Identifying and Measuring Factors that Impact Manual Wheelchair Rolling Resistance

by

Joseph Edward Ott

Bachelor of Science, Concentration: Mechanical Engineering, Robert Morris University, 2016

Master of Science, Concentration: Engineering Management, Robert Morris University, 2016

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This dissertation was presented

by

Joseph Edward Ott

It was defended on

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and approved by

Mark Schmeler, PhD, Associate Professor and Vice-Chair, Department of Rehabilitation Science and Technology

Alicia Koontz, PhD, Professor, Department of Rehabilitation Science and Technology

Carmen DiGiovine, PhD, Associate Professor, The Ohio State University

Mark Sullivan, BSE, President, Sullivan Consulting

Dissertation Director: Jonathan Pearlman, Ph.D., Associate Professor & Chair, Department of Rehabilitation Science and Technology

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Rolling resistance is a drag force that opposes the propulsion force, and it is linked to repetitive strain injuries in the upper extremities for manual wheelchair users. The higher the rolling resistance is, the more at risk the user is and there is relatively little actionable information in this area. To identify and measure the influential factors of manual wheelchair rolling resistance, a scoping literature review was conducted, a novel drum-based testing machine was developed, and a community-based study was conducted to determine the prevalence of misalignment in rear-wheels. The literature review classified the previous test methods into seven categories and found eight factors measured in those test methods. With variation in methods, repeatability, factors, and reporting, clinically meaningful information was difficult to discern. Therefore, a drum-based approach was developed to test wheels and casters independently through all eight factors at a component-level; demonstrating that toe, tire pressure, surfaces, and tire type can significantly increase rolling resistance. Pneumatic tires, even underinflated, have lower rolling resistance than airless inserts. Casters with an eight-inch diameter had higher rolling resistance than smaller four- or five-inch casters. The effects of combined factors on rolling resistance can be estimated as the addition of individual factors. Further characterization of wheels of casters can be done to guide product selection. The community-based study revealed that manual wheelchair users are lacking proper alignment on their devices and it comes at a cost to propulsion. Devices are harder to propel, and the user is at greater risk for upper extremity pain and injuries through prolonged propulsion. In order to mitigate those effects, proper design, manufacturing, setup, and maintenance of devices

are critical for the health of the end-users. Clinicians, manufacturers, and suppliers need to be aware of the effect of setup choices on the mechanical impact to the wheelchairs and ultimately the user. Lastly, the research needs to be communicated and translated effectively so that all stakeholders can make informed decisions about their devices in the effort of upper extremity preservation.

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Preface

This document is the culmination of years of work towards this PhD, which included many long days and nights, difficult problem solving, and a delicate work/life balance. Nevertheless, this journey has been rewarding, allowing me to find a passion for translational research and design as well as a meaningful results along the way. The process of this degree has taught me about research design, detailed notation, and scientific exploration of unsolved issues. The last four years would not have been possible without the help of some very gracious people.

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List of Abbreviations

μ_{RR}	Coefficient of Rolling Resistance
μ_X	Coefficients of Factors, includes Toe, Load, Tire
%	Percent
3D	Three Dimensional
4PO	4" Diameter Caster Polyurethane
5PO	4" Diameter Caster Polyurethane
5SR	5" Diameter Caster Soft Roll
8PN	8" Diameter Caster Pneumatic
8PO	8" Diameter Caster Polyurethane
8SP	8" Diameter Caster Semi-Pneumatic
AC	Alternating Current
ADL	Activities of Daily Living
AIS	Low-Pressure tire with Airless Insert
AMP	Amperage
AMPS	Anatomical Model Propulsion System
ANOVA	Analysis of Variance
AV	Audio Visual
B	Intercept

CM	Centimeter
CTS	Carpal Tunnel Syndrome
CTSI	Clinical and Translational Science Institute
D	Drum Surface
DAC	Digital to Analog Converter
DEG	Degrees
DF	Degrees of Freedom
DTM	Drum with Treadmill Surface
DV	Dependent Variable
F	F-Statistic, Variation Between Sample Means
FFT	Fast Fourier Transform
F_{RR}	Rolling Resistance Force
F_{RRDrum}	Drum Rolling Resistance Force
$F_{RRGround}$	Overground Rolling Resistance Force
F_t	Tangential Force
F_{tx}	X component of Tangential Force
F_{ty}	Y component of Tangential Force
F1	Factor 1
F2	Factor 2
HP	High-pile Carpet, Horsepower
HPP	High-Pressure tire on Performance Wheel
HPS	High-Pressire tire on Standard Wheel
HZ	Hertz

IADL	Instrumental Activities of Daily Living
ICC	Intraclass Correlation Coefficient
IGERT	Integrative Graduate Education and Research Traineeship Award
IRB	Institutional Review Board
ISWP	The International Society of Wheelchair Professionals
ISWP-SWG	The International Society of Wheelchair Professionals Standards Working Group
IV	Independent Variable
K0005	Medicare Code for Ultralightweight Wheelchair
K0009	Medicare Code for Custom Rigid Frame Wheelchair
K-Code	Medicare Codes for Reimbursement
KG	Kilogram
KLS	Knobby Tire on Standard Wheel
kPa	Kilopascal (pressure)
Lbs.	Pounds
LP	Low-pile Carpet
LPS	Low-Pressure Tire
M	Slope
MeSH	Medical Subject Headings
MIT	Massachusetts Institute of Technology
MFR	Manufacturer
MP	Medium-pile Carpet
M/S	Meter per Second

mVDC	MiliVolts Direct Current
M_w	Moment about the Wrist
MWC	Manual Wheelchair
MWU	Manual Wheelchair User
M_z	Moment about the Axle
N	Newton, Number of Participants
O	Overground
OD	Outer Diameter
OTM	Overground with Treadmill Surface
QTY	Quantity
P	P-Value, Probability Value
Pitt	University of Pittsburgh
PSI	Pounds per Square Inch (pressure)
PVC	Polyvinyl Chloride
PWE	Perceived Weight Equivalent
R	Radius of the Push-Rim
RPM	Revolutions per Minute
RR	Rolling Resistance
R_2	R-squared, Proportion of Variance
RSI	Repetitive Strain Injury
SCI	Spinal Cord Injury
SPM	Solid Polyurethane Tire on a Mag Wheel
SPSS	Statistical Product and Service Solutions Software

STD. DEV	Standard Deviation
Theta	Angle of Inclination
TM	Treadmill Surface
UE	Upper Extremity
V	Angular Velocity
VAC	Voltage Alternating Current
VDC	Voltage Direct Current
W	Load on the Axle, also Watts (power)
W_x	X Component of the Axle Load
W_y	Y Component of Axle Load
X	Horizontal Component, Equation Variable
X_2	Polynomial Equation Variable
Y	Vertical Component
Z	Point Representing Center of Rotation

1.0 Introduction

Multiple factors have the ability to give rise to rolling resistance (RR) in manual wheelchairs (MWCs) and have been examined through numerous studies and methods [1]. RR forces detract from the forward propulsion of the rear-wheels as a drag force caused by hysteresis and interaction of the tire on a surface, as shown in Figure 1 [2]. Factors such as material selection for the wheelchair frame come from the design of the device itself, with lower density, high-strength to weight ratio materials being ideal. Carbon fiber is a very lightweight high-strength material and has drastically cut the overall weight of MWCs [2, 3]. RR is directly proportional to weight; therefore, any increases or decreases in weight, are direct increases or decreases respectively [4]. For comparison, a steel frame device will have a higher RR due to the higher weight, if all other factors are equal. A coefficient of RR, denoted as μ_{RR}, can also be calculated by normalizing the RR by the force (W) acting downward on the wheel:

Equation 1 Coefficient of RR

$$\mu_{RR} = \frac{F_{RR}}{W}$$

The coefficient of RR can be useful when comparing and contrasting the overall RR performance of different wheels and tires because it normalizes by the downward force and is known to be linearly related to RR. W varies based on the wheelchair setup, wheelchair weight, and user weight.

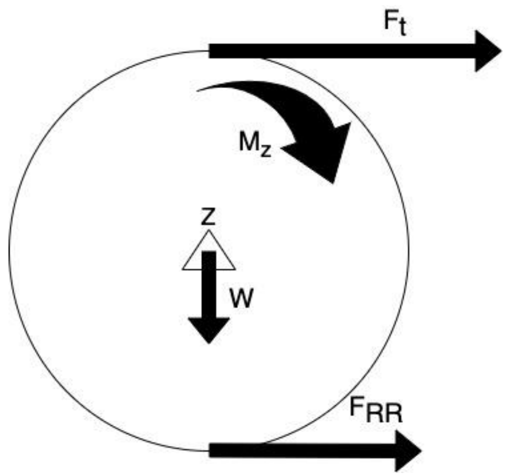


Figure 1 Rolling Resistance Free Body Diagram

F_t is the tangential force, V is the angular velocity, W is the load on the axle, F_{RR} is the rolling resistance force

In the short-term, RR acts as higher resistance to the manual wheelchair users (MWU) for propulsion. This requires a higher work output from the MWU, and fatigue could set in faster. However, this could impact a person's willingness to use their mobility device [5]. It could be more difficult to traverse thresholds or navigate certain terrains or environmental features [6]. Ultimately, that could lead to reduced activity and participation, which, over time, are linked to negative psychosocial effects [5, 7]. Every day, millions of people use wheelchairs worldwide as their primary means of mobility and would be affected by increased propulsion demands [8, 9].

The prolonged use of MWCs is linked to the deterioration of the shoulder, upper extremity (UE) pain and repetitive strain injuries, and carpal tunnel syndrome [7, 10-13]. Using a device with a higher RR escalates these complications, reduces the time to onset, or worsens existing issues [14]. Injuries are detrimental to the MWU because that further reduces their activity and participation until they recover. Additionally, it increases their health care costs and could result in lost wages [15]. If the shoulder and or UE weaken or become too painful to the MWU, he or she may be forced to switch to a powered mobility device [16]. That transition is not only costly but requires changes in routine, navigation of the environment, transportation, employment, activities of daily living (ADL), and instrumental activities of daily living (IADL) [5]. Long-term health factors need to be monitored for the indications of high RR.

RR influences from tires and wheels begin at the manufacturer with the material used to make the tire affecting its elastic deformation or hysteresis [17]. Hysteresis is one of three components that cause RR, in addition to friction (scrubbing of the tire), and air and bearing resistance [18]. At the typical propulsion speed (under 3 m/s) for MWUs, air resistance and bearing resistance are considered negligible [19, 20]. That leaves two main contributors for RR, hysteresis and friction. Three separate sources state that friction is not as large of a contributor as hysteresis, where hysteresis makes up 85-90 percent of the energy loss [17, 18, 21].

Hysteresis is considered to be cyclic as the tire rolls. The leading edge is deforming while the trailing edge is returning to its original shape. Figure 2 shows the stress-strain curve of the cyclic hysteresis. The shaded area is the energy loss during one cycle [18]. This loss is dissipated as heat into the tire [21]. For pneumatic tires, the increase in temperature raises the internal air temperature during prolonged use. Therefore, the air expands, increases the tire pressure, and combats underinflation [18]. Heat can also come from the friction between the surface and tire [21].

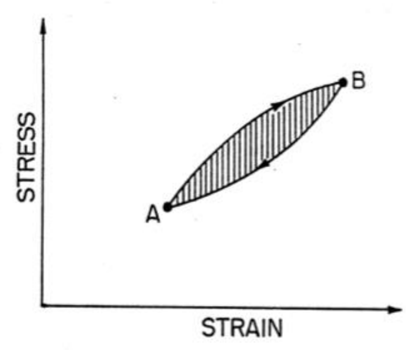


Figure 2 Stress-Strain Curve of Cyclic Hysteresis in Rolling Resistance [18]

The material composition of the tire will have a dramatic effect on how the tire responds to input factors such as heat. Furthermore, material properties will dictate how the tire responds to hysteresis [21]. Figure 3 shows the difference between a high-hysteresis polymer and a low-hysteresis polymer. The low-hysteresis polymer has a lower tendency to dissipate energy at a given strain; thus, there is less energy loss due to hysteresis and less RR.

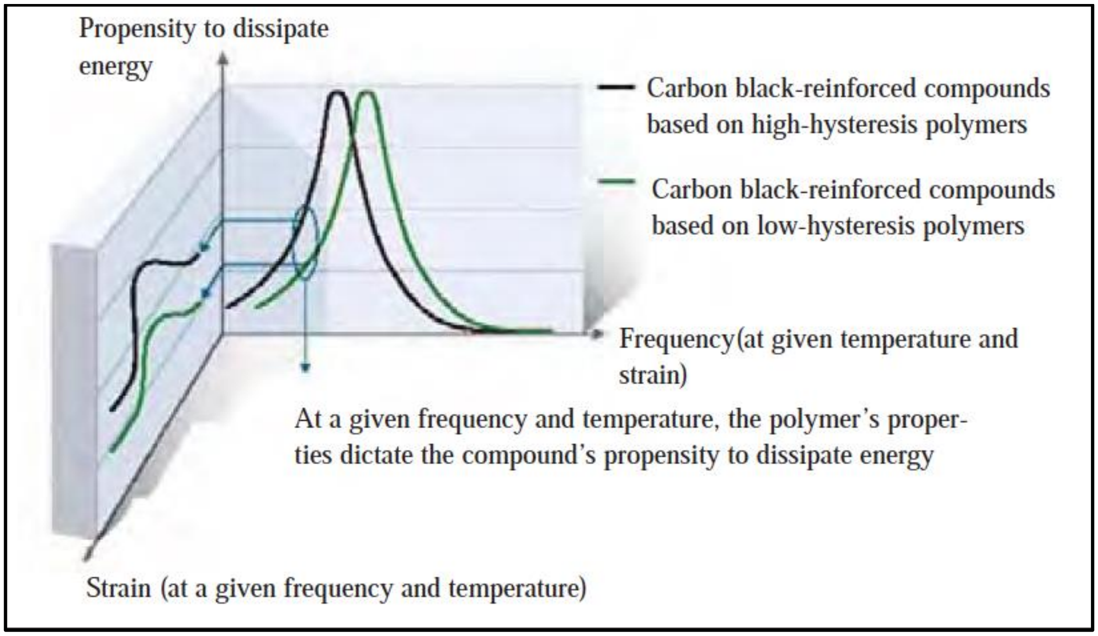


Figure 3 Strain and Frequency Graphs

Showing the Changes in Polymers Used in Tire Manufacturing [21]

The majority of the research in RR is restricted to pneumatic tires. One paper focuses specifically on comparing two solid tires, a natural rubber and a polyurethane tire. Figure 4 shows the comparison in stress strain curves during linear elastic deformation and how the polyurethane tire is more resistant to deformation. Therefore, it has lower hysteresis and a lower RR as seen in Figure 5 [17]. Solid tires do not have an air pocket inside; thus, all of the deformation is from the material itself. Additionally, solid tires have more mass than pneumatic tires, which can make them more difficult to propel [17]. One concern with more solid tires is vibration transmitting from the surface into the MWC and ultimately the MWU.

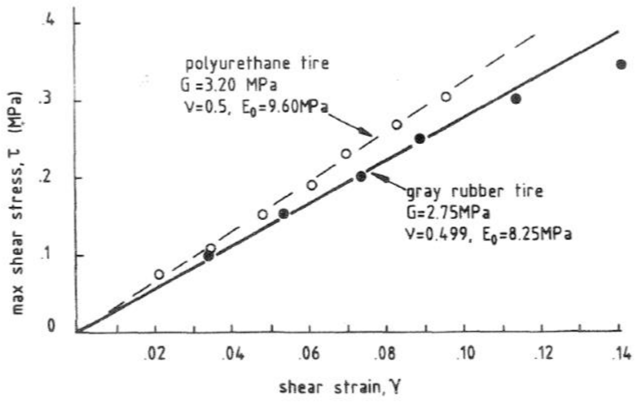


Figure 4 Stress versus Strain for Two Solid Tires [17]

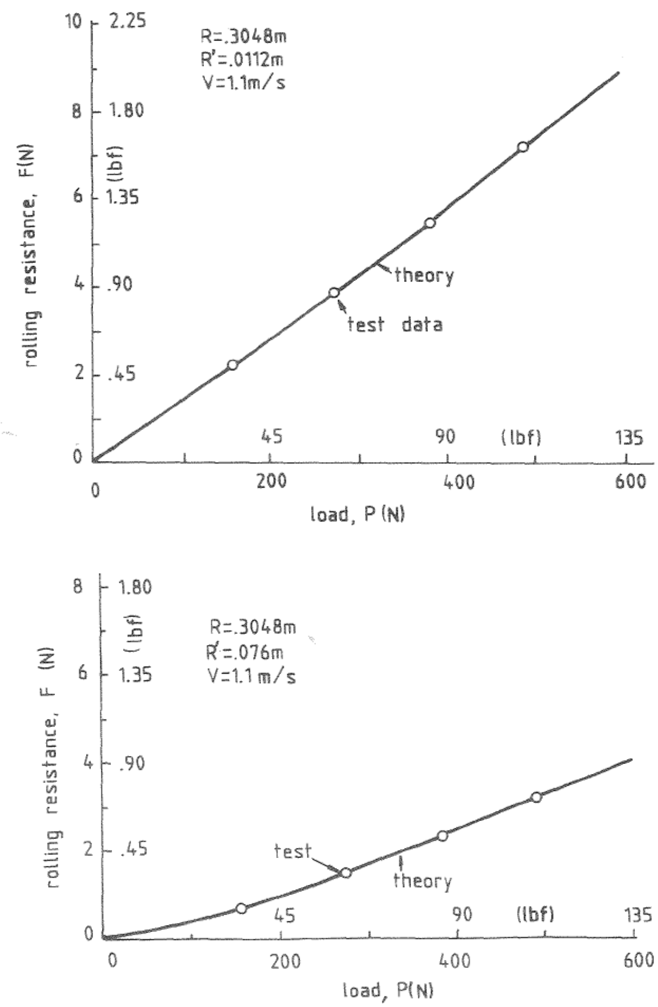


Figure 5 Load Versus Rolling Resistance for Rubber

(top) and Polyurethane Solid Tires (bottom) [17]

Additional factors of RR come from manufacturers, including the overall weight of the MWC, balanced wheels, and the quality of components. The weight of the system comprises of the weight of the MWC frame, the weight of wheels and tires, as well as the weight of add-on components. A wheel that is out of true or unbalanced could also induce friction by consistently changing the contact patch. Poor quality bearings in the wheel hub could create a higher resistance that adds to RR [19].

The manufacturing process can produce errors that can lead to the introduction of toe (misalignment) to a MWC. Overly large tolerances expedite manufacturing but can come at a cost to the consumer. If the rear-wheels are misaligned in toe, the RR will be higher than wheels that are aligned [22]. When the rear-wheels are in toe, they compete with each other to move forward in a straight line [4]. The battle back and forth introduces tire scrub across the surface, which elongates the contact patch and drags the tire back to straight. The constant corrections cause a higher RR due to energy loss in the tire. Low-quality bearings could also induce toe through bearing slop, or excessive movement in the wheel through tolerances in the axle mating components. If the bearings are not seated properly or pressed properly, toe can certainly be induced. Tangential force on the push-rim propels the MWC forward, but when toe is introduced, part of the force is diverted to in or out since the push-rim is not aligned with true forward. The tangential force would then have an x and y component causing a loss in force for forward movement. Figure 6 demonstrates the scenario and the respective loss as F_{tx}, the X component of the tangential force.

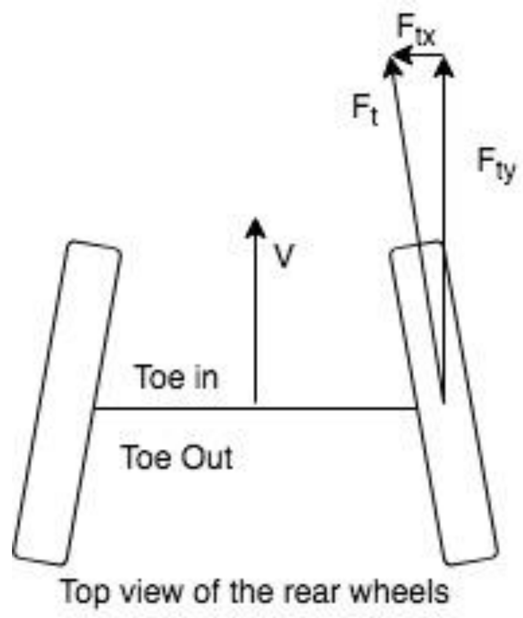


Figure 6 Toe Free Body Diagram

V is velocity, F_t is the tangential force, F_{tx} is the tangential component in the x direction, F_{ty} is the tangential component in the y direction

While manufacturing design can influence RR, the device prescription and fitting of a MWC to the user can also greatly impact RR as well. For example, camber is a user preference of the rear-wheels setup, but the effect of camber on RR is inconclusive [22]. With camber, the inside of the tire is used more than the outside, changing the loading profile of the tire as well as how the load is transferred to the ground. Since an angle is introduced, the weight of the device now has an x and y force component as seen in Figure 7. Unlike a toe scenario, there is no scrubbing in camber scenarios, and most studies reported it as not influential [4].

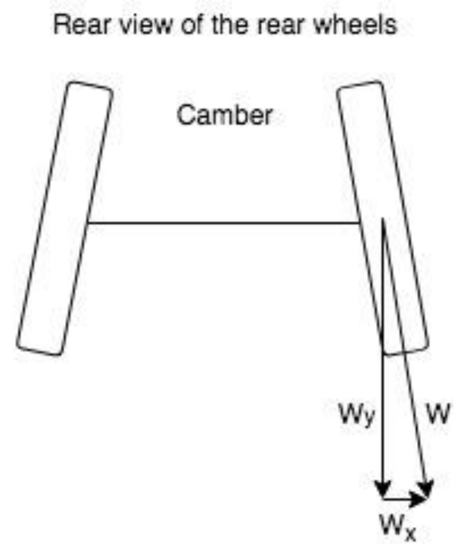


Figure 7 Camber Free Body Diagram

W is load, W_x is the x component of the load, W_y is the y component of the load.

Another setup factor is the rear axle position, which is not adjustable on all MWCs. While some axles can be adjusted vertically for overall seat height, seat dump (seat angle), and access to the push-rims, the more influential direction for RR is the horizontal axle adjustments. An anterior axle position changes the center of gravity of the device, putting more of the load on the rear-wheels and less on the front casters [6, 23]. The larger diameter of the rear-wheels can handle larger loads than the casters [22]. With a larger diameter, there is a smaller contact patch on the surface; therefore, the load is concentrated and there is lower RR than with a posterior axle position [6]. Adjustable axle positions have an influence on tire and wheel selection, chosen by clinicians, because axle position changes the MWU's access to the push-rim [2].

High-pressure pneumatic tires have been shown to have the lowest RR, however, different tread designs and materials affect RR [24, 25]. The overall diameter of the tire, the tread, and the profile will have a significant influence [26, 27]. If the needs of the client deem the use of a specific tire, clinicians need to be aware of the impact of the product choices. Furthermore, many of the principals relating RR and tires are also applicable to the casters. The caster has many of the same principles as the tire affecting it, such as diameter, material, and load will also affect the RR of casters [27]. The caster angle or the position of the stem bolt affects how the load is carried from the device to the ground, thus affecting the load offset of caster forks and ultimately RR [27].

One reason to choose a different tire option is the maintenance needed to maintain pneumatic tires. Underinflation increases RR because the contact patch is larger. With a larger contact patch, there is more friction between the tire and the surface [28]. However, an airless insert adds weight and rigidity to the tire. Both factors affect how easily the tire rolls and thus, RR.

Factors outside of design, prescription, and setup factors can also influence RR. With RR being weight dependent, the weight of the device and the weight of the user are contributors. It is known that the MWU's trunk shifts during propulsion; therefore, the center of gravity fluctuates during propulsion [23]. The overall weight of the user plays an important role in load distribution [29]. An increase or decrease in the user weight would increase or decrease RR, respectively [6]. The surface the user propels on also impacts RR. Softer surfaces, such as sand or loose gravel, are more difficult to propel over because the wheelchair sinks into the surface since the load is concentrated at four points [30]. When the MWC sinks into the surface and has to push the surface material out of the way to move forward. Some testing suggests matching the surface hardness to the tire hardness, causing the load to distribute over more surface area [31].

Items such as ramps are harder to propel on due to pushing against the vertical component added to the system [6]. Figure 8 shows a standard ramp with an angle of inclination, Theta. The vertical component, Y, indicates the height that must be overcome to ascend the ramp. The X component would be the same as flat ground. As theta increases, the Y component increases, and therefore, it is harder to propel on an inclined surface [32].

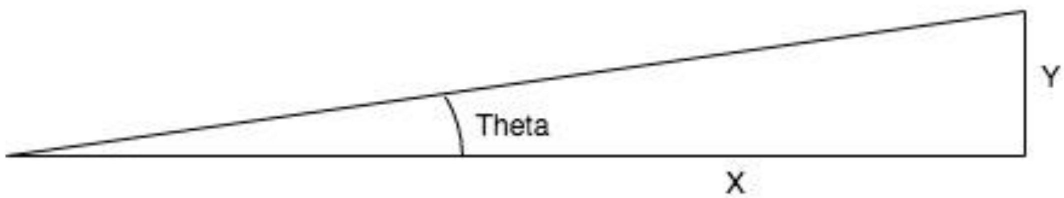


Figure 8 Free Body Diagram of a Ramp

Theta is the angle, X is the horizontal component, Y is the vertical component

Although many factors contribute to the RR, there are many ways to be able to reduce RR through design, proper prescription, setup, and maintenance [14]. In the design process, manufacturers need to be aware of how design decisions ultimately affect the propulsion of MWUs. If toe is induced due to low-quality bearings, poor manufacturing processes, and high tolerances, there will be a significant impact on RR [22]. Toe is the number one influential factor in RR, with only a degree or two doubling RR [4, 22]. Therefore, with toe present, the MWU will always be forced to push harder than necessary to maintain speed or propel slower on average. To mitigate this, the quality control of manufacturers needs to be thorough in adhering to tight tolerances, as well as the quality of parts and materials used. Manufacturing can also induce resistance in other measures such as improper placement of bearings or damage during installation [19].

Tire selection is the second most influential factor and provides many opportunities to contribute to the reduction in RR [24]. The tread and profile within tire design are influential with more aggressive treads having a higher RR [33]. As previously mentioned, the tire material composition will affect the hysteresis and elastic deformation of the tire, which contributes to 85-90 percent of the energy loss [17, 18, 21]. Designing a tire with a tread that allows for adequate traction on most surfaces while not being too aggressive is ideal for reducing RR. Furthermore, the tire should have a rubber compound that rebounds as much as possible while maintaining durability. Lastly, the design should be of the lowest possible weight, be true, and balanced for the best mitigation of RR. The manufacturing and design of the wheelchair and tires are only part of the efforts to reduce RR.

The next step in reduction is the proper prescription of products. Clinicians need to be aware of how the selection of products has lasting effects on the UE of MWUs [14]. The selection of tires can change the RR drastically with research showing that high-pressure pneumatic tires have the lowest RR, but they may not be the best option for every client [34]. Some clients may prefer airless inserts or solid based on terrain or the maintenance-free incentive, however, a 25 percent inflated tire can have a lower RR than a solid tire [33]. A solid tire or solid inserts can have 91 to 300 percent higher RR than a pneumatic tire [34]. Clinicians have few resources on the influence of their decisions and need specific guides on the impact of RR. Along with the choice of tires, the proper setup of camber and tire pressure are also important and options that need to be discussed with the client. Ensuring that controllable factors are mitigated is the best option for clinicians.

An uncontrollable factor is the surfaces a MWU will encounter, which have the potential to increase RR up to five times that of a smooth surface [25, 35]. One study demonstrated an 88 percent increase in forces at the wheels just with surface change alone, making it the third most impactful influencer [6]. Soft or loose surfaces are detrimental to effective propulsion and should be taken into consideration for commercial and residential design.

Lastly, the maintenance of devices can influence RR. The Wheelchair Maintenance and Training Program highlights the proper maintenance schedule for MWCs [36]. Bearings can wear out or become clogged with dirt and debris. A change in the condition of the bearings is bound to increase the resistive force in the wheels by binding the internal components [19]. A commonly overlooked maintenance procedure is the proper inflation of the rear-wheels. Mitigating this factor comes down to routine checks. It is the fourth most impactful factor and can increase RR by up to 32 percent [33, 37, 38]. The prescription of an airless insert may remove the maintenance procedure but can be more harmful than an underinflated tire [28, 33].

One challenge for reducing RR is to determine which factors most heavily contribute to RR. If a factor is not a heavy contributor, personal preference could outweigh the implication of increased RR, due to the convenience for MWU in their everyday lives. Toe and tire selection are known to be the heaviest influencer on RR [4, 22, 33, 34]. Surfaces are the next big influencer but are not controllable [6]. Tire pressure comes in fourth, followed by the weight and load distribution on the device [29, 33, 37]. The overall weight and load distribution have conflicting results as to their level of importance. While they both have effects under 20 percent increases, multiple studies have varying conclusions as to which is more important, but all agree that there should be no more than 40 percent of the load on the front casters [6, 29, 39]. With the appropriate load distribution, casters were found to not be a major factor [27]. Camber is also a low-level influencer [4, 22]. While all factors should be considered, it is clear that some have a more substantial impact on RR.

The complexity of RR and influence in many different steps of the manufacturing and service delivery process leads to no one simple answer for its reduction. Factors need to be independently tested and measured on a uniform system to determine which are the most impactful. Until then, manufacturers need to ensure quality products are being designed and produced. Additionally, the prevalence rate of factors in the community has yet to be determined to see if issues such as toe are affecting MWUs. Clinicians need to be aware of how all of the aforementioned factors and device components can have long term ramifications for MWUs.

Lastly, the proper maintenance of devices by the user or service provider needs to ensure that RR does not increase over time.

To investigate RR in MWCs, a scoping review was conducted to identify previous research including the methods and factors tested. However, variations in test methods, factors, and reporting were identified. While the aforementioned research is a valid starting point, a standardized test of RR for MWCs does not exist. Previous testing was conducted at a system-level, whole wheelchair or cart, and did not evaluate how these factors are influenced at a component-level, one wheel or caster. Furthermore, the prevalence of these issues in the community is unknown. The shortcomings of the previous research conducted provide the foundation and motivation for this project to explore the factors at a component-level after developing a novel drum-based testing machine as well as exploring misalignment in MWC wheels in the community.

2.0 Scoping Review of the Rolling Resistance Testing Methods of Manual Wheelchairs

This chapter is in preparation to be submitted to the journal of Rehabilitation and Assistive Technology Engineering. The introduction to this chapter has been condensed to minimize the redundancy information already presented in the dissertation.

2.1 Introduction

The International Society of Wheelchair Professionals (ISWP) established a Standards Working Group (ISWP-SWG) in 2015, which included experts in wheelchair design, manufacturing, and testing. The ISWP-SWG identified RR measurement as a high priority to improve wheelchair performance and product quality. One issue raised by the ISWP-SWG was a lack of information regarding RR over both rough and soft terrains that are important to wheelchair use in adverse conditions. A second issue was a concern that toe-in or toe-out of MWC propulsion wheels were common in the community, but the consequences on RR were unknown. Based on these issues, a recommendation by the ISWP-SWG was to identify or develop a RR test method that could explore these factors.

The ISWP-SWG recommendations as well as the research evidence that propulsion demands are linked to secondary injuries, highlight the need to either identify or develop a testing methodology that can determine the influence of individual design and environmental factors on RR to inform stakeholders, including clinical service providers, wheelchair users, and wheelchair designers/manufacturers. The factors commonly reported to influence RR include camber, toe, tire type, tire pressure, load distribution, and surface type. To better understand the established test methods, this paper reviews the existing literature for RR and compiles a summary of their testing methods, capabilities, and limitations. The results of this review are intended to catalog previous testing methods from a functional standpoint to inform future RR testing methods.

2.2 Methods

An online literature search of the National Center for Biotechnology Information's PubMed (1946-2018) was initially conducted on June 17th, 2018. Articles were found using the keywords RR, wheelchair(s) and Medical Subject Headings (MeSH) terms wheelchairs and friction. Lastly, some articles were discovered at the recommendation of the ISWP-SWG.

PubMed searches resulted in 51 articles from 3 searches. Additionally, 37 articles were provided from the ISWP-SWG for a total of 88 articles. This reduced to 64 articles after duplicates were removed between the articles from the ISWP-SWG and all of the PubMed searches. Abstracts were reviewed to identify if RR was measured in the protocol, which reduced the article count to 41. Appendix A.1 provides a detailed breakdown of the article search.

The type of test method was identified from each of the remaining articles. Motivated by discussions with the ISWP-SWG, each testing method was categorized according to whether it reported RR directly (Direct methods) or through a proxy measure (Indirect Method). Similarly, each method was categorized as a system (e.g. front/rear-wheels simultaneously) or component-level (e.g. individual wheels) testing and the ability to test multiple surfaces was determined. The following criteria were used to select manuscripts for inclusion into this study: 1) the manuscript reported methods that either directly or indirectly measured RR 2) the publication was peer-reviewed, and 3) the article was written in English.

2.3 Results

Seven test methods were identified and include drag test, treadmill, motor draw, deceleration, physiological expenditure, ergometer/dynamometer, and robotic test rig. Tables 1 through 7 include lists of each article, the test method used, the style of the test (direct or indirect), the level of the test (system or component), if it can test surfaces (yes or no), and key outcomes reported. Some articles combine test types and could fall into multiple test types but are only listed once in the category that was the overarching test for simplicity. For example, a test with physiological only expenditure measured on a treadmill is only listed in the treadmill category.

2.3.1 Drag Tests

A drag test is performed by measuring the force required to pull or push a wheelchair or cart with wheelchair wheels across a surface [4]. A variation of the test has been conducted where the wheelchair is pushed by the handlebars [1]. The method is similar to treadmill testing (described below) and is accomplished by pulling a wheelchair and measuring the force on a loadcell. This category has the most diversity in how the actual test was performed, as seen in Table 1. The source used to pull the wheelchair or cart ranged from water (in a bucket as a variable weight), a motor, and a power wheelchair. While most drag test method required a large area to perform the test, one component-level bench test was developed that measured the forces a wheel applied to an instrumented table [40]. Overall, these tests are a direct testing method at a system-level that can test multiple surfaces.

Table 1 Drag Tests

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[41]	Pulled the wheelchair backward using water as weights	Direct	System	Yes	Forces ranged from 31 to 740 Newtons (N) to overcome RR.
[40]	Bench test to measure force from the wheel to a surface	Direct	Component	Yes	Used a bench test to establish that surface properties and tire characteristics affect dynamic wheel behavior and contact forces.
[4]	Pulled a 3-wheel cart	Direct	System	Yes	Increased misalignment in rear-wheels is related to an increase in RR for MWUs
[42]	Pulled by power wheelchair (E-fix)	Direct	System	Yes	Could not establish a difference in the global RR from rear-wheels and casters of MWCs.
[43]	Pulled a 3-wheel cart	Direct	System	Yes	The interaction between surface and wheel can have an impact on RR.

2.3.2 Treadmill

During the treadmill test, a wheelchair is typically placed on top of a treadmill and a load cell is used to measure the pullback force on the chair [44]. Most of the test methods in this category are system-level, direct tests, although a component-level test could be possible. Two tests used propulsion data on the treadmill and are therefore indirect test methods, while two more used direct and indirect testing methods. One study compared a push technique to a drag test and that is the only study able to test multiple surfaces. Table 2 includes details of the 11 articles that involved a treadmill for testing RR. For this style of test, it was very common for it to be combined with another test style. Most of the treadmill tests used a wheelchair except one study used a specialized cart [45]. Other studies reported using instrumented push-rims on a treadmill so that physiological measurements could be collected [28, 46].

Table 2 Treadmill Testing

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[44]	Treadmill based drag test	Direct	System	No	Designed a treadmill attachment system to use it as an ergometer. The system was reliable and held the MWC in place. Resistance was measured with a blood pressure cuff but bearing resistance could not be distinguished from RR.
[2]	Treadmill based drag test	Direct	System	No	Developed a formula to calculate RR based on load distribution.
[45]	Treadmill based drag test using a cart	Direct	System	No	Used mechanical testing and two-wheel cart drag tests on a treadmill to evaluate the mechanical properties of tires.
[47]	Treadmill based drag test	Direct	System	No	Developed a formula to calculate RR that factors in the center of gravity. The formula was validated with data from the treadmill test. RR increased with weight and decreased with tilt.
[22]	Treadmill based drag test	Direct	System	No	Total resistance is the sum of rolling and air resistance with consideration of slope.
[1]	Treadmill based drag test compared to handlebar push	Direct and Indirect	System	Yes and No	Drag test showed similar results to the handlebar push test. Handlebar height and velocity varied RR between the two tests.
[28]	Treadmill based drag test and propulsion, instrumented push-rims, physiological measures	Direct and Indirect	System	No	RR was first determined by drag test prior to user testing. The result was used for calculating the power output of subjects.

Table 2 (Continued)

[48]	Treadmill based drag test and propulsion, instrumented push-rims, a physiological measure	Direct	System	No	MWC wheels had a lower RR than power-assisted. A specialized power-assisted wheel with higher torque and power increased propulsion efficiency. Only the specialized power assist was beneficial with the reduction of energy expenditure overcame increased RR.
[27]	Treadmill based drag test	Direct	System	No	Performed a simple drag test since differences in wheelchair setup factors. Air resistance and bearing resistance were assumed to be negligible.
[46]	Treadmill based propulsion; physiological measures compared to a track	Indirect	System	No	RR is dependent on velocity and tire pressure.
[49]	Treadmill based propulsion with induced drag	Indirect	System	No	A lower cadence with a higher induced drag (35 W) had higher gross mechanical efficiency as compared to a higher cadence with lower induced drag. Propelling cadence needs to vary based on resistance.

2.3.3 Motor Draw

One type of RR test method measures the draw of an electric motor while pulling a whole MWC across a surface [30]. With a change in a testing factor (e.g. different load), a change in motor current is measured and is compared to the baseline testing. The amperage across the motor is based on the amount needed to pull the wheelchair. Table 3 outlines the only article that measured the motor draw, which is an indirect, system-level test with the ability to test multiple surfaces. It is difficult to validate this test method with only one study completed using this method. However, the main outcome of proportionality to weight is confirmed through deceleration and physiological expenditures testing [6, 50].

Table 3 Motor Draw

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[30]	Motor Draw	Indirect	System	Yes	RR is directly proportional to weight and inverse to diameter.

2.3.4 Deceleration

Deceleration testing, commonly referred to as coast down testing, is an indirect test method that is commonly used in conjunction with a ramp. A wheelchair or cart with a known weight is given potential energy (released down the ramp) and then travels across a surface at the bottom [25, 33]. It has also been tested with a person propelling or a wheelchair being pushed to a given velocity and then coasting to a stop [20, 38]. Table 4 details the 11 deceleration testing articles showing mainly indirect, system-level testing with the ability to test multiple surfaces. This testing style has been used to test types of wheelchairs, tires, surfaces, and load distribution factors. There was a relatively large variation of the methods of deceleration testing reported. For instance, over half of the articles had a wheelchair pushed and the deceleration was measured as it slowed down. Other tests used self-propulsion or a ramp to generate velocity. One study compared the coast down result to treadmill results and concluded that the treadmill results (direct test method) had about 50 percent lower RR than the coast down [26]. This highlights the variance in testing methods as well as the need for standardized testing procedures.

Table 4 Deceleration Testing

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[26]	4-wheel cart on a ramp coast down and treadmill drag test	Direct and Indirect	System	Yes	Treadmill yielded about 50 percent lower RR than the coast down.
[20]	Self-propelled coast down on a track	Indirect	System	Yes	Air resistance and internal friction were negligible. Deceleration was found to be linear. Total resistive forces varied from 9.8-22.6N.
[51]	Ramp coast down	Indirect	System	Yes	When the knees of the MWU are flexed, RR was 21 percent lower.
[25]	Pushed coast down	Indirect	System	Yes	RR can vary up to 50 percent depending on the wheelchair, its configurations, and its wheel, tire and caster combination. RR may be velocity dependent.
[33]	Ramp coast down compared to propulsion	Indirect	System	Yes	Compared average rolling distance from an 8-degree ramp onto a gymnasium floor.
[38]	Pushed coast down	Indirect	System	Yes	RR was found to not be linear with velocity.
[50]	Pushed coast down	Indirect	System	Yes	Discusses a model for estimation of RR and found it to be similar to measured results.
[52]	Pushed coast down	Indirect	System	Yes	From the multiple tests, a model to estimate RR was derived.
[23]	Pushed coast down compared to propulsion	Indirect	System	Yes	The total mass shifts during propulsion and load distribution does not remain constant. Therefore, RR is not constant during propulsion.
[29]	Pushed coast down	Indirect	System	Yes	RR is higher when turning due to tire scrub.
[53]	Cart pushed coast down	Indirect	System	Yes	Used accelerometers to measure the deceleration of a cart over tile and carpet

2.3.5 Physiological Expenditures

Physiological expenditures such as heart rate and oxygen consumption can be measured during propulsion and have been used as proxy measurements for RR [37]. Similarly, instrumented push-rims measuring the force and torque applied to the wheelchair wheel have been developed to study wheelchair biomechanics, including the impact of RR. In these systems, force sensors are embedded into the push-rim to measure the kinetic forces on the push-rim [54]. The influence of RR is then reported based on changes in forces or torques required to maintain a constant speed.

The studies involving instrumented push-rims have a large focus on the impact of different surfaces. This may be because it would be difficult to change out tires or have multiple designs of these instrumented push-rims. It should be noted that the instrumented push-rims are typically heavier than standard wheels, thus having an impact on the overall weight of the device which influences RR. However, across all of the studies in Table 5, a consistent result is an increase in RR when traversing a rougher surface, and the consequences on propulsion biomechanics. This demonstrates the importance to be able to test multiple surfaces in RR testing. Physiological expenditures testing has produced results that are consistent with other tire pressure-related studies found by other testing methods [29, 38]. Overall, these studies were indirect, system-level tests with the ability to test multiple surfaces.

Table 5 Physiological Expenditures

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[31]	Propulsion over surfaces with 1 test subject	Indirect	System	Yes	Used a SMARTwheel to compare work done by propulsion.
[35]	Propulsion over surfaces with 11 test subjects	Indirect	System	Yes	Compared kinetic and kinematic measurements to examine propulsion. Wheel torque decreases after the first stroke until it levels out at stroke 5.
[37]	Heart rate monitoring during propulsion	Indirect	System	Yes	Increases in RR were correlated to higher energy expenditure.
[55]	Propulsion over surfaces with 14 test subjects	Indirect	System	Yes	Contrasted propulsion forces over different surfaces using a SMARTwheel.
[6]	Propulsion over surfaces with 53 test subjects	Indirect	System	Yes	Velocities can decrease as much as 63 percent across multiple surfaces. As RR increases, stroke length decreases and propulsion frequency increases.
[56]	Propulsion over surfaces with 13 test subjects	Indirect	System	Yes	Propulsion forces increased as RR increased. Propulsion power was higher in the dominant extremity during higher demand propulsion.

2.3.6 Ergometer and Dynamometer

The ergometer is a device used to simulate propulsion using rollers to measure forces or the amount of work done, while a person propels a wheelchair on the rollers. An ergometer measures the forces produced or work done by the subject. Dynamometer tests measure forces or work output on the rollers and are commonly combined with physiological measures and/or instrumented push-rims to give a complete picture. Additionally, a drum-based measurement does not directly translate to flat ground measurements due to the curvature of the drum [57]. One extensive ergometer study measured kinetic and kinematic data [58]. This process was very extensive in data collection. It required a lengthy setup process and post-testing analysis. Dynamometers from different facilities have been shown to be inconsistent in their measurements across four different locations [59]. One research team used an instrumented push-rim on a dynamometer, as shown in Table 6 [60]. Table 6 shows the studies in this category are indirect, system-level tests where attaching surfaces would be difficult given the small diameter of the drums.

