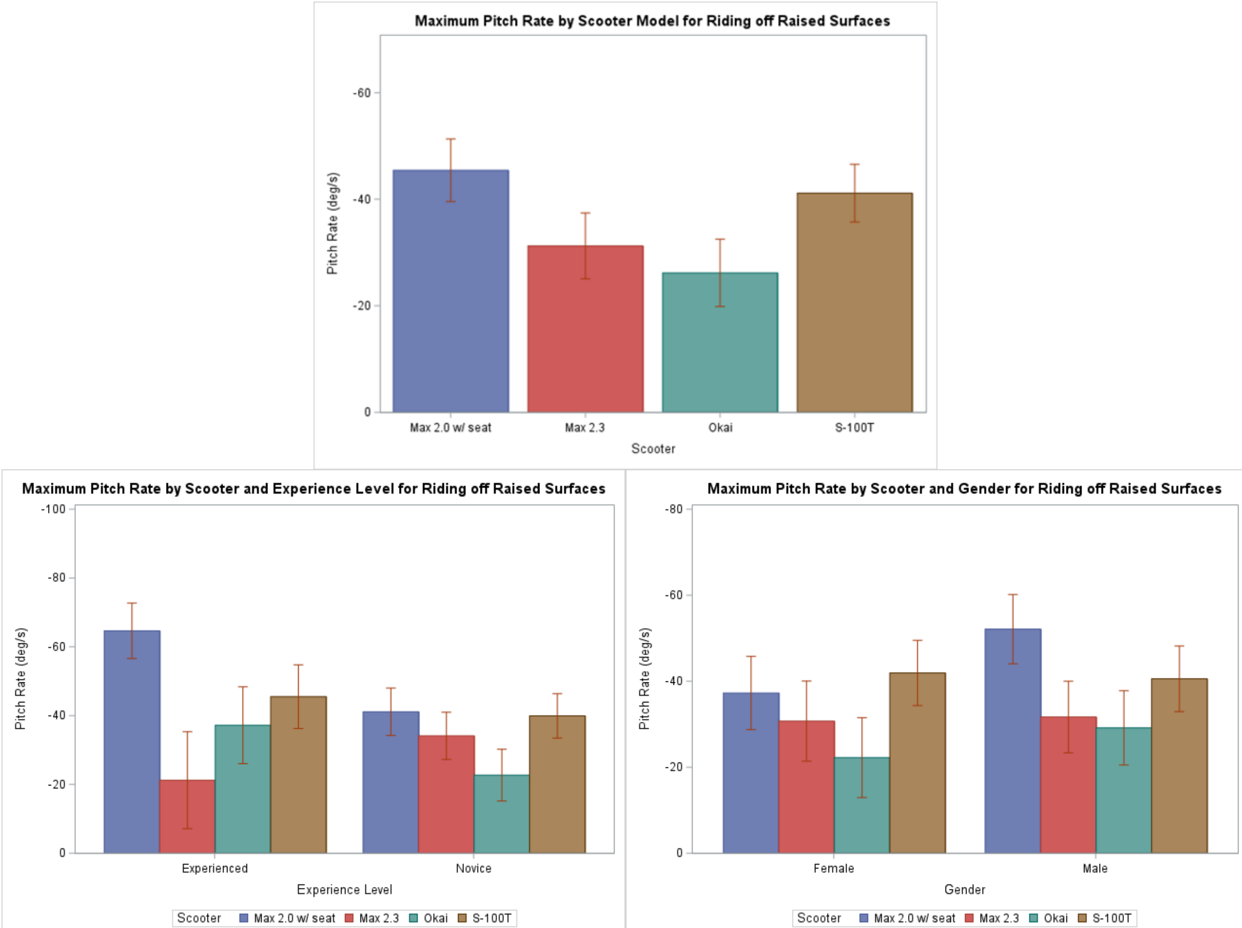


Figure 33. Maximum pitch rate for riding off raised surfaces. Top: pitch rate by scooter. Bottom left: pitch rate by scooter and experience level. Bottom right: pitch rate by scooter and gender. (*-p<0.05, **-p<0.01)