Table 6 Ergometer and Dynamometer

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[58]	Ergometer based propulsion, physiological measures with 6 subjects	Indirect	System	No	An ergometer was designed to simultaneously test the kinetic factors of the wheelchair as well as physiological measures of the user. Results were consistent with other studies. Torque increased with the frictional load. Propulsion cycles were identified. Oxygen usage increased with velocity.
[60]	Dynamometer deceleration compared to instrumented push-rims deceleration	Indirect	System	No	Compares dynamometer to coast down with instrumented push-rims. Inertia and friction torque were smaller on the dynamometer. Therefore, weights need to be added to the drum of the dynamometer and braking system to increase the frictional torque.
[59]	Dynamometer with instrumented push-rims with 42 subjects	Indirect	System	No	Forces, moments, and deceleration times were different across sites. Thus, RR varied across the different dynamometers.
[34]	Dynamometer deceleration	Indirect	System	No	Used a dynamometer propelled to a known velocity to examine coast down times for different tires.
[24]	Ergometer with physiological measures (oxygen consumption and heart rate) with 8 subjects	Indirect	System	No	Examined wheelchair basketball wheels on an ergometer and on a basketball court to establish tire difference. Too low of a RR may not be ideal for adaptive sports.

2.3.7 Robotic Test System

The robotic test system was developed to measure forces and torques during propulsion. It is a highly instrumented and sophisticated system to operate [61]. While the computer-controlled propulsion gives consistency, its goal is to realistically reflect propulsion from an MWU through precise motor control. Given the complexity of the device, it is unclear how RR is being measured other than changes in motor voltage similar to the motor draw study. The robotic test system was developed to have specific control on the wheels during simulated propulsion and allow proper coasting by applying a small amount of power to the motor during deceleration. Table 7 lists the two indirect, system-level studies using this method that have the ability to test multiple surfaces.

Table 7 Robotic Test System

Citation	Test Method	Style	Level	Surfaces	Main Outcomes
[61]	Anatomical Model Propulsion System (AMPS)	Indirect	System	Yes	RR is not constant during acceleration and deceleration. AMPS was able to measure acceleration and deceleration consistently. RR was higher for acceleration as compared to constant velocity. RR decreased for deceleration.
[39]	Anatomical Model Propulsion System	Indirect	System	Yes	The robotic device is valid to measure the mechanical properties of the system but does not reflect differences seen in biomechanical propulsion.

2.4 Discussion

The main purpose of this review was to find a testing method capable of meeting the requirements determined by the ISWP-SWG, which included defining previous testing methods, their capabilities, and their limitations. Through the review, a wide range of RR measurement techniques have been identified in the literature, and most have data that is unique to that technique, making them difficult to compare. Specifically, seven RR test methods were identified. Five of the seven test methods were found to be mainly **indirect testing** and **all** of the methods tested at a **system-level**. Additionally, the ability to test multiple surfaces was present in five out of seven test methods. Table 8 shows the specific breakdown of the results.

Table 8 Summary of RR Test Methods

Test Method	Direct or Indirect	System or Component-Level	Ability to test multiple surfaces
Drag	Direct	System	Yes
Treadmill	Direct	System	No
Motor Draw	Indirect	System	Yes
Deceleration	Indirect	System	Yes
Physiological Expenditures	Indirect	System	Yes
Ergometer Dynamometer	Indirect	System	No
Robotic Test Rig	Indirect	System	Yes

A direct test such as a treadmill or drag test will provide results that are easily comparable across studies. An indirect test may not be as valuable to stakeholders as a direct test because it uses a proxy measurement. The proxy measurement is taken and then correlated to a change in RR and while it may be quantifiable, they are not easily comparable across different studies. With the combination of some of the testing methods during an individual study, the data analysis becomes very extensive and less clear. Tests that analyze the whole wheelchair make it difficult to isolate the influence of individual wheels/tires or wheelchair setup on RR. Therefore, the results are difficult to interpret and may not provide clinicians, manufacturers, or end-users with actionable information for device setup, product development, or product selection.

The wide variety of RR testing methods and related non-uniformity in reporting approaches makes it challenging to more broadly understand the influence of the range of factors influencing RR. Consequently, it is difficult to guide design, selection and setup of MWCs based on the published RR literature, and using the methods reported. Key limitations to the existing methods are that the majority of methods rely on proxy measurements for RR, and the test methods are system rather than component-level tests.

The need for component-level testing to ensure a complete understanding of the resistive forces at each component is demonstrated with all of the methods being system-level testing. The test methods often had limitations. Caster flutter or the wheelchair not decelerating in a straight line would skew the result [25]. For studies involving human subjects, fatigue during testing can bias the results. Furthermore, results can vary greatly across users with varying skill levels, thus impacting the results of the RR measured. If the test relies on an experimenter pushing the wheelchair, it is difficult to be sure that a constant speed was maintained which has been shown to be related to RR [1]. A strength of many of the methods is the ability to test multiple surfaces.

The results of this scoping review motivate the need to develop a standardized test method for directly measuring RR at a component-level under a range of common conditions that are known to influence RR. This is consistent with the need identified in the AMPS work, where component-level testing for wheels and casters was mentioned as a goal [61]. A new component-level test method may be able to provide the appropriate actionable information to all stakeholders on how to reduce RR: clinicians and users selecting products, wheelchair manufacturers and designers aiming to develop products with low RR, and researchers investigating factors influencing wheelchair propulsion and use. Through standardized methods, results should be more easily interpreted, and the appropriate clinical recommendations could be provided based on the results.

A limitation of this paper is that it is only a scoping review and therefore there may be additional articles in the grey literature addressing this topic. Additionally, this review did not cover what factors (tire type, tire pressure) were tested, and what levels they were tested at through the various test methods. There may be other test methods that have not previously been used on wheelchairs but may exist for similar devices, such as bicycles or the automotive industry. Exploration of those test methods is part of future work to develop a standardized RR test method.

2.5 Conclusion

RR of MWCs has is explored extensively because of the influence it has on wheelchair propulsion and risks to the UE. Unfortunately, because of the varied testing and reporting approaches, it is difficult to draw broad conclusions about the factors that influence RR, making it difficult to use the information to inform design, selection, and setup of MWCs and related components. Motivated by these limitations, we recommend that a standardized test-method be developed that can directly measure RR of individual components (wheels/tires/casters) across a range of settings that are consistent with real-world conditions.

2.6 Future Work

Several threads of future work could exist in this area. As noted above, it is important to develop a standardized, component-level test method that can measure RR directly. Following the development and validation of this method, measurement of a range of wheel/tire combinations under real-world scenarios of different wheelchair setup (e.g., camber, axle position), environmental (surfaces) and maintenance (tire pressure, toe-in/out) conditions would help establish core information about the factors influencing RR that can guide design, selection and setup of MWCs to reduce RR.

3.0 Scoping Review of the Factors that Impact Manual Wheelchair Rolling Resistance

This chapter is in preparation to be submitted to the journal of Rehabilitation and Assistive Technology Engineering. The introduction to this chapter has been condensed to minimize the redundancy information already presented in the dissertation.

3.1 Introduction

While MWCs provide mobility to millions of people worldwide, years of propulsion can have detrimental effects on wheelchair users. For MWUs, pain and injuries commonly occur in the UE. Evidence suggests that 64% of individuals with paraplegia and 55% of individuals with quadriplegia experienced UE pain [7]. For individuals with spinal cord injuries (SCI), nearly 40% developed shoulder pain with standard MWC use over a three year period [12]. With the prevalence of UE pain and injuries and related consequences, prevention has been a major focus of researchers. Several studies have investigated the interaction between the user and their mobility device. One critical step is to understand the forces being applied to the push-rim by the hand [62]. Research comparing musculoskeletal efficiency to mechanical efficiency was conducted and found that biomechanically efficient propulsion does not align with mechanically efficient propulsion [63-65]. One method of comparing the efficiencies is to view the stroke pattern and the forces applied to the push-rim [66, 67]. Furthermore, there are additional factors that have been shown to impact the MWC propulsion, including environmental factors, surface type, personal factors such as type of disability, as well as the physical characteristics and setup of the MWC [32, 35, 68-71].

In order to better educate clinicians on the relationship between MWC propulsion and UE pain and injuries, a clinical practice guide was developed which recommends larger diameter wheels, high-quality bearings, low device weight, optimized seating position (farther back), and a forward axle position. [14]. The objective of this scoping review was to identify the factors which are known to impact RR. A primary goal of this work is to inform stakeholders (clinicians, wheelchair users, wheelchair designers) of the factors that increase RR so that they can be mitigated in an effort to reduce the repetitive strain injury (RSI) risk of MWUs. A secondary goal is to identify what gaps may exist in understanding the influence of these factors to motivate future research.

3.2 Methods

A literature search on June 17th, 2018 was conducted using the National Center for Biotechnology Information's PubMed (1946-2018). Keywords for the searches were RR, wheelchair(s) as well as MeSH terms, wheelchairs and friction. Articles were also provided at the recommendation of colleagues who were part of an international working group focused on wheelchair standards testing, International Society of Wheelchair Professionals Standards Working Group (ISWP-SWG). Appendix A shows a flowchart of the article search process.

A total of 89 articles were identified and after removing duplicates 66 articles were reviewed for inclusion. Article selection was conducted by the primary author based on an abstract review of the following criteria. The article 1) directly or indirectly measured RR 2) evaluated a factor that was hypothesized to impact RR, 3) was peer-reviewed, and 4) was written in English. Overall, 33 articles were removed for not meeting the selection criteria, leaving 33 articles included in this literature review. The breakdown of article selection is shown in Appendix A.2.

3.3 Results

The 33 publications included in this scoping review were organized and analyzed according to specific testing factors: camber, toe, tire type, tire pressure, caster type, increased mass (weight added to the device), mass distribution (weight to the rear axles versus the front casters), and surface type. Some articles provide input on more than one factor and appear in multiple tables.

3.3.1 Camber

Camber was evaluated in four studies which provide contradictory results about the impact of camber on RR as shown in Table 9. Three out of the four studies found that camber had minimal impact on RR as shown in Table 9 [4, 22, 50]. A fourth study utilizing a new bench test method found that camber increased RR, but because of the design of the method, this would always be the case. (Silva et al, 2016). This method will always result in increased forces being measured when camber changes because load cells are placed on all four sides of a platform in order to measure the displacement forces.

Table 9 Camber Summary

Citation	Main Outcomes
[22]	Camber had little effect on RR. Wheel alignment can change with different loads (from the patient weight) on folding frame wheelchairs.
[50]	MWC setups with camber had a slightly higher RR than no camber.
[40]	Camber affected the propulsion force as much toe due to study design flaws.
[4]	Camber showed no significant effect on RR.

3.3.2 Toe

The effect of toe was examined in three of the studies and was found to have a significant impact on RR (Table 10). Specifically, one test showed that one degree of toe can induce a 25.5% increase in RR and that RR increases non-linearly as toe increases. The increase in RR is 96.3% and 212 % at two and three degrees, respectively [4].

Table 10 Toe Summary

Citation	Main Outcomes
[22]	Toe has a significant effect on RR. One to two degrees of toe can double RR.
[40]	As toe increased, force increased across along the surface plate due to scrub.
[4]	Toe's effect on RR: 25.5 percent increase for 1°, 96.3 percent increase for 2°, 212 percent increase for 3°, 374 percent increase for 4°, and 580 percent increase for 5°.

3.3.3 Tires

Eleven studies evaluated and tested different types of tires including pneumatic, solid, and solid inserts. The overwhelming majority of the studies found that pneumatic tires have a lower RR than solid tires or solid inserts (Table 11). Studies concluded that solid tires and solid inserts had up to 91% more RR when compared to a properly inflated high-pressure pneumatic tire (>100 psi) with a low profile [22, 34]. Additional studies confirm that while the RR was lower, the physiological demand was also lower [24, 28]. Lastly, one study established that RR in inversely proportional to rear tire diameter but the effect is negligible on soft surfaces [26].

Table 11 Tires Summary

Citation	Main Outcomes
[26]	Larger diameter wheels have a lower RR, but it is negligible on soft surfaces.
[45]	Pneumatic tires had the lowest RR. Although high-pressure pneumatic tires are the best option, foam tires may be preferred by some individuals due to reduced maintenance.
[22]	Tires are the most important factor for RR on level terrain. Pneumatic tires required 25 percent of the force required by solid tires.
[25]	High-pressure pneumatic tires had lower RR over solid tires.
[33]	Solid tires had the highest RR compared to pneumatic, higher than even 25 percent inflated pneumatic tires.
[34]	Pneumatic tires had a 91 percent lower RR than solid inserts and solid tires by (up to 3 times lower). Pneumatic tires had 29 percent less increased RR due to mass changes as compared to solid tires. Higher pressure pneumatic with a lower profile had the lowest RR.
[50]	RR was higher with solid tires compared to pneumatic tires.
[28]	Solid tires required more force output by the wheelchair user and had an interaction with the increased mass as compared to pneumatic tires.
[24]	High-pressure pneumatic tires had the lowest RR and physiological demand.
[43]	Pneumatic tires had lower RR than non-pneumatic.
[53]	Mag wheels were 135% higher in RR than the lowest pneumatic tire when tested on tile.

3.3.4 Tire Pressure

Seven studies investigated the impact of the inflation level of pneumatic tires, typically at intervals of 25% of max inflation pressure (Table 12). RR can be three times higher with deflated tires [38]. At 25% inflation in a pneumatic tire, MWUs experience reduced contact angle of the hand during propulsion, reduced propulsion cycle length, and significantly harder propulsion [28].

It was also shown that oxygen consumption and heart rate increase as tire pressure decreases [33, 37].

Table 12 Tire Pressure Summary

Citation	Main Outcomes
[33]	Two of the pneumatic tires showed a significant decrease in RR from 50 percent to 100 percent inflation. Oxygen consumption was inverse to tire pressure.
[37]	When compared to fully inflated (100 psi), tires inflated to 25 psi required 15% more energy for propulsion and tires inflated to 50 psi required 8% more energy.
[38]	Deflated tires had three times more RR compared to tires inflated to the maximum pressure.
[28]	Propulsion was significantly harder, in addition to reduced contact angle and cycle length at 25 percent inflation compared to 100 percent inflation.
[29]	RR was 10 percent greater in straight lines and 14 percent greater on turns with tires at 75 percent inflation compared to 100 percent inflation.
[48]	RR was higher at 50 percent inflation as compared to 100 percent.
[46]	RR is dependent on velocity and tire pressure. Tire pressure at 30 kPa required more energy expenditure as compared to 200 kPa.

3.3.5 Casters

Front casters, which included a variety of material compositions and diameters, were evaluated in five articles (Table 13). It was found that a four-inch caster had 16% higher RR than five or six-inch casters and caster shimmy in deceleration tests was found to increase RR [25, 42].

Table 13 Casters Summary

Citation	Main Outcomes
[30]	The lowest RR was observed with a larger front caster.
[50]	Standard casters had the highest RR followed by soft casters and then roller casters. A caster with a smaller radius has a higher RR.
[27]	Caster diameter is inversely related to RR.
[42]	The 4-inch caster had higher RR (16 percent) as compared to the 5 and 6 inch. It showed the highest RR on all indoor surfaces and coarse gravel.
[53]	Significant variations across models and diameters in which RR can double.

3.3.6 Increased Mass

Seven articles investigated the total weight of the wheelchair and rider on RR or simply the addition of weight to a test rig (Table 14). It was determined that RR did increase as weight increased, self-selected velocities decrease with increased mass, and an increase in torque was required for propulsion as mass increased [6, 39, 47]. It was also reported that RR of pneumatic tires are less sensitive to increases in mass compared to solid tires [34]. Conversely, one study found that a 10 kg increase in mass had no effect on RR, which is likely due to the placement of the added mass [28].

Table 14 Increased Mass Summary

Citation	Main Outcomes
[47]	RR increased with increased weight and decreased with MWC tilt.
[6]	Increased mass increases RR and peak propulsion forces while decreasing self-selected velocities.
[34]	Across all five tires evaluated, increased mass results in higher RR.
[28]	Extra mass (10 kg) showed no effect on RR.
[39]	Adding 5.5 kg required more torque on tile and carpet by 7.4 percent and 5.8 percent, respectively, during straight acceleration.
[53]	As mass increased, RR increased for all tires and casters evaluated.

3.3.7 Mass Distribution

Mass distribution was studied in 10 articles and evaluated where the person's center of gravity is positioned in the wheelchair (Table 15). Mass distribution is similar to increased mass because it changes the weight on the rear-wheels or front casters. One article reported that a change in the center of gravity did not have a significant effect on a cart with four identical wheels [26]. Overall, decreased RR was seen when the mass distribution was increased on the rear-wheels (from 55% to 70%) and decreased on the front casters, which changes straight line propulsion and turning [29, 39, 52]. It was found that if 30% or less of the mass is on the front casters, caster diameter does not matter [27]. A common way to change the mass distribution is to move the rear axle position [30, 50]. Additionally, a posterior axle position decreased self-selected velocity [6]. Lastly, research on propulsion has found that the person shifts their mass when propelling, and therefore, the mass distribution is not constant during propulsion [23].

Table 15 Mass Distribution Summary

Citation	Main Outcomes
[2]	Developed a formula to calculate RR based on mass distribution. Moving the center of gravity rearward will reduce stability, however, it will also decrease downhill turning tendency on side slopes.
[26]	Movement of the center of gravity had no effect on RR if it is a cart with four symmetrical wheels.
[30]	RR was higher when more than 30% of the weight is on the front casters.
[6]	A posterior axle position decreases self-selected velocities while increasing peak forces and RR. Lower forces were observed with an anterior axle position.
[50]	RR decreased by moving the axle forward and applying more mass over the rear-wheels.
[52]	Total drag forces on the front wheels ranged from 2.7 N with 37 percent mass on the front wheels to 6.9 N with 69 percent mass on the front wheels.
[23]	RR increases with a mass on the front casters. RR is dependent on the total mass and fore-aft position of the rear axle. If the mass on the front caster increases, a smaller radius caster will have a higher RR. The total mass shifts during propulsion and mass distribution does not remain constant. Therefore, RR is not constant during propulsion.
[29]	Mass distribution can have a greater effect than an increase in wheelchair user weight. While RR decreased by 17 percent with more mass over the rear-wheels (from 55 to 70 percent) in a straight line, it increased by 30 percent when turning with the increase in mass over the rear-wheels.
[39]	Adding 5.5 kg required more torque on tile and carpet by 7.4 percent and 5.8 percent, respectively, during straight acceleration. When the mass distribution was reduced to 55 percent on the rear-wheels, the torque required increased for straight motion on tile (13.5 percent), straight motion on carpet (11.8 percent), turning acceleration on tile (16.5 percent), turning motion on carpet (4.1 percent), steady-state turning on tile (73 percent), steady-state turning on carpet (5.1 percent).
[27]	Mass distribution has a larger effect than caster size. If 30 percent or less of the mass distribution is on the casters, the diameter does not have an influence.

3.3.8 Surfaces

The impact of surfaces was reported in 16 articles (Table 16). A common finding was that carpet had approximately 3 times higher RR than linoleum or concrete [1, 25, 50]. Greater torque was needed to accelerate on carpet [39]. Typically, a smooth surface such as level concrete was used as the reference. Tile also had low RR [1, 6, 41].

Table 16 Surfaces Summary

Citation	Main Outcomes
[26]	Nyfloor, Flotex, and vinyl flooring had similar RR values.
[31]	Sand and pea gravel were considered inaccessible. Cedar chips required 30 percent more work than wood fiber surfaces.
[25]	Carpet had 2 to 5 times higher RR compared to linoleum.
[1]	Carpet had the highest RR, three times higher than tile. Tile and tarpaulin had the lowest RR.
[35]	Forces at start-up on carpeted surfaces can be 1.8 to 3.5 times higher and torque can be 2.0 to 3.5 times higher than smooth concrete. Low-pile carpet had the lowest start-up forces and torques, while the ramp had the highest. Stroke count increased on the ramp. Greater forces and torques were found on grass, interlocking pavers, and the ramp. Mean effective forces can range from 1.3 to 3.1 times higher during start-up.
[41]	RR measured on tile was 30 N, open-cell foam was 100 N, and 12.5 cm wooden blocks were 740 N.
[55]	Propulsion frequency was higher on smooth and aggregate concrete as compared to tile and carpet. Aggregate concrete had the greatest forces and moments, 37 to 50 percent greater than tile, and 20 to 25 percent higher than carpet and smooth concrete. Tile had the lowest forces and moments.
[6]	Increases of RR on surfaces decreases self-selected velocities while increasing peak forces. Forces can increase as much as 88 percent and velocities can decrease as much as 63 percent across multiple surfaces. The highest RR was on the ramp, followed by high-pile carpet, low-pile carpet, and tile.
[56]	Propulsion power was higher in the dominant extremity during higher demand propulsion (aggregate concrete and the ramp).
[50]	RR was higher on carpet than concrete.
[39]	When the load distribution was reduced to 55 percent on the rear-wheels, required torque increased for straight motion on tile (13.5 percent), straight motion on carpet (11.8 percent), turning acceleration on tile (16.5 percent), turning motion on carpet (4.1 percent), steady-state turning on tile (73 percent), and steady-state turning on carpet (5.1 percent).
[40]	A rubber floor had a higher RR than a smooth tile floor.
[42]	A 4-inch caster had the highest RR on all indoor surfaces and coarse gravel compared to smooth concrete.
[46]	The coefficient of RR was 0.011-0.012 on the treadmill made of synthetic rubber. The coefficient of RR on the track (PVC based) was 0.016 at 200 kPa and 0.026 at 30 kPa.
[43]	Packed dirt had the highest RR followed by carpet.

Table 16 (Continued)

[53]	Carpet had a higher RR than tile across all tires and casters.

3.4 Discussion

Overall, the goal of this was review was met by identifying the key factors that influence RR The ability to understand their relative levels of influence of each factor was also uncovered. However, it also highlighted that RR has been tested in a variety of manners for MWCs and the test methods can be categorized into seven categories: deceleration, motor draw, treadmill, physiological expenditure, drag test, ergometer/dynamometer, and robotic test rig. Since the measurements were taken using a variety of different methods, it can be difficult to compare results across publications and thus reduces the clinical value of the literature.

3.4.1 Camber

With the majority of studies citing that camber had little effect on RR, it may not be a critical factor to consider in product selection or setup. Commonly, camber is chosen by the client, and their preference may outweigh any implications from camber. With typical camber angles of 5 degrees or less and a pneumatic tire, the contact patch from the tire to the surface would not change a lot. With little change, a significant difference in RR would not be found. Only one study found camber increased RR and that was due to study design [40]. Increased camber is known to increase access to the push-rim and increases lateral stability which is commonly seen in adaptive sports [24].

3.4.2 Toe

Most of the published literature found that toe has a significant impact on RR. Based on the limited number of papers exploring this topic, and some conflicting studies, it is a potential area for further study, especially to understand whether it is frequently observed in the community.

3.4.3 Tires

Types of tires were one of the most heavily studied factors in the literature. Many studies have found that pneumatic tires have significantly lower RR than solid tires. With the amount of variation in styles and materials, it is a relatively easy factor to test. Furthermore, with quick-release axles commonly found on wheelchairs, it is easy to change from one set of tires to the other. Since RR is relative to weight, it indicates that heavier tires and wheels are harder to propel. Therefore, solid tires should have a higher RR than pneumatic tires. The literature supports this, but with so many tire variations, it is hard to discern how much more RR is due to solid tires and not a difference in setup or material composition of the tires. With numerous tire variations on the market, more testing needs to be conducted so that clinicians and MWUs can make more informed decisions on what tires would be best for a MWU.

3.4.4 Tire Pressure

Overall, a lower tire pressure, commonly measured as a percentage of the max pressure, increases RR. The trend is nonlinear, with RR increasing at a faster rate as pressure decreases. With a reduced tire pressure, the contact patch to the surface enlarges and increases the friction between the tire and the surface. It is expected that RR would increase, and that propulsion would be more difficult without a properly inflated tire.

3.4.5 Casters

The overarching theme from the literature is that caster diameter is inversely related to RR, meaning that smaller wheels have a higher RR than larger wheels. With the majority of the load on the rear-wheels, casters become less important, because RR is directly proportional to load. However, depending on the surface, casters can be crucial to effectively navigate the terrain. When testing RR, caster flutter can skew the results by adding RR.

3.4.6 Increased Mass

An increase in mass is expected to increase RR, and the measurement of RR is based on the total weight of the system. It is important to note that the location of the increased mass may affect the results more than just the addition of increased mass. The weight placed over the rear axle should have a minimal effect, since the majority of the loading goes through the rear-wheels, whereas increased weight on the front casters would be more impactful to RR. Manufacturers have made a continuous effort to reduce wheelchair weight, but this effect is small compared to the MWU's weight on the overall RR. Additionally, accessories such as backpacks will add to RR and only necessary items should be carried.

3.4.7 Mass Distribution

Mass distribution in wheelchairs has been theorized since the 1980s to impact RR [2]. Even though changes in rear axle position is the easiest way to change the mass distribution, an adjustable rear axle is not found on all MWCs and the design of some rigid frame wheelchairs does not allow for this adjustment. When ordering a wheelchair, clinicians have to determine the correct placement of the rear axle before ordering the frame to ensure proper mass distribution. Even a small change in the mass distribution can have a significant impact on RR and therefore propulsion forces. However, it is still more beneficial for the majority (60% or greater) of the mass to go through the rear-wheels and not the front casters [6, 29, 39].

3.4.8 Surfaces

Multiple surfaces are the hardest factor to control because clinicians do not know every surface their clients may come in contact with. However, understanding the effects of different surfaces on RR can provide insight on which surfaces to limit exposure to. Reduced exposure to high RR surfaces would help in the preservation of the UE. Coarse surfaces and high-pile carpet are shown to increase RR (increased propulsion effort) as compared to a smooth concrete surface. Clinicians can advise patients of the risks from extended propulsion on certain types of surfaces.

3.5 Conclusion

An overview of the influence of each factor discussed in the literature is shown in Table 17. Based on the various reporting methods, the level of influence relative to each factor is difficult to discern. The ranking was based on the studies that reported percent change or raw data where percent change could be calculated. Toe has the potential to be a very significant influencer, however, there are very few studies done on it and its prevalence is unknown [4, 22]. Tire type was reported to have a large influence on RR [33, 34]. Surfaces were reported to have the third-largest influence on RR, but are often difficult to control [6]. Tire pressure is the fourth biggest influencer, followed by the weight and mass distribution on the device [29, 33, 37]. The effect of overall weight and mass distribution have conflicting results, as reported in various studies relating to their level of importance. While varying both overall weight and mass distribution resulted in less than 20% change to RR, the multiple studies have varying conclusions as to which factor is more important, but all concluded that there should be no more than 40 percent of the mass on the front casters [6, 29, 39]. With the appropriate mass distribution, casters were found to not be a major factor contributing to RR [27]. Camber is also a nonsignificant influencer [4, 22]. While all factors should be considered, it is clear that some have a more substantial impact on RR.

Table 17 Factors of Influence in Rolling Resistance

Factor	Influence	Type of Factor
Toe	100% or more increase in RR from two degrees	Design
Tire Type	90% increase of RR due to material and tire type	Design
Surfaces	Greater than 80% increase	Environmental
Tire Pressure	Up to 32% increase	Maintenance
Load	Up to 20% change	Design
Mass Distribution	Up to 25% change	Setup
Casters	Not a strong factor if the mass distribution is under 40%	Design
Camber	Little to none	Setup

Despite a wide range of approaches to measuring RR, common themes can be seen in the findings of this scoping analysis. Wheelchair configurations have a significant impact on RR and propulsion, and small changes to configurations such as toe can have a substantial impact. Furthermore, the type of tire or size of the casters can significantly influence RR. Any changes in weight or the distribution of the load between the front and rear casters also impacts RR, and the position of the rear axle is critical in adjusting the mass distribution. Lastly, it is shown that changes in the surface affect RR.

Over the numerous studies and tests that have been conducted to evaluate RR, it is clear that this drag force has a direct impact on MWC propulsion. As previously discussed, the prevalence of UE injury and pain is high for MWUs. A focus by clinicians to decrease RR would help to ensure the preservation of the UE. In the long term, UE injury has a significant impact on the independence of the MWU and the ability to carry out activities of daily living.

The goal for clinicians is to optimize the MWC set-up for the patient to minimize RR, and therefore, reduce the prevalence of pain and injuries to the UE. High-pressure pneumatic tires properly inflated with no toe in the rear-wheels is the most ideal set-up for minimizing RR. Routine maintenance of proper tire inflation and inspection of alignment will help to mitigate RR. The mass distribution should be primarily on the rear-wheels with over 60% of the overall weight going through the rear-wheels. A clinician should instruct the user as to safe propulsion techniques over surfaces with higher RR, such as coarse surfaces.

A limitation of this paper is that only a scoping review was conducted. It is possible that there may be more articles discussing this topic. Additionally, this did not cover the various testing methods, their level of accuracy, and their ability to test a single component to measure these factors. Some testing methods were less direct measurements of RR and variability could be seen in how tests were performed. Additionally, all of the testing, with the exception of one study, was done testing a whole wheelchair or cart. Therefore, it is more difficult to discern the impact of one component versus systemic error. Variations in testing methods, as well as variations in what products were tested, could be causes for differing results.

3.6 Future Work

With the gaps in knowledge outlined earlier in the results of the testing factors and lack of consensus in the literature on the impact of various factors for RR, there is a need to further investigate RR in MWCs. Future testing should be able to consistently test many of the factors above in a systematic manner. Each factor needs to be tested independently and then in combination with other factors. It would also be beneficial to test parts of the wheelchair independently to see the individual effects with components, reduce systemic error, and not as part of the whole wheelchair. Lastly, a system to measure RR more accurately needs to be developed and employed to overcome the variations across and within the established testing methods. ISWP-

SWG has a standardization goal for the development of new testing equipment, which isolates the RR force and tests on a component-level. This would be able to test all of the factors above and provide the appropriate information to clinicians and manufacturers alike. With detailed product-level information, clinicians can make more informed decisions on product use and setup factors to optimize configurations for their clients. A more mechanically efficient device will be more biomechanically efficient and therefore reduce the risk of RSIs to end-users.

4.0 Development and Calibration of Drum-based Rolling Resistance Testing Machine for Manual Wheelchair Components

This chapter is in preparation to be submitted to the journal of Technology and Disability. The introduction to this chapter has been condensed to minimize the redundancy information already presented in the dissertation.

4.1 Introduction

Although evidence-based recommendations exist, they do not provide more complex insight, which is valuable to stakeholders. For example, the benefits or drawbacks of using different types of wheels and tires over different types of terrains; the relative impact of RR based on the setup of the device (camber and rear axle position) compared to the impact of RR due to changes that may occur after the user receives their wheelchair, such as tire deflation or wheel misalignment. The lack of detailed recommendations on the factors influencing RR and approaches to mitigate them is due to the scope and type of data on wheelchair wheel RR.

While previous methods had capabilities to evaluate surfaces or other factors, not one system was able to measure RR across all factors and at a component-level. Therefore, a new approach needed to be implemented to ensure the goals were met. After a thorough review, a drum-based approach provided the desired outcome which is what the tire industry uses to measure RR [72]. The drum-based method is employed with an axle transducer to measure the forces. However, passenger car tires can have a larger diameter and most often a larger width than wheelchair tires.

Therefore, more forces are experienced during their testing. It was a concern that it would be difficult to detect the smaller forces seen in wheelchair wheels if the same measurement style was employed. The drum used for passenger care tire testing was a 5.6-foot diameter drum, in which it was assumed there was a negligible difference between the curvature of the drum and the flat ground [72]. The difference can be calculated by a formula establishing the relationship of the contact patches on a curved surface versus a flat surface [57]. The goal of this project was to address these limitations by developing and validating a drum-based RR test equipment and a test method for wheelchair wheels based on the gold standard test method used to measure RR of tires for passenger cars and trucks [73].

4.2 Methods

We performed a multi-stage, iterative design process to ensure that the final test method was robust and valid. The following stages were completed, and the methods are described in detail below: Ideation (Stage 1), Design Iteration (Stage 2), Final Design (Stage 3), and Characterization of the System (Stage 4).

In the Ideation Stage (1), we established a core design team of subject matter experts and convened a series of brainstorming sessions. These sessions were informed from the experience of the members of the design team as well as relevant literature that was shared among the team. The results of these brainstorming sessions included sketches of the proposed test equipment as well as the design and performance specifications shown in Table 18.

Table 18 Design and Performance Specifications

Rear-wheels			
Factor	**Range**	**Increment**	**Justification**
Camber	0 to 5 degrees	1 degree	User preference where most devices do not allow more than 5 degrees.
Load	Up to 150 lbs.	20 lbs.	75 lbs. represents the load on one wheel with a 60/40 distribution of 250 lbs.
Toe-in/Out	-2.5 to +2.5 degrees	0.5 degree	Community-based data suggest that less than 2 degrees are commonly found.
Speed	Up to 1 m/s	0.5 m/s	Common propulsion speed is 1 m/s
Tire Pressure	Up to 100% of max	20% of max	Smaller interval than previous tire pressure studies
Surfaces	Carpet to start	Level of pile	Common heights of commercial-grade carpet.
Tire Type	6 – 24” rear-wheels varied by type	1 wheel	Recommended by industry experts
Casters			
Factor	**Range**	**Increment**	**Justification**
Load	Up to 100 lbs.	10 lbs.	50 lbs. represents the load on one caster with a 60/40 distribution of 250 lbs.
Speed	Up to 1 m/s	0.5 m/s	Common propulsion speed is 1 m/s
Tire Pressure	Up to 100% of max	20% of max	If applicable, some pneumatic casters on the market
Surfaces	Carpet to start	Level of pile	Common heights of commercial-grade carpet.
Caster Type	6 casters varied by type	1 caster	Recommended by industry experts

In the Design Iteration Stage (2) one of the individuals from the core design team led the component-level design of the system using SOLIDWORKS. Weekly meetings were held to review the design progress until a final design was established. A prototype was then built, and preliminary testing was performed to evaluate whether design and performance specifications were met.

In the Final Design Stage (3), the lead designer refined the design based on the preliminary testing of the prototype. Similar to Stage 2, weekly meetings were held to review component-level and system-level designs until the design was finalized and fixed. Fabrication of the system was then performed using in-house prototyping equipment, as well as contracted services for parts that required high-precision manufacturing.

In the Characterization of the System (Stage 4), a systematic approach was used to test the repeatability and sensitivity of the system across all of the factors that could be compared, including load, camber, toe-in/out, tire pressure, and tire-type. External validity was performed by comparing drum-based RR measurements to those collected on a treadmill (simulating overground rolling) under the following conditions detailed in Table 19. The drum-based machine was operated with the same treadmill belt material placed on it. Due to the vinyl backing of the belt and the powder coating of the drum, rug anti-slip tape had to be applied to the drum to keep the treadmill belt material from moving under toe factor testing. Additionally, 1” binder clips were used to secure the belt to the drum.

Table 19 Overground Comparison Factors

Rear-wheels			
Factor	**Range**	**Increment**	**Justification**
Load	55 to 95 lbs.	20 lbs.	75 lbs. represents the load on one wheel with a 60/40 distribution of 250 lbs.
Toe-in	0 to +2 degrees	1 degree	A subset of the full scale
Tire type	4 rear-wheels	1 wheel	From a selection of 6 wheels based on clinical recommendations.
Casters			
Factor	**Range**	**Increment**	**Justification**
Caster type	3 casters	1 caster	A selection of 3 wheels based on clinical recommendations.
Load	40 to 60 lbs.	10 lbs.	50 lbs. represents the load on one caster with a 60/40 distribution of 250 lbs.

The four rear-wheels tested, as seen in Table 20, are the high-pressure on a standard wheel (HPS), low-pressure with airless insert (AIS), knobby low-pressure tire (KLS), and solid polyurethane mag (SPM). Additionally, the three casters tested, as seen in Table 21, are the 4” diameter poly (4PO), 5” diameter softroll (5SR), and 8” diameter poly (8PO).

Table 20 Tire and Wheel Types

Tire Types	
HPS	High-Pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1” width, low tread Maximum air pressure 145 psi
LPS	Low-Pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1.375” width, medium tread Maximum air pressure 75 psi
KLS	Knobby Low-Pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1.375” width, high tread, Maximum air pressure 65 psi
AIS	Airless Insert in a low-pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1.375” width, medium tread
SPM	Solid Polyurethane tire on a Mag style wheel Dimensions: 24” diameter and 1” width, no tread

Table 21 Caster Types

Caster Types	
4PO	Four by One Poly Dimensions: 4” diameter with 1” width, polyurethane on an aluminum hub, no tread
5SR	Five by One and a half Softroll Dimensions: 5” diameter and 1.5” width, polyurethane on an aluminum hub, no tread
8PO	Eight by One Poly Dimensions: 8” diameter and 1” width, polyurethane, rounded profile, on a plastic hub

The setup of the testing will follow these following general steps:

1. The parallel rods are aligned co-linear to the belt of the treadmill.

2. An initial zeroing testing is run to evaluate RR forces from -0.5 to +0.5 toe angle, and if needed, minor alignment adjustments can be made, to ensure that the lowest RR force is associated with the 0 setting for toe angle.

3. The nominal load is it is set at 75 pounds for a rear-wheel or 50 pounds for a caster.

4. All testing is run at 1 m/s.

5. Factors will be changed based on Table 19 above.

To determine the precise offset between the drum and overground measurements, an only main-effects ANOVA model was built with RR force of the overground treadmill as the dependent variable (DV), RR force of the drum as a covariate, and load, toe, and tire type as factors. The results were significant ($p < 0.05$) for all factors and factor estimates were included in the model. The same analysis was run for casters and resulted in an equation to adjust casters to an overground testing scenario.

Sensitivity was performed for load, toe and tire pressure factors Outlined in Table 22. Load was tested in 1 lb increments over an 11-pound range. Toe was tested in 0.25-degree increments from -1 to 1 degrees. Tire pressure was tested at 5 psi increments for ± 15 psi of max inflation pressure. Repeatability was performed by examining the reference trials of each rear-wheel and each caster through their collective mean and standard deviation to determine repeatability. One-way ANOVAs were used to determine the amount of statistically significant change that could be detected. Post-hoc testing between the increments was analyzed to see where statistical differences exist at $p < 0.05$.

Table 22 Sensitivity Levels

Rear-wheels				
Factor	**Goal**	**Test Range**	**Test Increment**	**Justification**
Load	10 lbs.	65 to 75 lbs.	1 lb.	75 lbs. represents the load on one wheel with a 60/40 distribution of 250 lbs.
Toe-in/Out	0.5 degree	-1 to 1 degrees	0.25 degree	Toe is more influential farther from 0, testing around 0 gives the hardest scenario to determine sensitivity.
Tire Pressure	20% of max	60 to 90 psi	5 psi	Smaller interval than previous tire pressure studies and max inflation was 75 psi.

As part of the characterization and external validity steps, preliminary evaluation of RR on four 24" wheel/tire combinations (Table 20) and 1 caster (Table 21) was also performed and the results compared to previously published data to confirm the results were consistent with previous RR research. All products were blinded in order to provide broader recommendations about types of tires versus a specific brand or model. Three tires were all on the same spoked wheel with two pneumatic tires (HPS, LPS) and one airless insert (AIS). The fourth tire was a solid polyurethane on a mag wheel (SPM). As expected, the pneumatic tires had a lower RR than the airless insert or solid tires with the solid insert tire having a higher RR than the solid tire. A tire pressure test was also conducted with two pneumatic tires at 40, 70, and 100% of max inflation pressure. Lines of best fit were applied to the graphical representations of each factor. Summary statistics were used to compare the data across factors as well as to previously reported results.

4.3 Results

4.3.1 Stage 1 Ideation

The design team was a subcommittee of The International Society of Wheelchair Professionals Standards Working Group (ISWP-SWG) which was sponsored by a grant through the University of Pittsburgh by U.S. Agency for International Development to strengthen wheelchair product standards. Norm Reese of LeTourneau University led the design team which includes Jon Pearlman (Pitt), Matt McCambridge (MIT), and Anand Mhatre (Pitt). The previous test methods were reviewed, evaluated, and ranked based on effectiveness to meet the following goals:

- To measure the RR force with a repeatability of 10% as measured on the reference trials.
- To test the factors of load, toe, tire pressure, surfaces, casters, camber, speed, tire type at community-relevant levels detailed in Table 1 and sensitivity levels outlined in Table 3.
- To test the factors independently and combined at a component-level.

4.3.2 Stage 2 Design Iteration

The drum-based system is shown in Figure 9 and includes a lower frame to support the drum, and an upper frame that supports the arm assembly where the wheels are attached, and the force sensing system is located. The drum-based method provides the ability to test every factor identified in previous literature, as well as, test on a component-level. It has the adjustability to test a variety of wheels and tires and has an adjustment for toe and camber testing.

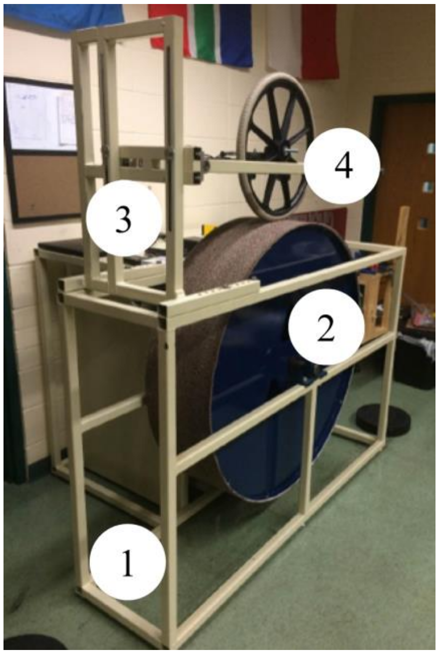


Figure 9 RR Testing Machine at LeTourneau University

(1) Lower Frame, (2) Drum, (3) Upper Frame, (4) Arm Assembly

Furthermore, the loading of the tire can be adjusted, and surfaces can be added to the drum. Although the first prototype met all of the design specifications, the repeatability and sensitivity of the system did not meet the performance specifications. The shortcomings were identified, and the design of a revised drum-based method was developed.

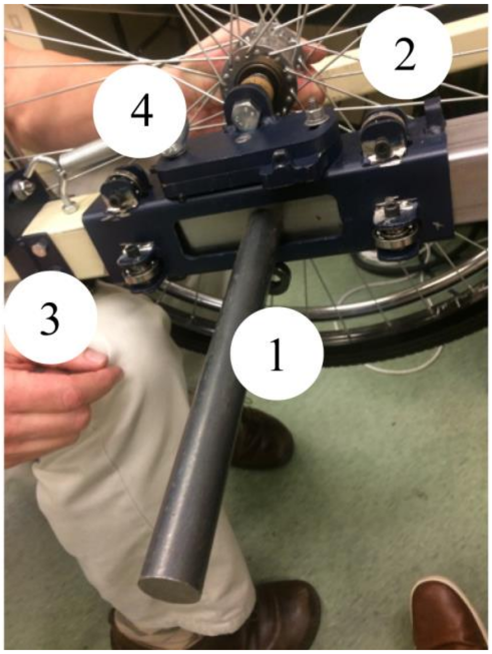


Figure 10 Truck of LeTourneau Machine

(1) Weight Bar, (2) Roller Bearings, (3) Camber Adjustment, (4) Toe Adjustment

4.3.3 Stage 3 Final Design

The goal of the second machine was to address the shortcomings of that device and Table 23 shows a detailed comparison, which largely focuses on the lack of repeatability in this design. Figure 10. Additionally, the measurement of toe and camber were changed to incremental to increase repeatability of the factor level. The new system was increased to 240 volts alternating current (VAC) with a 3-phase motor, prompting a complete redesign of all the electrical components. The data collection system was also redesigned but uses similar components. Lastly, the loading system and factor adjustment setups were required to be all newly developed after the numerous design changes.

Table 23 Comparison of LeTourneau Machine to Pitt Machine

Unmet Goal	Weakness	Corrective Action
Efficient Design	Overall size	Redesigned to have a smaller footprint
Repeatability	Mass for vibration dampening	Frame tubing diameter increased
Repeatability	Drum Deviations	Increased thickness, turned, and balanced
Repeatability	Friction in the measurement system	Air bushings replaced roller bearings
Repeatability	Continuous measurement for toe and camber	Moved to preselected levels

The second RR test apparatus can be broken down into four modular components: (1) lower frame, (2) drum and drive system, (3) upper frame and arm assembly, (4) data collection. These four components work together and in conjunction with a computer to collect the RR force of the tested component through the selected factor(s).

4.3.3.1 Lower Frame and Drum

To ensure horizontal stiffness as well as vibration dampening, the majority of the frame has been constructed from 2” steel tube. The drum assembly consists of 48” outer diameter (OD) drum with a ± 0.010” tolerance, 12” wide, made of low-carbon steel with a black powder-coated finish (Figure 11). The 1-1/2” keyed shaft runs through pillow block bearings and is capable of carrying a load of 150 pounds on the drum and rotating at a speed of 1.33 m/s. The load is derived from a 90/10 rear to front distribution of a wheelchair with a 300-pound user and device weight. The loading would be 135 pounds on each rear-wheel. A ten percent factor of safety rounds it out to 150 pounds. After construction, the drum was spun balanced and turned, maintaining the ± 0.010” tolerance and allowing for manual turning to attach the surfaces. The drive system contains a 1horsepower (HP), 3-phase, motor (model number MTRP-001-3BD18), a 40.08:1 inline gear reducer (model number 13-1552-40-56C), a 2" timing belts and pulleys, and is controlled by a PowerFlex 525 alternating current (AC) Driver by Allen Bradley (model number 25B-A4P8N104).

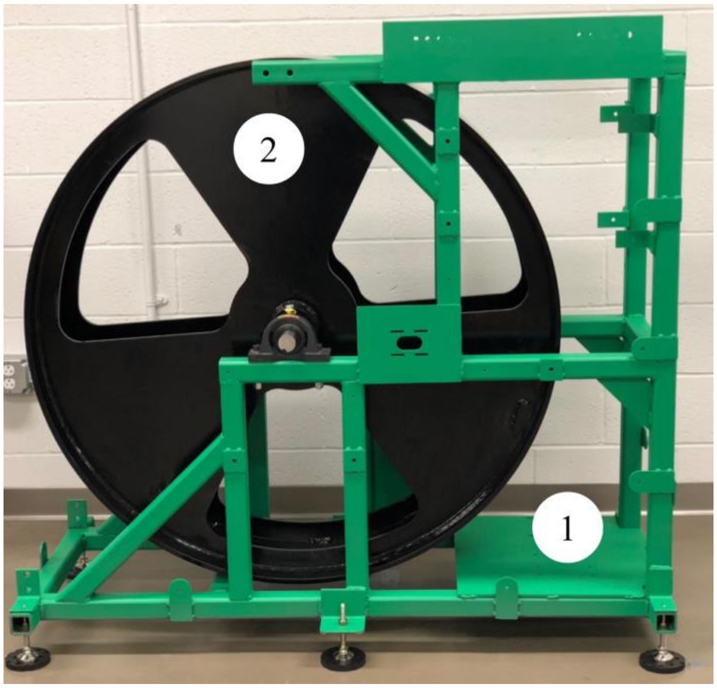


Figure 11 Lower Frame Assembly with the Steel Drum

(1) Lower Frame, (2) Drum

One unspecified goal of the second machine was to compact the design and make it more space-efficient by embedding the motor footprint as the drum instead of behind it. The mass of the frame was increased with larger diameter tubing and thicker walls to absorb vibrations that can affect the load cell and increase stiffness. The drum was made with thicker materials to increase lateral stiffness, it was turned for a precise outer diameter, and it was spin balanced to reduce any variance from the drum. The arm assembly was redesigned with the incorporation of frictionless air bushings instead of roller bearings that were inducing friction in the system.

4.3.3.2 Arm Assembly

The main components of the arm assembly, as shown in Figure 12, are two 1.5” diameter x 48” precision linear shafts from Thomson Linear (part number 1 1/2 L TU CTL) [74]. On the parallel shafts is a quad setup of four 1.5” air bushings (part number S303801) and mounting blocks from Newway (part number S8038P02) [75]. On top of the air bushing blocks are two plates that have a pivot point allowing for the top plate to swivel to ± 2.5 degrees of toe-in/out in 0.25-degree increments. Additionally, the camber blocks mount to the top plate and a loading rod attaches to the bottom plate. The tire mounts into the camber block using a wedge clamping axle. Spacers were made so that every wheel is at a consistent distance from the center of the air bushings. A caster mount was made to replace the camber blocks when testing casters.

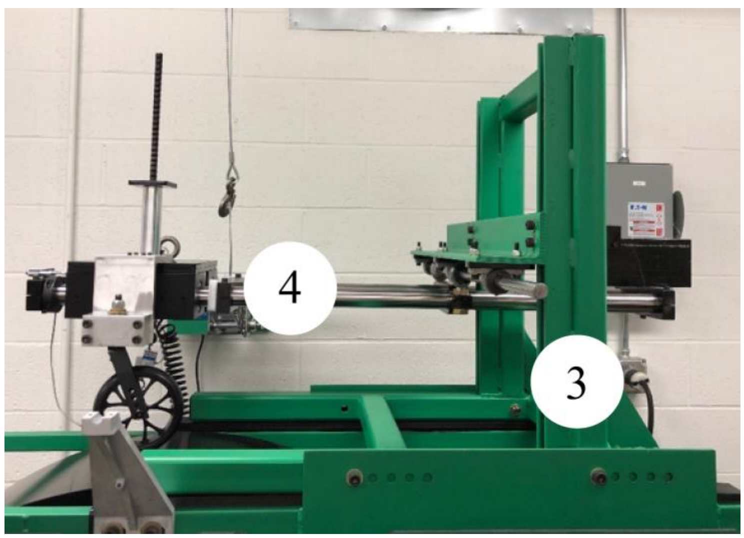


Figure 12 Upper Frame and Arm Assembly

(3) Upper Frame, (4) Arm Assembly

4.3.3.3 Control and Power

At the front end of the arm, a load cell from Interface (part number MB-25) is mounted horizontally [76]. That signal is read into a computer through a National Instruments Data

Acquisition Card (model number NI-9201) and chassis (NI-9171) [77]. MATLAB ® runs a code to read the digital to analog converter (DAC), process the data, and export it to an excel file [78]. For safety, the machine is completely controlled by the computer connected to it. A test protocol was developed to describe the proper order of operations to ensure consistent reliable testing procedures. The system is adjusted to the appropriate configuration based on the desired factors to be tested. Next, the arm is leveled in both axes. A lifting hook with an inline load cell is used to measure the weight of arm and wheel combination, which determines the normal force acting on the tire from the drum. Once the factors are set, the testing code is run. The MATLAB code prompts the tester for input factors, to turn on the air supply, and start the drum [78]. Voltage data is collected through the DAC for two minutes. After that, a moving average filter is applied to the data and truncates to the center sixty seconds to eliminate variances during startup or slow down. Based on the loading equation of the load cell, the voltages are converted into force pounds. All of the data is then exported in a .xslx format. Figure 13 shows the completed system.

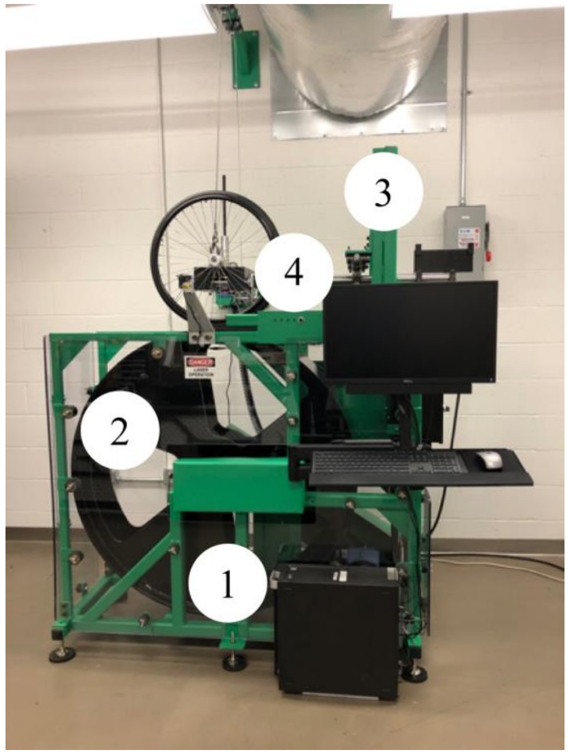


Figure 13 Completed Second Prototype

(1) Lower Frame, (2) Drum, (3) Upper Frame, (4) Arm Assembly

4.3.4 Stage 4 Characterization of the system

4.3.4.1 Machine Calibration

Prior to data collection, it was necessary to identify a proper sampling frequency for the load cell. To begin, testing was done at 1000 hertz (hz) and a Fast Fourier Transform (FFT) was performed, which resulted in no significant peaks over 20 hz with the exception of one at 60 hz. The 60 hz peak was assumed to be electrical interference. Finally, a sampling frequency of 150 hz was selected because it ensured the capture of any cyclic anomalies in the system from the tire as well as the actual force signal. The load cell loading performance yielded a positive linear relationship between force (weight applied) and voltage, which resulted in an R^2 value of 1.0. The loading equation is used in the code to convert the voltage to pounds-force.

4.3.4.2 Drum versus Overground External Validity

To enhance the characterization of the drum-based testing, a relationship to overground measures was determined through the use of an instrumented treadmill along with the upper frame and arm assembly from the drum-based machine (Figure 14). The results show similar trends in a proportional offset between the two testing methods.

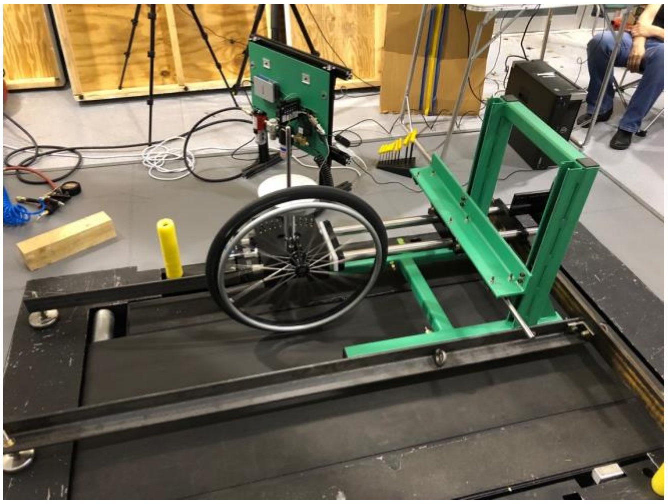


Figure 14 Treadmill Testing

Figure 15 shows the details with all of the drum trials having a higher RR than the treadmill counterpart sorted by the tire type. This provides validation to the data collection system that can be adjusted to represent real-world scenarios. An interesting result from the caster testing revelaed less of a difference between caster models during treadmill testing as compared to the drum. This could be due to an interaction with the curvature of the drum surface instead of the flat treadmill surface.

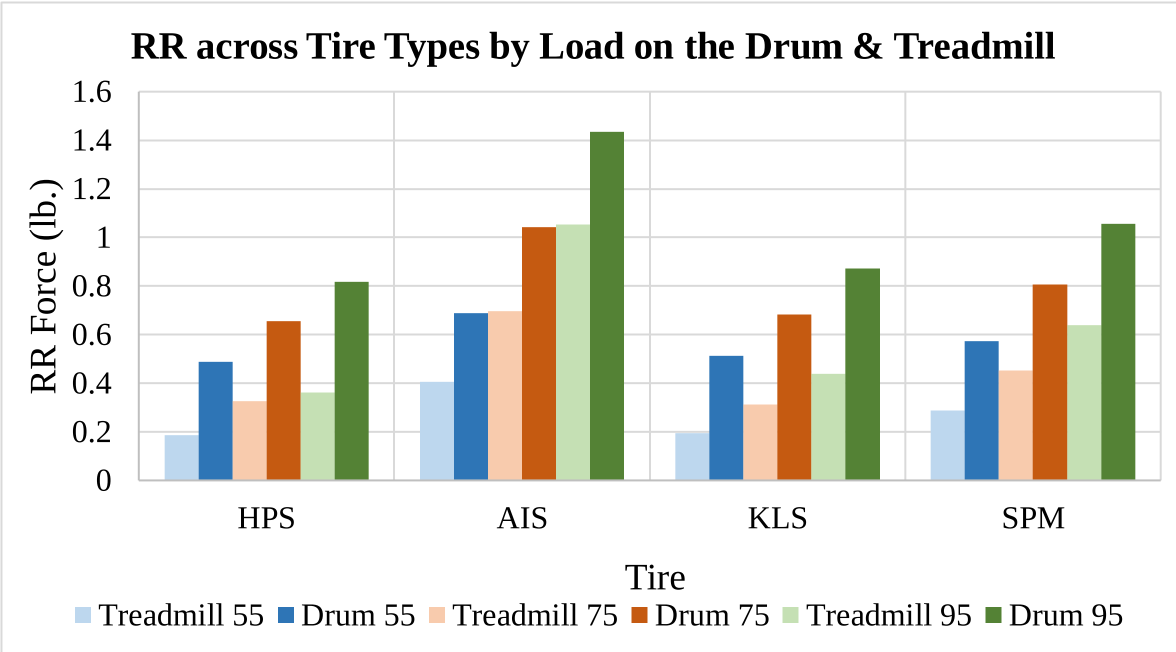


Figure 15 RR on Instrumented Treadmill compared to Drum Testing by Tire by Load

The results from the statistical analysis are displayed in Table 24 along with the results for the coefficients. Equation 2 is derived from the main effects ANOVA that identifies the relationship between the drum and treadmill testing. A coefficient is developed for every factor and its testing increments. To convert results from the drum to overground, the following formula would be used:

Equation 2 Overground Comparison

$$F_{RR_{Ground}} = \mu \; of \; F_{RR_{Drum}} * F_{RR_{Drum}} + \mu_{Intercept} + \mu_{Toe} + \mu_{Load} + \mu_{Tire}$$

For example, the HPS tire run at a 75-pound load, 1 degree of toe would be

Equation 3 Overground Comparison for HPS

$$F_{RR_{Ground}} = 0.917 * 0.74 - 0.131 - 0.049 + 0.050 - 0.054$$

Equation 4 Overground Comparison for HPS Final

$$F_{RR_{Ground}} = 0.495$$

Table 24 Coefficients for Rear-wheels

Factor	Coefficient
$\mu_{Intercept}$	-0.131
μ_{Toe} where Toe=0	-0.159
μ_{Toe} where Toe=1.0	-0.049
μ_{Toe} where Toe=2.0	0a
μ_{Load} where Load=55	0.084
μ_{Load} where Load=75	0.050
μ_{Load} where Load=95	0a
μ_{Tire} where Tire= KLS	-0.061
μ_{Tire} where Tire= SPM	-0.058
μ_{Tire} where Tire= HPS	-0.054
μ_{Tire} where Tire= AIS	0a
$\mu\ of\ F_{RR_{Drum}}$	0.917
a This factor is set to zero because it is redundant.	

The same formula would be applied for casters with the substitution of the correct coefficients displayed in Table 25. This information could be used to build a system model of RR and provide values based on factors and overground measurements.

Table 25 Coefficients for Casters

Factor	Coefficient
$\mu_{Intercept}$	0.907
μ_{Load} where Load=40	-0.368
μ_{Load} where Load=50	-0.203
μ_{Load} where Load=60	0a
μ_{Tire} where Caster= 8PO	0.174
μ_{Tire} where Caster= 4PO	-0.005
μ_{Tire} where Caster= 5SR	0a
$\mu\ of\ F_{RR_{Drum}}$	-0.239
a This factor is set to zero because it is redundant.	

4.3.4.3 Sensitivity Testing

The load was tested to see if the machine was properly detecting changes since the load is proportional to the reaction force and has a positive linear relationship to load as seen in Figure

16. The results of this test revealed a linear relationship with an R^2 value of 0.999, confirming that the RR measurements are aligned with RR theory. The results of load sensitivity testing show that the machine is able to detect RR changes in load greater than 7 pounds or about a 3 percent change in a 100 kg dummy ($F = 154.289$, $df = 10, 44$, $p < .001$, Partial Eta Squared = .972). The results show that casters also have a positive linear relationship to load and the trendline has an R^2 value of 0.983. Changes in toe were able to be detected at every 0.25-degree interval from -1 to 1. Tire pressure was tested on a tire at 15 psi below and 15 psi over max inflation with 5 psi increments. The machine is able to detect significant changes in RR for rear-wheels over 10 PSI ($F = 1288.688$, degrees of freedom (df) = 10, 44, $p < .001$, Partial Eta Squared = .997).

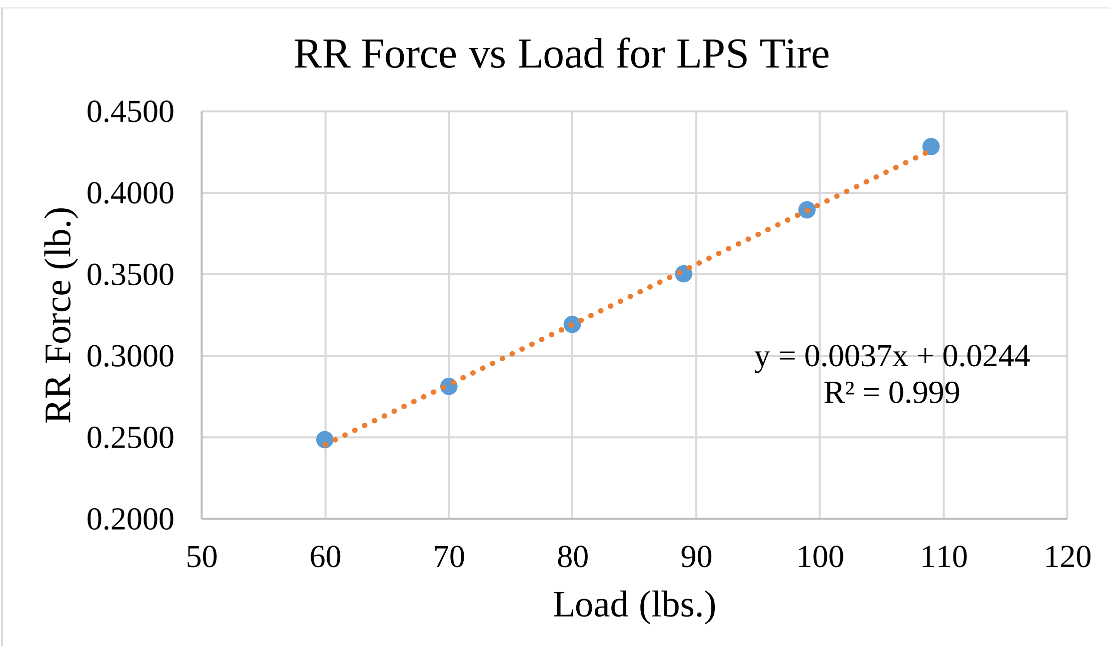


Figure 16 RR Force versus Load with a Trendline

4.3.4.4 Preliminary Results

Camber was tested with camber blocks that were machined from 0 to 5-degrees in 1-degree increments. The results were inconclusive and did not show a relationship between camber and

RR. Speed was also tested at 0.25 m/s increments from 0.2 5 to 1.25 m/s. There is a very minor increase in RR as speed increases. The medium-pile carpet showed a 21-174 % increase in RR. Pneumatics tires showed a higher increase as compared to the airless insert or solid tires with the airless insert being the least affected. A decrease in 60% inflation can have an increase of 43-53% of RR. This shows that tire pressure and RR have an inverse nonlinear relationship. Toe was also found to have a non-linear relationship to RR with Figure 17 showing the results for the LPS tire. One degree of toe can lead to an increase of 52-222 % and 2-degrees of toe can lead to an increase of 146-566% in the coefficient of RR depending on the tire tested.

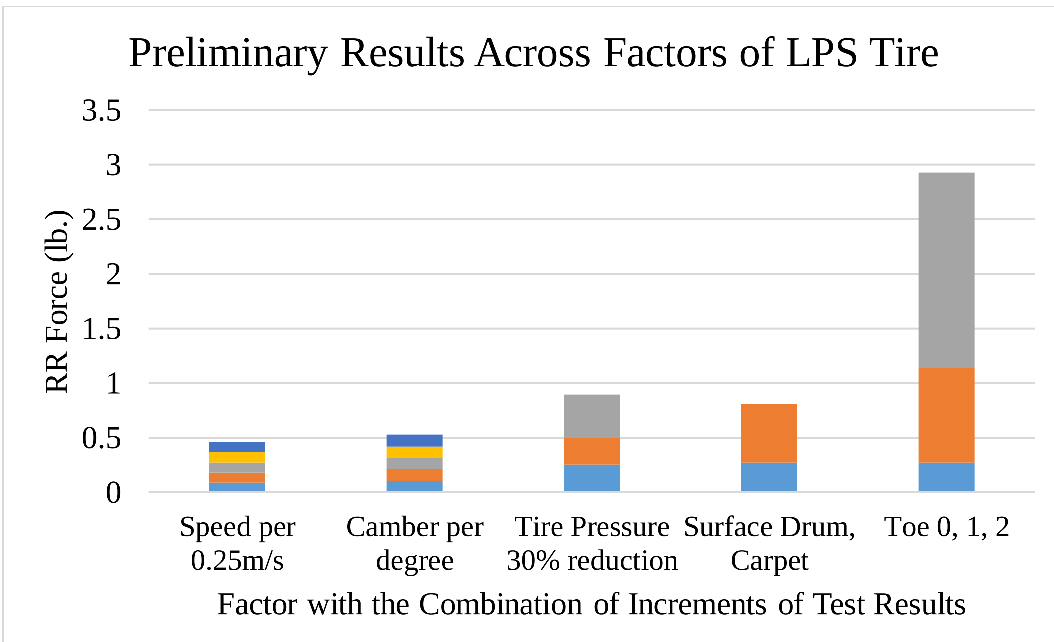


Figure 17 Preliminary Results of LPS Tire

Additional information about the development of the drum-based machine can be found in Appendix A.3. Additional information overground external validity can be found in Appendix D.

4.4 Discussion

RR is a complex topic that can be affected by many environmental and design factors that all have a biomechanical impact on MWUs, which are associated with injuries. RR should be minimized by the optimization of design factors to reduce the risk of UE pain and injuries. The newly developed drum-based RR testing machine should allow for a comprehensive understanding of how RR is influenced by different factors. The system provides a direct measurement of RR rather than a proxy measurement. Component-level testing provides insight not previously researched, with all of the previous testing methods testing a whole wheelchair. Overall, the machine met the required design criteria set forth by the ISWP-SWG and is functioning well. The operation is standardized with a detailed protocol to ensure repeatability in the results.

When a pneumatic rear-wheel was tested against increasing loads, the relationship was linear and proportional at any weight. The sensitivity of the system to detecting RR changes with weight changes were 7.0lbs. That is a relatively small change in the load of RR compared to a change in user weight or weight on a wheel/caster due to a change in rear axle position, allowing researchers to measure the benefits/drawbacks of changes in setup and other factors that influence weight (e.g. body weight, backpacks, weight of the wheelchair). The machine is accurate enough to discern the changes in force at small loads and the change maintains its relationship proportionally to load. This partially validates the results. Furthermore, the results show a strong R_2 value of 0.999 for load over multiple trials, which compares to a recent publication of deceleration based RR testing that reported R_2 values between 0.97 and 1.00 for a cart on tile [53].

The toe testing provided some new insights that have not previously been reported. The two pneumatic tires had the lowest RR across all three toe-out settings. Surprisingly the airless insert had a higher RR than the mag wheel across all three setups. RR increased in tires at a rate of 171% for the HPS, 223% for the LPS, 52% for the AIS, and 77% for the SPM at 1° of toe. At 2° of toe, there was an RR increase of 463%, 566%, 147%, and 217%, respectively. While there are lower increases in RR of the non-pneumatic tires due to toe, they also have a higher RR at 0° of toe. These results are higher than what was found with the three-wheeled cart drag study but are similar to the results of treadmill-based testing [4, 22].

Tire pressure testing was conducted with the HPS and LPS tires. As expected, RR increases as tire pressure decreases but not linearly. The increase was less than 10% for both tires from 100% inflation to 70% inflation and increased to 32% for the HPS and 61% for the LPS from 70% to 40% inflation. The results show that even a severely underinflated pneumatic tire has a lower RR than the airless insert or solid polyurethane tire. These results are similar to other RR studies. Sawatsky and Dension showed an 8% increase in RR with a 50% decrease in tire pressure [37]. Lin, Huang, & Sprigle showed a 10% increase at a 25% reduction in pressure [29]. While the percentages vary slightly, the amount of force on one tire is only a portion of the RR of the system. Furthermore, the forces measured are under 1 pound of force and the percentages are of very small forces. Last, the test factors could cause the minute variances.

Only a medium-pile level loop carpet was tested in this study. All four tires showed an increase in RR as compared to the drum surface. The pneumatic tires showed the largest increases of 175% for the HPS and 100% for the LPS. The high-pressure tire (HPS) had a lower overall RR but was more susceptible to change in surfaces than a standard tire (LPS). The airless insert had an increase of 22% and the SPM had an increase of 38%. The pneumatic tires are more susceptible to the change in surface but even on carpet still have a lower RR than the non-pneumatic. Sauret found the same increase when comparing carpet to concrete [50]. Two studies found carpet to be over twice as higher RR [1, 25]. This was correlated to a decrease in self-selected velocity and an increase in push-rim forces [6]. With the difference in carpet styles and materials, as well as the testing factors, it is difficult to determine how the studies directly compare.

Similar to the rear-wheel load testing, casters had a linear relationship. These results confirmed that the machine is able to test casters at a lower weight range than what was applied to the rear-wheels. Furthermore, it emphasizes that the machine is accurately measuring RR forces because the trendline has a high R_2 value of 0.983. Therefore, there is confidence in the results produced by this device.

Camber is not a strong influencer at small increments because it rotates the loading profile on the tire, which is not altering the contact patch in a significant way. These results are consistent with prior literature [4, 22]. This may be different at a higher level of camber seen in the adaptive sports community. Also, the test was conducted on a pneumatic tire, whereas a solid tire may yield a different result. Speed yields very similar results. The increase in speed was not influential and the variation was less than 0.01lbs.

As seen through some of the testing, the tire type is can have a significant effect on the RR. While not every factor has been tested, multiple tires, toe, tire pressure, and surfaces do show significant differences that were consistent with prior work. Pneumatic tires are across the board lower in RR than non-pneumatic. At 0° of toe, the LPS was 146% higher, the AIS was 606% higher, and the SPM was 429% higher than the HPS tire. Both pneumatic tires were very low compared to the non-pneumatic counterparts. While non-pneumatic tires are less susceptible to the setup factors, their baseline RR forces are commonly higher than pneumatic tires across most factors. Numerous other studies yielded the same conclusion that pneumatic tires had a lower RR [22, 24, 25, 28, 33, 34, 43, 45, 50].

HPS results were examined across the factors to compare the influence of each factor respectively. The load is a constant linear trend and each tire will behave linearly. It is not something comparable since it is the baseline. Toe was found to have the largest impact on RR at 222-566% for 1° and 2° respectively, compared to 0°. Surface had the second-largest impact on RR at 175% for carpet, compared to a solid drum. Tire type had the third-largest impact on RR, ranging from 146-606% compared to the HPS (our standard). Tire pressure is fourth with an 8-44% influence for HPS. Camber and speed are at the bottom of the list as not strong influencers. Knowing the relative impact of each factor helps clinicians, MWUs, and manufacturers make informed decisions on the set up of MWCs. With camber not being a big influence, MWUs can choose what degree suits them best and retain the benefits of increased access to the push-rim and increased stability.

Overall, the machine was able to detect changes in all of the factors which were defined in the design goals. Additionally, the results show high repeatability through a randomized testing order, in which the error bars are very small at one standard deviation. Further statistical analysis is needed to confirm this for all of the factors. With the additional exploration of the factors, clinical recommendations can be made to inform clinicians, MWUs, service providers, and manufacturers of the effects of RR. From there, clinical practices can be updated to mitigate RR through setup and device maintenance. Therefore, a MWU would be at a lower risk for UE RSI and improved long-term MWU use.

4.5 Limitations

Although we took a comprehensive and iterative approach to designing and fabricating the system, there are always trade-offs that result in limitations to the types and accuracy of the measurements. Most notably is that the system measures RR when tires are contacting a round surface (the drum) compared to flat ground, which introduces a bias in the results. We have largely addressed this by developing a calibration to convert to overground RR, but this calibration may not be accurate for all scenarios, especially when testing multiple factors simultaneously (low-pressure, on carpet, with toe). Fortunately, the calibration can be improved by repeating the approach we reported in this study, with the same setup factors on a treadmill. Operationally, the system requires a relatively small footprint (especially compared to coast-down test methods), but some of the setup procedures can be difficult and require two people-- for example, shifting from caster to rear-wheel testing. Although the design and manufacturing of the machine were very purposeful, there is always room for error. Tolerances in machining can add friction or misalignment to the system. A significant effort was made to mitigate any instances of this occurring. The load cell presents a source of error since the signal is amplified into the DAC; however, the load equation for the load cell was found with this in place and it is consistent for all measurements. Protocols have been established that the machine is adjusted and run in the same manner every time to limit any operational errors. There are limitations to the range within each factor than can be tested but the system was designed to replicate common instances in the community of average MWUs. The machine has some difficulties to adjust to different sized casters and wheels. The arm assembly is heavy and requires two people to adjust properly, but that has been mitigated with the use of a jack so one person can run the system independently. Lastly, drum-based testing is constrained in surface testing to only those that can be attached to a drum.

Irregular or soft surfaces are not easily placed on a drum; however, the impact of some indoor surfaces can be identified.

4.6 Future Work

The natural progression of this project leads to further testing. With every testable factor comes a list of possible studies to conduct. Initially, testing will be conducted on the strongest influencers. Furthermore, a comprehensive study is planned to explore all of the factors through 6 wheels and 6 casters and even the combinations of two factors. This is the information necessary to provide to the clinicians, manufacturers, and end-users about the impact of products and setup factors. One area for future study is the effects of temperature on RR. A pneumatic tire would increase inflation pressure as it warms up. It would be interesting to see the effect of temperature has on RR because tires would generate heat as they are used. Lastly, a series of studies will be done to assess the prevalence of factors found to be most influential. Influential factors need to be evaluated with interventions in the community and eventually standards to combat the issues. Toe and bearing and axle slop in users' devices may be substantial contributors to RR, but their prevalence has not been examined in the community.

A measurement system and protocol were developed to complete the study. Future tests will also include randomized testing order with an integrated standard trial mixed in. The standard trial is to be considered the baseline test with no factor adjustments.

The end goal is to be able to understand the effects of every factor at a component-level. If all of the factors are appropriately characterized, a model can be constructed which demonstrates how each factor will change the propulsion of the MWC at a system-level. After future testing, the results can be provided to clinicians, manufacturers, and end-users on how to mitigate RR and the best options for MWUs. An online tool could be created that shows the impact of RR as factors are changed. This would be useful for all stakeholders.

5.0 Evaluation of Rolling Resistance in Manual Wheelchair Wheels and Casters using Drum-based Testing

This chapter is in preparation to be submitted to the journal of Disability and Rehabilitation: Assistive Technology. The introduction to this chapter has been condensed to minimize the redundancy information already presented in the dissertation.

5.1 Introduction

To address the limitations identified by previous test methods, a new drum-based machine was developed through an iterative design process and employed to measure RR (Figure 18). Through pilot and sensitivity testing, it was determined that the equipment measured all factors with high repeatability (variance less than 5%) and was sensitive to 0.25 degrees of toe, 10 psi of tire pressure and 7 pounds load changes. The full capabilities of the machine can be seen in Table 26. Furthermore, a calibration was developed to relate drum-based results to simulated overground measurements.

Figure 18 Drum-based Testing Machine

The primary aim of this research was to determine the influence of factors on wheelchair wheel and caster RR. To accomplish this, testing of a clinically relevant range of wheelchair wheels and casters was conducted under a series of conditions independently and in combination. With the testing of combined factors and individuals factors separately, it is theorized that RR acts in a cumulative nature. The results from the combined data analysis can be compared to the addition of those two conditions individually. If they are in fact cumulative, the individual factors addition should be a decent representation of the result of the combined factors.

A secondary aim and design goal for the development of this machine was to have a repeatability under 10 percent after changes in testing conditions. Therefore, the reference trials can be averaged with a standard deviation. The percent of the standard deviation relative to the mean will determine the variance across a repeated test condition and must be under 10 percent to meet the design goal.

The first hypothesis is that there is an interaction effect between combined factors with the inclusion of tire/caster type that causes a statistically significant change in RR Force. The second hypothesis is that there is an interaction effect between combined factors without the inclusion of tire/caster type that causes a statistically significant change in RR Force. The third hypothesis is that there is an interaction effect between individual factors with the inclusion of tire/caster type that causes a statistically significant change RR Force. The fourth hypothesis is that there are significant differences in RR Force across the testing increments of individual levels of each factor. The fifth hypothesis is that RR acts in a cumulative manner when multiple factors are involved. The final goal of this research is to inform clinical decision making by providing clinical recommendations based on the results in an effort to preserve the UEs for MWUs.

Table 26 Rear-wheel and Caster Testing Capabilities

Rear-wheels				
Factor	**Range**	**Increment**	**Sensitivity**	**Justification**
Camber	0 to 5 degrees	1 degree	1 degree	User preference where most devices do not allow more than 5 degrees.
Load	Up to 150 lbs.	20 lbs.	7 lbs.	75 lbs. equal to the load on one wheel with a 60/40 distribution of 250 lbs.
Toe-in/Out	-2.5 to +2.5 degrees	0.5 degree	0.25 degree	Community data suggest that less than 2 degrees are commonly found.
Speed	Up to 1 m/s	0.5 m/s	0.25 m/s	Common propulsion speed is 1 m/s
Tire Pressure	Up to 100% of max	20% of max	10 psi	Smaller interval than previous tire pressure studies
Surfaces	Carpet to start	Level of pile	Per carpet level	Common heights of commercial-grade carpet.
Tire Type	24" rear-wheels varied by type	1 wheel	Per tire type	Recommended by industry experts
Casters				
Factor	**Range**	**Increment**	**Sensitivity**	**Justification**
Load	Up to 100 lbs.	10 lbs.	7 lbs.	50 lbs. equal to the load on one caster with a 60/40 distribution of 250 lbs.
Speed	Up to 1 m/s	0.5 m/s	0.25 m/s	Common propulsion speed is 1 m/s
Tire Pressure	Up to 100% of max	20% of max	10 psi	If applicable, some pneumatic casters on the market
Surfaces	Carpet to start	Level of pile	Per carpet level	Common heights of commercial-grade carpet.
Caster Type	Casters varied by type	1 caster	Per caster type	Recommended by industry experts

5.2 Methods

To ensure that clinically relevant products, as well as a variety of styles, were being tested, six colleagues working as clinical seating therapists or service providers were consulted at the Center of Assistive Technology, Pittsburgh, PA. Following guidance on the selection of products to be tested, the test factors were established based on the capabilities of the machine as well as what is clinically relevant. For rear-wheels and tires, it was determined that testing would include a range of camber, toe, tire pressure, load, speed, and multiple surfaces, with the details being outlined in Table 27. Casters were tested through a range of load, surfaces, and speed with the single pneumatic caster being tested for inflation pressures. The single-factor testing gives a comprehensive understanding of the influence of each factor on RR.

Table 27 Single-factor Testing Scope

Rear-wheels				
Factor	**Range**	**Increment**	**Trials**	**Justification**
Camber	0 to 5 degrees	1 degree	18	User preference where most devices do not allow more than 5 degrees.
Load	35 to 115 lbs.	20 lbs.	12	75 lbs. equal to the load on one wheel with a 60/40 distribution of 250 lbs.
Toe-in/Out	-2 to +2 degrees	0.5 degree	24	Community data suggest that less than 2 degrees are commonly found.
Speed	0.5 to 1 m/s	0.5 m/s	3	Common propulsion speed is 1 m/s
Tire Pressure	40 to 100% of max	20% of max	9	Smaller interval than previous tire pressure studies
Surfaces	Drum, low-pile, medium-pile, high-pile	N/A	9	Common heights of commercial-grade carpet.
Tire Type	6 rear-wheels	1 wheel	N/A	Recommended by industry experts
Total Trials per wheel= 75 for pneumatic, 66 nonpneumatic				
Casters				
Factor	**Range**	**Increment**	**Trials**	**Justification**
Load	30 to 70 lbs.	10 lbs.	15	50 lbs. equal to the load on one caster with a 60/40 distribution of 250 lbs.
Speed	0.5 to 1 m/s	0.5 m/s	3	Common propulsion speed is 1 m/s
Surfaces	Drum, low-pile, medium-pile, high-pile	1 type	9	Common heights of commercial-grade carpet.
Caster Type	6 casters	1 caster	N/A	Recommended by industry experts
Total Trials per caster = 27 for nonpneumatic, 36 pneumatic				

Rear-wheels can easily be changed out for testing and an additional bracket was made to mount casters. Adjustments for all factors are easily controlled to preset values or levels to ensure consistency. Tire pressure is the exception but is standardized by using the percent of max inflation. To ensure a comprehensive data set, each factor is tested with every possible permutation of the other factors, however, testing all possible combinations of factors was too large a study to complete. To accomplish this, a limited range of conditions were selected based on average community observations and previous research. For example, in a sample of 200 MWCs, the average amount of toe was 0.90 degrees, the average camber was 3 degrees, and the average tire pressure was 40% of max inflation. Therefore, these levels of factors were selected for the combined factors testing as shown in Table 28. Camber was tested with toe-out, tire pressure, load, surfaces, and each rear tire respectively. Between the individual factor and the combined factor testing, pneumatic rear-wheels went through 171 tests and the non-pneumatic tires went through 120 tests each not including the extra reference trials mixed into the testing order.

Table 28 Combined Factors Testing Scope

<table>
<tr><td colspan="5">Combined Factors Tests</td></tr>
<tr><td colspan="5">Rear-wheels</td></tr>
<tr><th>Factor 1</th><th>Factor 2</th><th>Increment (F1/F2)</th><th>Trials</th><th>Justification</th></tr>
<tr><td>Camber</td><td>Load</td><td>3/55, 3/95</td><td>6</td><td rowspan="4">Average value from community data</td></tr>
<tr><td>Camber</td><td>Toe</td><td>3/-1, 3/-0.5</td><td>6</td></tr>
<tr><td>Camber</td><td>Tire Pressure</td><td>3/40%, 3/60%</td><td>6</td></tr>
<tr><td>Camber</td><td>Surfaces</td><td>3/LP, 3/HP</td><td>6</td></tr>
<tr><td>Toe</td><td>Load</td><td>-1/55, -1/95, -0.5/55, -0.5/95</td><td>12</td><td rowspan="3">Average from community data of 0.9 degrees; Toe-out is more prevalent</td></tr>
<tr><td>Toe</td><td>Tire Pressure</td><td>-1/40%, -1/60%, -0.5/40% -0.5/60%</td><td>12</td></tr>
<tr><td>Toe</td><td>Surfaces</td><td>-1/LP, -1/HP, -0.5/LP, -0.5/HP</td><td>12</td></tr>
<tr><td>Load</td><td>Tire Pressure</td><td>55/40%, 55/60%, 95/40%, 95/60%</td><td>12</td><td rowspan="2">Understand the load relationship with other factors</td></tr>
<tr><td>Load</td><td>Surfaces</td><td>55/LP, 55/HP, 95/LP, 95/HP</td><td>12</td></tr>
<tr><td>Surfaces</td><td>Tire Pressure</td><td>LP/40%, HP/60%, LP/40%, HP/60%</td><td>12</td><td>Community data show an average of 40% of maximum pressure. Low-pile is common while high-pile is an extreme case</td></tr>
<tr><td colspan="5">Total Trials per wheel = 96 for pneumatic, 54 nonpneumatic</td></tr>
<tr><td colspan="5">Casters</td></tr>
<tr><th>Factor 1</th><th>Factor 2</th><th>Increment (F1/F2)</th><th>Trials</th><th>Justification</th></tr>
<tr><td>Load</td><td>Surfaces</td><td>40/LP, 40/HP, 60/LP, 60/HP</td><td>12</td><td>Understand the load relationship with other factors</td></tr>
<tr><td>Load</td><td>Tire Pressure</td><td>40/40%, 60/60%, 40/40%, 60/60%</td><td>12</td><td>Only one pneumatic caster but it was important to see the effects.</td></tr>
<tr><td>Surfaces</td><td>Tire Pressure</td><td>LP/40%, HP/60%, LP/40%, HP/60%</td><td>12</td><td>Low-pile is common while the high-pile is an extreme case</td></tr>
<tr><td colspan="5">Total Trials per caster = 12 for nonpneumatic, 24 pneumatic</td></tr>
</table>

To ensure a consistent approach to the testing, a set of reference conditions were established which include 0 degrees of camber and toe, 100% of max tire pressure, 1 m/s surface speed, the steel drum surfaces, 75 lbs. downward force for rear-wheels, and 50 lbs. downward force for casters. For this research, a ‘reference trial’ is defined as a test comprised of all the standard run conditions and was utilized throughout testing to verify the repeatability of test results. A computer-generated randomized testing order was used to ensure each setup was independent, which included each test condition appearing exactly three times to confirm within-conditions repeatability of the results. Randomization was used for all conditions except carpet surfaces and tire pressure because installing carpet on the drum is time-consuming and tire pressure was difficult to change quickly. With the randomized testing order, a ‘reference trial’ was run at the beginning of testing as well as approximately every ten conditions to confirm results were repeatable after conditions where changed on the system. With this being the first large scale study with a new machine, it was important to assess repeatability through its operation. The operating protocol was standardized, so the same steps occur in the same order for every test and all casters followed the same randomized testing order as the rear-wheels with the factors adjusted to caster testing increments.

First, the results of each individual factor is viewed graphically to look at the relationship to RR. Next, the evaluation of the combined factors is examined to see if the factors act in a cumulative manner. Then, reference trials are evaluated for repeatability. Finally, a statistical approach is implemented to determine the relationship between factors.

5.2.1 Data Analysis

The analysis had to be completed in a series of stages to perform a comprehensive analysis of all of the trials. All repeated trials of the same condition were included in the analysis in order to maintain more statistical power. Stages 1 is to determine if there is an interaction effect between combined factors with the inclusion of tire/caster type that causes a statistically significant change in RR Force. In stage 1, we performed ten three-way independent ANOVAs using the combined factors along with tire type as independent variables (IV) and RR Force as the dependent variable (DV) since every tire was tested for all of the combined factors. One three-way ANOVA was completed for casters across load and surfaces. Table 29 shows the conducted tests to determine if there are statistical differences in RR Force of combined factor levels with tire/caster type included in the model.

Table 29 Stage 1 Analysis Plan

<table>
<tr><td colspan="4">Stage 1 Combined Factors with Tire Type</td></tr>
<tr><td colspan="4">Rear-wheels</td></tr>
<tr><th>IV 1</th><th>IV 2</th><th>IV 3</th><th>DV</th></tr>
<tr><td rowspan="4">Camber (3 deg)</td><td>Load (55, 95 lbs.)</td><td rowspan="10">Tire Type
(6 rear-wheels)</td><td rowspan="10">RR Force</td></tr>
<tr><td>Toe (-1, -0.5 deg)</td></tr>
<tr><td>Tire Pressure (40, 60 %)</td></tr>
<tr><td>Surfaces (LP, HP)</td></tr>
<tr><td rowspan="3">Toe (-1, -0.5 deg)</td><td>Load (55, 95 lbs.)</td></tr>
<tr><td>Tire Pressure (40, 60 %)</td></tr>
<tr><td>Surfaces (LP, HP)</td></tr>
<tr><td rowspan="2">Load (55, 95 lbs.)</td><td>Tire Pressure (40, 60 %)</td></tr>
<tr><td>Surfaces (LP, HP)</td></tr>
<tr><td>Surfaces (LP, HP)</td><td>Tire Pressure (40, 60 %)</td></tr>
<tr><td colspan="4">Casters</td></tr>
<tr><th>IV 1</th><th>IV 2</th><th>IV 3</th><th>DV</th></tr>
<tr><td>Load (40, 60 lbs.)</td><td>Surfaces (LP, HP)</td><td>Caster Type
(6 casters)</td><td>RR Force</td></tr>
</table>

Stage 2 was to determine if there is an interaction effect between combined factors without the inclusion of tire/caster type that causes a statistically significant change in RR Force and if there is an interaction effect between individual factors with the inclusion of tire/caster type that causes a statistically significant change RR Force. This comprised of was ten two-way independent ANOVAs for combined factors of rear-wheels, three for caster combined factors, six for each factor across rear-wheels, and three for factors across the casters. Table 30 shows the combined factors independent ANOVAs to determine if there are statistical differences across RR Force of combined factor levels without the inclusion of tire/caster type. Table 31 displays the independent ANOVAs performed to see if there is a statistical difference between levels of individual factors when tire type is included.