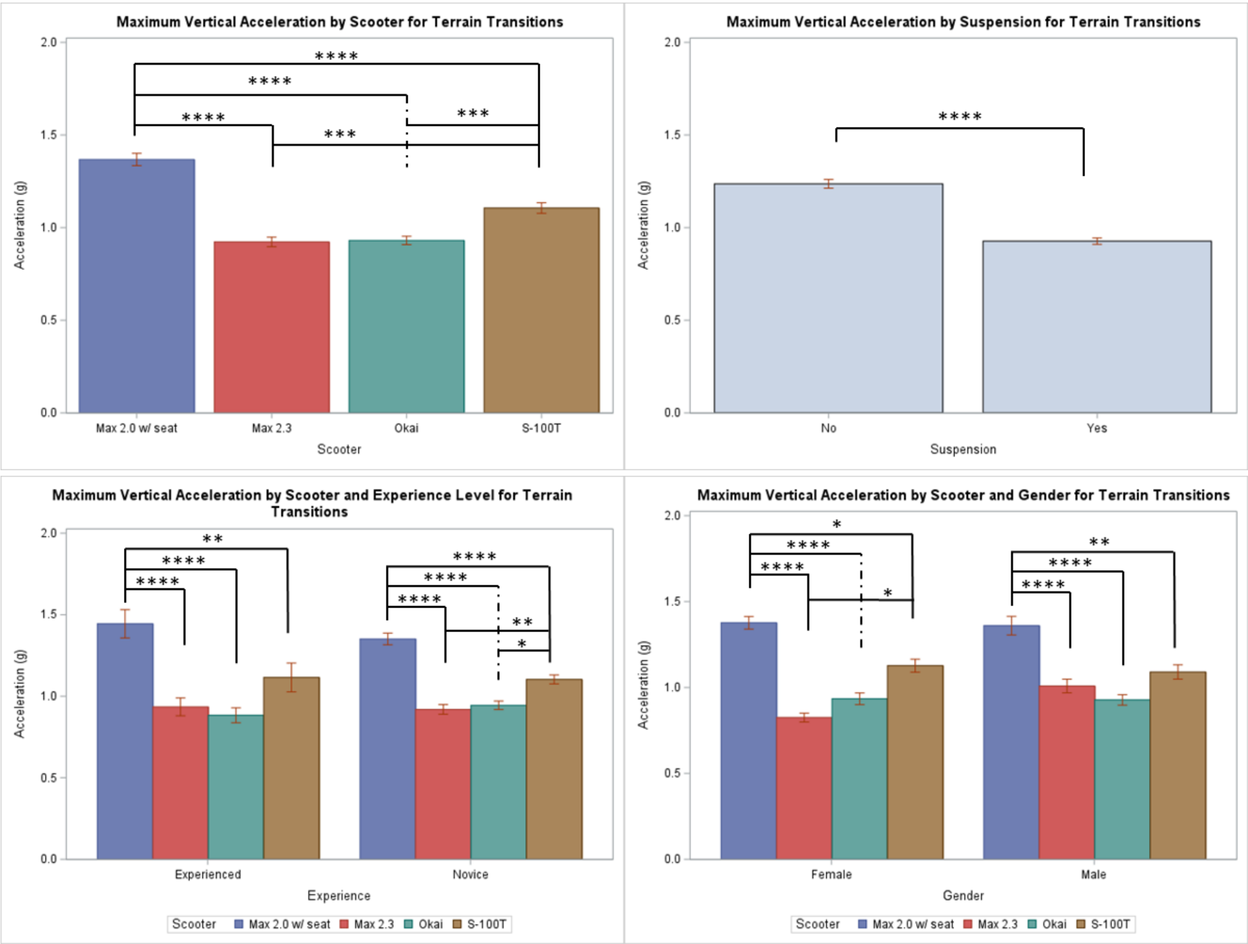


Figure 34. Maximum vertical acceleration for terrain transitions. Top left: vertical acceleration by scooter. Top right: vertical acceleration by suspension. Bottom left: vertical acceleration by scooter and experience level. Bottom right: vertical acceleration by scooter and gender. (*-p<0.05, **-p<0.01, *-p<0.001, ****-p<0.0001)**