Table 30 Stage 2 Analysis Plan of Combined Factors

Stage 2 Combined Factors without Tire Type		
Rear-wheels		
IV 1	**IV 2**	**DV**
Camber (3 deg)	Load (55, 95 lbs.)	RR Force
	Toe (-1, -0.5 deg)	
	Tire Pressure (40, 60 %)	
	Surfaces (LP, HP)	
Toe (-1, -0.5 deg)	Load (55, 95 lbs.)	
	Tire Pressure (40, 60 %)	
	Surfaces (LP, HP)	
Load (55, 95 lbs.)	Tire Pressure (40, 60 %)	
	Surfaces (LP, HP)	
Surfaces (LP, HP)	Tire Pressure (40, 60 %)	
Casters		
IV 1	**IV 2**	**DV**
Load (40, 60 lbs.)	Surfaces (LP, HP)	RR Force
	Tire Pressure (40, 60 %)	
Surfaces (LP, HP)	Tire Pressure (40, 60 %)	

Table 31 Stage 2 Analysis Plan of Single-factors

Stage 2 Single-factors with Tire Type		
Rear-wheels		
IV 1	**IV 2**	**DV**
Camber (0-5 deg)	Tire Type (6 rear-wheels)	RR Force
Load (35-115 lbs.)		
Toe-in/Out (-2-2 deg)		
Speed (0.5, 1 m/s)		
Tire Pressure (40-100%)		
Surfaces (D, LP, MP, HP)		
Casters		
IV 1	**IV 2**	**DV**
Load (30-70 lbs.)	Caster Type (6 casters)	RR Force
Speed (0.5, 1 m/s)		
Surfaces (D, LP, MP, HP)		

Stage 3 is to determine if there are significant differences across the testing increments of individual levels of each factor and it was comprised of seven one-way independent ANOVAs for rear-wheels by each factor and five for casters by each factor (Table 32). With multiple ANOVAs being compared, the p-value was set to 0.01 to address the risk of type I error in the results.

Table 32 Stage 3 Analysis Plan

Stage 3 Single-factors	
Rear-wheels	
Factor	**DV**
Camber (0-5 deg)	RR Force
Load (35-115 lbs.)	
Toe-in/Out (-2-2 deg)	
Speed (0.5, 1 m/s)	
Tire Pressure (40-100%)	
Surfaces (D, LP, MP, HP)	
Tire Type (6 rear-wheels)	
Casters	
Factor	**DV**
Load (30-70 lbs.)	RR Force
Speed (0.5, 1 m/s)	
Surfaces (D, LP, MP, HP)	
Tire Pressure (40-100%)	
Caster Type (6 casters)	

We converted RR forces to a perceived weight gain, by using the linear relationship to loading weight, to help convey the influence of changes in all of the independent factors or the effect of combined factors. This was determined by calculating the increased weight associated with an increase RR based on the relationship between weight and RR measured for each tire. The perceived weight calculation assumes a factor (such as tire pressure) affect both rear-wheels under steady-state propulsion conditions, rather than start-up and a fixed user and device weight of 250 pounds.

5.3 Results

Through discussions, a set of six rear-wheels (Table 33) and a set of six casters (Table 34) were identified by colleagues to be tested. Specific tire and caster makes, and models were blinded to not recommend the influence of a particular brand but rather identify general differences across styles of tires and casters. Two high-pressure pneumatic tires (100 or more max psi) were chosen with one on a performance wheel. A common low-pressure pneumatic tire (under 100 max psi) was evaluated on a lite-spoke rim without an airless insert and a second one with an airless insert. Lastly, a knobby tire for softer terrains was picked along with a low polyurethane tire that was mounted on a mag style wheel. All wheels tested were nominal 24" diameter. For casters, four and five-inch diameter polyurethane and soft roll casters were chosen. Additionally, three eight-inch casters were picked to include a solid, semi-pneumatic (a light foam with easy compression and air pockets in the material), and a pneumatic tire (similar to a pneumatic rear tire with an inner tube).

Table 33 Tires Tested

Tire Types	
HPP	High-pressure tire on Performance wheel Dimensions: 24” diameter and 1” width, low tread Maximum air pressure 100 psi
HPS	High-Pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1” width, low tread Maximum air pressure 145 psi
LPS	Low-Pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1.375” width, medium tread Maximum air pressure 75 psi
KLS	Knobby Low-Pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1.375” width, high tread, Maximum air pressure 65 psi
AIS	Airless Insert in a low-pressure tire on a Standard lite spoke Dimensions: 24” diameter and 1.375” width, medium tread
SPM	Solid Polyurethane tire on a Mag style wheel Dimensions: 24” diameter and 1” width, no tread

Table 34 Casters Tested

Caster Types	
4PO	Four by One Poly Dimensions: 4” diameter with 1” width, polyurethane on an aluminum hub, no tread
5PO	Five by One Poly Dimensions: 5” diameter with 1” width, polyurethane on an aluminum hub, no tread
5SR	Five by One and a half Softroll Dimensions: 5” diameter and 1.5” width, polyurethane on an aluminum hub, no tread
8PO	Eight by One Poly Dimensions: 8” diameter and 1” width, polyurethane, rounded profile, on a plastic hub
8SP	Eight by One and three quarters Semi-Pneumatic Dimensions: 8” diameter and 1.75” width, polyurethane, ribbed tread, on a plastic hub
8PN	Eight by One and a quarter Pneumatic Dimensions: 8” diameter and 1.25 “ width, pneumatic, ribbed tread, on a plastic hub Maximum air pressure 36 psi

The RR force as a function of force across tire type is shown in Figure 19. Our results indicate that pneumatic tires have a lower RR than airless insert (highest RR) solid polyurethane (second highest), and the knobby tire (third highest), and are linearly related to load. Camber was found to have little influence on RR and Figure 20 displays mostly horizontal lines.

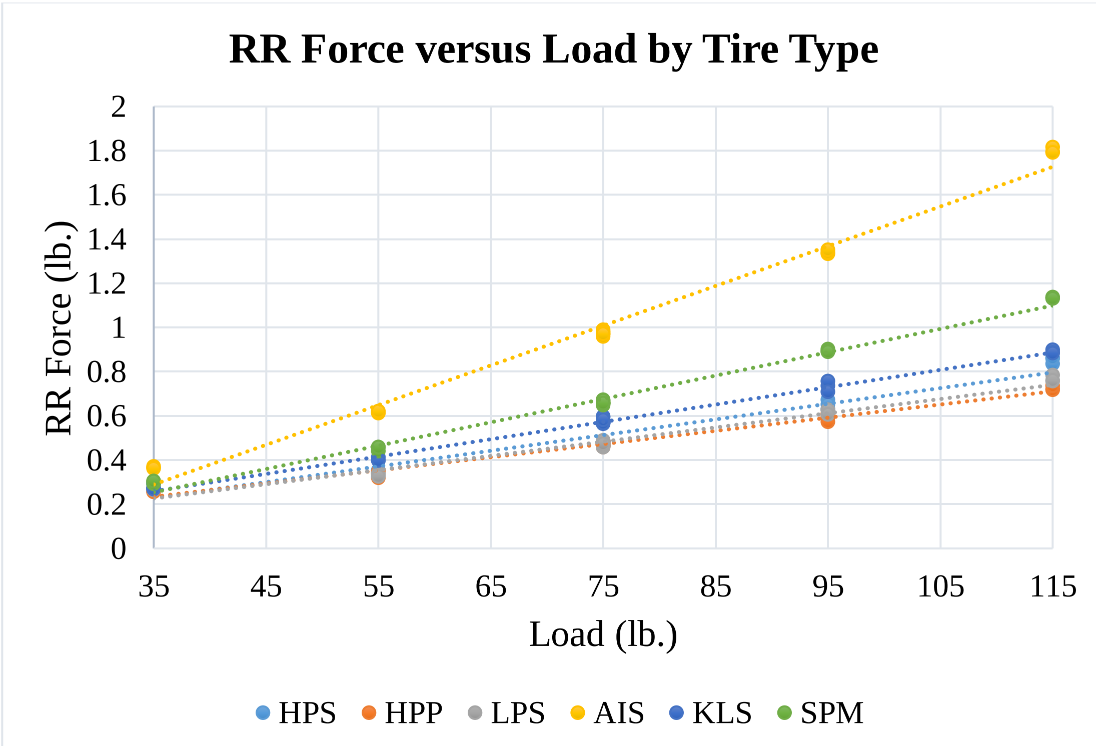


Figure 19 RR Force versus Load For Rear-wheels with Linear Lines

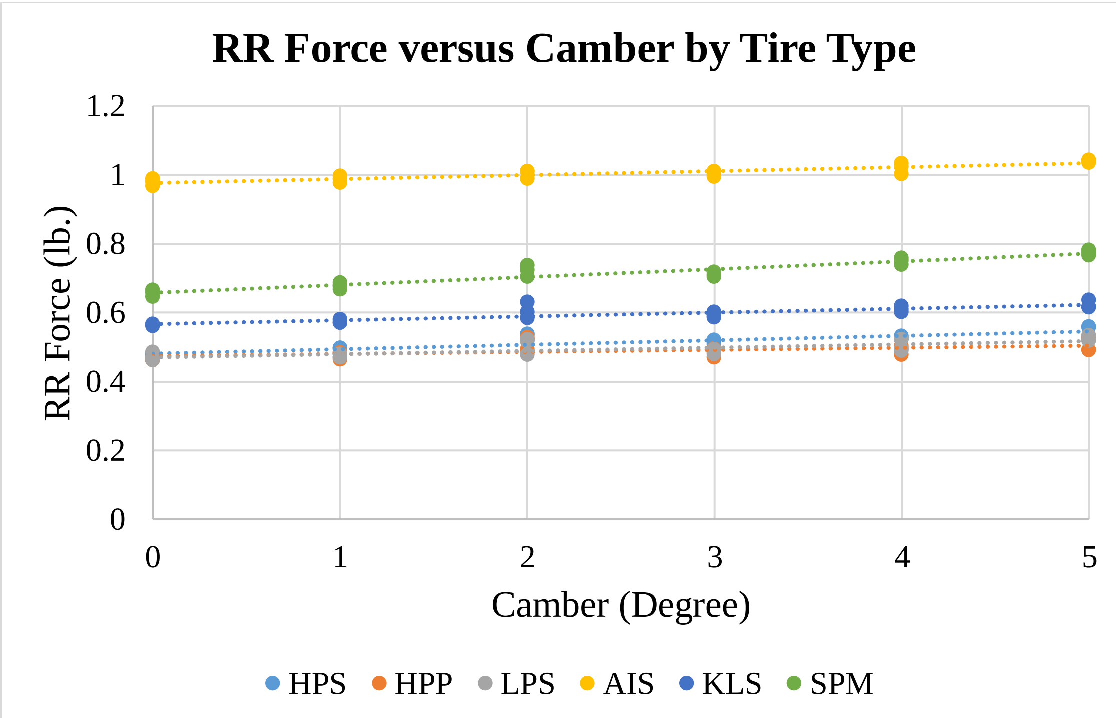


Figure 20 RR Force versus Camber for Rear-wheels with Linear Lines

The RR force as a function of toe angle has a non-linear relationship and RR increases in conditions of both positive and negative toe angle (Figure 21). The RR of the airless insert was least influenced by the toe angle (flatter curve) but has, on average, a higher RR across all angles tested.

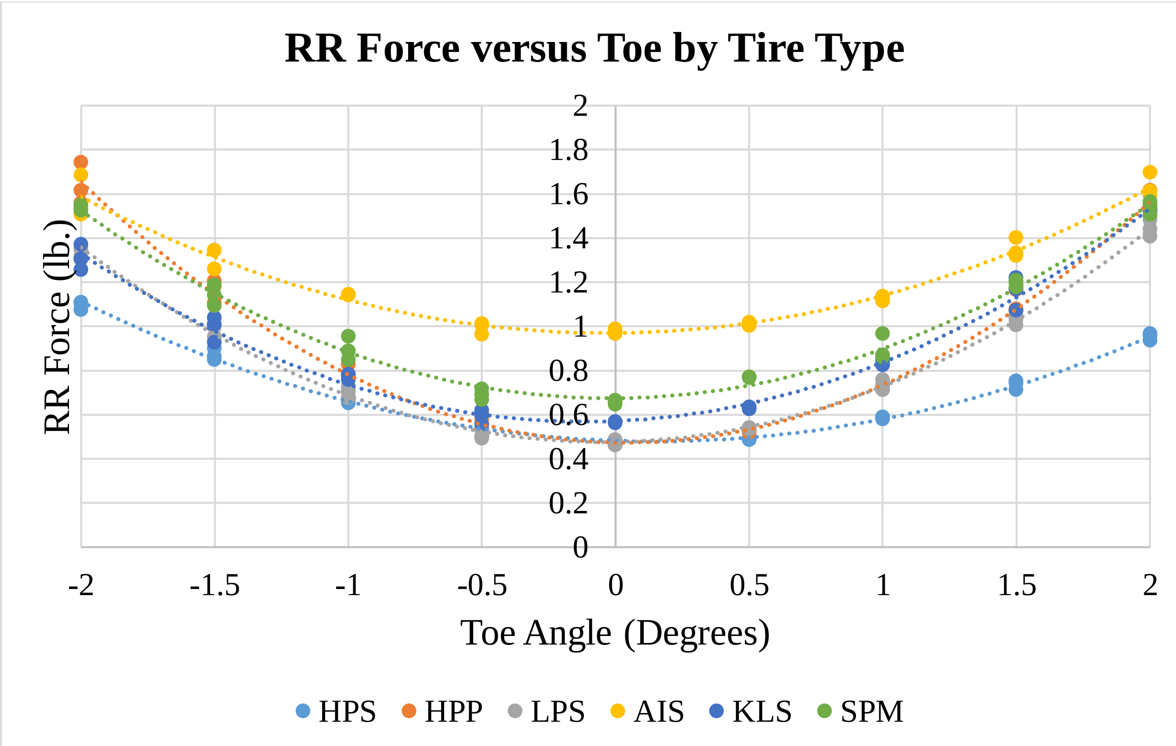


Figure 21 RR Force versus Toe for Rear-wheels with Polynomial Lines

Speeds were verified using a tachometer to ±0.05 meter per second (m/s). Speed was tested at two levels, 0.5 and 1m/s. Figure 22 shows little change in the two levels across all six wheels.

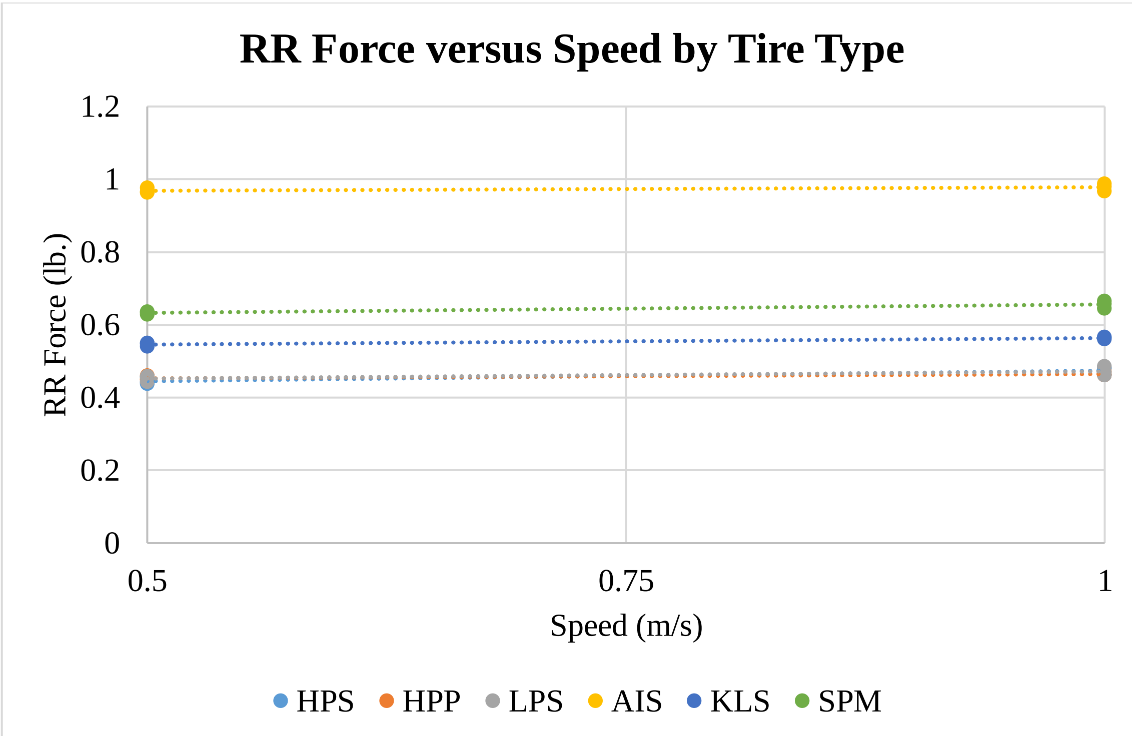


Figure 22 Force versus Speed for Rear-wheels with Linear Lines

Tire pressure has an inverse and non-linear relationship to RR, where a decrease in tire pressure increases RR. Figure 23 shows the relationship between RR for different tires and at different pressures as a percentage of max inflation. Only four pneumatic tires were included in this testing for tire pressure. Table 35 shows the values for the tire pressure test compared to the airless insert tire (AIS). All four pneumatic tires had a lower RR at 40% inflation than the airless insert at the reference trial.

Table 35 RR Force versus Tire Pressure

Tire Pressure*	HPS - 145 psi**	HPP - 100 psi**	LPS - 75 psi**	KLS - 60 psi**	AIS**
40%	0.561	0.652	0.673	0.800	N/A
60%	0.508	0.551	0.551	0.675	N/A
80%	0.486	0.500	0.497	0.615	N/A
100%	0.474	0.465	0.472	0.564	0.978
*percent of max inflation, **RR force in pounds					

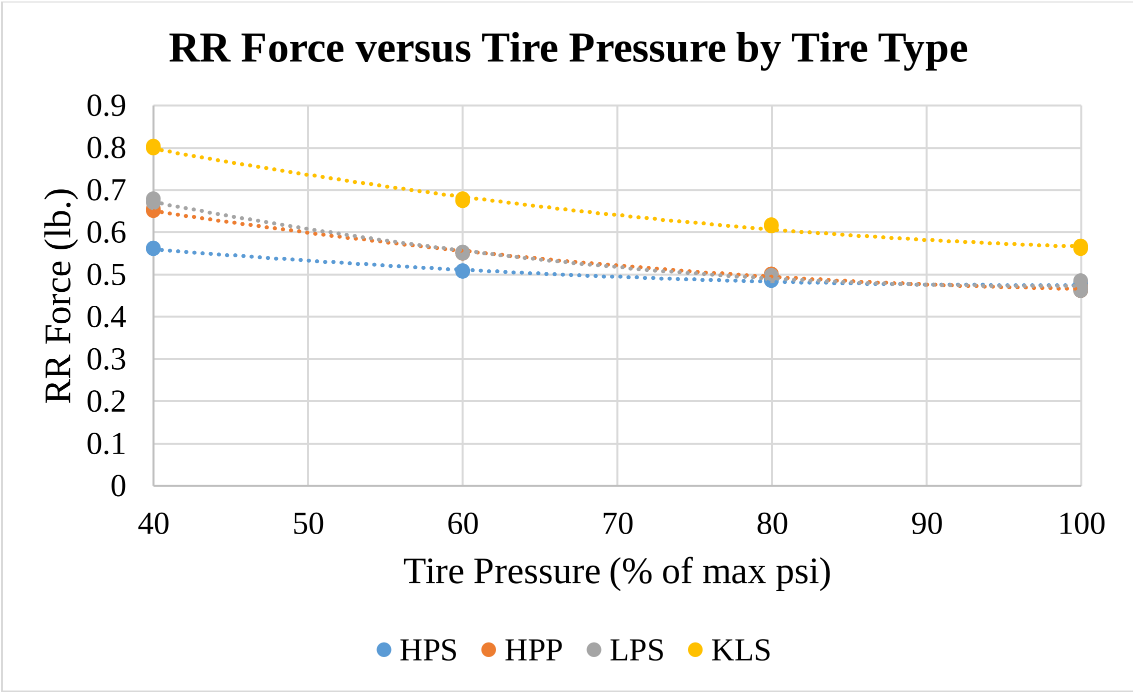


Figure 23 RR Force versus Tire Pressure for Rear-wheels with Polynomial Lines

RR force measurements on the steel drum were the lowest RR, and medium-pile carpet was the highest (Figure 24). Surface type showed variance based on the pile of carpet and tire type. For some tires, low-pile was the carpet with the least RR, while for other tires it was the high-pile.

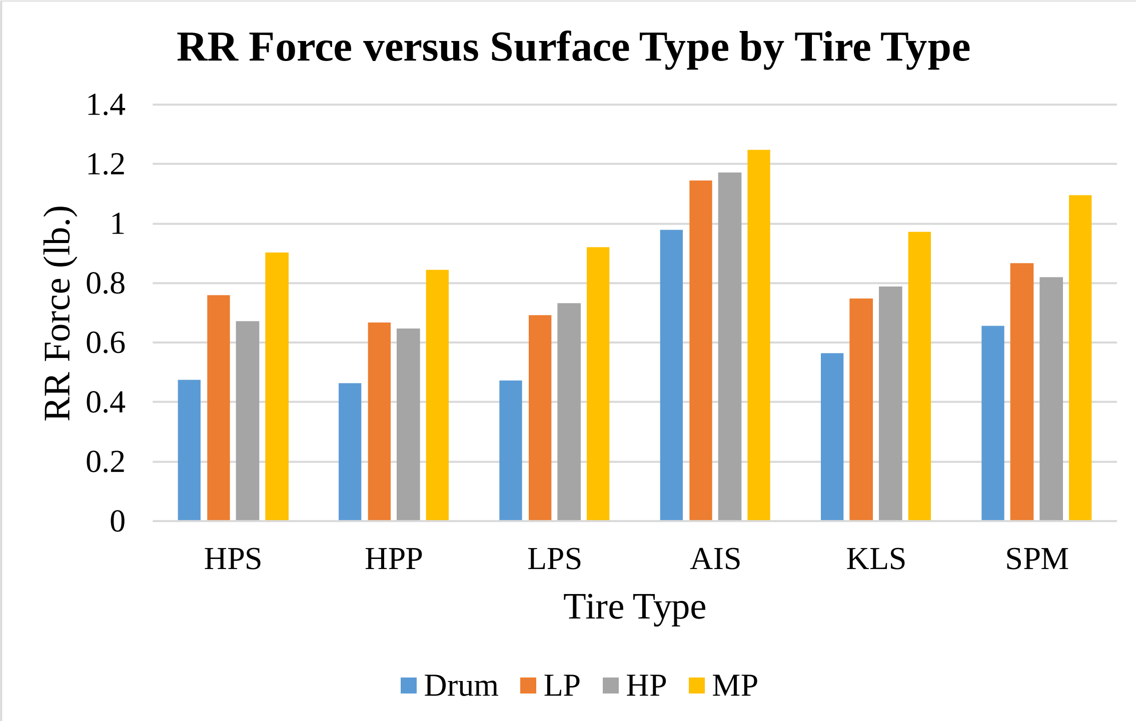


Figure 24 Force versus Surfaces for Rear-wheels

The influence of factors on the RR of casters and rear-wheels were similar. A positive linear relationship for load and RR was found for all casters tested. One interesting result is that all the eight-inch casters had higher RR than the four and five-inch casters. Overall, the four and five-inch casters are fairly similar through loading scenarios as seen in Figure 25.

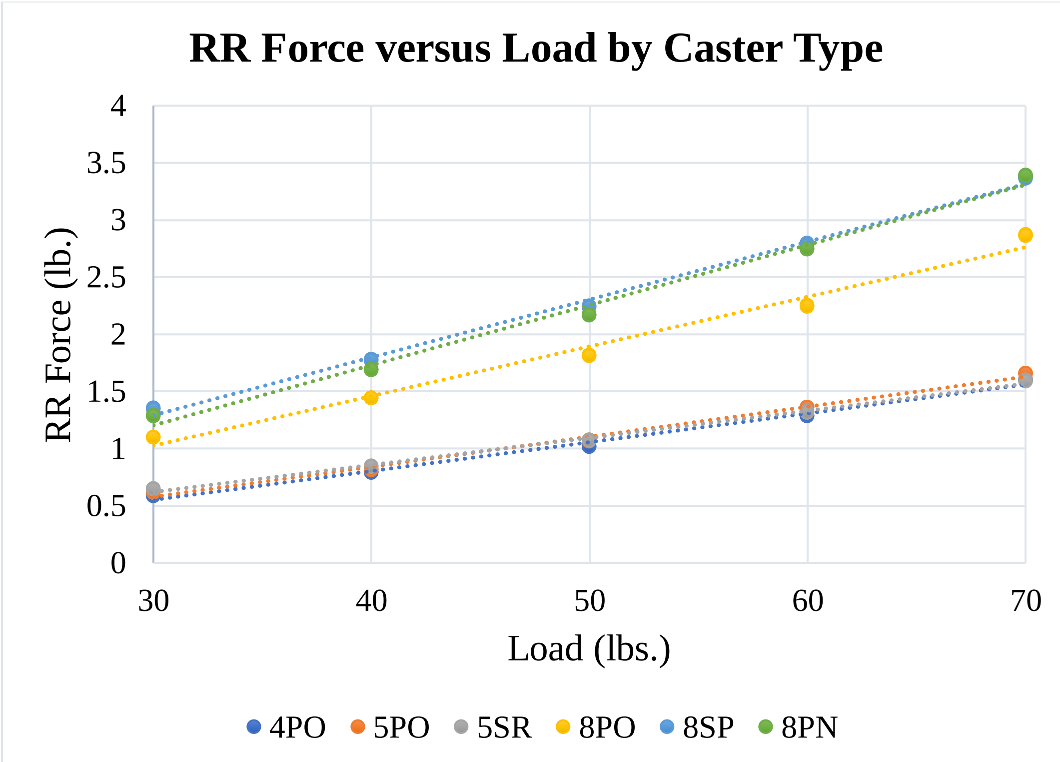


Figure 25 RR Force versus Load for Casters with Linear Lines

The influence of caster speed on RR was minimal, similar to the rear-wheels. Evaluating tire pressure, the single caster that was pneumatic also showed an inverse non-linear relationship similar to the rear-wheels. On the drum surface (D), it visually appears that smaller diameter casters have a lower RR than the eight-inch casters. With low and medium-pile carpet, these differences between casters were less pronounced. (Figure 26). Medium-pile carpet (MP) surface resulted in the highest RR for all casters, but low-pile carpet (LP) recorded higher RR than the high-pile carpet (HP).

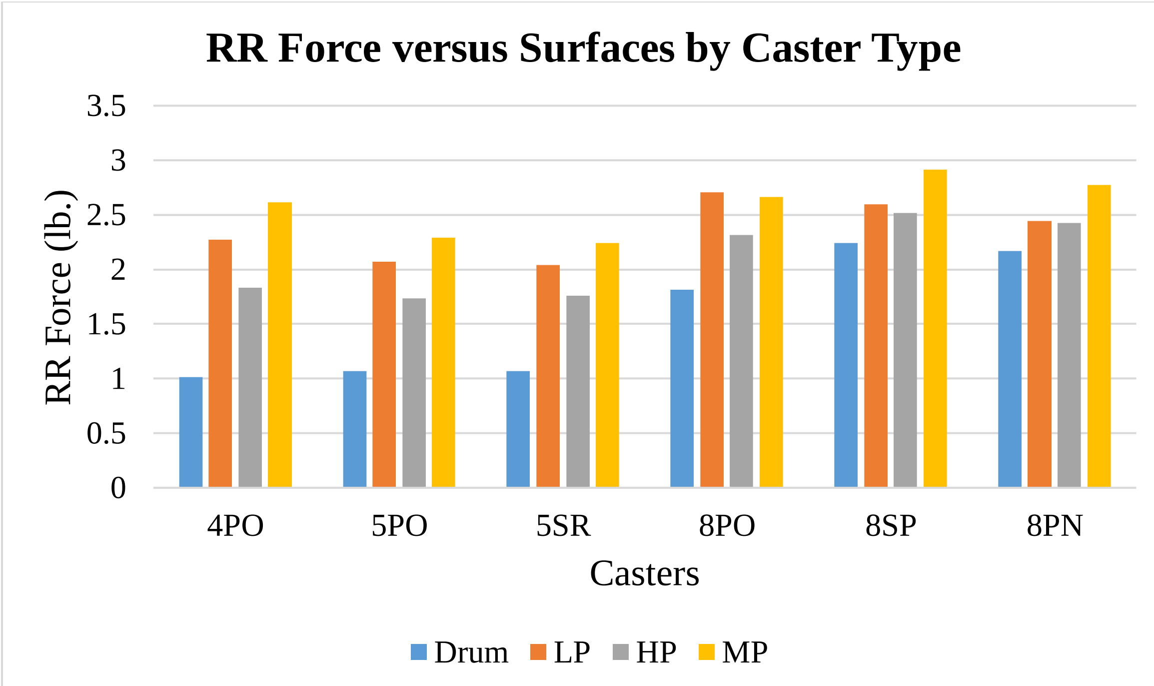


Figure 26 RR Force versus Surfaces for Casters

System-level understanding of the results is best to convey in Figure 27, which shows some possible tire and wheel combinations. It was made under the assumptions of a 250 pounds user with a device that had a 60/40 rear to front distribution. The first combination is a high-pressure tire (HPS) and a 4-inch caster (4PO), which represents an active user over a hard surface replicated by the drum. The second combination is an airless insert (AIS) with an 8-inch caster (8PO), representing a depot style device. The third combination is the first setup traversing medium-pile carpet.

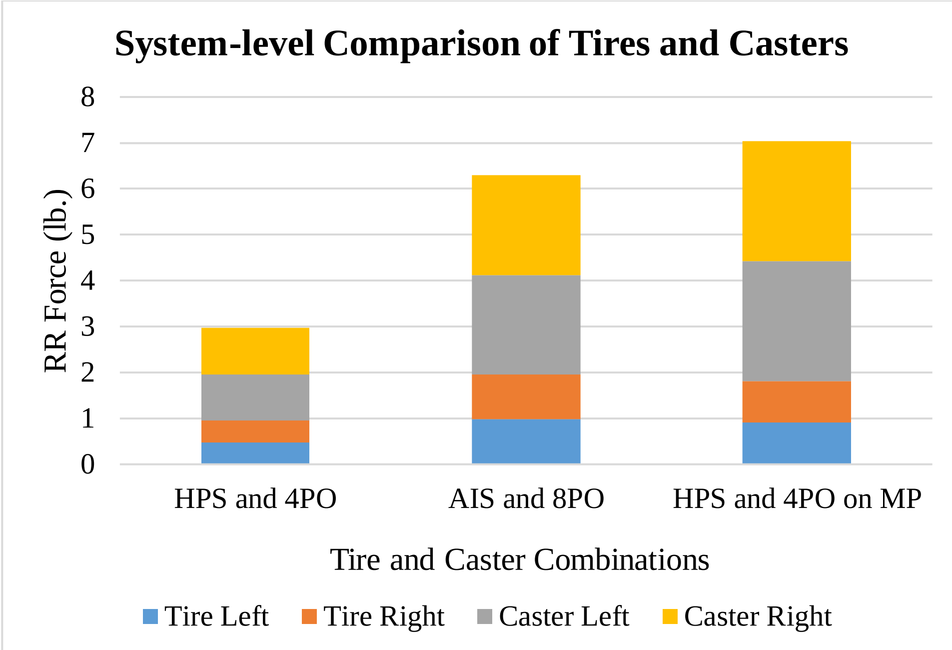


Figure 27 System-level Comparison of Tires and Casters

As noted in the methods, each individual factor was tested with every permutation of a secondary factor for all rear tires and casters. As a preliminary step, the testing results from single-factor testing were combined to determine if the linear addition of RR due to the individual factors would predict the combined factor RR testing results. This was evaluated for each testing permutation and these predictions varied less than ten percent from what the actual combined factors tests reported. The RR measured with combined factors where the conditions were most extreme compared to the reference setup (40% tire pressure at 55 lbs.) was 14% lower than would be predicted by summing the RR increases that occur due to the same conditions individually, suggesting a relatively small error (Table 36). Table 36 shows a slight overestimate from the addition of the factors compared to their measured value but overall, there was an equal variance of overestimation and underestimation. Therefore, we argue that RR from combined factors can be estimated accurately by adding the contributions of RR from individual factors.

Table 36 Comparison of Single-factor Addition versus Combined Factor Testing

	Load (lb.)	HPS @ 58 psi*	HPP @ 40 psi*	LPS @ 30 psi*	KLS @ 26 psi*	Average
Addition of Load and Tire Pressure 40 % Single-factor RR Results	55	0.434	0.521	0.531	0.637	N/A
	95	0.735	0.776	0.820	0.969	N/A
Combined Factors RR Results at 40% Tire Pressure	55	0.388	0.470	0.447	0.521	N/A
	95	0.686	0.816	0.871	0.999	N/A
Error between combined factors testing vs. summing effects of single-factors testing (% of Single-factor)	55	-11%	-10%	-16%	-18%	-14%
	95	-7%	5%	6%	3%	2%
*RR Force in pounds						

Reference trials were evaluated for repeatability with the calculation is based on 12 or more tests for each tire. Table 37 shows the mean, standard deviation and confidence levels and confirms that repeatability is very high during random repeated tests. The standard deviations observed are far less than ten percent of the mean as stated in the design goals. The repeatability was also evaluated for casters and the overground testing and results were similar in amount of variance as shown in Appendix C.3.

Table 37 Mean, Standard Deviation, and Confidence Interval for Rear-wheels on Drum

	HPS*	HPP*	LPS*	AIS*	KLS*	SPM*
Mean	0.477	0.473	0.466	0.959	0.566	0.654
Standard deviation	0.013	0.010	0.012	0.018	0.015	0.010
Confidence level	0.008	0.005	0.006	0.012	0.008	0.005
Conf. interval low	0.469	0.468	0.460	0.947	0.557	0.648
Conf. interval high	0.484	0.478	0.473	0.971	0.574	0.659
Variance (Std. Dev/Mean)	2.73%	2.11%	2.58%	1.88%	2.65%	1.53%
*RR Force in pounds						

5.3.1 Statistical Analysis

To determine if there are statistical interaction effects between combined factors with the inclusion of tire/caster type that causes a statistically significant change in RR Force (Stage 1), nine of the ten three-way independent ANOVAs had significant main effects ($p < 0.01$) as seen in Table 38. For simplicity, only the three-way interaction effect results has been reported. The camber*surface combination did not produce a significant result. The significant three-way independent ANOVAs indicate significant differences across the averages of the combined factors when accounting for tire type. For the caster three-way ANOVA of load*surface*caster, it also had a significant result indicating an interaction.

Table 38 Stage 1 ANOVA Results

Stage 1 ANOVA Combined Factors by Tire Type			
Rear-wheels			
Factor 1	**Factor 2**	***p-value***	**Interpretation**
Camber	Load	0.003	Significant interaction
	Toe	0.004	Significant interaction
	Tire Pressure	0.007	Significant interaction
	Surfaces	0.354	No Significant interaction
Toe	Load	< 0.001	Significant interaction
	Tire Pressure	< 0.001	Significant interaction
	Surfaces	< 0.001	Significant interaction
Load	Tire Pressure	< 0.001	Significant interaction
	Surfaces	< 0.001	Significant interaction
Surfaces	Tire Pressure	< 0.001	Significant interaction
Casters			
Factor 1	**Factor 2**	***p-value***	**Interpretation**
Load	Surfaces	< 0.001	Significant interaction
	Tire Pressure	N/A	Not possible with only one caster
Surfaces	Tire Pressure	N/A	Not possible with only one caster
Significance when $p < 0.01$			

To test whether interaction effect between combined factors without the inclusion of tire/caster type that causes a statistically significant change in RR Force, Stage 2 testing of combined factors (Table 39) removed the tire type variable from the Stage 1 model and reran the independent ANOVAs. For simplicity, only the two-way interaction effect results has been reported. No collapsing or averaging was done, but the tire type variable was no longer included in the model. It did not yield any significant results for rear-wheels. Thus, tire type is a dominating factor across combined factor testing. For casters, the load*surface main effect was not significant, but surface*tire pressure and load*tire pressure were significant. The caster results for pressure should be interpreted with caution since only one caster was pneumatic.

Table 39 Stage 2 ANOVA Combined Factors Results

Stage 2 ANOVA Combined Factors			
Rear-wheels			
Factor 1	**Factor 2**	***p-value***	**Interpretation**
Camber	Load	0.981	No Significant interaction
	Toe	0.727	No Significant interaction
	Tire Pressure	0.917	No Significant interaction
	Surfaces	0.562	No Significant interaction
Toe	Load	0.856	No Significant interaction
	Tire Pressure	0.745	No Significant interaction
	Surfaces	0.972	No Significant interaction
Load	Tire Pressure	0.174	No Significant interaction
	Surfaces	0.893	No Significant interaction
Surfaces	Tire Pressure	0.369	No Significant interaction
Casters			
Factor 1	**Factor 2**	***p-value***	**Interpretation**
Load	Surfaces	0.835	No Significant interaction
	Tire Pressure	< 0.001	Significant interaction
Surfaces	Tire Pressure	< 0.001	Significant interaction
Significance when $p < 0.01$			

The Stage 2 analysis, to determine if there is an interaction effect between individual factors with the inclusion of tire/caster type that causes a statistically significant change RR Force, found that five of the six factors result in significant two-way independent ANOVAs (Table 40). For simplicity, only the two-way interaction effect results has been reported. Two-way independent ANOVAs for casters revealed a significant relationship between RR and all three of the factors when evaluated by caster type. Consequently, the tire and caster type have a significant main effect on single-factors as well as combined factors with one exception being the speed of rear-wheels. An interesting post-hoc result from Stage 2 is that the LPS and HPP tires are not statistically significantly different in camber results, as well as two and four degrees of camber, respectfully. Additionally, HPP and LPS were not significantly different in tire pressures when the model is controlled for by tire type. Lastly, 5SR and 5PO are not significantly different when analyzing speed or surfaces and controlling for caster type.

Table 40 Stage 2 Single-factors ANOVA Results

Stage 2 ANOVA Single-factors by Tire		
Rear-wheels		
Factor	***p-value***	**Interpretation**
Camber	0.001	Significant interaction
Load	< 0.001	Significant interaction
Toe-in/Out	< 0.001	Significant interaction
Speed	0.351	No Significant interaction
Tire Pressure	< 0.001	Significant interaction
Surfaces	< 0.001	Significant interaction
Casters		
Factor	***p-value***	**Interpretation**
Load	< 0.001	Significant interaction
Speed	< 0.001	Significant interaction
Tire Pressure	N/A	Not possible with only one caster
Surfaces	< 0.001	Significant interaction
Significance when $p < 0.01$		

Stage 3 is the single-factor analysis of rear-wheels (Table 41) to determine if there are significant differences in RR Force across the testing increments of individual levels of each factor, which is the most critical point to this analysis. Camber angle was not significant across all levels when evaluated individually. Toe was more complex to analyze with an overall significant main effect, but post-hoc testing revealed there was no statistical difference from 0 to ± 1-degree. When examining percent tire pressure levels, one hundred percent was statistically significant from eighty and sixty percent inflation as well as eighty from sixty percent independently. This contrasts the Stage 2 results of significant differences at all levels when controlled for by tire type. The analysis of load determined that the increments are not significantly different in a range of ± 20 lbs. when not controlling for tire type. While using the load data, tire type was also analyzed and determined that every tire except SPM is significantly different from AIS, the airless insert. Similar to Stage 2, speed had no significant difference in results between the two levels. Conversely, surfaces exhibited significant differences in RR except for HP and LP when not controlling for tire type, but all carpet was significantly different from the drum.

Table 41 Stage 3 ANOVA Results

Stage 3 ANOVA Single-factor		
Rear-wheels		
Factor	***p-value***	**Interpretation**
Camber	0.903	No Significant interaction
Load	< 0.001	Significant interaction
Toe-in/Out	< 0.001	Significant interaction
Speed	0.971	No Significant interaction
Tire Pressure	< 0.001	Significant interaction
Surfaces	< 0.001	Significant interaction
Tire Type	< 0.001	Significant interaction
Casters		
Factor	***p-value***	**Interpretation**
Load	< 0.001	Significant interaction
Speed	0.915	No Significant interaction
Tire Pressure	< 0.001	Significant interaction
Surfaces	< 0.001	Significant interaction
Caster Type	< 0.001	Significant interaction
Significance when $p < 0.01$		

The Stage 3 analysis for casters determined that there are significant differences in RR across levels of tire pressure but only one caster was pneumatic. Analysis of the impact of load on the casters revealed similar results to the rear-wheels where ± 10 lbs. was not significantly different when not controlling for caster type. For rear-wheels and casters, this contrasts Stage 2 results where load was significant across all levels when controlled by tire or caster respectively. Casters were found to be significantly different based on diameter. All eight-inch casters were significantly higher in RR than the four and five-inch casters. Speed had no significant difference between the two levels tested for casters. When surfaces were compared for wheels, LP was found to not be significantly different from MP and HP, but all carpet was significantly different from the drum.

The perceived weight equivalent was calculated to convey the relative impact of each factor by viewing a change in load back calculated off of the relationship between load and RR for every caster or tire. For example, HPS' RR measurements from drum testing can be used to compare the standard trial conditions of each factor as perceived weight increases as seen in Table 42. Simply switching from a high-pressure tire to an airless insert has a detrimental effect and can add the equivalent of ninety-six pounds to a user and their device based on the assumption of a 250 pound user and device. That is a large portion of the MWU's weight being added in addition to their own weight plus the device weight. Furthermore, if the MWU propels over carpet with low tire pressure, they are approximately doubling the resistance felt during propulsion on a hard surface, such as smooth concrete, with a fully inflated tire.

Table 42 Perceived Weight Equivalents for Rear-wheel Factors

Factor	Level	Perceived Weight Equivalent (lbs.)
Speed	0.5	-5.6
Camber	3	6.3
	5	13.9
Tire Pressure	40%	16.5
	80%	2.3
Toe	-1.0	19.6
	-2.0	59.6
Surface	LP	62.3
	MP	81.7
Tire Type	SPM	34.6
	AIS	96.0

Additional information about the testing on the drum-based machine can be found in Appendix A.4. Additional information about the results from the drum-based machine can be found in Appendix B for rear-wheels and Appendix C for Casters. Additional information on the perceived weight converter can be found in Appendix F.

5.4 Discussion

The major takeaway from the statistical analysis is that RR is significantly related to the majority of the individual and combined factors. Not only does this demonstrate the importance of component-level testing, but it also indicates that more research needs to be done to measure and report the RR of additional tires and casters on the market. With combined factors not statistically interacting without tire or caster type, it indicates that single-factor testing is sufficient, and it validates the previous approach of adding the two or more single-factors together to estimate the combined effect. While the approach of cumulative estimation is not exact, it provides a reference for understanding the relationship between the factors. It is possible, due to error, to over or underestimate the effect, but that would be a relatively low amount of false approximation with most calculated differences being less than 10 percent.

Related to load on the wheel, it is important to note that the relationship with RR for all the pneumatic tires had loading equations whose slope was less steep and that the airless insert and mag higher RR overall. Casters also displayed a linear relationship similar to the rear-wheels for load tests. A previous study stated that RR is inversely proportional to wheel diameter [26] and another study states that caster diameter is inversely proportional to RR [27]. With smaller diameter casters, we found contradictory results indicating eight-inch casters had a higher RR than four and five-inch casters. This suggests that other factors, such as tire material, may be the dominant factor influencing RR of casters. With casters having a higher RR overall, it is best practice to have a forward axle position to have more of the MWC and MWU's weight loading in the rear. The rear axles should be as forward as possible without compromising the safety of the user, which is consistent with Clinical Practice Guidelines [14].

The statistical analysis revealed that load was significant regardless of the caster or rear-wheel type. However, one increment up or down (± 20 lbs., ± 10 lbs.) was not significant without tire or casters type included in the analysis. That can be interpreted as small changes are not influential across all tires and casters but are significant when tire/caster type is included in the model. These recommendations for a forward axle position has been verified but it increases the understanding of what a significant weight change is. From a RR perspective, device weight should not be a heavily considered factor when choosing a MWC, since the weight difference is not enough to significantly impact RR. Accessories should be kept to a minimum as well since overall weight can add up easily. A clinician could prescribe an ultralight or lightweight device without being concerned about the weight difference in terms of RR, but the adjustability of the ultralight may be favorable for rear axle potion and higher quality components. Conversely, if a MWU has a substantial change in weight, it will affect RR and therefore, their long-term health in multiple aspects.

While we found a trend that camber slightly increases RR, it may not be enough to make a long-term difference in the health of the MWU. Statistically, camber showed no difference across the levels without tire type, therefore camber is not a significant influencer of RR. Camber is also largely a user preference while providing increased stability, greater access to the push-rim, and easier passage through doorways.

Toe angle has a significant impact on RR which has not been heavily researched in previous literature. Toe could occur due to tolerances in the axles or wear in the bearings over time, factory misalignment of the frame, or poor set up of the MWC, but its prevalence has not yet been explored. Toe could occur if a MWC setup includes camber and /or the axle tube is rotated out of alignment, caster size or height is changed, or seat dump (seat angle) is changed. From the statistical analyses, toe was found to be significantly different after one-degree in either direction from zero. To properly define this, toe should be tested across tires at 0.25-degree increments to find the exact threshold, but across all tires, toe should be less than one-degree.

With only two levels tested for speed, the exact relationship between RR and speed was not explored, but the slope of the line is very low. Casters showed the same trend as the rear-wheels with very minor influence due to speed changes. Speed was only significant with casters with them involved in the model, which means that deceleration testing of casters may be prone to error. Therefore, caster selection is impacting the MWU when propelling at different speeds, when included in the model but not when considering the data from all casters. The variance between casters is great enough to be detected but may be normalizing when the caster type is removed from the model, and therefore, speed is not a significant influencer of RR. Additionally, speed is selected by the MWU and would be very difficult to control in a real-world setting.

The relationship for tire pressure and RR means that tires should always be properly inflated, which is especially important if they fall below 80% of max pressure. A maintenance program developed specifically for MWCs states that tire pressure should be checked weekly [36]. In addition, tire pressure should be checked when travel includes a substantial change in elevation or air travel. Severely underinflated tires could have significant long-term ramifications to the UE of the MWU and their wheels locks would not be effective. The pneumatic caster also followed a similar curve as the rear-wheels with an inverse non-linear relationship to RR.

Carpet increased RR and should be a consideration, especially for MWU's choices for their home environment and accessibility considerations for commercial buildings. Once again, the pneumatic tires performed had a lower than the airless insert, which the highest RR across all surfaces. It is impossible to control what surfaces a MWU will encounter in the community, but our results confirmed that harder surfaces are more accessible. Casters showed large variance over surfaces with the 8-inch casters still having a higher RR on carpeted surfaces. Compared to the rear-wheels, some casters performed better on high-pile carpet versus low-pile carpet. The high-pile quickly matted down, which most likely reduced its effect. It would be unrealistic to have a new piece of carpet for every tire to be able to prevent this issue. With casters having an overall higher RR across the loading ranges, their selection is critical as well. However, the weight on the casters should be kept as low as possible. Additionally, the larger diameter caster saw less of an increase on the carpet relative to the drum meaning larger diameter casters are better suited for softer surfaces. Weight should be distributed with the majority to the rear-wheels where tires are less likely to sink into softer surfaces. With statistically significant differences across surfaces for both tires and caster when not included in the model, surfaces are an important point to discuss with MWUs, so they are aware of the impact.

Repeatability of test results was verified for all operating conditions with a variance of less than 5%. Therefore, the machine was designed and built effectively to measure RR through a variety of factors. It was further demonstrated with the arm and air bearing mechanism having performing well on the drum for extended periods of time collecting large amounts of data.

The influence of tire or caster type on RR is demonstrated graphically and statistically, with that the airless insert (AIS) having the highest RR compared to all other tires. This system-level chart (Figure 27 above) demonstrates the cumulative nature of component-level testing, as well as the relative influence of casters being higher than rear-wheels. This study can also confirm that even a significantly underinflated pneumatic tires have less RR than an airless insert, which may negate the benefits of the reduced maintenance when using an airless insert [33]. Therefore, airless inserts should be used on a very limited basis such as MWU's who are propelled by a caregiver, when a wheelchair is used only temporarily or part-time. AIS was followed by the low polyurethane (SPM) for the highest RR, but that was still a statistically significant difference. The knobby tire (KLS) comes in as the third-highest but was not far behind the performance of the three pneumatic tires. These results confirm previous studies that reported that pneumatic tires have lower RR [24, 25, 45]. Therefore, if a MWU prefers a slightly wider tire with lower inflation pressures, it does not come with a significant increase in RR and thus, energy expenditure. Ultimately, the best tire choice should meet the needs and wants of the MWU to include contextual factors such as personal, health, or environmental requirements.

The perceived weight equivalent conversions are helpful to identify the most impactful factors that can affect wheels and the same calculations can be done for casters. It is important to remember that the factors that influence RR can be estimated to act in a cumulative manner, and thus, a device can feel significantly heavier than it is due to RR during steady-state propulsion. This tool can be expanded and published to help the understanding of the impact of factors.

The biomechanical consequences of increased push-rim forces that are related to increases in RR have been reported previously in the literature; the results we present here can further inform that work by describing the relative impact of different factors on RR. For instance, the published guidelines state MWC's should use high-quality bearings, low chair weight, larger diameter wheels, optimized seating position (farther back), and a forward axle position. [14]. High-quality bearings are critical because low-quality bearings likely lead to slop and misalignment of the rear-wheels causing toe. A low chair weight is not harmful but small changes in device weight will be less impactful than a large change in the MWU's weight. Larger diameter wheels as a recommendation are slightly misleading since most of the industry used standard rear-wheel sizes for research and device prescription for most cases. An optimal seating position and forward axle position are good recommendations that are confirmed to place more of the weight over the rear-wheels which have lower RR than casters. In addition to the current guidelines, our results suggest that both camber and speed do not significantly impact RR. While surfaces are non-controllable, MWUs should be educated on their long-term health impact. Tire pressure should be monitored closely and maintained at over eighty percent of the max inflation pressure. Toe is a significant influencer and clinical tools need to be developed to measure toe-in MWCs and maintenance options need to be developed to reduce toe to an acceptable level (under one-degree). Additionally, the impact of tire type needs to be communicated so clinicians can make more informed decisions. If it is clinically acceptable to give a MWU an airless insert tire with a perceived weight gain of almost one hundred pounds on the rear axles alone, then implementing standards related to other factors, such as toe should be acceptable. While this information provides insight, it does not outweigh clinical judgment and all MWC issuances should meet the wants and needs of the client but also not put them at unnecessary risk for injury.

5.5 Limitations

A limitation of this study is that this is a newly developed machine with no similar test equipment for comparison and validation, however, it was shown to have highly repeatable results. A downside of this study is the small number of wheels and casters included. Due to the amount of data collected, the number of tire and caster samples tested had to be kept small but can always be expanded on in the future. This also applies to the overground and combined factors testing since not every level of every factor was included. Lastly, this steady-state testing did not address any issues that may develop over time such as wear between components leading to toe.

5.6 Future Work

The future for this work has many possibilities including continued testing to define a precise threshold for toe, conduct a larger overground comparison, exploring the relationship between speed and casters, exploring the impact of more surfaces, and expand testing of combined factors. A primary goal would be to test more wheels and casters in order to develop an expansive data set that could inform product selection. Studies to investigate whether RR is impacted by wheelchair use, temperature, and the prevalence of influential conditions (e.g. toe, low tire pressure) in the community would inform and guide this work.

Additionally, dissemination of this information is imperative, and a reference tool could be built to showcase a model calculated by the sum of the factors. The goal would be to model a MWC as a system and be able to adjust factors to see the effect on RR. This would be a valuable training and clinical tool if developed with enough rigor, requiring more drum and overground testing to have enough data to build such a tool. The alternative is to follow a mathematical model previously developed [57]. The main take away would be for stakeholders to understand the impact of setup choices for MWCs.

6.0 A High Prevalence of Manual Wheelchair Rear-wheel Misalignment Could Be Leading to Increased Risk of Repetitive Strain Injuries

This chapter is in preparation to be submitted to the journal of Archives of Physical Medicine and Rehabilitation. The introduction to this chapter has been condensed to minimize the redundancy information already presented in the dissertation.

6.1 Introduction

The MWU is at increased risk for UE RSIs when RR is increased, and toe was found to be a significant influencer of RR in Chapter 5. Only one published paper from the literature search identified the misalignment of MWC propulsion wheels with a small community study of 50 wheelchairs in an African country, which resulted in an average of 0.2 degrees. Furthermore, over half (53%) of the devices were greater than 0.5 degrees and 24% were greater than 1 degree of misalignment [4]. Other published studies utilized equipment for studying and measuring RR forces resulting from misalignment, or toe angle. To evaluate RR force versus toe angle, Silva et al developed a bench test using three load cells showing displacement forces from toe, VanderWiel et al. utilized a dragged cart to demonstrate increase RR due to toe and McLaurin & Brubaker utilized a test cart on a powered treadmill [4, 22, 40]. All three papers identified the tire as a very important part of transferring forces related to RR, but the cart testing was not conducted at a component-level and the bench test utilized static wheel tests. These studies demonstrated increased force but only in specific scenarios that need to be verified as prevalent in the community.

The lack of standardization and a lack of highly accurate measuring equipment of toe for MWCs are potential reasons for the absence of community-based studies on this topic. Through benchmarking, an alignment jig developed for wheelchair racing was discovered, but equipment capable of accurately measuring toe angle on MWCs did not exist [79]. In order to proceed with this study, the development of a portable system capable of precision measurement of the distance across the front and rear of rear-wheels was required. In addition to a lack of measurement equipment, currently, there is not a common adjustment mechanism for toe angle or slop on MWCs. Potential mitigation of slop and toe issues could be explored using maintenance, product design and product setup, and is an area for potential future work. This research study determines the prevalence and severity of toe-in/out misalignment and slop of rear-wheelchair wheels in the community. In order to accomplish this, the aims are to develop a portable measurement device and to collect data from 200 community-based MWUs.

6.2 Methods

The research study was completed in two stages which include design and fabrication of a testing system (Stage 1) and collecting data on the rear-wheel misalignment of community-dwelling MWUs (Stage 2).

6.2.1 Stage 1 Device Development

We were unaware of a device available to measure misalignment of the rear-wheels of MWC so proceeded with an iterative design and fabrication process. The conceptual design was developed through team discussions, the specifications outlined in Table 43 were developed. Specifications were determined in order to accommodate as many MWUs as possible as well as to minimize unnecessary risk during testing.

Table 43 Design Specifications

Need	Specification	Rationale
Portability	Overall size not bigger than 40" wide and 26" deep	It will be easily transported in most vehicles.
Toe Measurement	Reach the front and rear of a 24" wheel	24" wheel is a very common size.
Slop Measurement	Apply pressure with the rear-wheels unloaded	Force needs to be applied to take up tolerances in order to measure the amount of tolerance, which cannot be performed with the rear-wheels under load.
Accuracy	1.5 mm or less	Equals less than a 0.25 degree of toe on a 24-inch wheel.
Adjustability	Height of measurement from 10 to 14 inches	Will be able to adjust to axle height of 20 to 28" wheels.
Device Accommodation	Fit devices from 14 to 32 inches in width	Very few MWUs would have a device under 14 inches and 32 inches is the width of a standard doorway.
User Accommodation	Lifting capacity of 300 pounds	Most standard MWC can accommodate 250 lbs. with a 20% factor of safety.
Rigidity	Flex less than 0.25 inch across the system	Rigidity is important to mitigate flex which ensures accurate measurements.
Speed of Collection	Less than 10 minutes per person	Voluntary study where we did not want to detract from the events going on.

6.2.2 Stage 2 Community Data Collection

6.2.2.1 Recruitment

The study was submitted for institutional review board (IRB) approval (Pitt IRB #PRO12080311) and deemed exempt since no personally identifiable information was being collected. Participants were recruited via flyers and web-based postings and approached at events such as wheelchair basketball practice, wheelchair games, fundraising events, and wheelchair washes. The targeted participants for this research are MWU's who are active, self-propellers and utilize their MWC at least 5 days per week. Additionally, identifying the source of the misalignment was important and therefore, descriptive specifications about the devices and user habits were collected. Participants were also compensated with a $5 gift card for their time.

The inclusion criteria were identified as being a MWU 18 years old or older with a weight under 300 pounds, and the wheelchair width between 14 and 32 inches. The age requirement was set because an IRB would be required for users under 18. A 300-pound user weight was identified because most manual devices (non-bariatric) have a max capacity of 250 or 300 lbs. The lifting devices are rated at 1100 pounds each, providing an adequate factor of safety. The device-width criteria were based on the design of the laser system and its capabilities relative to distance that it can accurately measure. It is able to accommodate any wheelchair that can fit through a standard doorway of 32 inches, and the smallest a device can be is 14 inches wide.

6.2.2.2 Data Collection Procedure

MWC device specifications were recorded and input into a Kobo Toolbox form using a tablet and offline data collection capabilities [80]. The first 25 participants were collected with the Kobo form, but the study transitioned to Qualtrics in order to use their offline survey app [81].

Qualtrics also provided the ability to insert instructions into the collection form and was easier to use for researchers. Training was provided in-person to all researchers who assisted with data collection, and a training manual and video were available. The questionnaire included both device and user information, as well as measuring and recording the diameter of the wheel rim and caster. A detailed list of the information collected about the user's wheelchair and their activity levels are shown in Table 44. Based on our observations that tires were commonly underinflated we began measuring tire-pressure with a handheld digital tire gauge after data collection had begun.

Table 44 Device Information to be Collected

Device make – categorical
Device model – categorical
Age of device – categorical
Hours used per day – categorical
Days per week – categorical
Tire type – categorical
Tire make – categorical
Wheel diameter – continuous
Wheel type – categorical

The data was collected in two-person teams, where one researcher prompted the user with questions from the tablet, and a second researcher measured the tires, casters, tire pressure, and identified the type of tires and wheels. The first researcher, with the tablet, proceeded through the device specifications questions to input all the information obtained. The second researcher guided the wheelchair user to a standard area, where the slope of the floor was measured and recorded to adjust the camber measurements. The measurements were collected in the following order:

1. The laser device was moved to the axle area of the MWC.
2. Both lasers were adjusted vertically to the center of the axle.
3. The system was moved to the front of the rear-wheels and was adjusted so the laser light was visually seen on the edge of each rim, directly adjacent to the tire.

4. The measurements were recorded for both the left and right side.
5. The laser device was moved to the backside of the rear-wheels and was again adjusted so the laser light was visually seen on the edge of each rim
6. The measurements were recorded for both the left and right side.
7. The lifting device was then placed under the wheelchair and lifted the user, so the rear tires were approximately one-quarter of an inch off of the ground.
8. A force of two pounds (from two constant force springs rated at about 1 pound each) was applied to the inside of the rear-wheels, as shown in Figure 28.
9. The measurements were recorded for both the left and right side.
10. The applied force was moved to the outside of the wheels.
11. The measurements were recorded for both the left and right side.
12. The force springs were removed, and the lifting device was lowered.

Figure 28 Measurement Device in Operation

Arrow repersents applied force from force spring.

6.2.2.3 Data Analysis

There is no previous literature to reference for an effect size, in order to assist in determining the needed number of participants for this study. Typically, studies including predictors for regression require 15 participants per predictor. With nine predictors, a minimum of 135 participants is required. The study participant goal was set to 200 based on the original ten predictors and an overestimation to account for missing data. Additionally, the power analysis for regression with an alpha level of 0.05 and 80% power was calculated and showed that there is a 0.085 effect size with ten predictors and 200 samples. G*Power was used for this calculation [82]. The effect size is considered small to medium for a regression.

In order to conduct the analysis, the data had to be grouped in a logical approach that was guided by a clinician seating therapist, a rehab engineer and an industry expert based on the results of the study. Groupings were largely based on the diversity of the responses in order to ensure large enough subgroups for statistical analysis. The categories of device make, model, tire make, tire type, and wheel type had to be logically grouped. Device make was grouped by manufacturer, and any device make with less than 9 responses per manufacture were grouped as other. Model proved to be too diverse to be able to give statistical power to the groupings, therefore, Medicare K code was employed. A large number of custom rigid frame devices or former K0009 and a small number of ultralight devices were seen with K0005 codes. Currently, the K0005 code includes all devices that previously would have been designated K0009 devices. Tire type was broken into four categories including high-pressure pneumatic (100 psi and over), low-pressure pneumatic (under 100 psi), solid or airless inserts, and a group of unknowns. Tires were also broken down by manufacturer in a similar fashion to device make. Wheel type classified some models as performance due to stronger materials used for construction and enhanced engineering as compared to a standard lite-spoke wheel with additional categories of solid and other.

For statistical analysis, each of the nine predictors from Table 44 was plotted against toe and slop, respectively. A non-parametric data analysis approach was employed due to a positively skewed, non-normal distribution in both toe and slop. Nine Kruskal Wallace tests were run with each predictor and both toe and slop as dependent variables.

6.3 Results

The research approach to develop a device was followed in accordance with the design specifications outlined in Table 43. After development, 200 participants were recruited over the course of about two months. Lastly, data analysis was conducted to interpret the results.

6.3.1 Measurement Device

A search was conducted to evaluate methods to measure 1.5 mm reliably to detect misalignment of the rear-wheels. Mechanical measurement devices, such as Vernier calipers, were initially examined but ultimately ruled out because contact with the device could not ensure consistency in the results if slop was present in the system. Ultimately, a pair of model Q4X lasers based on their 300 mm range and 1 mm repeatability [83].

The next step was to develop a system to hold the lasers, provide a constant force to assess slop, and unload the rear-wheels for the slop measurement. A rigid frame for mounting the laser measuring system, a tensioning mechanism for applying constant force and a lift mechanism for unloading the rear-wheels were developed. For the rigid frame, extruded aluminum was chosen because it is lightweight and can provide torsional rigidity if the proper sizing is used. Furthermore, linear slides accompany the extruded tubing to enable quick adjustments and provide an easy means to mount the lasers with height adjustability. Figure 2 shows the final device for laser measurement.

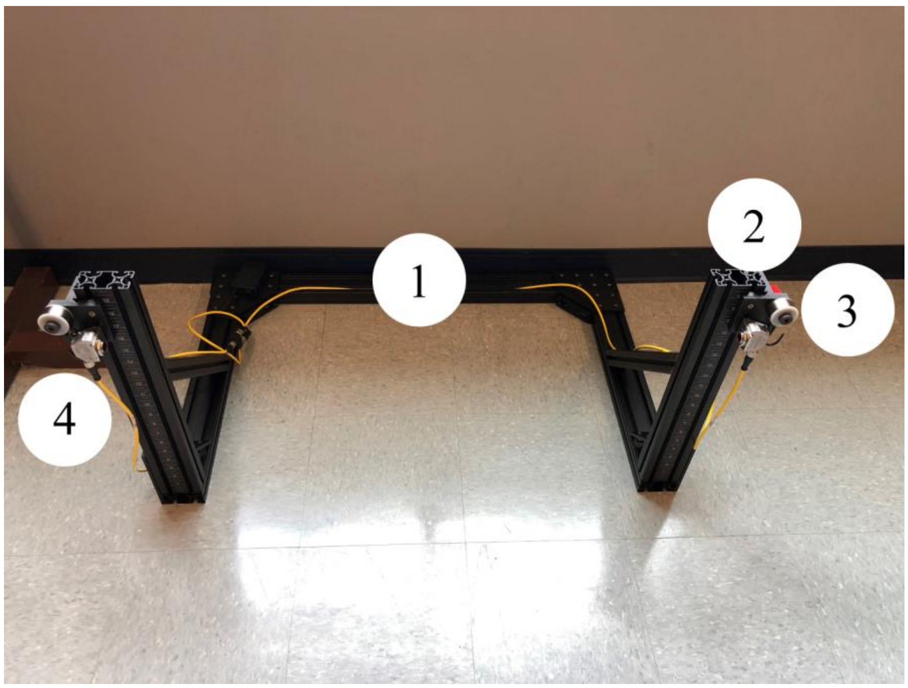


Figure 29 Laser Measurement Frame

(1) Frame, (2) Linear Slide, (3) Spring with Hook, (4) Laser

To be able to apply a constant force to the rear-wheels, the device needs to be lifted. A set of simple motorcycle jacks were employed, and the tops were covered with rubber to prevent any damage to MWCs. Once the MWC was safely lifted, the constant force application was applied with the use of 1-pound constant force springs mounted on a spacer spool, allowing extension and retraction of the force spring, with a rubber dipped hook affixed to the end, as shown in Figure 30. The constant force springs used to apply a nominal force while simulating a toe-in scenario and were able to mount to the same linear slides that the lasers were mounted to.

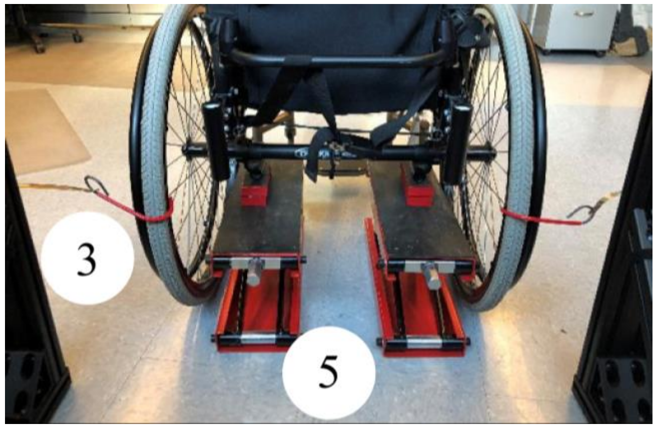


Figure 30 Rear View of Slop Measurements

(3) Spring with Hook, (5) Jack

The tensioning mechanism for simulating a toe-out scenario was the third piece of the system developed. This consisted of a piece of extruded aluminum with the two constant force springs mounted near the top, which provides tension for the slop measurement for a toe-out scenario and can be seen in Figure 31.

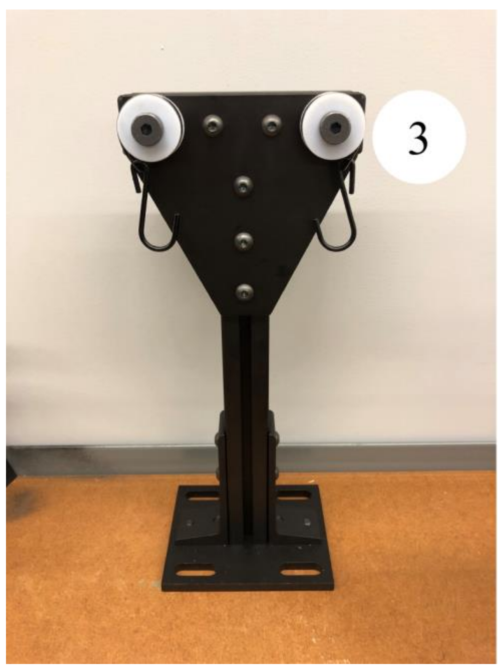


Figure 31 Toe-out Slop Tensioner

(3) Spring with Hook

6.3.2 Recruitment

Participants were recruited mainly at adaptive sporting events, where sizable gatherings of MWUs enabled measurement of many devices before and after matches. These events took place largely on weekends and were held across multiple states. One assisted living facility and a few education and training events were also used for subject recruitment. The research lab was used for a handful of subjects and a seating clinic was used for two participants. Table 45 shows the exact breakdown of how the participants were recruited. Due to an app error, three participant's data were lost and were unrecoverable, however, subject recruitment continued until 200 subjects were recruited. Given the nature of community recruitment, some information was not obtainable based on the MWU's knowledge or a lack of labeling on the MWC. The oversampling of participants was to ensure that this would not affect the data analysis.

Table 45 Manual Wheelchair Community-based Study Recruitment

Manual Wheelchair Community-based Study Recruitment

Recruitment Event	N	(%)
Adaptive Sports*	164	(82)
Assisted Living	14	(7.0)
Education & Training	15	(7.5)
Research Lab	5	(2.5)
Seating Clinic	2	(1.0)

Note. Total, N=200 *Lost three participants

6.3.3 Data

The data also shows that predominantly six manufacturers were observed in the community. Manufacturer A comprised almost half of all the devices measured in the community.

The results have been blinded to not identify a specific brand or company as better or worse than the other. The purpose of the study was to identify misalignment and its predictors. Table 46 shows the breakdown of the blinded manufacturers observed.

Table 46 Manual Wheelchair Community-based Study Manufacturers

Manual Wheelchair Community-based Study Manufacturers

Wheelchair Make	N	(%)
Manufacturer A	91	(45.5)
Manufacturer B	40	(20.0)
Manufacturer C	25	(12.5)
Manufacturer D	21	(10.5)
Manufacturer E	9	(4.5)
Other	14	(7.0)

Note. Total, N=200

To further classify the distribution of devices, the model information was collected and was intended to be used. However, a diverse group of over 45 different models was observed, which would not give enough power to groups for statistical analysis. In lieu of the model, the K code of the devices was used as seen in Table 47.

Table 47 Manual Wheelchair Community-based Study K Codes

Manual Wheelchair Community-based Study K Codes

Frame Description	N	(%)
Wheelchair Frame		
Custom Rigid (Former K0009)	171	(85.5)
K0005	13	(6.5)
Other/Unknown	16	(8.0)

Note. Total, N=200

The next potential predictor recorded was the age of the device, which showed a broad distribution across the categories. The largest category was MWUs with MWCs over 4 years old as seen in Table 48. This is encouraging, because it may mean that most of the devices are durable enough to withstand the daily use of the participants for the current Medicare reimbursed replacement timeframe of 5 years.

Table 48 Manual Wheelchair Community-based Study Age

Manual Wheelchair Community-based Study Age Data

Wheelchair Information	N	(%)
Approximately how many years have you had this wheelchair?		
<1 year	27	(13.5)
1-2 years	42	(21.0)
3-4 years	50	(25.0)
>4 years	79	(39.5)
No response	2	(1.0)

Note. Total, N=200

Along with the age of the device, we wanted to know how frequently the device was being used. Hours per day and days per week were grouped in categories when the MWU was surveyed. Table 49 shows that 75 percent of the participants were active users, in their device over 10 hours a day and over 5 days a week. Additionally, 93 percent reported that the MWC was their primary source of mobility and over 96 percent identified as self-propelling. The responses to these questions indicate that this study met its target to gather information on very active users because they are at a higher risk for propulsion related injuries.

Table 49 Manual Wheelchair Community-based Study Use Data

Manual Wheelchair Community-based Study Use Data

Wheelchair Use Frequency	N	(%)
Approximately how many hours per day do you use your wheelchair?		
<5 hours	13	(6.5)
5-10 hours	34	(17.0)
10-15 hours	73	(36.5)
>15 hours	77	(38.5)
No response	3	(1.5)
Approximately how many days per week do you use your wheelchair?		
1 day	3	(1.5)
2-3 days	3	(1.5)
4-5 days	11	(5.5)
> 5 days	181	(90.5)
No response	2	(1.0)

Note. Total, N=200

Specifications about the rear-wheels and tires were also collected during the study. Roughly half of the participants were using a high-pressure tire as shown in Table 50. Additionally, two tire manufacturers account for 75 percent of the tires observed (Table 51).

Table 50 Manual Wheelchair Community-based Study Tire Types

Manual Wheelchair Community-based Study Tire Types

Tires by Type	N	(%)
High-pressure (100 psi and over)	108	(54.0)
Low-pressure (under 100 psi)	36	(18.0)
Solid or Airless Inserts	37	(18.5)
Unknown	19	(9.5)

Note. Total, N=200

Table 51 Manual Wheelchair Community-based Study Tire Manufacturers

Manual Wheelchair Community-based Study Tire Manufacturers

Tires by Manufacturer	N	(%)
Manufacturer A	79	(39.5)
Manufacturer B	70	(35.0)
Manufacturer C	15	(7.5)
Manufacturer D	8	(4.0)
Manufacturer E	6	(3.0)
Other	22	(11.0)

Note. Total, N=200

Wheels were also an area of focus for the study in relation to diameter and type. Overall, 24-inch wheels were the most common followed by 25-inch, as seen in Table 52. Table 53 shows that a large portion of MWUs have performance wheels. Lite-spoke wheels were the second most common wheel type.

Table 52 Manual Wheelchair Community-based Study Wheel Diameter

Manual Wheelchair Community-based Study Wheel Diameter

Wheel Measurements	N	(%)
Overall Wheel and Tire Diameter (in.)		
22	7	(3.5)
24	117	(58.5)
25	53	(26.5)
26	23	(11.5)

Note. Total, N=200

Table 53 Manual Wheelchair Community-based Study Wheel Type

Manual Wheelchair Community-based Study Wheel Type

Wheels by Type	N	(%)
Performance	123	(61.5)
Lite-Spoke	56	(28.0)
Solid	14	(7.0)
Other	7	(3.5)

Note. Total, N=200

The average amount of toe was 9.06 mm or 0.92 degrees with the more common direction being toe-out for 62% of participants. Toe out versus in was not compared and no relationship between toe and slop was found. Additionally, slop was an average of 5.98 mm or 0.61 degrees of slop. That is a total of 1.53 degrees of toe which is equivalent to adding 47 pounds to the MWU and MWC at all times. A break down in the results can be seen in Figure 32. During the study, our researchers offered to inflate tires for the MWUs as a partial appreciation of the participant's time. Out of the last fifty participants, twenty-nine had pneumatic tires and twenty-one had solid or airless inserts. The average tire inflation pressure was forty percent calculated by the result of the digital tire pressure gauge measurement averaged across both rear-wheels compared to sidewall labeled maximum inflation pressure.

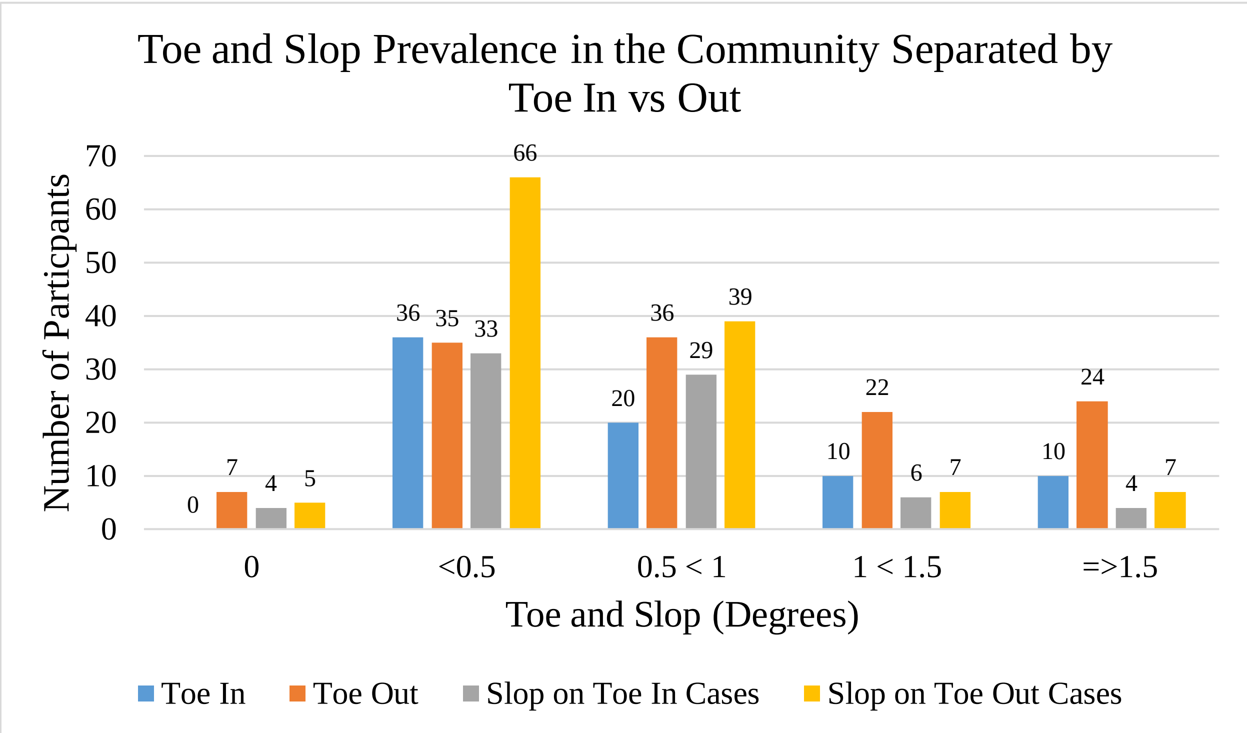


Figure 32 Toe and Slop Prevalence in the Community

6.3.4 Statistical Analysis

The graphical analysis did not provide detailed insight into the data but did show some outliers. No predictor was shown to be statistically significant ($p < 0.05$) from statistical analysis in relation to toe, but two were significant predictors of slop, which included tire manufacturer (Figure 33 and Table 54) and wheel diameter (Chi square = 12.80, p = 0.03, df = 5 and Chi square = 8.94, p = 0.30, df = 3). Pairwise comparisons were conducted post-hoc with a Bonferroni adjustment and found the tire manufacturer D was significantly lower in slop than manufacturer E

(p = 0.02). These results should be used cautiously since the counts are drastically higher for A and B.

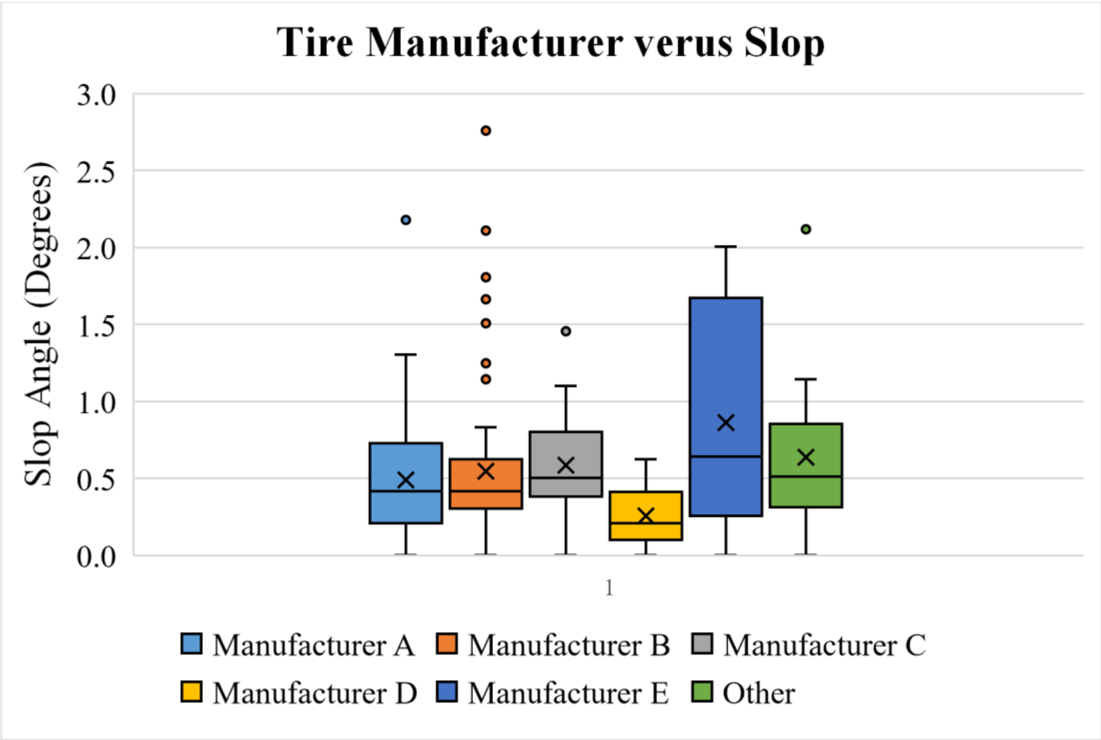


Figure 33 Tire Manufacturer versus Slop

Table 54 Tire Manufacturer versus Slop

	Mfr. A	Mfr. B	Mfr. C	Mfr. D	Mfr. E	Other
Average (deg)	0.49	0.54	0.59	0.26	1.04	0.64
Std Dev (deg)	0.37	0.49	0.36	0.21	0.71	0.46
N (qty)	79	70	15	8	6	22

The pairwise comparisons for wheel diameter show that the 22-inch wheels are significantly higher in slop compared to 24-inch wheels (p = 0.02), with the 24-inch grouping dominating the sample. Figure 34 and Table 55 show the graphical representation and descriptive statistics from wheel diameter groupings.

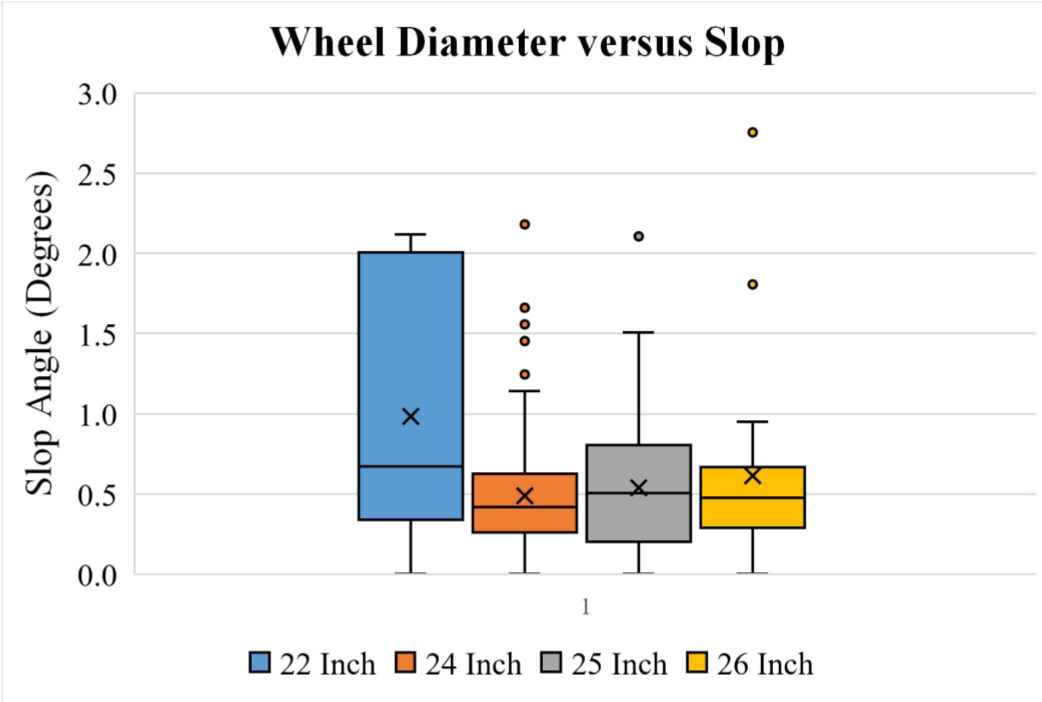


Figure 34 Wheel Diameter versus Slop

Table 55 Wheel Diameter versus Slop

	22 Inch	**24 Inch**	**25 Inch**	**26 Inch**
Average (deg)	1.14	0.49	0.54	0.64
Std Dev (deg)	0.75	0.37	0.40	0.59
N (qty)	7	117	53	23

Additional information about the development of the testing system can be found in Appendix A.5 and additional results can be found in Appendix E.

6.4 Discussion

This community-based study identified the prevalence of factors that give rise to RR and provides insight into the unaddressed misalignment of toe and slop, and underinflation of tires that

MWUs are being exposed to on a daily basis. The MWCs are not as mechanically efficient as they should be and therefore, put the MWUs at risk for UE RSIs. While mechanical efficiency alone does not completely prevent RSIs, it needs to be monitored. Toe provides no benefit to the user when propelling and only adds to RR, therefore increasing the required propulsion force for the MWU to move their wheelchair. Theoretically, slop acts in a toe-out manner and thus increases RR in a cumulative manner with toe. This is constant and can only get worse over time due to increased slop or reduced tire pressure. Tire pressure can be easily mitigated with routine checks. Furthermore, this sample represented very active users, with the majority using their devices more than five days per week for over ten hours per day. If very active users have this severity of issues and are constantly facing excessive RR forces, then they are at very high risk for UE RSI due to prolonged use with elevated forces.

A drum-based testing machine (Figure 35) was used to measure RR on MWC components, and it can provide insight into the impact these issues have on the MWU. The most common tire found in the community was tested through a range of toe, camber, loading, and tire pressure settings on the drum. With a linear relationship between load and RR, the loading equation can easily be derived for a tire. The loading equation is an equation estimating the impact of increased RR from a factor, such as toe or low tire pressure, in terms of a load that would cause the same increase in RR. With the relationship between toe and RR being non-linear, RR increases exponentially as toe increases. Tire pressure also follows a non-linear curve where lower tire pressures increase RR.

Figure 35 Drum-based Testing Machine

To convey the impact of toe angle on RR, the loading equation was used to back-calculate the perceived weight equivalent added to the rear axle of a device and is shown in Table 56. Camber of 3 degrees (average in the community) had little increase and is equivalent to the weight of a backpack commonly used by MWUs. Reduced tire pressure at 40% of maximum is equivalent to putting a twenty-pound weight on the MWU's lap and having them propel around in that state all the time. Camber and tire pressure calculations assume that both wheels are in the same state and the result is doubled. Toe is measured across both rear-wheels and is therefore not doubled. While toe and slop do not appear to be drastically impactful on their own, when they are combined into a worst-case alignment scenario, the equivalent weight is forty-seven pounds. Additionally, drum-based testing has shown that the factors act in a cumulative manner if more than one factor is present. Therefore, the absolute worst-case scenario is toe + slop + tire pressure + camber for an approximation of combined perceived weight equivalent of 74 pounds (F_{RR} increase of 0.517 lbs. from a standard condition of 0.474 lbs.). That would be a significant addition to most MWUs, and that is the current reality for MWCs in the community.

Table 56 Average Results from the Community-based Study

Measurement	Average	Standard Deviation	Perceived Weight Equivalent
Toe (mm)	9	12	24 lbs.
Toe (Deg)	0.9	1.4	
Slop (mm)	6	8	5 lbs.
Slop (Deg)	0.6	0.8	
Toe + Slop	1.5	N/A	47 lbs.
Camber (deg)	3.0	1.5	7 lbs.
Tire Pressure	40%	24%	20 lbs.

The overarching goal of this research is to provide information for rehabilitation engineers and clinicians and to improve education, guidelines, and standards for wheelchairs. Currently, this is the only study to measure the misalignment of MWC wheels in a United States community that we are aware of. End-users, manufacturers, clinicians, and service providers need to be aware of these issues, the prevalence of toe, slop and tire underinflation in MWCs. For stakeholders to be more cognizant of the misalignment and maintenance issues on MWCs, they need to start with the sources of toe and slop. Manufacturers need to ensure they are supplying quality MWCs, where axle tubes are properly aligned, and frames are square. Wheels should also be trued from the factory. During the setup and final fitting of device issuance, care should be taken not to induce toe into the rear-wheels. This can happen from a camber tube being rotated forward or backward, a change in seat dump, or a change in caster diameter. End-users and providers need to be vigilant of maintenance issues related to age and use of the device such as worn bearings or axles, wheels out of true, and other maintenance issues including underinflated tires. In most cases, it is not recommended to switch to a solid or airless insert because they have a higher RR than severely under inflated pneumatic tire [33].