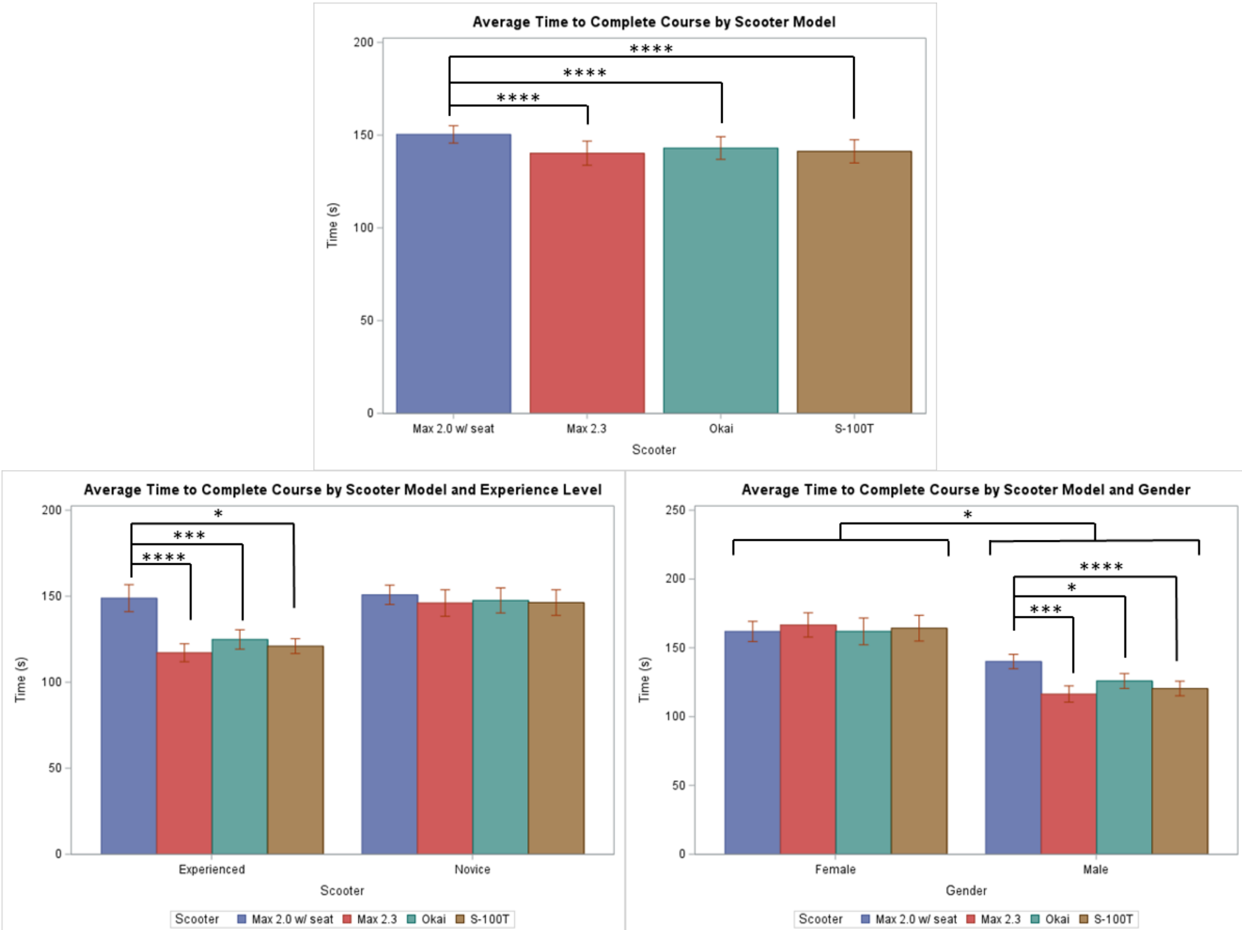


Figure 35. Average time to complete the course. Top: time by scooter. Bottom left: time by scooter and experience level. Bottom right: time by scooter and gender. (*-p<0.05, *-p<0.001, ****-p<0.0001)**