6.5 Limitations

There are a few limitations to note from this study, which include the questionnaire, the novel test rig, the adjustments over the course of data collection, static conditions measurements, results groupings, and that it is a convenience sample. The questionnaire was developed by the research team, which included a clinical coordinator's assistance, but it is not a validated tool. Moreover, the majority of the questionnaire pertained to the objective measure of data about the MWC provides valuable insight into community prevalence. The novel test rig is the only one that exists and therefore, it is also not validated or compared to a gold standard approach for this research. Without a gold standard, a device had to be developed along the specifications set forth, but the positive outcome is that a measurement system now exists. The lasers were over-specified to assure accuracy and the rig was designed according to the specifications to meet the demands of all scenarios. One area that could be improved would be expanding the tire pressure data collection because it only captured on 50 participants (25% of the total population). Some participants, before the tire pressure was being recorded, may have been using airless inserts but were not recorded in that manner, but that would have little influence on the overall study results. For the results groupings, a team approach was employed to ensure they were grouped in a logical manner, but others may have differing opinions on this approach. With the variations in community-based data, it was the only plausible option that would produce relevant results, but some large groupings could have dominated the results. This was also a convenience sample of those at adapting sporting events that wanted to participate. While the sample size was relatively large, it may not be representative of a cross-section of the MWU population.

6.6 Future Work

There is a large number of MWUs with misalignment in the community based on the lack of readily available measuring equipment and standardization of misalignment in the rear-wheels of MWCs and the evidence in this study. Accompanying with future testing, there would also have to be a standard or threshold of compliance of misalignment. Toe measurements could be implemented into durability testing by strengthening MWC standards to include rear-wheel alignment testing. This would help to ensure that this issue does not develop during use in the community. Other options to mitigate this issue is to check toe and slop over time, which would require the development of a low-cost test jig that can be easily used in clinics or by providers. Continuation of this research could help increase the ability to group predictors and be able to find statistically significant predictors. Furthermore, attention to maintenance issues and methods of adjustment need to be developed and implemented. Tires do not always have to be at one hundred percent of their max pressure but should be checked regularly or when changing altitude. Further study of tire inflation prevalence would be valuable to expand the data available. Improvements to the ease of measuring tire pressure and inflating tires for MWU's would be of value. Another area to continue research is to test toe and slop under dynamic scenarios that replicate propulsion. Therefore, it could be understood if the misalignment is exacerbated during movement. There is also potential future work to understand toe angle and slop prevalence and severity differences in developed versus developing countries, and for other demographic and geographic considerations.

7.0 Translation and Dissemination of Results

Knowledge translation is defined as having two parts, creation and action [84]. The previous chapters have identified the part of the creation of novel knowledge in the field through academic research. In order to action on that knowledge, it must be synthesized and developed into tools and products as seen in Figure 36.

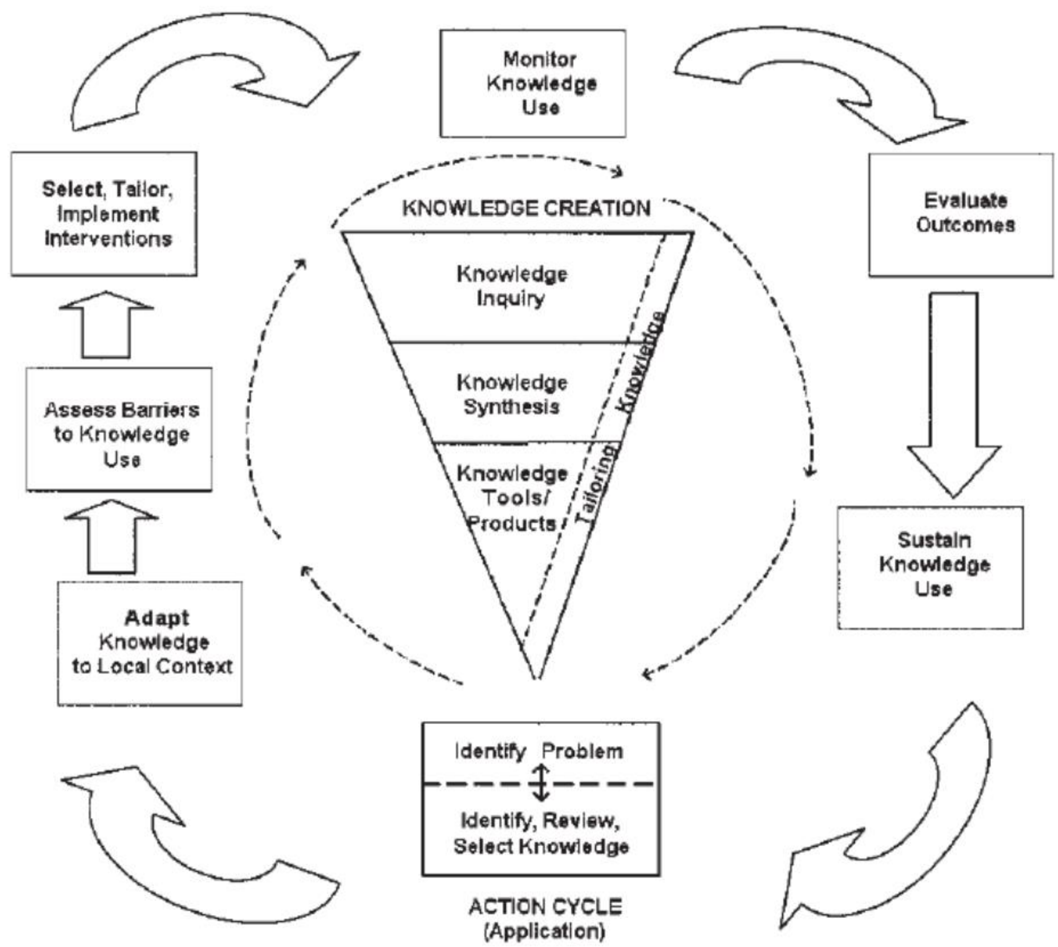


Figure 36 Knowledge to Action Process [84]

The research contained in this dissertation is some of the first of its kind, that yielded innovative insights to RR and factors that influence it. It drew new conclusions and identified areas where clinical practice can be updated to reflect the results of this research. The translation and dissemination of the information is an important aspect of the research in order to preserve the health of current and future MWUs.

An effective method of translation was needed to move from the synthesis of results to tools and products. To do this, industry experts from stakeholder groups were consulted for preliminary ideas including equating it to propelling against headwinds, propelling up a slope, and propelling with additional weight. After reviewing these ideas, the selected concept was to convert the changes in RR force into an equivalent weight estimation. To do this, a perceived weight equivalent (PWE) converter was developed to transform forces the difference in RR force to additional weight based on the tire type. The converter uses the loading equation developed from RR testing to see what the equivalent weight added or removed would be for that specific change in force as shown in Table 57. Typically, it is compared to a reference trial which is representative of a 250-pound user and device weight.

Table 57 Perceived Weight Equivalents of MPE Tire

Factor	Level	Perceived Weight Equivalent (lbs.)
Speed	0.5	-5.6
Camber	3	6.3
	5	13.9
Tire Pressure	40%	16.5
	80%	2.3
Toe	-1.0	19.6
	-2.0	59.6
Surface	LP	62.3
	MP	81.7
Tire Type	SPM	34.6
	AIS	96.0

The downside to this PWE converter is that it must assume a loading distribution to model a complete wheelchair. However, in the future, it can be expanded to include caster RR testing results or have separate outputs for rear-wheels and casters. The clinician feedback obtained suggested that the conversion to weight was easy to understand by the potential stakeholders. For instance, changing from the HPS pneumatic tire to AIS airless insert is the equivalent of the MWU propelling around with additional ninety-six pounds over the rear axle with HPS tires. The future of this work would be to build a database for the results where a stakeholder could input specific setup conditions for a MWC, make adjustments and obtain the results as a perceived weight equivalent gained. The testing of more tires and casters would need to be completed to ensure a more comprehensive database.

In addition to the converter, a visual translation of the information is needed to carry the main outcomes through the action cycle. A fact sheet (Figures 37 & 38), in the form of infographics, was developed to convey the information to all stakeholders. The fact sheet is a two-sided, high-level page that explains what RR is and why it important. It provides details and specifics about the factors, their impact on RR, and brief recommendations on how to reduce RR for MWUs. Furthermore, it describes the lack of standardized testing and makes recommendations to specific stakeholders.

The next step in knowledge transfer is to distribute the fact sheet in the action cycle. Distribution can be handled through ISWP including marketing channels, conferences, and newsletters to supplement the information disseminated in the publications of Chapters 2 through 6. Further curtailing of information to specific stakeholder groups may help to reduce barriers faced in dissemination. Increased awareness of component selection, rear-wheel alignment, and proper tire inflation will induce intervention in clinical practice, standardization, and testing for RR.

Figure 37 Fact Sheet Page 1

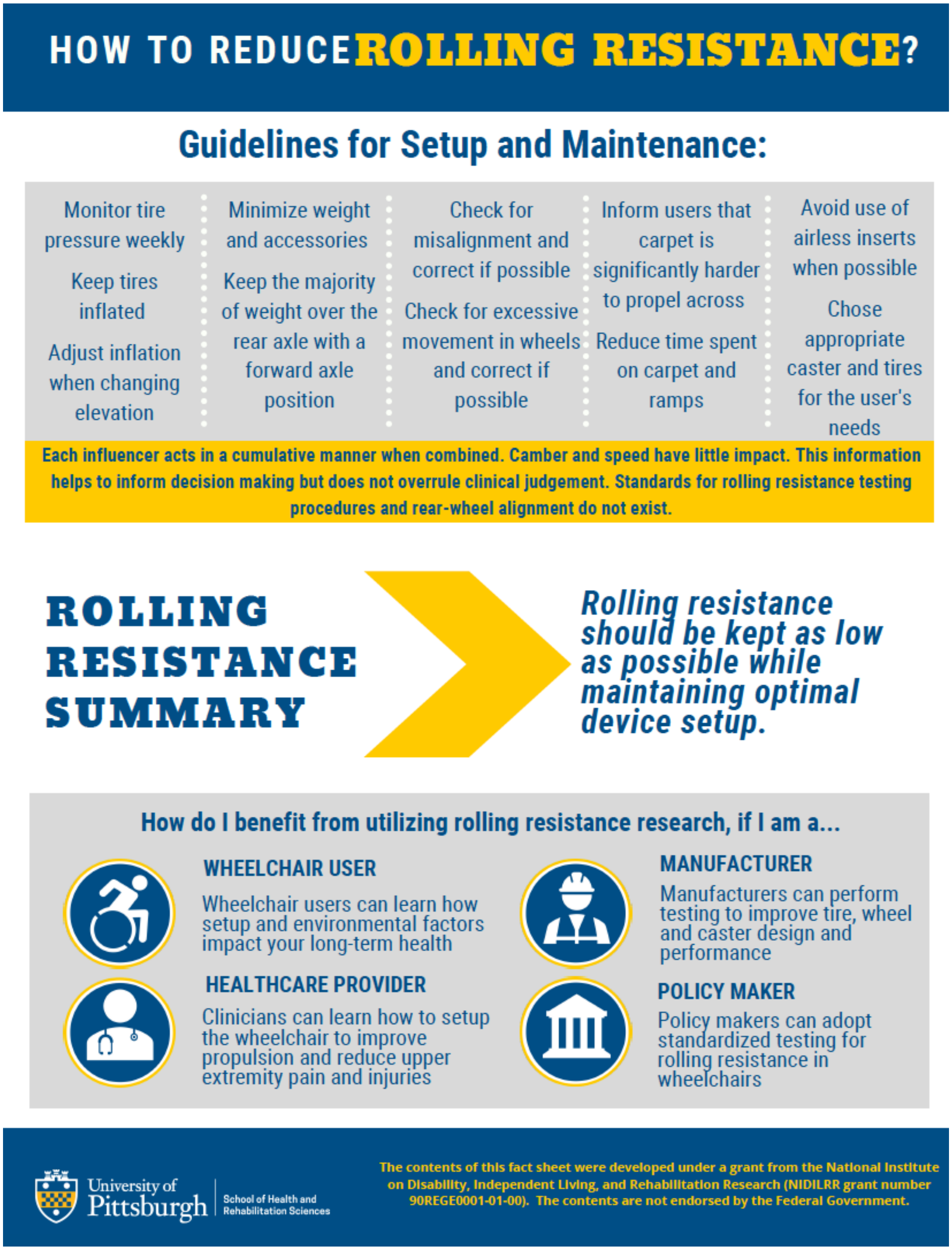


Figure 38 Fact Sheet Page 2

8.0 Conclusion and Future Work

8.1 Conclusion

The research outlined in this dissertation is an important step forward to learn how to make informed decisions about the clinical prescription of MWCs and ultimately prolong the health of MWUs. The literature reviews were a fundamental piece in identifying the knowledge gaps as well as identifying what has previously been researched. Seven different testing methods were employed to evaluate RR, all with various capabilities, strengths, and limitations. All of the previous testing methods were system-level tests and mostly indirect testing methods, which highlighted the need for a repeatable component-level, direct testing method. Additionally, the reporting of factors resulted in some factors as clearly influential to RR such as tire type, toe, surfaces, and tire pressure. Camber was found to have mixed results and speed is mostly user selected. The variations in test result reporting increased the difficulty of interpretation of the results across studies which was exacerbated by a multitude of testing methods. The selection of products or levels or factors has also varied across the numerous studies. The need for a component-level, direct testing method also needed to be able to uniformly test factors and products for ease of interpretation of results.

The solution to this need was a drum-based testing method that isolated the RR force for measurement while having the ability to have multiple factors influence it. Through the exploration of testing, its sensitivity and repeatability far exceeded the design specifications set forth. It showed linear and nonlinear relationships between factors and RR while identifying differences between factor levels. It proved its ability to test combined factors and to have a relationship to correlate results to overground testing. The only downside is that the testing is only measuring RR force simulating the MWU propelling in a straight line, which excludes any changes in RR during turning. The machine is a new testing method that could become the standard of MWC RR component testing.

The community-based study was the first of its kind in the United States and identifies the high prevalence of conditions that lead to increased RR, including low tire pressure and misalignment of the rear-wheels. The level of misalignment, excessive play (slop), and tire underinflation are putting MWUs at increased risk for UE pain and injuries. With the novel measurement device that was developed, it was able to accurately detect misalignment in the community where MWUs are having to unnecessarily propel harder consistently. Overall, the study highlighted maintenance issues that need to be addressed in the community.

The key results from our work include:

- ♦ Tire and caster type are critical influencers to RR.
- ♦ Airless inserts should only be used on a limited case basis due to high RR
- ♦ Smaller diameter casters have a lower RR than larger diameter casters.
- ♦ Toe and slop should be minimized.
- ♦ Tire pressure should be maintained above eighty percent.
- ♦ Camber and speed should be set by MWU preference.
- ♦ Load (weight) should be kept to a minimum and the majority placed over the rear axle.
- ♦ MWUs should understand the impact of traversing difference surfaces.
- ♦ Factors act in a cumulative manner when combined.

Clinical practice guidelines [14] should be refined based on these results and implemented into practice. For example, more attention should be paid to user and accessory weight and not just the device weight. Also, a forward axle position may not be as influential as a substantial weight change in the user. The use of this knowledge should benefit all stakeholders and propel the field forward with more informed decision making. Implementing these recommendations should help to preserve the UE health of current and future MWUs.

8.2 Future Work

There are four main recommendations to guide future work of this research including, additional testing of wheels/casters, design innovations to reduce RR, strengthening product standards to reduce misalignment, and raising awareness of the consequences and strategies to mitigate RR. While this dissertation covers substantial progress in this area of research, it is only the first step. Further expansion can only offer more insight and understanding of RR and how it is influenced.

8.2.1 Further Testing

To improve our understanding of the RR performance of casters and tires, further research should be conducted to evaluate more tires and casters. The testing could be as comprehensive with all factors and levels, but more data is needed on the numbers of tires and casters on the market. Furthermore, little research has been conducted on devices during left and right turning. The overground comparisons could be expanded to include other factors and additional wheels and casters. Additional factors such as temperature or wear could also be studied and Table 58 details further laboratory study options. Likewise, toe, slop, and tire, pressure could be continued to be studied in the community with the expansion of the geographical area as shown in Table 59. Future testing would expand help define clearer product selection and provide more insight in RR for all stakeholders.

Table 58 Additional Laboratory Testing

Study	Justification
Expansion of Combined Factors	Test any combination of factors not tested in order to build a complete model for detailed statistical analysis. Could test the combination of more than 2 factors.
Expand Overground Comparison	Would be able to better adjust the drum results of there were more data points from the treadmill side.
Expand Surface Testing	Identify and test additional surfaces that can be placed on the drum to understand their effect on RR.
RR During Turning	Not well explored.
Test the Impact of Temperature	Temperature can change material properties and tire inflation pressures. It may be helpful to understand its effect.
Tested Aged or Worn Components	Age, wear, and corrosion could all impact RR.
Test Rear-wheel Size	Understand its relationship with RR.
Test Performance versus Standard Rims	Understand its relationship with RR.
More Tires and Casters	With a bigger database of results can provide more detailed recommendations.
Explore the Relationship between Speed and Caster	Interesting results from the statistical analysis that could be explored further.
Misalignment in Durability Testing	To identify points of failures in durability testing that could lead to toe/slop and correct them before they develop over time.
Dynamic Toe Study	Need to understand how toe and slop act under a dynamic scenario when propulsion occurs.

Table 59 Additional Community Testing

Study	Justification
Prevalence of Tire Pressure	Preliminary results show this is an issue that needs to be addressed.
Toe Prevalence	Expanding to other geographical or demographical areas.

8.2.2 Additional Development

To help facilitate the increase in testing, an important step may be to develop a low-cost tool to measure the misalignment during final fittings or service calls. Using this tool, it would be possible to monitor misalignment over time during follow-up evaluations. Moreover, products could be designed to mitigate toe or slop in products so they can be managed throughout their useful life. With numerous testing results, stakeholders need a way to easily compare products. A database or clinical reference tool could be built to be able to easily compare factors and their influence on RR. For example, what is the difference between the two tires? It would help all stakeholders understand the RR impact if it is converted to perceived weight equivalents. Lastly, better product development, innovations should be pursued to help mitigated RR as much as possible. This could be through the development of better tires of casters or tolerancing in the axles. Maybe there is a possible design for an airless tire that performs as well as a pneumatic tire without routine maintenance. There could also be developments to address the underinflation of tires with self-inflating designs or onboarding on monitoring systems to alert MWUs to refill their tires. Creative solutions could help to mitigate RR in the long-term for MWCs and reduce the risk of injury (Table 60).

Table 60 Development Items

Item	Justification
Measurement of Toe/Slop Tool	Simple, effective tool that all stakeholders can use to measure misalignment in a device.
Clinical Database	Area to host testing results and inform stakeholders of the results.
Mitigation of Toe/Slop	Ability to correct misalignment on a device.
Mitigation of Tire Underinflation	Ability to correct tire pressure on a device.
Better Products	New wheels and casters that have reduced RR.

8.2.3 Standardization

With the high prevalence of misalignment, we found in the community-based study, it motivates strengthening standardization in the industry (Table 61). The amount of toe and slop present in MWCs increases the risk of UE pain and injury on a daily basis compared to a well-aligned device. Therefore, better mitigation standards as well as preventing toe and slop in MWCS needs to be implemented. To address the maintenance aspect, stakeholders need to be educated on the ramifications of underinflated or misaligned wheels. One option is to implement misalignment testing before and after durability testing as a way to check the bearings, axle, and axle tube tolerances for excessive wear through use. That would be an additional aspect of the standardization of RR for MWCs. Additional standardization in the field would help provide better products to MWUs and preserve their UE health.

Table 61 Standards Development

Standard	Justification
Threshold of Toe/Slop in the Community	A threshold is needed to say whether a device is considered “out” of alignment in the community
Threshold of Toe/Slop during Durability Testing	A threshold is needed to say whether a device is considered “out” of alignment or gains slop during durability testing
Testing Procedure of RR	Need a reproducible way that ensures it is being tested in the same manner every time.

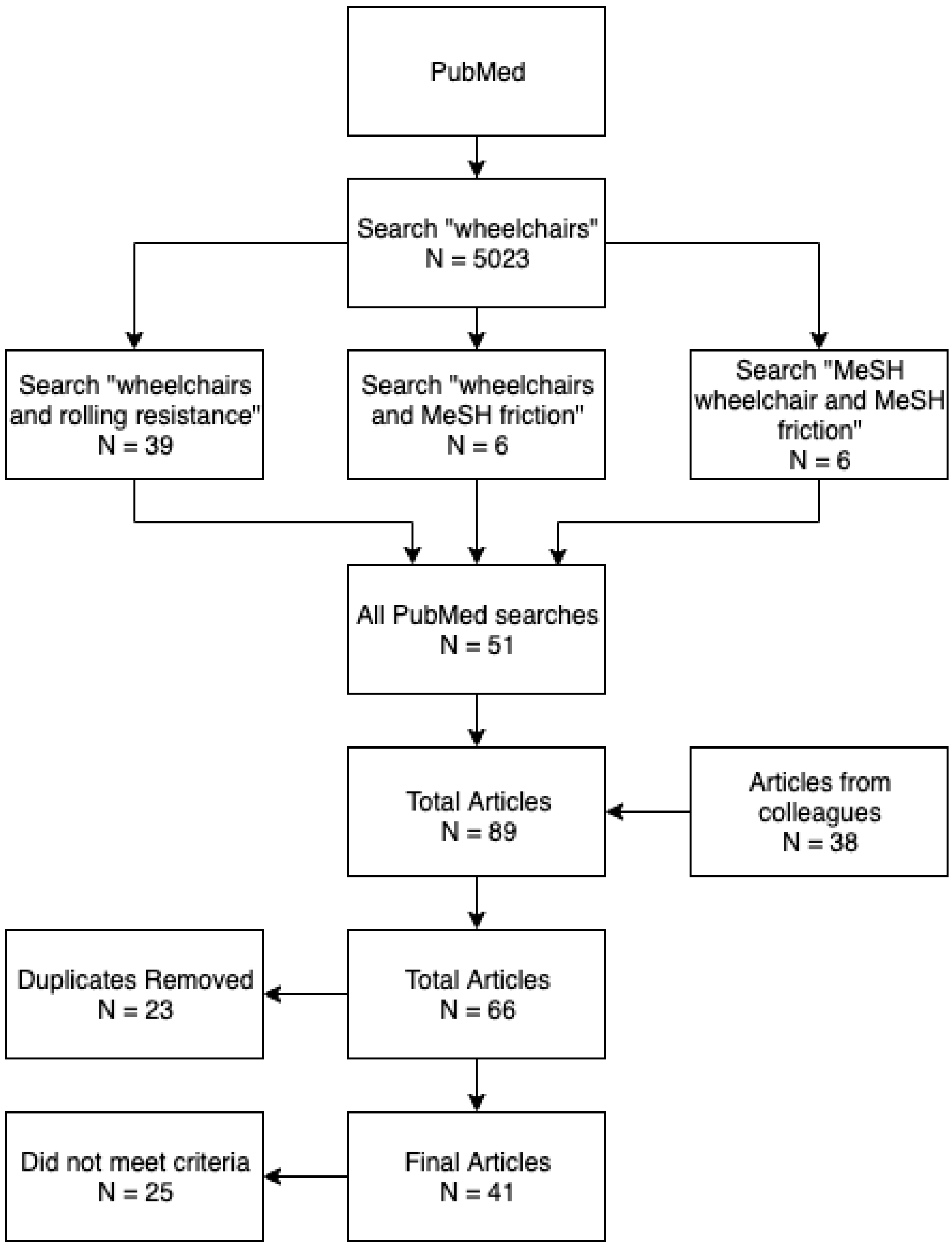
8.2.4 Education

The last component is educating stakeholders since research should impact care when conveyed effectively to stakeholders. This dissertation lays the groundwork with the development of perceived weight converter and the first fact sheet. Through the continued testing, innovation, and standardization, the amount of influential information from this research will continue to increase. Publications and conference presentations are the easiest way to educate stakeholders. Ensuring that stakeholders are aware of these issues is paramount to helping reduce UE injuries. With the insightful conclusions from this and future work, updates to clinical practice will continue to ensure safer propulsion for MWUs.

The research in this dissertation covers a segment of its influence of RR but it is only a piece of the amount of research that can be conducted on RR. The continuation of testing, the push for standardization of industry testing, design innovations in the industry, and the further education of the field can only help to improve the understanding of RR. The future of this research is bright and has many more years to come.

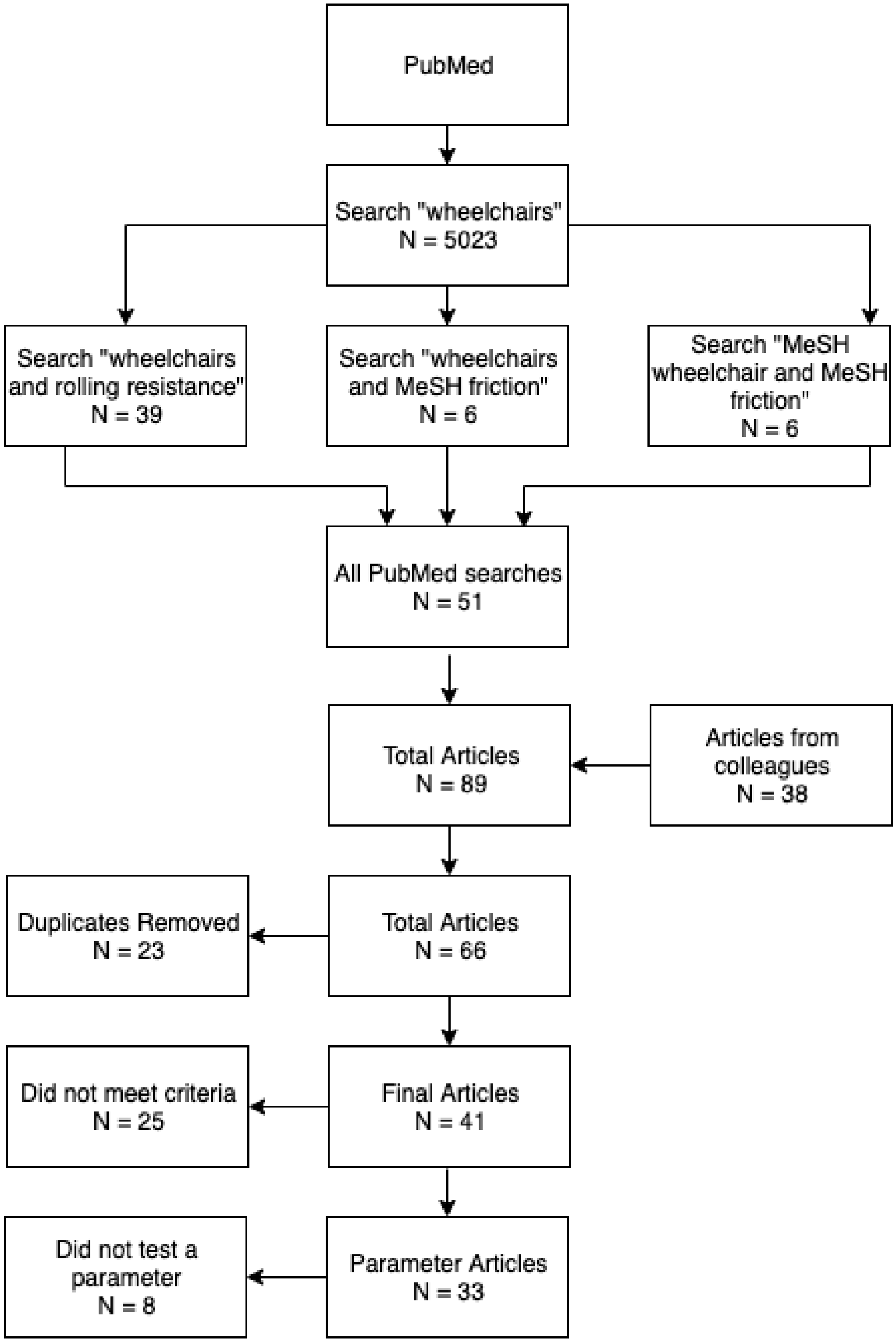
Appendix A Additional Information

Appendix A.1 Methods Scoping Review



Appendix Figure 1 Methods Article Selection Flowchart

Appendix A.2 Factors Scoping Review



Appendix Figure 2 Factors Article Selection Flowchart

Appendix A.3 Development Paper

Appendix A.3.1 Redevelopment Timeline

The redesign of the drum-based RR testing machine started in the second quarter of 2017. The three-dimensional (3D) SOLIDWORKS model of the first machine was the basis for the start of the design [85]. Evaluation of the first machine was done with an in-person visit to it in November of 2017. A thorough discussion ensued about the capabilities and shortcomings of its design and functions. Following this, the 3D SOLIDWORKS model began to take shape [85]. The frame was modeled piece by piece. Available components such as hardware from websites, such as McMaster-Carr, were downloaded and included in the model [86]. By the first quarter of 2018, the new model was completed for the lower half of the machine. To break up heavy building stages, the modeling of the upper assembly continued, while the building of the lower frame began. The bulk of the machine was built by the end of the third quarter of 2018. Concurrently with the fabrication of the machine, motor control and data collection systems were designed and installed.

After the building process was completed, setup and calibration of the machine began in the fourth quarter of 2018. Every factor was individually tested to see if the machine was capable of detecting changes within those factors. Furthermore, the sensitivity of the machine was studied to see the minimal amount of change in factors the machine could detect. Furthermore, calibration and filtering of the load cells were conducted. Reliability testing was also completed to see the variance in repeated measurements. By the end of the second quarter of 2019, the machine is fully functioning, calibrated, and every factor was preliminarily tested.

Appendix A.3.2 Lower Frame

The frame can further be broken down into two segments main and secondary. The main segment (Appendix Figure 3) has a ¼” steel plate to support the motor and gear reducer and the drum bearings. To enable access to the drum, a removable 1-1/4” tube secondary frame assembly was added to the left side of the main frame. The entire frame consists of 24 separate tube elements supported with steel gussets and ¼” steel plates for mounting additional components.

Appendix Figure 3 Lower Frame Assembly Main Segment

Appendix A.3.3 Drum and Drive System

It contains two internal circular spokes each of which are offset 2” inward from the outer edge of the rim and contains 3 equally spaced cutouts. The offset allows for interchangeable materials on the outer rim of the drum for the testing of different surfaces. Both the drum’s circular rim and internal spokes have a thickness of ½”. To maintain horizontal stiffness, internal supports were added between the spokes. Each of the spokes has a flanged collar welded on to fit a 1-1/2” keyed shaft.

The drive system (Appendix Figure 4) contains a 1P, 3-phase, 208-230/460 volts alternating current (VAC), 1800 revolutions per minute (rpm) motor (model number MTRP-001-3BD18) from Automation Direct [87] coupled with a 40.08:1 inline gear reducer (model number 13-1552-40-56C) from Surplus Center [88]. There is a further 2:1 reduction using the 2” timing belts and pulleys. The motor is controlled by a PowerFlex 525 AC Driver by Allen Bradley (model number 25B-A4P8N104) [89]. An incremental encoder from Automation Direct (model number TRDA25RN360VWDMS) ensures that the drum rotates at a constant rate [87]. For safety, the main control panel has a 15-amp breaker and an emergency stop switch connected to the driver.

Appendix Figure 4 Drive System

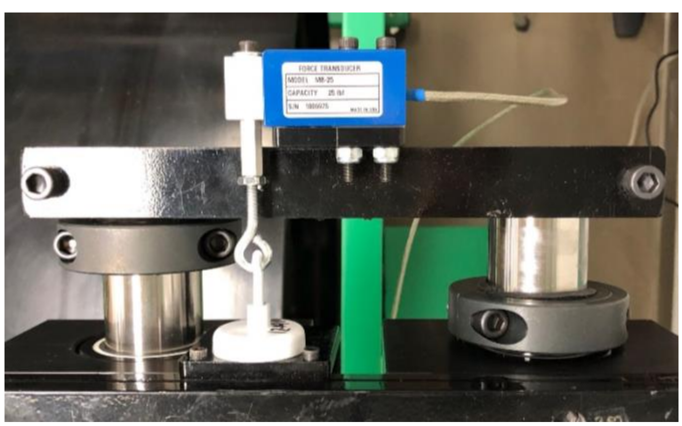
Drive system with the AC driver in the control box and the motor and gear reducer underneath

Appendix A.3.4 Upper Frame

The upper frame is also constructed of 2” steel tubing. It sits on top of the main frame separated by ½” rubber and supports the arm assembly. It provides vertical adjustment of the arm through two parallel 1-5/8” strut pieces. It creates a pivot point with a ¾” rod mounted in bushings, so the arm can be loaded and have proper weight distribution. The rod also provides horizontal adjustment of the arm assembly. They are held parallel by five custom mounting blocks that were made custom for this application. One mount is wider to be able to house tie rod ends that become a pivot point for the arm.

Appendix A.3.5 Force Measurement

An eyebolt connects the load cell to a magnet that attaches to the quad setup of air bushings (Appendix Figure 5). The magnet is rated to release at a lower force than the load cell and will break contact before the load cell can be overloaded. The load cell is excited via an Omega Amplifier (model number DMD4059-DC) that also converts the load cell signal from 0-30 millivolts direct current (mVDC) to 0-10 volts direct current (VDC) [90].



Appendix Figure 5 Load Cell Attached to Air Bushings with Magnet

Appendix A.3.6 Operation

First, the testing factors are defined, and the machine is powered up. The fixture is adjusted to the desired camber and toe values, and the correct wheel is attached. The load cell linkage is adjusted so the tire sits just behind the top dead center of the drum. The average is taken, and the coefficient of RR is also calculated based on the weight of the arm. Appendix Figure 6 shows a sample portion of the code, where it truncates the data, converts the voltage to force pounds, calculates the coefficient of RR, mean, and standard deviations.

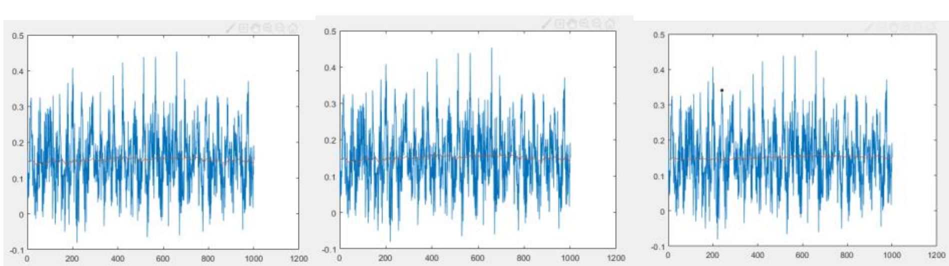
```
%get center 60 seconds
truncated_data = filt_data(4501:13500);

% convert to lbf
% 25 lb load cell
% data_lbf = 2.0544*truncated_data -0.0794;

% 5 lb load cell
data_lbf = 0.4713*truncated_data - 0.0184;


% convert to Newtons
data_newtons = data_lbf*4.448;
load_newtons = load*4.448;

%divide by load for coefficeint
data_coef = data_lbf./load;

%get mean and standard deviations
data_avg = mean(data_lbf);
data_std = std(data_lbf);
coef_avg = mean(data_coef);
coef_std = std(data_coef);
```

Appendix Figure 6 Sample Portion of Code.

Appendix A.3.7 Data Sampling

With these results, the sampling frequency was downsampled to 400 hz and showed similar results. After the sampling frequency was established, the processing of the data was the next step. A moving average filter was applied over 200 units (load cell readings). Moving averages over 400 units and 800 units were also tested as shown in Appendix Figure 7. Upon review of the FFTs, a Butterworth filter was recommended by a colleague as a test to improve the signal and was tested with high and low pass at 0.1 and 0.01 hz, respectively. The established sampling frequency and second and third-order filters were reviewed. Ultimately, the moving average filter was deemed sufficient at 800 units, which is less than one rotation of the drum, and then averaged over the middle sixty seconds.

Additionally, every possible combination of running factors, motor on/off, compressed air on/off, and the arm lifted off or touching the drum, was tested and the FFTs were performed. The only trials that showed any frequencies appearing were the standard operation with the motor on, compressed air on, and the arm touching the drum, demonstrating no abnormal vibration interfering with the signal for the load cell. MATLAB code was written to test the load cell calibration [78]. Known calibration weights with a weighted hanger were suspended from the load cell and the voltages were recorded.



Appendix Figure 7 Moving Average Filter Testing

Moving Average Filter Testing from Left to Right 100-unit, 200 unit, and 400 units

Appendix A.3.8 External Validity

A large drum diameter was used to be able to reduce the effect of this since a 24-inch wheel is half the diameter of the drum. Appendix Figure 8 shows the belt material on the drum.

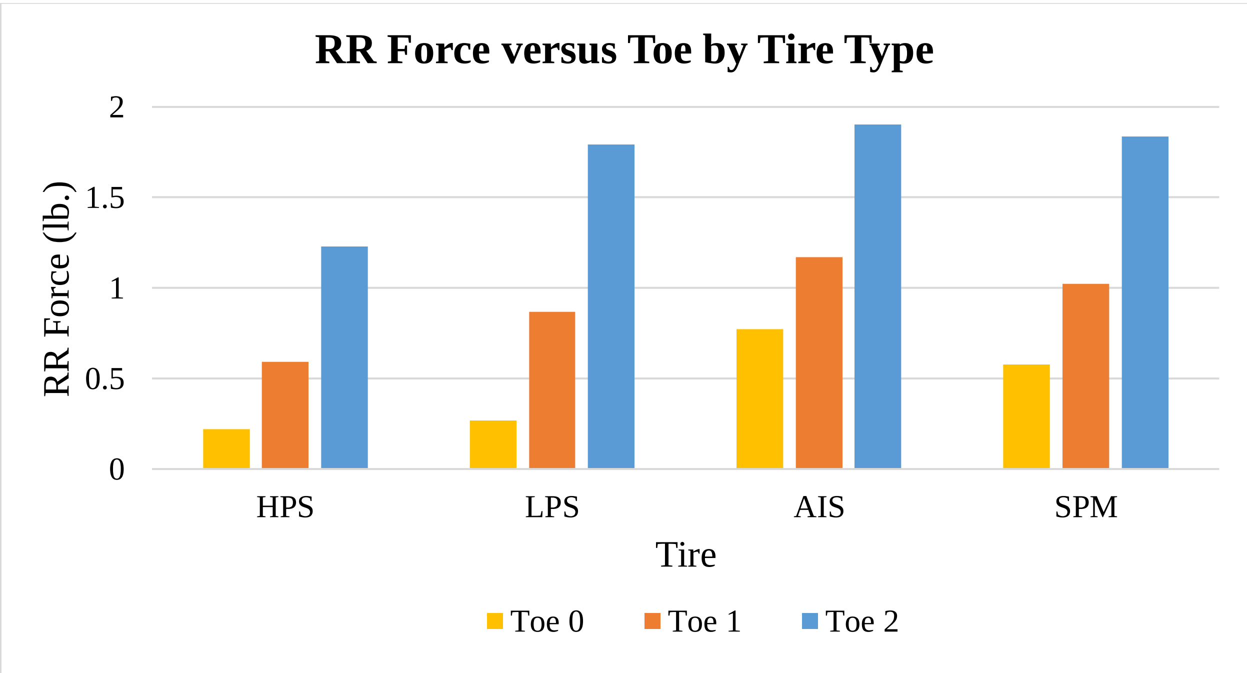
Appendix Figure 8 Treadmill Belt Material on the Drum

Appendix A.3.9 Sensitivity Analysis

An ANOVA was run with post hoc testing on Statistical Product and Service Solutions (SPSS) software to determine the smallest load change that results in a significant change in RR [91]. The linear relationship between force and RR, as well as the relatively high sensitivity of the RR measurements, gives us confidence that the system can be used to measure the influence of RR across a range of factors.

Appendix A.3.10 Preliminary Results Continued

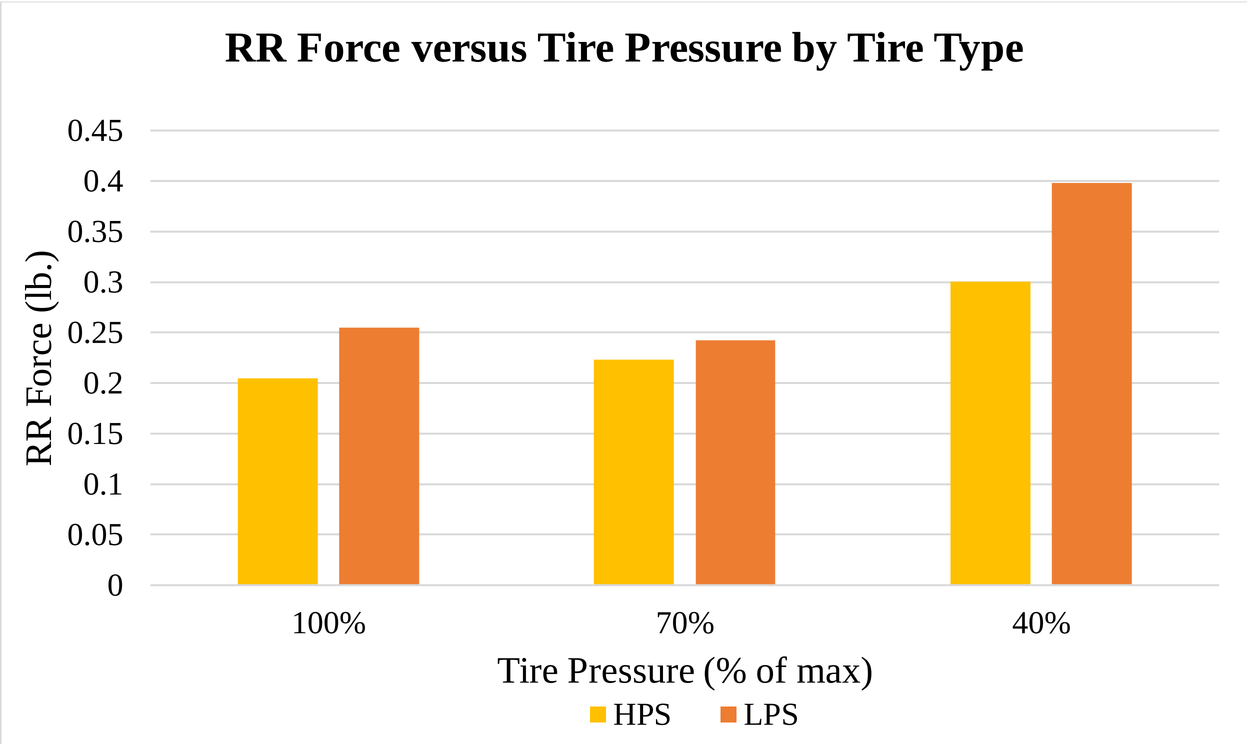
Toe was tested in 0.5-degree increments because we know that small increments of toe can have a large impact on RR, and changes were detected. An interesting result was that the 0.5-degree tests had a lower result than the 0-degree tests. However, the alignment of the arm relative to the drum can be adjusted and then retested to correct this. Moreover, in the coefficient of RR as compared to 0-degree toe (Appendix Figure 9). Solid inserts and solid tires had higher RR but were less susceptible to the effects of toe as compared to pneumatic tires. A test of 4 tires shows a statistically significant impact of toe with an ANOVA ($F = 49572.007$, $df = 2$, $p < .001$, Partial Eta Squared = 1.000).