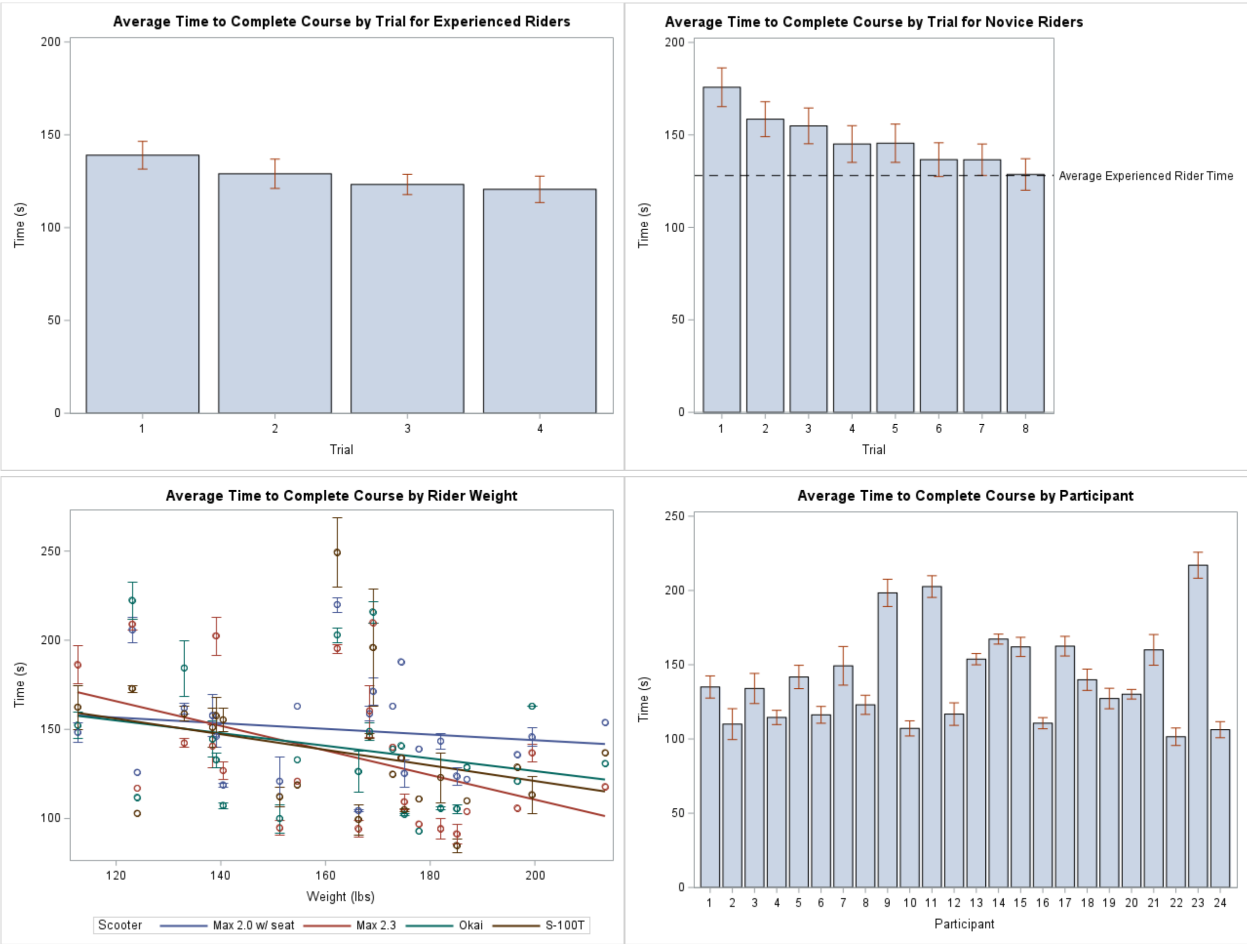


Figure 36. Average time to complete the course. Top left: time by trial for experienced riders. Top right: time by trial for novice riders. Bottom left: time by scooter and rider weight. Bottom right: time by participant.