Appendix Figure 9 Force versus Toe

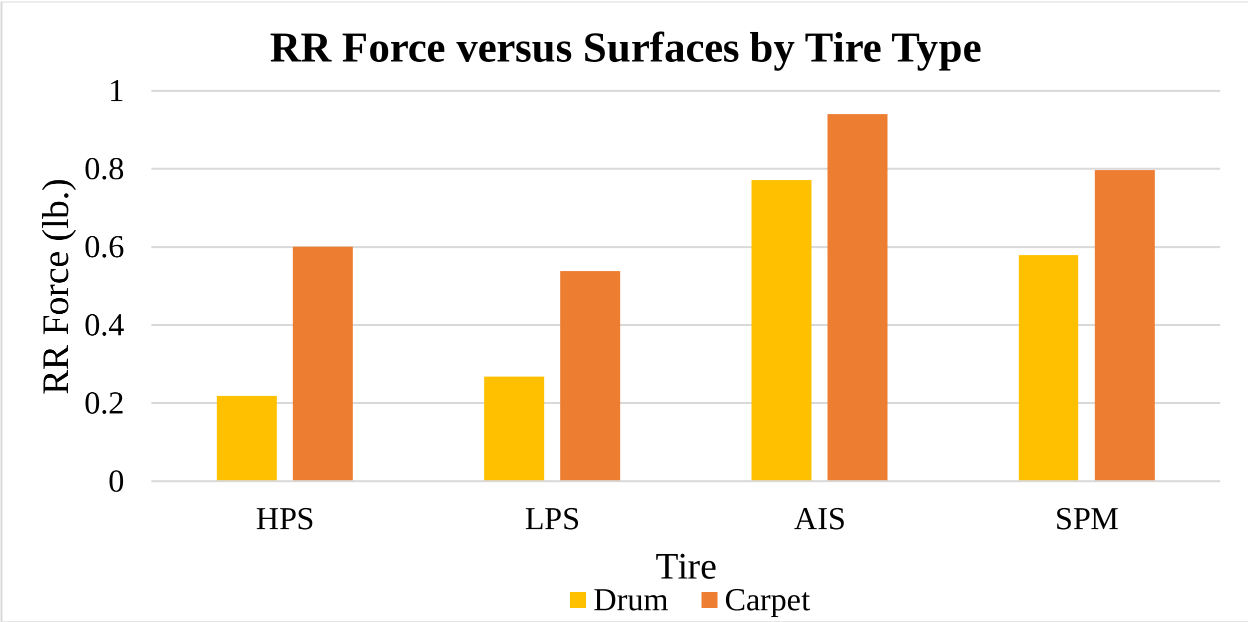
Organized by Tire, Pneumatic (HPS, LPS), Airless Insert, Solid

During the analysis an interaction effect was found between toe and tire type ($F = 388.410$, $df = 6$, $p < .001$, Partial Eta Squared = .993) as well as a main effect for tire type ($F = 2440.866$, $df = 3$, $p < .001$, Partial Eta Squared = .999). The results show a statistically significant impact of tire pressure ($F = 155.548$, $df = 2$, $p < .001$, Partial Eta Squared = .975) in Appendix Figure 10.



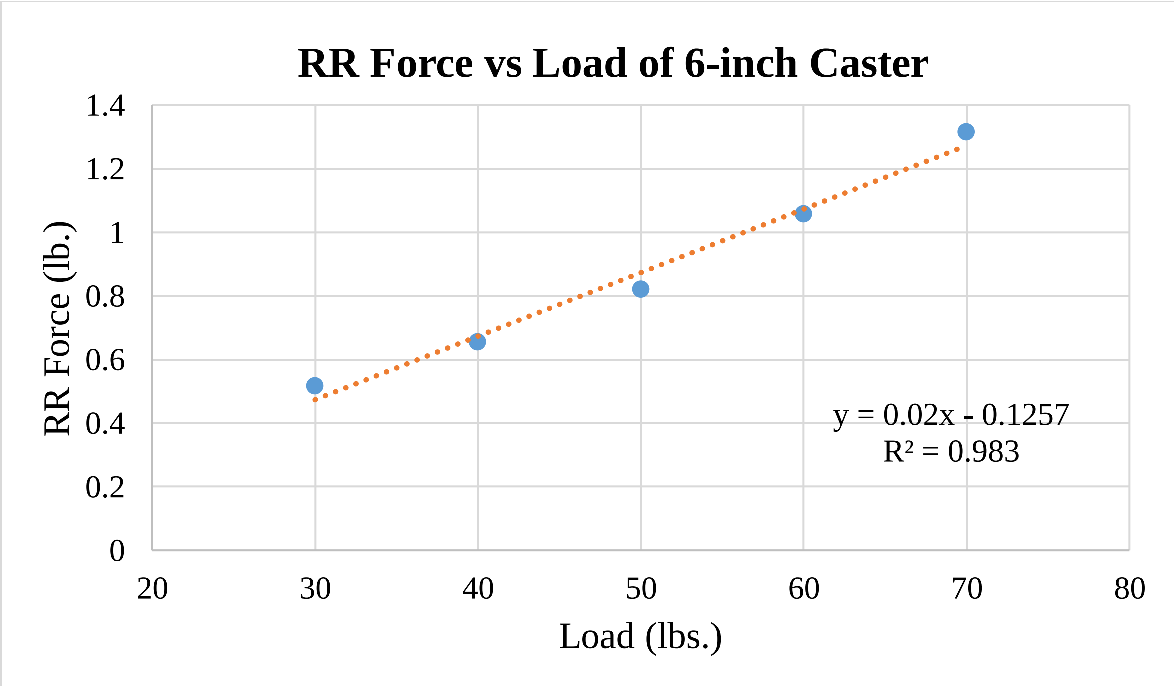
Appendix Figure 10 RR Force versus Tire Pressure Organized by Tire

One downside to the position of the wheel relative to the drum is that the tires always track in the same spot on the carpet. The carpet quickly becomes matted in this area. Further testing will conclude if this is a confounder of the results. Appendix Figure 11 demonstrates the results.



Appendix Figure 11 RR Force versus Surfaces Organized by Tire.

The caster stem bolt was vertical for testing and no flutter was experienced. It appears to remain proportional across loading trials as shown in Appendix Figure 12.



Appendix Figure 12 RR Force versus a Load of a 6-Inch Caster with a Trendline

Appendix A.4 Factor Testing Results

Furthermore, the variance is very low when the load cell amplification is factored in because the signal is scaled from the load cell to the computer input. One aspect of this is the high frequency of data sampling and then subsequent averaging of this data. Additionally, the machine is mainly measuring forces ranging from less than a pound to a couple of pounds. Therefore, the precision of the load cell is also of the quality needed for this level of instrumentation.

Surfaces were a challenging factor to test. The rolls of carpet were unrolled and placed flat to stretch out prior to drum installation. Then, they were left on the drum overnight, briefly removed, and reinstalled to ensure the best possible adherence. The carpet was installed against the direction of its pile to provide a worst-case scenario of RR.

Appendix A.5 Community-based Study

Appendix A.5.1 Recruitment

IRB approved registries developed by the Human Engineering Research Laboratories All registry participants have provided informed consent to be contacted for future research studies. The approved flyer for this study will be provided to the registry investigators to distribute to potential subjects according to the procedures established in the registry approved protocols. In response to the flyer, potential subjects will directly contact the research team if interested in participating. In addition, participants may be recruited through the Clinical and Translational Science Institute (CTSI) research participant registry and personal contacts.

Flyers may be posted in local rehabilitation facilities, outpatient facilities, and disability organizations. The flyers and advertisements instruct potential subjects to contact the study researchers for additional information.

Appendix A.5.2 Device

Rectangular 1.5 x 3-inch extrusions were used such that a u-shaped device would be torsionally stiff if lifted or moved from only one side. Appendix Figure 13 shows the laser and Appendix Figure 14 shows the jack. Additionally, wood blocks, covered with rubber, were used on top of the jack to avoid applying lifting force to anything mounted to the axle or frame, such as anti-tippers or power add-on mounts. Therefore, no matter the distance, the force applied would be consistent and the rubber hooks would not damage or mark the wheels or tires.

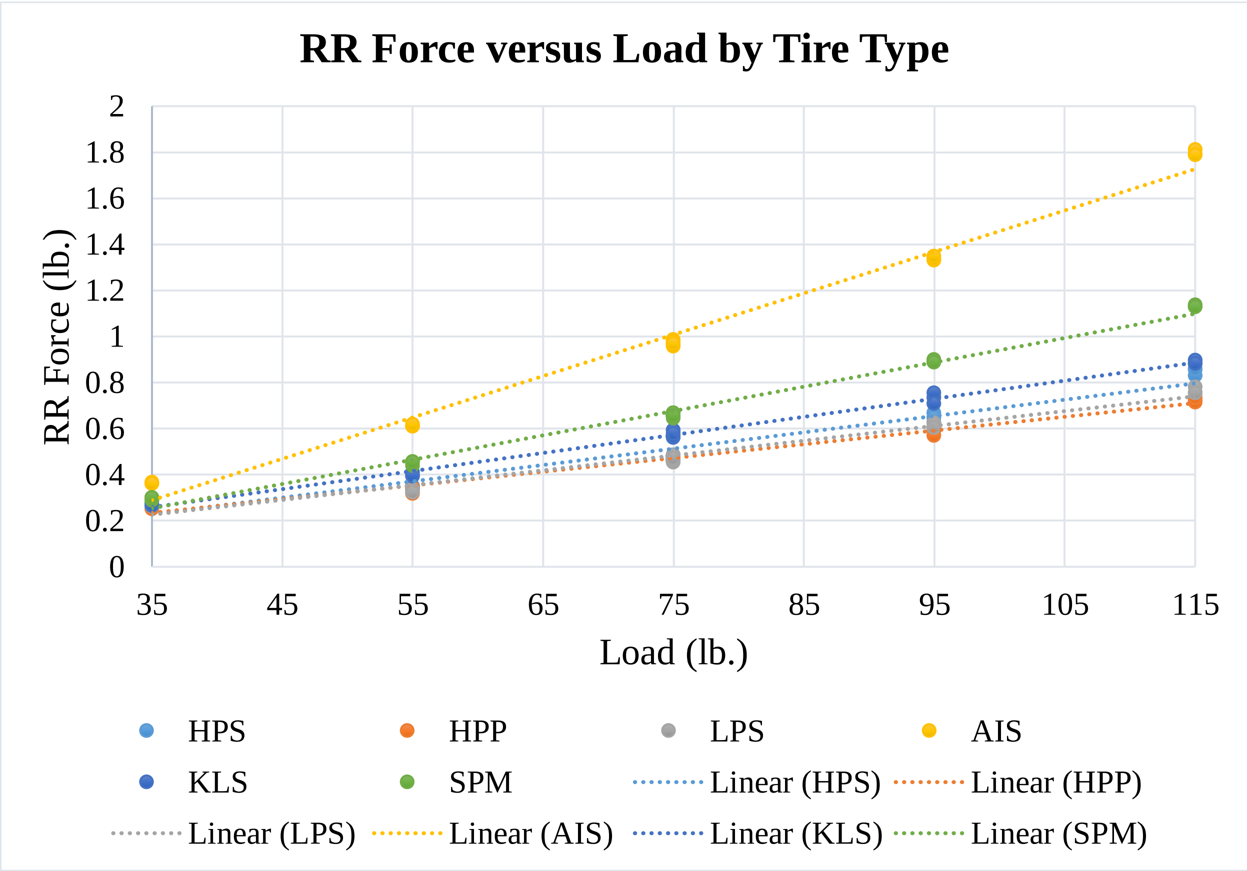
Appendix Figure 13 Banner Q4X Laser [83]

Appendix Figure 14 Motorcycle Jack

Appendix B Tire Rolling Resistance Testing Results and Analysis

This Appendix contains all scatterplots from RR testing for wheels. It is organized by single-factor, combined factor, and scatterplots for the HPS tire, which was the most common tire found in the community-based study. Factors evaluated included load, camber angle, toe angle, speed, tire pressure, and a variety of surfaces. Standard testing conditions are 75 lb. load, 1 m/s speed, 0 toe angle, 0 camber angle, 100% tire pressure and drum surface. These conditions or subsets of them are assumed when not otherwise noted. Below each scatterplot will be a table showing the coefficient from lines of best fit in accordance with that chart.

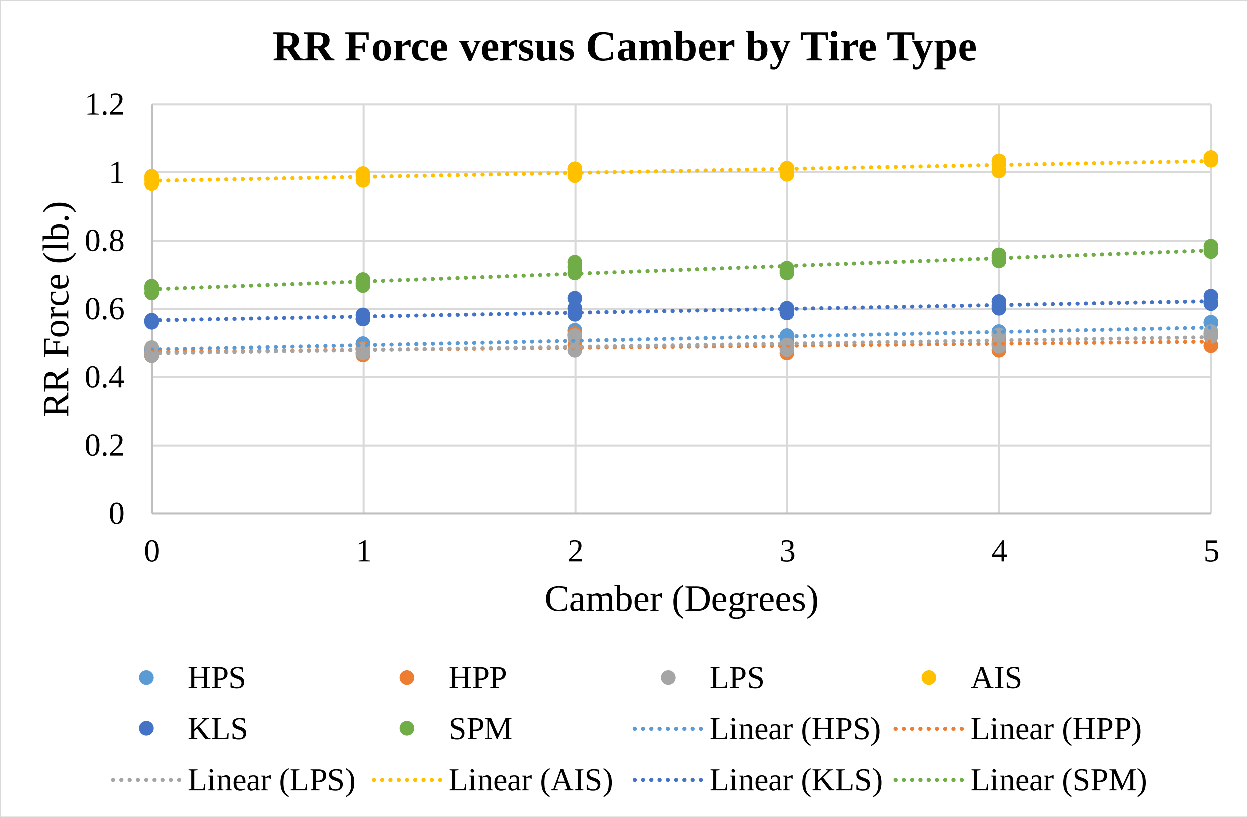
Appendix B.1 Single-factors



Appendix Figure 15 RR Force versus Load

Appendix Table 1 RR Force versus Load

	Slope (m)	Intercept (b)	R_2
HPS	0.0071	-0.0187	0.9475
HPP	0.0060	+0.0254	0.9885
LPS	0.0064	+0.0012	0.9752
AIS	0.0180	-0.3399	0.9879
KLS	0.0078	-0.0159	0.9949
SPM	0.0106	-0.1160	0.9892

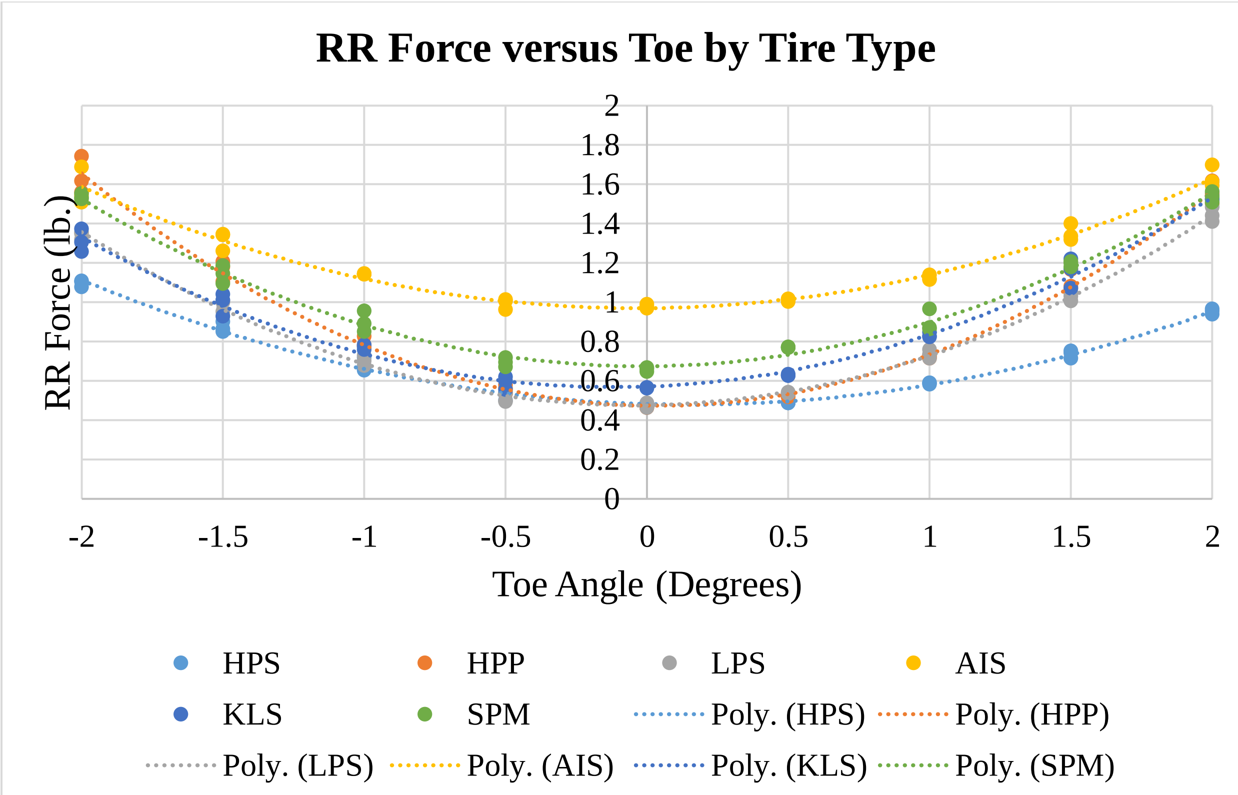


Appendix Figure 16 RR Force versus Camber

Appendix Table 2 RR Force versus Camber

	Slope (m)	**Intercept (b)**	**R_2**
HPS	0.0129	0.4809	0.6726
HPP	0.0060	0.4740	0.2633
LPS	0.0094	0.4700	0.5426
AIS	0.0115	0.9762	0.8005
KLS	0.0112	0.5666	0.6967
SPM	0.0228	0.6576	0.8994

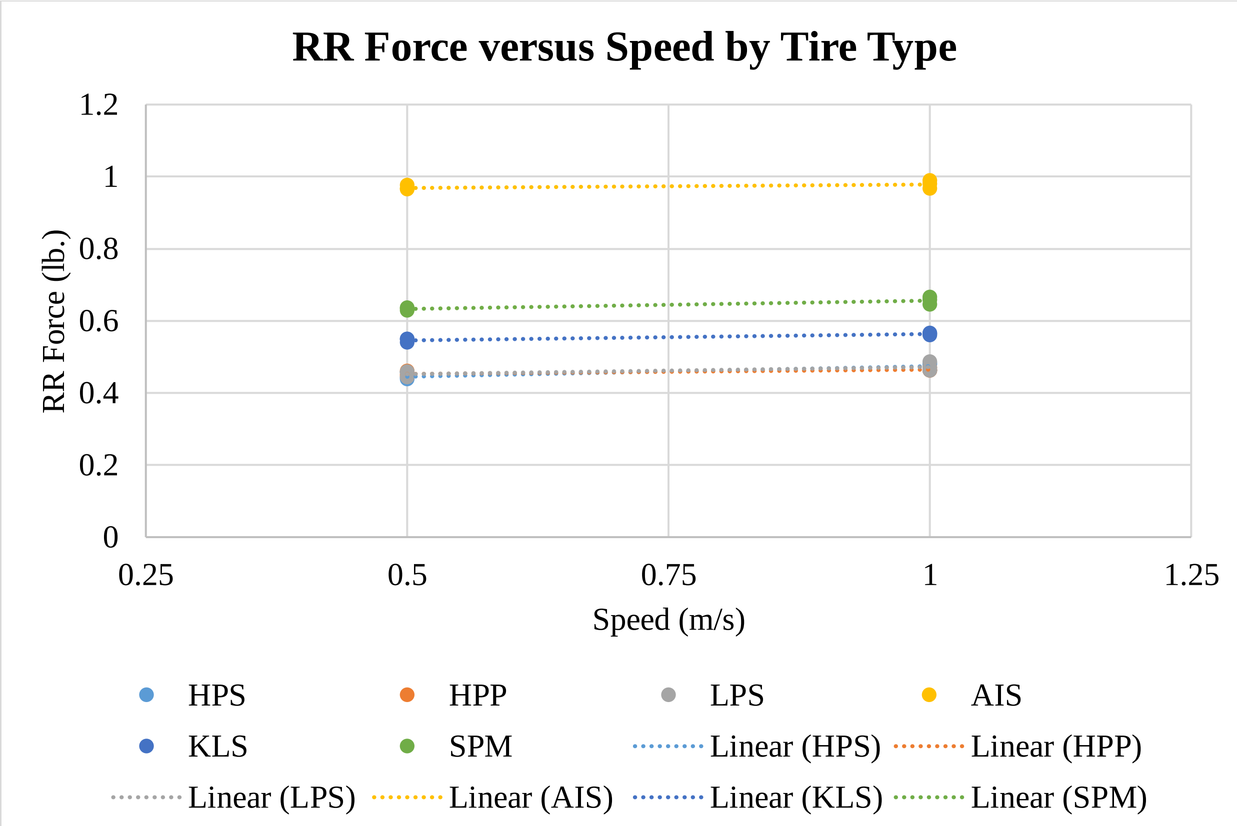
NOTE: Camber changes the positioning of the wheel tread contacting the drum, and this varies with different tread designs. For some wheels, RR forces at 3 camber are higher than measured at 4 or 5 camber. This causes very low R_2 for some best fit lines.



Appendix Figure 17 RR Force versus Toe

Appendix Table 3 RR Force versus Toe Angle

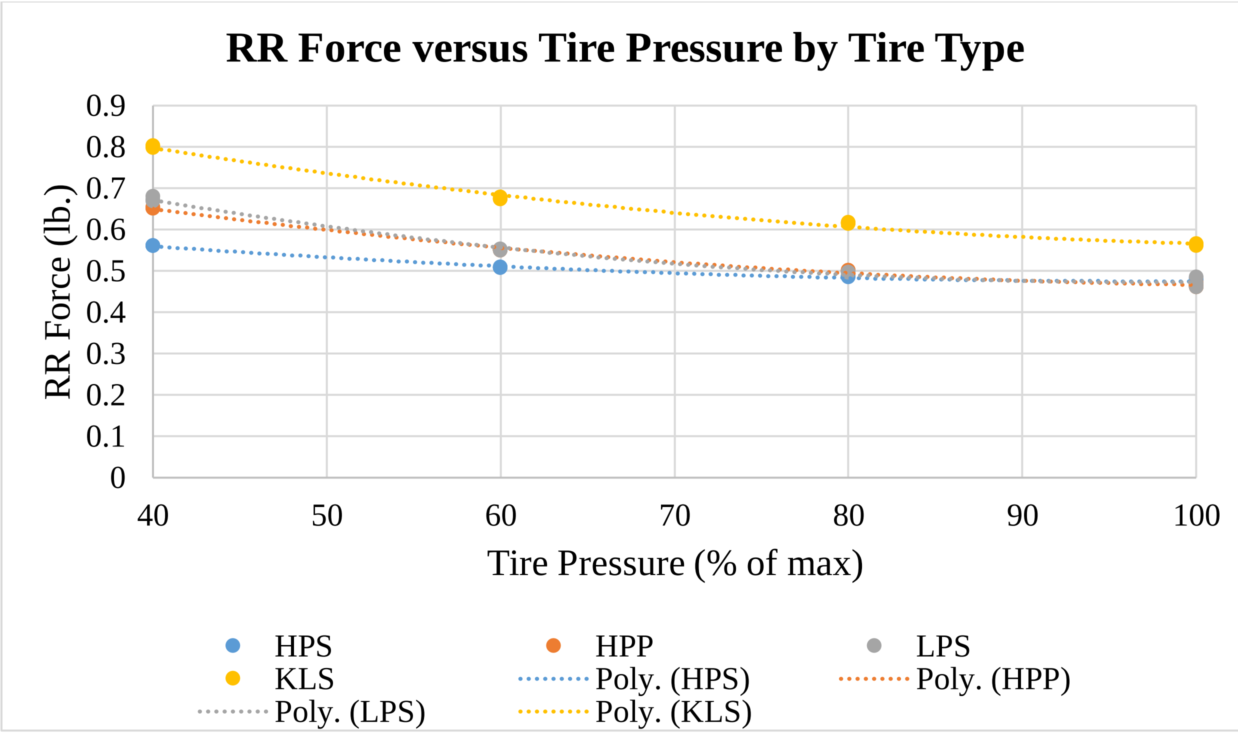
	Coefficient (X^2)	Coefficient X	Constant	R^2
HPS	0.1377	-0.0401	0.4822	0.991
HPP	0.2839	-0.0228	0.4739	0.9907
LPS	0.2308	0.0211	0.4766	0.9954
AIS	0.1595	0.0102	0.9698	0.9745
KLS	0.2151	0.0506	0.5713	0.9872
SPM	0.2165	0.0080	0.6748	0.9882



Appendix Figure 18 RR Force versus Speed

Appendix Table 4 RR Force versus Speed

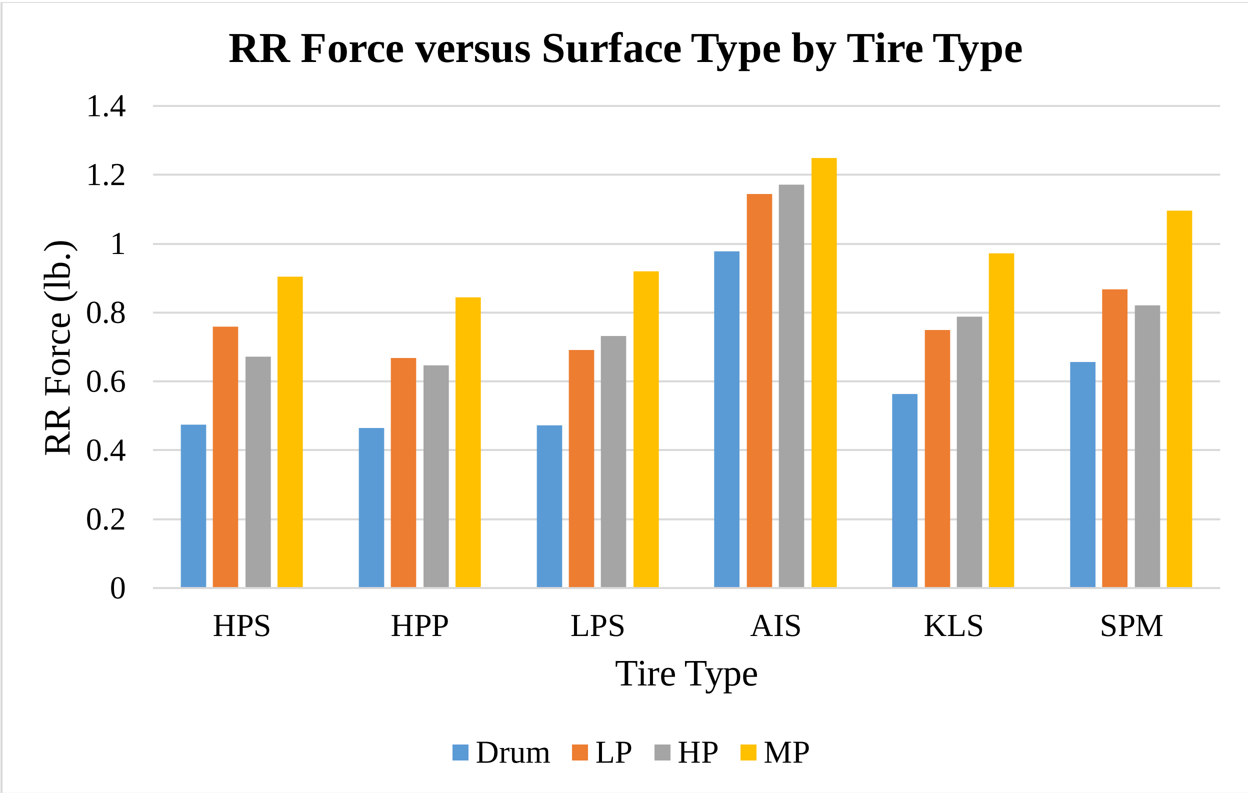
	Slope (m)	Intercept (b)	R_2
HPS	0.0584	0.4158	0.7482
HPP	0.0240	0.4407	0.6407
LPS	0.0391	0.4327	0.5739
AIS	0.0194	0.9588	0.3241
KLS	0.0358	0.5278	0.8583
SPM	0.0464	0.6097	0.7793



Appendix Figure 19 RR Force versus Pressure

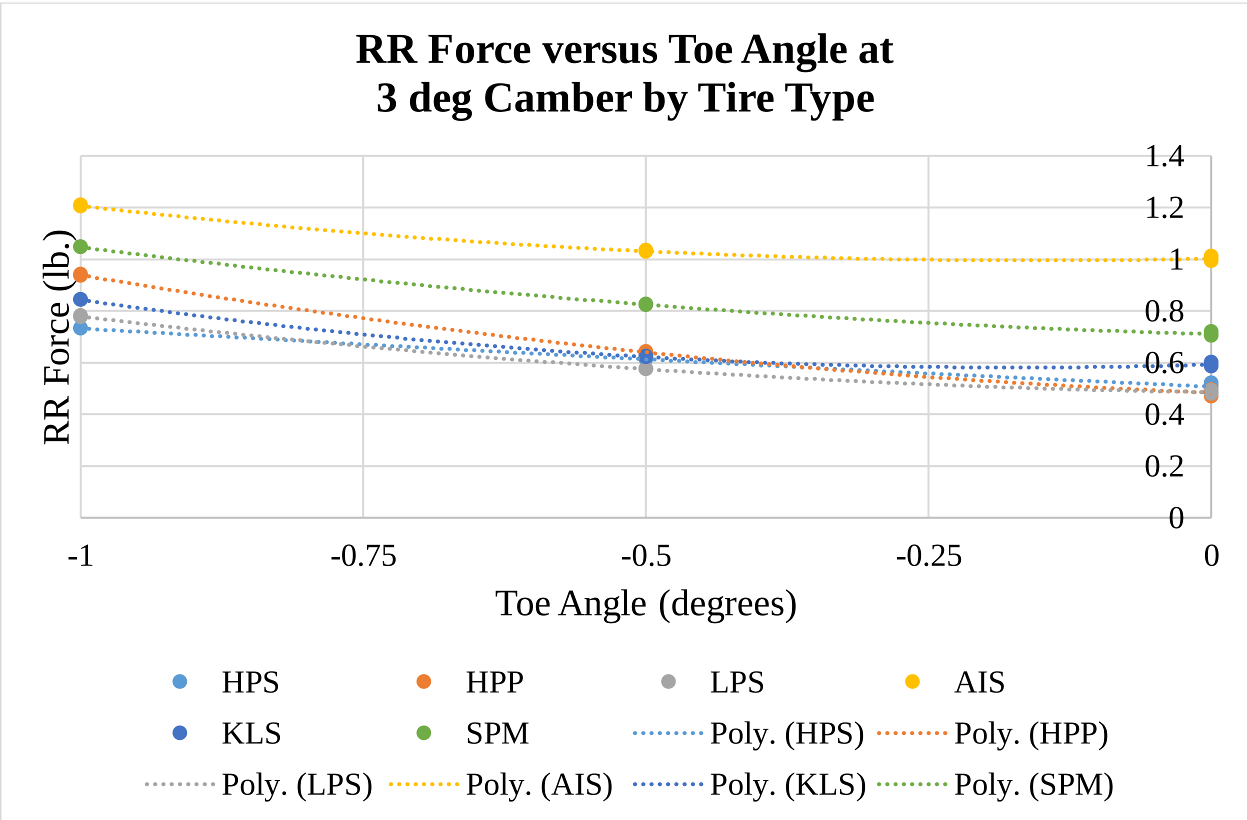
Appendix Table 5 RR Force versus Tire Pressure

	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
HPS	3E-05	-0.0050	0.7180	0.9772
HPP	4E-05	-0.0088	0.9378	0.9957
LPS	6E-05	-0.0119	1.0481	0.9920
KLS	5E-05	-0.0103	1.1351	0.9941



Appendix Figure 20 RR Force versus Surfaces

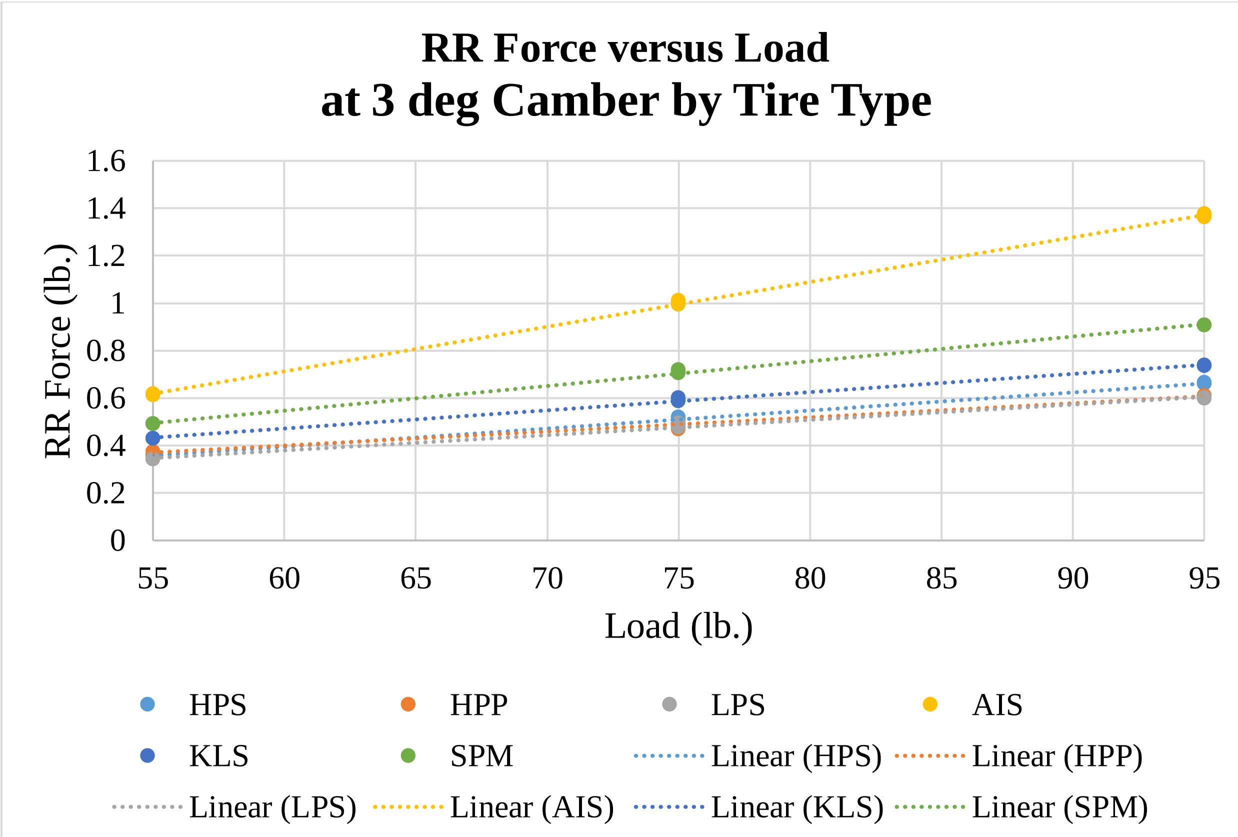
Appendix B.2 Combined Factors



Appendix Figure 21 RR Force versus Toe Angle at 3 Camber, Drum Surface

Appendix Table 6 RR Force versus Toe Angle, 3 Camber, Drum Surface

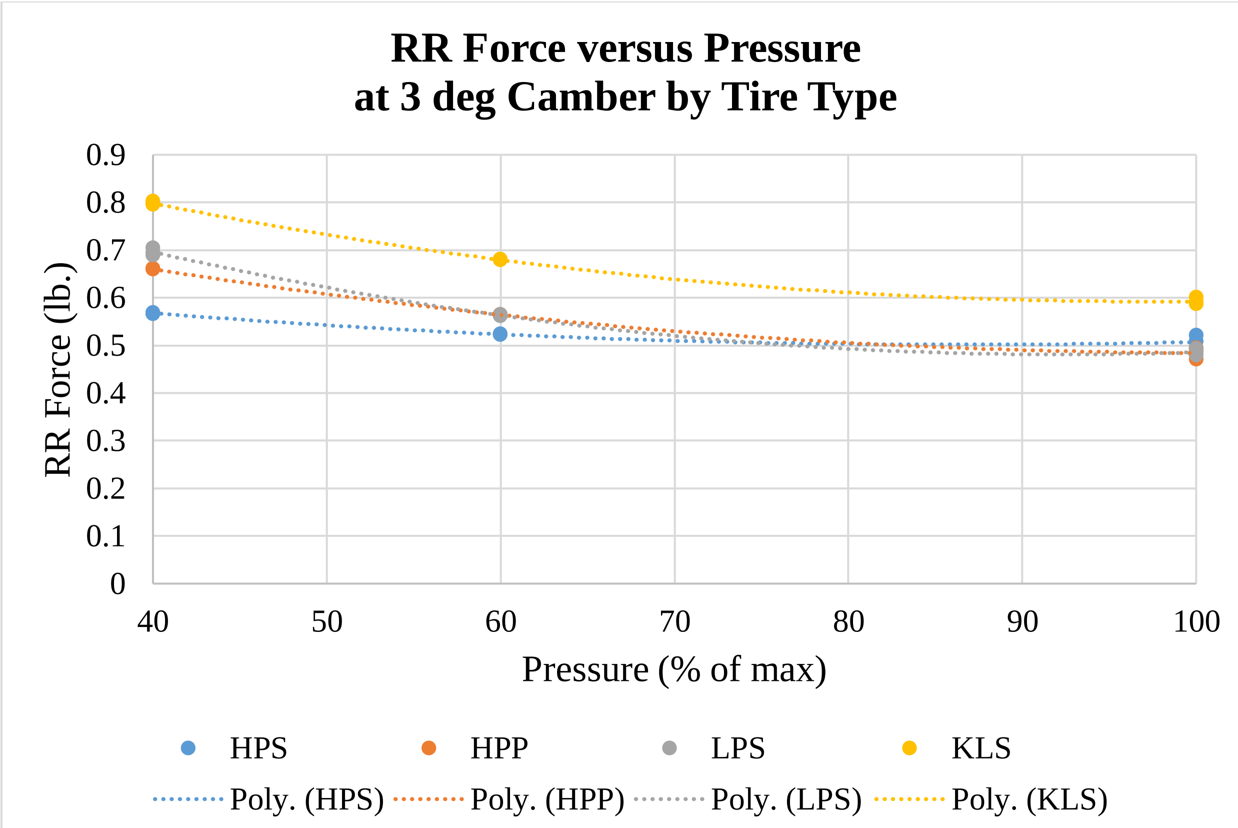
	Coefficient (X_2)	Coefficient (X)	Constant	R_2
HPS	0.0278	-0.1974	0.5072	0.9948
HPP	0.2846	-0.1698	0.4842	0.9989
LPS	0.2289	-0.0643	0.4857	0.9992
AIS	0.2943	0.0899	1.0022	0.9976
KLS	0.3826	0.1317	0.5925	0.9999
SPM	0.2173	-0.1190	0.7105	0.9994



Appendix Figure 22 RR Force versus Load at 3 Camber, Drum Surface

Appendix Table 7 RR Force versus Load at 3 Camber, Drum Surface

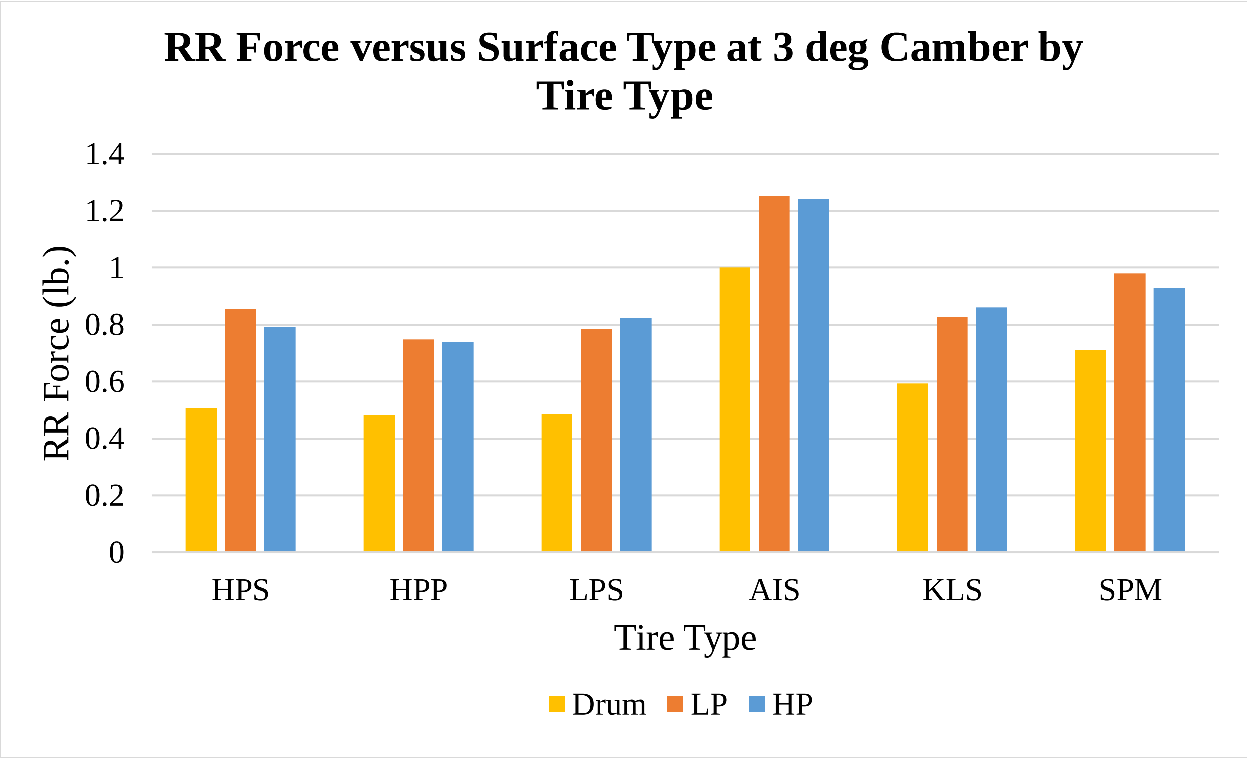
	Slope (m)	**Intercept (b)**	**R_2**
HPS	0.0076	-0.0610	0.9967
HPP	0.0059	0.0440	0.9950
LPS	0.0064	-0.0070	0.9947
AIS	0.0188	-0.4167	0.9994
KLS	0.0077	0.0111	0.9982
SPM	0.0104	-0.0782	0.9986



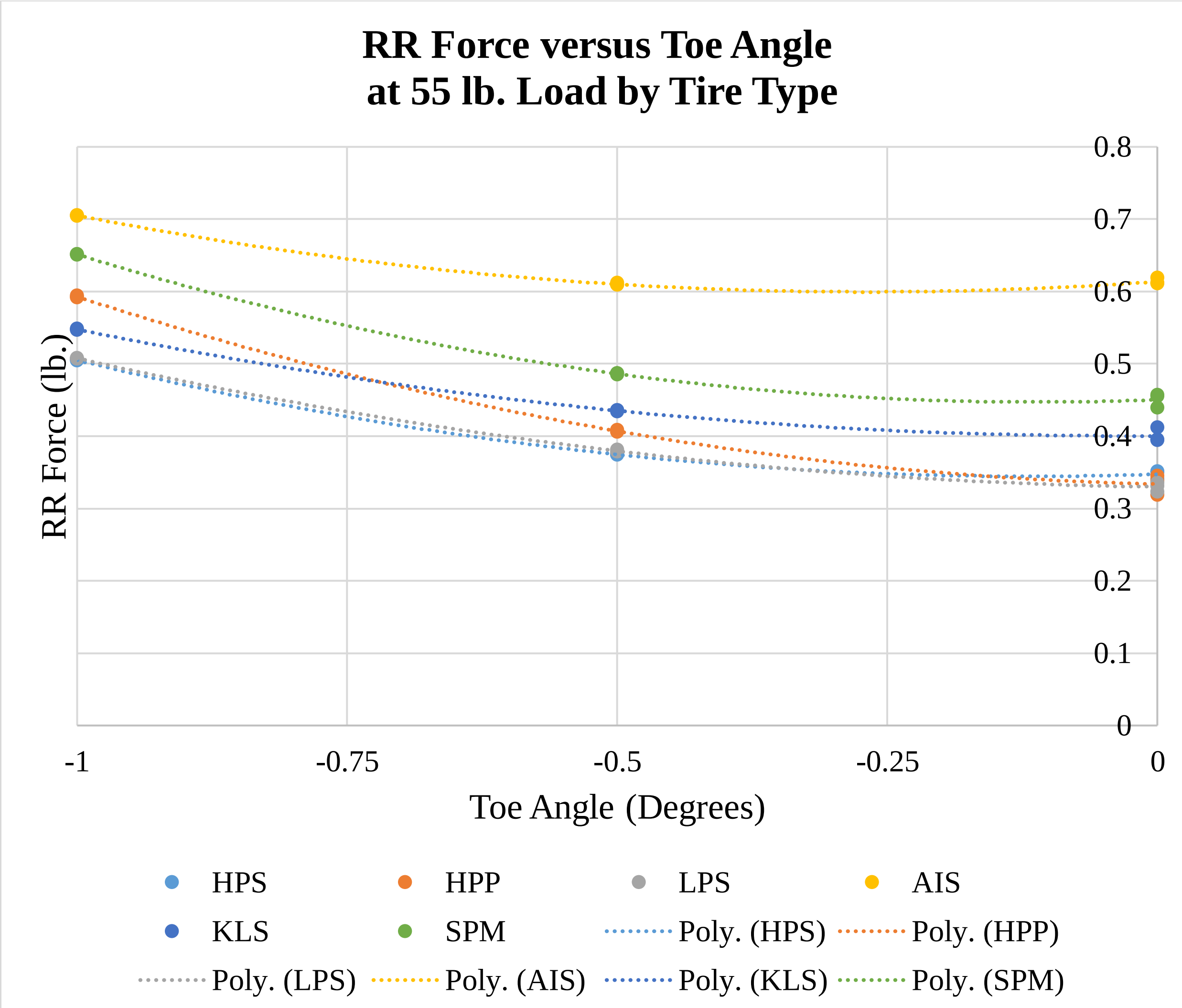
Appendix Figure 23 RR Force versus Pressure at 3 Camber, Drum Surface

Appendix Table 8 RR Force versus Tire Pressure at Camber 3, Drum Surface

	Coefficient (X_2)	**Coefficient (X)**	**Constant**	**R_2**
HPS	3E-05	-0.0053	0.7301	0.9359
HPP	5E-05	-0.0095	0.9641	0.9931
LPS	3E-05	-0.0145	1.1503	0.9966
KLS	6E-05	-0.0122	1.1859	0.9979



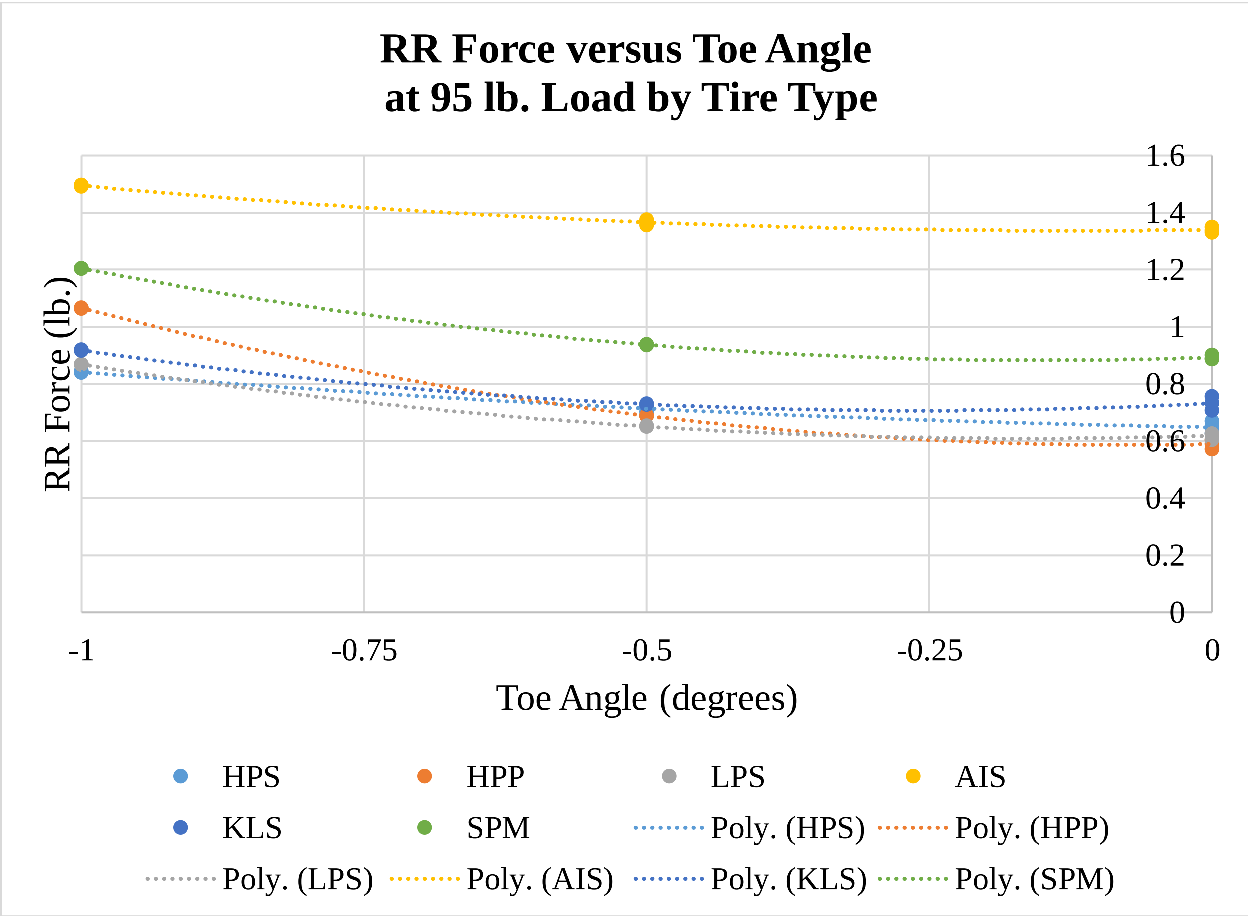
Appendix Figure 24 RR Force versus Surfaces at 3 Camber



Appendix Figure 25 RR Force versus Toe Angle at 55 lb. Load, Drum Surface

Appendix Table 9 RR Force versus Toe Angle at 55 lb. Load, Drum Surface

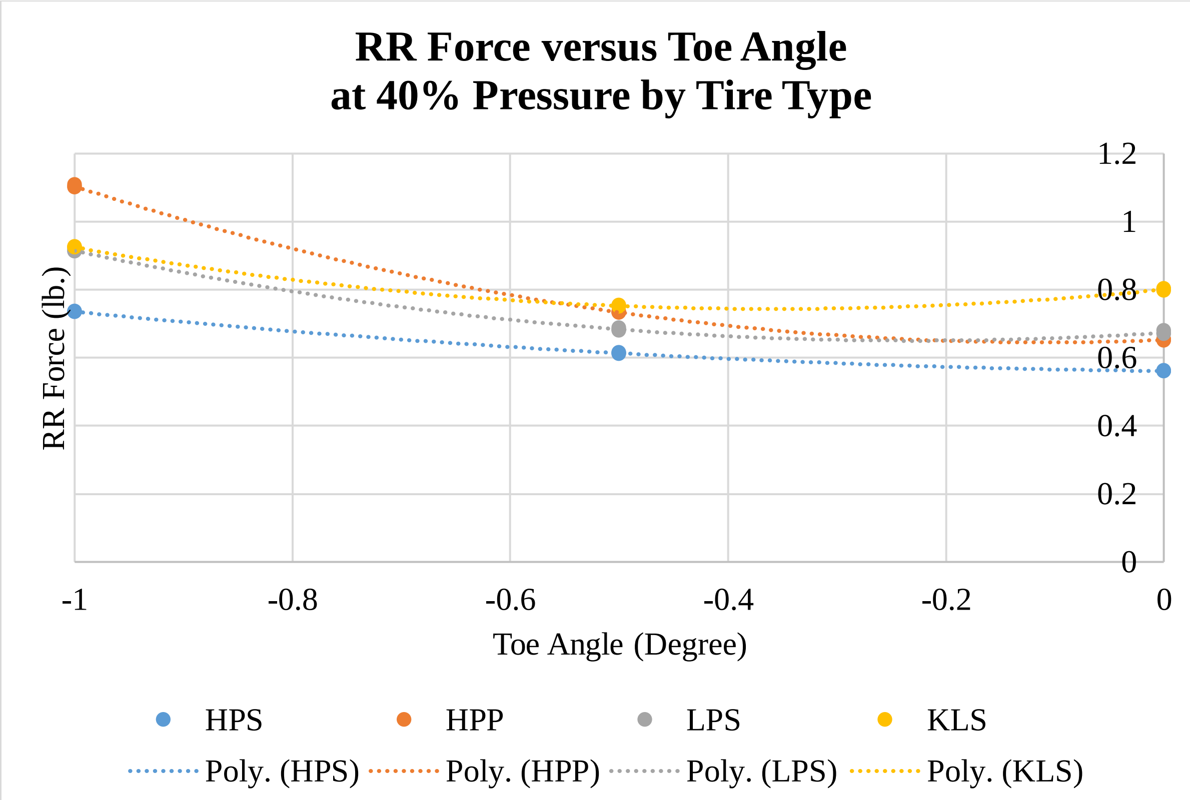
	Coefficient (X^2)	Coefficient (X)	Constant	R^2
HPS	0.2067	0.0490	0.3474	0.9983
HPP	0.2254	-0.0338	0.3337	0.9964
LPS	0.1573	-0.0205	0.3298	0.9982
AIS	0.1978	0.1065	0.6138	0.9973
KLS	0.1554	0.0083	0.4005	0.9946
SPM	0.2589	0.0581	0.4504	0.9971



Appendix Figure 26 RR Force versus Toe Angle at 95 lb. Load, Drum Surface

Appendix Table 10 RR Force versus Toe Angle at 95 lb. Load, Drum Surface

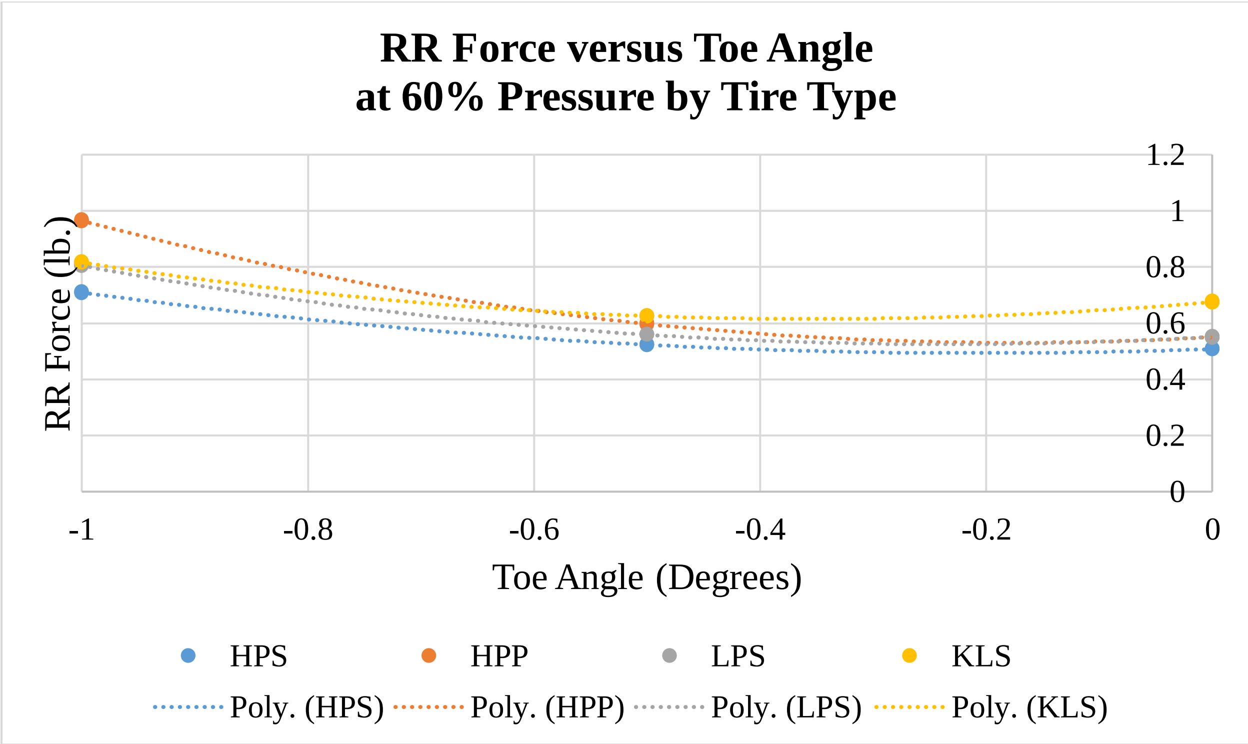
	Coefficient (X_2)	Coefficient (X)	Constant	R_2
HPS	0.1259	-0.0676	0.6484	0.9823
HPP	0.5562	0.0797	0.5892	0.9984
LPS	0.3693	0.1197	0.6185	0.9974
AIS	0.2038	0.0489	1.3399	0.9918
KLS	0.3833	0.1977	0.7322	0.9840
SPM	0.4464	0.1342	0.8929	0.9994



Appendix Figure 27 RR Force versus Toe Angle at 40% Pressure, Drum Surface

Appendix Table 11 RR Force versus Toe Angle at 40% Pressure, Drum Surface

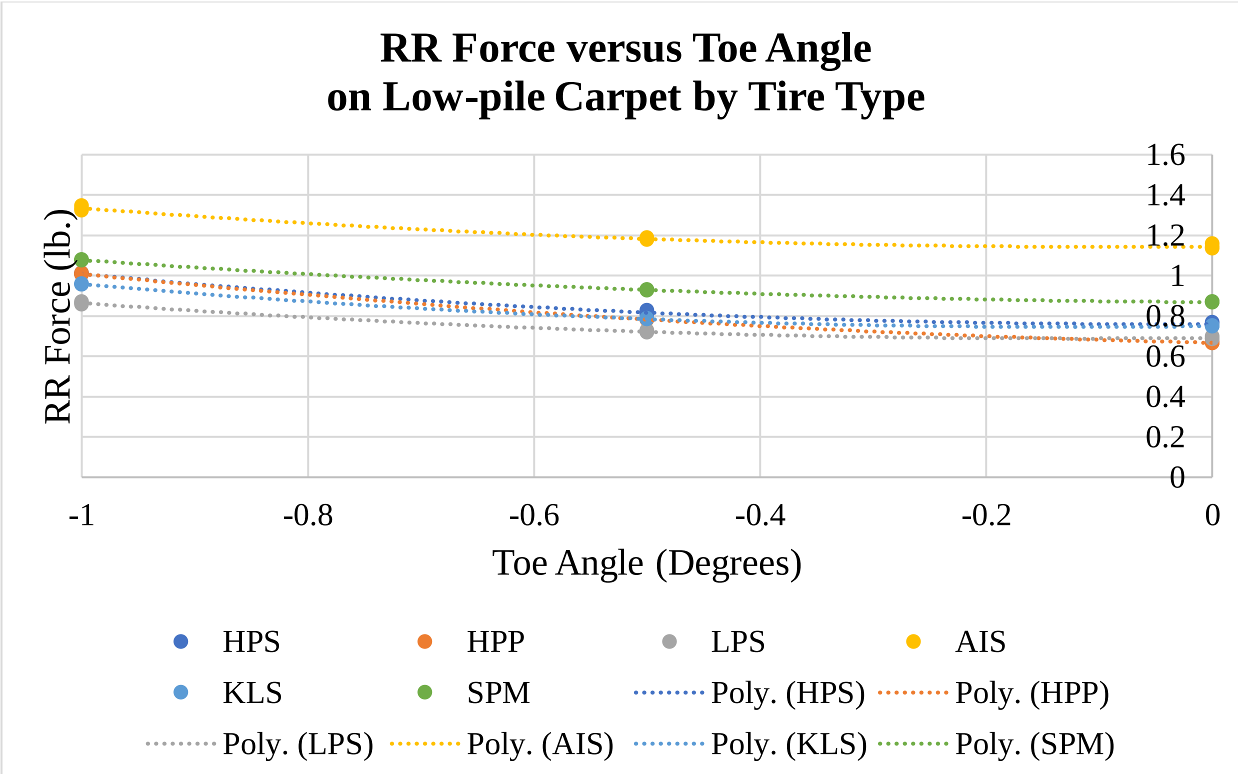
	Coefficient (X_2)	Coefficient (X)	Constant	R_2
HPS	0.1399	-0.0343	0.5610	0.9998
HPP	0.5781	0.1267	0.6522	0.9999
LPS	0.4441	0.2029	0.6734	0.9989
KLS	0.4415	0.3172	0.8005	0.9994



Appendix Figure 28 RR Force versus Toe Angle at 60% Pressure, Drum Surface

Appendix Table 12 RR Force versus Toe Angle at 60% Pressure, Drum Surface

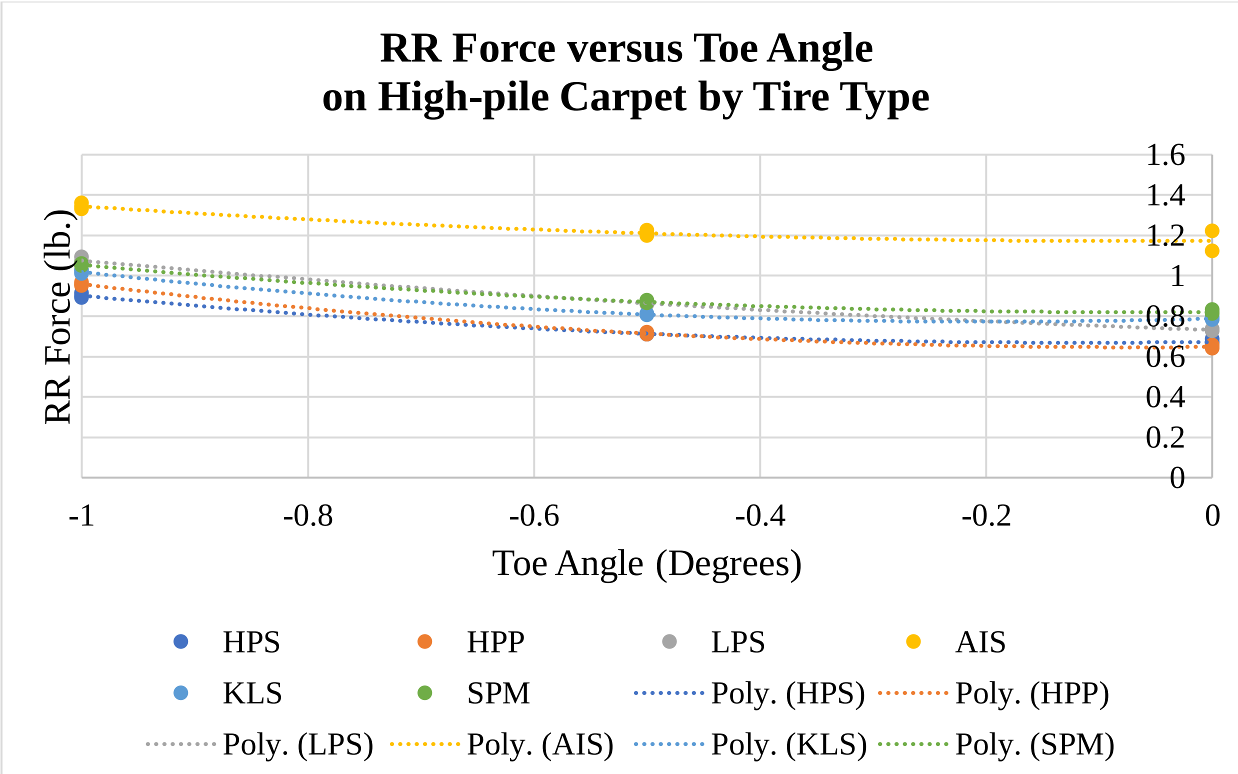
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
HPS	0.3423	0.1412	0.5080	0.9999
HPP	0.6405	0.2263	0.5506	0.9999
LPS	0.4759	0.2221	0.5509	0.9999
KLS	0.4823	0.3409	0.6752	0.9997



Appendix Figure 29 RR Force versus Toe Angle and Low-pile Carpet

Appendix Table 13 RR Force versus Toe Angle and Low-pile Carpet

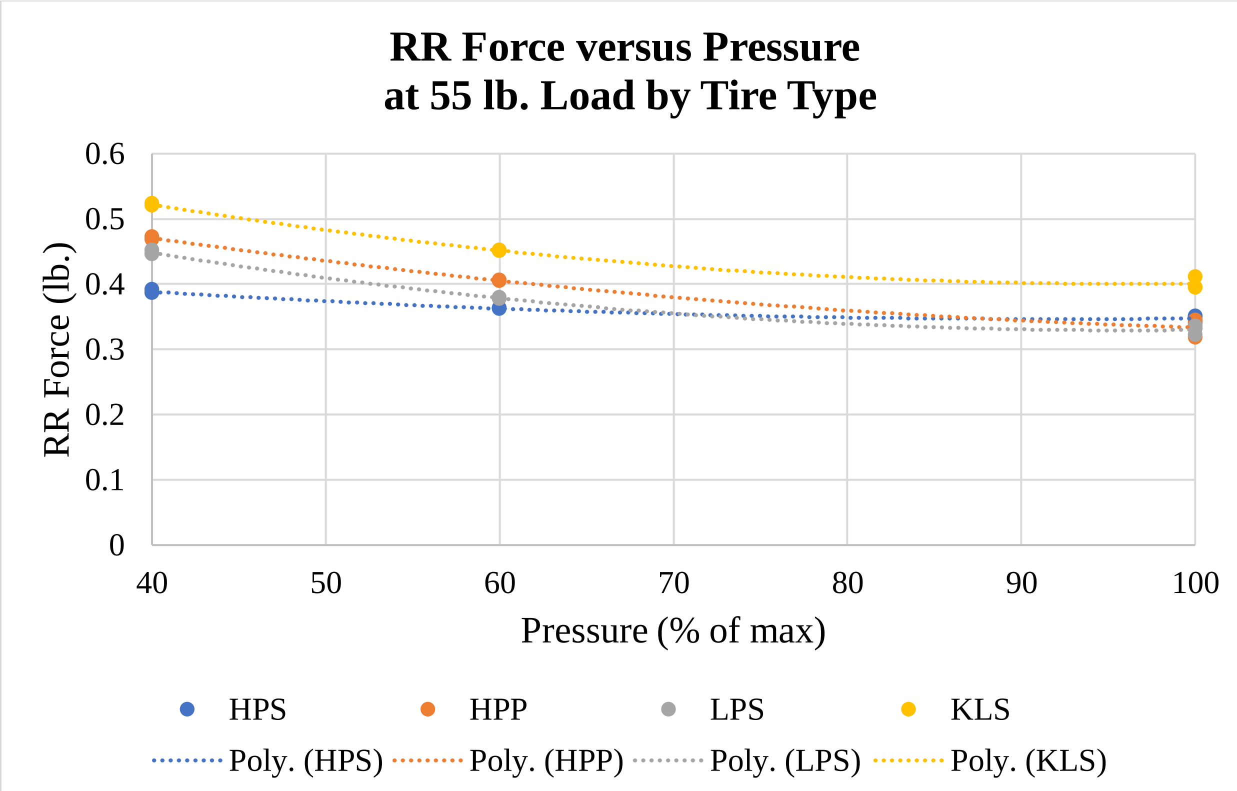
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
HPS	0.2705	0.0214	0.7597	0.9970
HPP	0.2222	-0.1186	0.6673	0.9997
LPS	0.2242	0.0517	0.6912	0.9958
AIS	0.2303	0.0399	1.1446	0.9890
KLS	0.2743	0.0665	0.7494	0.9998
SPM	0.1748	-0.0344	0.8681	0.9998



Appendix Figure 30 RR Force versus Toe Angle and High-pile Carpet

Appendix Table 14 RR Force versus Toe Angle and High-pile Carpet

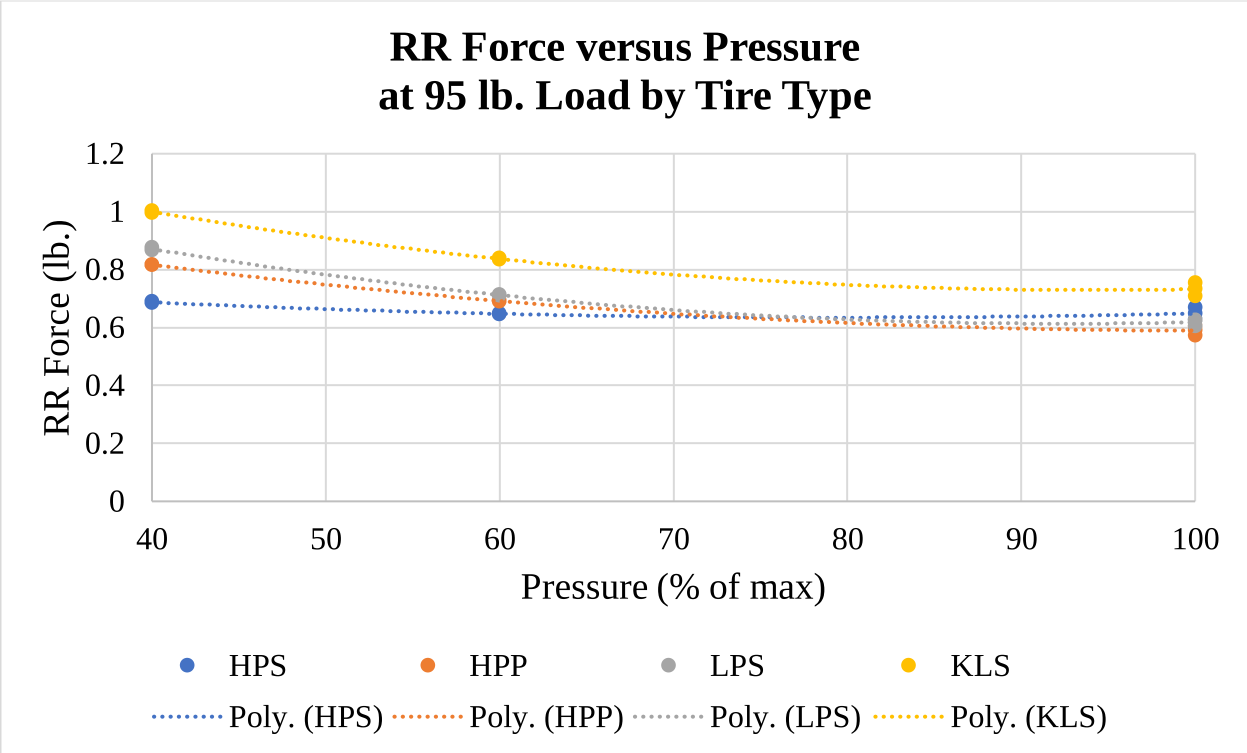
	Coefficient (X_2)	Coefficient (X)	Constant	R_2
HPS	0.2974	0.0685	0.6727	0.9941
HPP	0.3579	0.0470	0.6476	0.9982
LPS	0.1581	-0.1860	0.7316	9.9965
AIS	0.1932	0.0212	1.1724	0.8824
KLS	0.3816	0.1499	0.7875	0.9975
SPM	0.2667	0.0336	0.8207	0.9965



Appendix Figure 31 RR Force versus Pressure at 55 lb. Load, Drum Surface

Appendix Table 15 RR Force versus Pressure at 55 lb. Load, Drum Surface

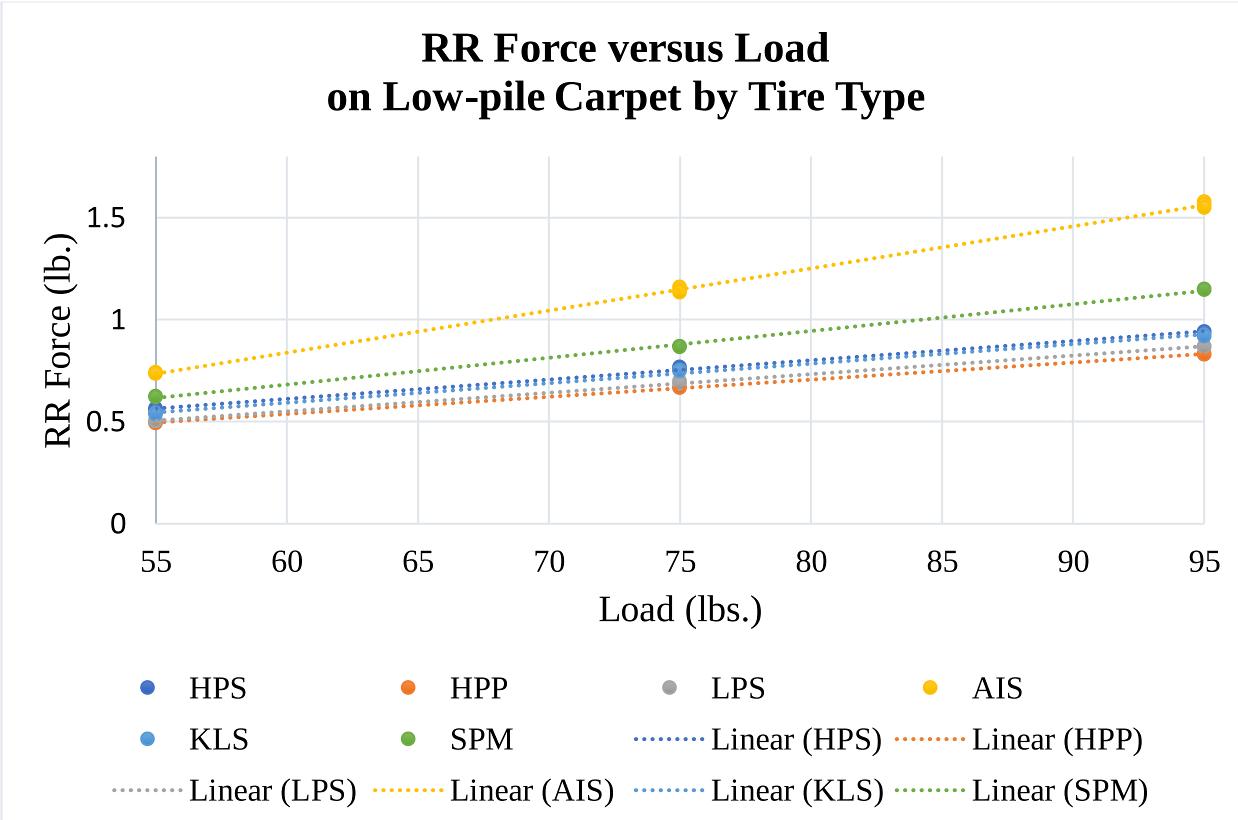
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
HPS	2E-05	-0.0028	0.4766	0.9653
HPP	2E-05	-0.0057	0.6612	0.9865
LPS	4E-05	-0.0072	0.6774	0.9949
KLS	4E-05	-0.0073	0.7527	0.9913



Appendix Figure 32 RR Force versus Pressure at 95 lb. Load, Drum Surface

Appendix Table 16 RR Force versus Pressure at 95 lb. Load, Drum Surface

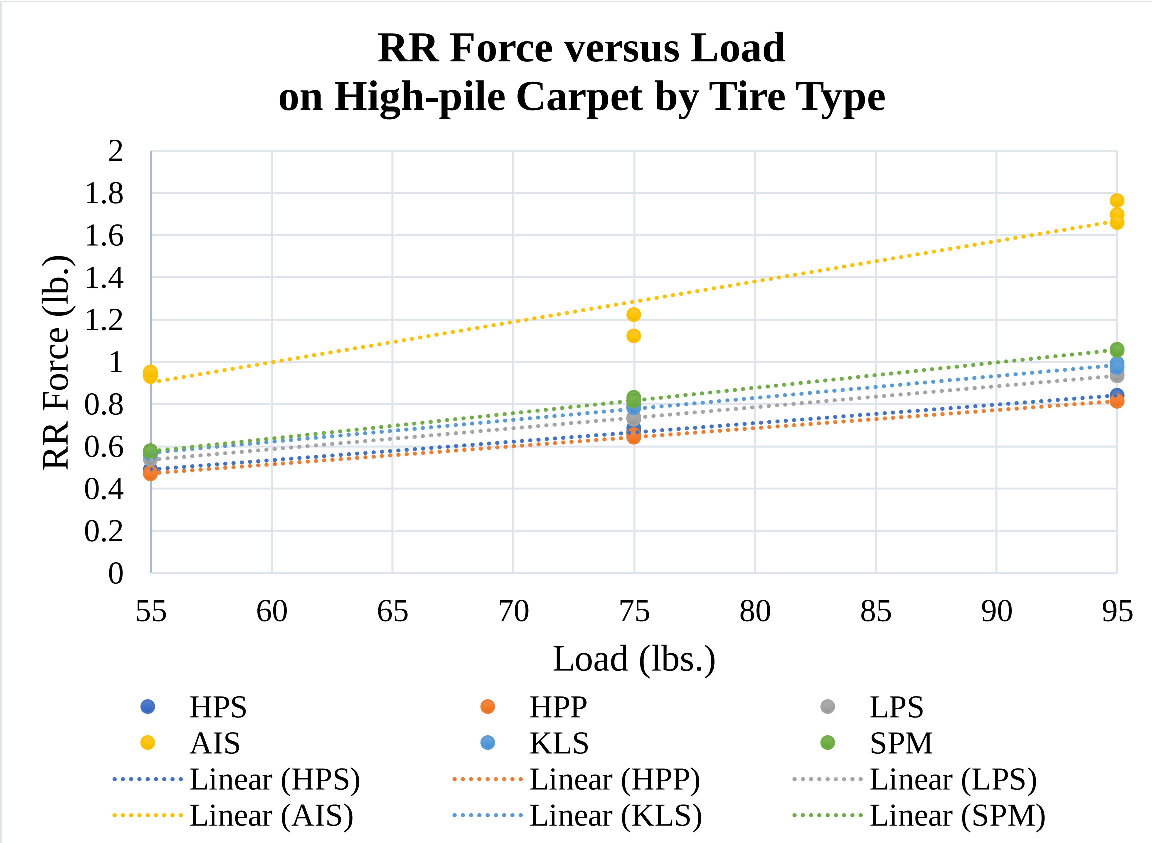
	Coefficient (X2)	**Coefficient (X)**	**Constant**	**R2**
HPS	3E-05	-0.0053	0.8460	0.7838
HPP	6E-05	-0.0124	1.2145	0.9925
LPS	9E-05	-0.0174	1.4154	0.9967
KLS	9E-05	-0.0174	1.5474	0.9895



Appendix Figure 33 RR Force versus Load and Low-pile Carpet

Appendix Table 17 RR Force versus Load and Low-pile Carpet

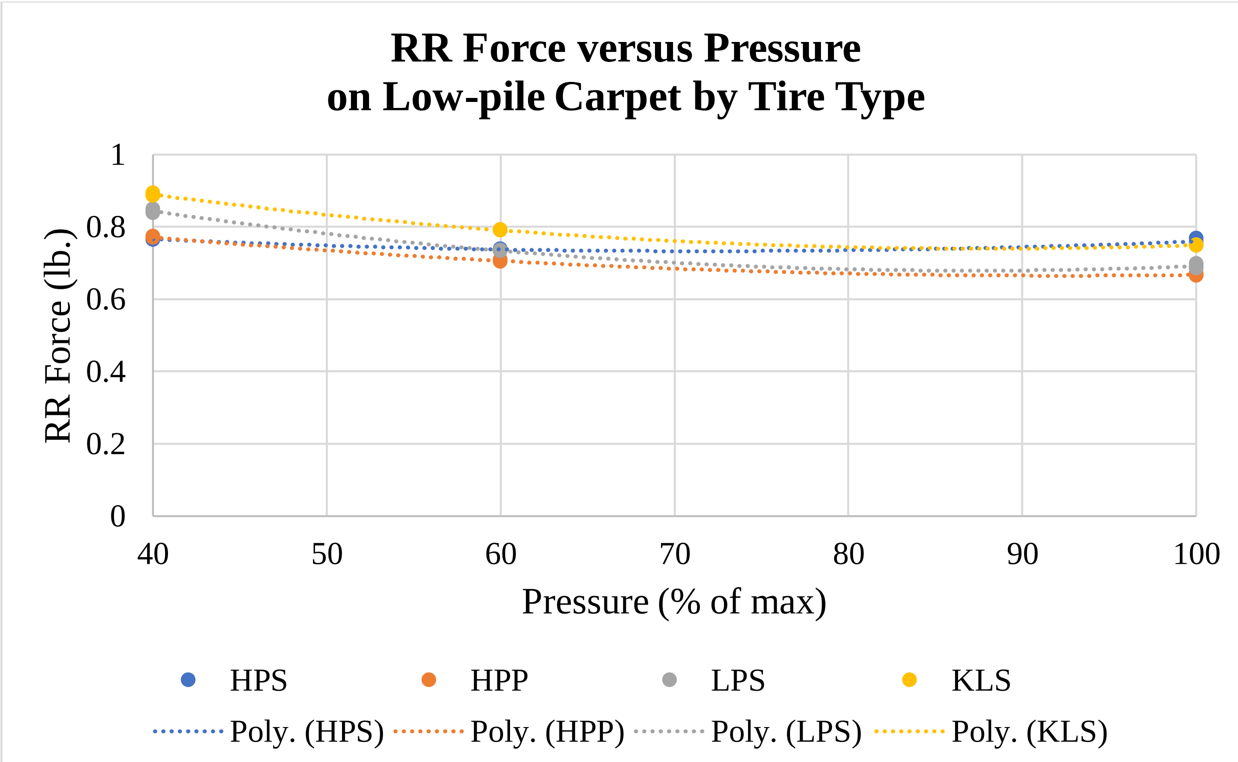
	Slope (m)	Intercept (b)	R^2
HPS	0.0095	0.0442	0.9986
HPP	0.0084	0.0338	0.9997
LPS	0.0091	0.0040	0.9991
AIS	0.0207	-0.4006	0.9991
KLS	0.0096	0.0191	0.9966
SPM	0.0131	-0.1056	0.9986



Appendix Figure 34 RR Force versus Load and High-pile Carpet

Appendix Table 18 RR Force versus Load ad High-pile Carpet

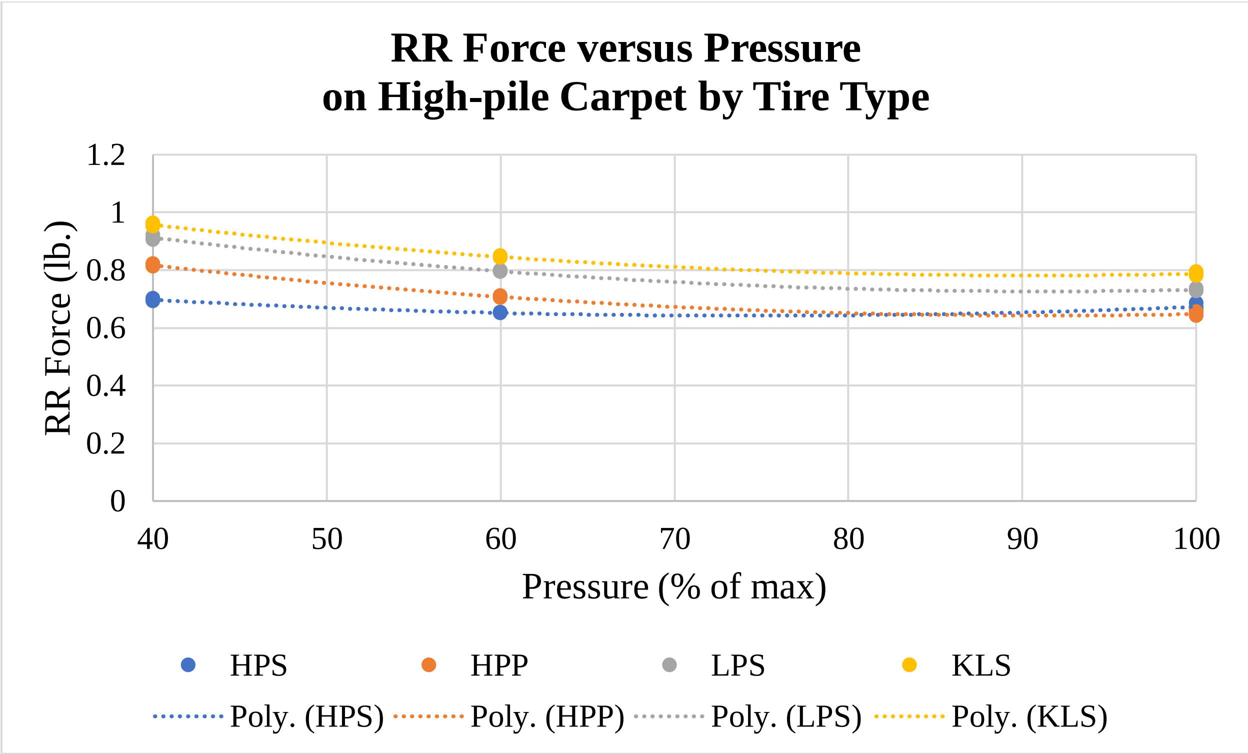
	Slope (m)	**Intercept (b)**	**R_2**
HPS	0.0088	0.0094	0.9976
HPP	0.0086	0.0019	0.9989
LPS	0.0099	-0.0098	0.9992
AIS	0.0191	-0.1485	0.9515
KLS	0.0104	0.0001	0.9971
SPM	0.0120	-0.0826	0.9993



Appendix Figure 35 RR Force versus Pressure and Low-pile Carpet

Appendix Table 19 RR Force versus Pressure and Low-pile Carpet

	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
HPS	3E-05	-0.0047	0.9030	0.9137
HPP	4E-05	-0.0072	0.9972	0.9976
LPS	7E-05	-0.0129	1.2402	0.9958
KLS	6E-05	-0.0114	1.2415	0.9991

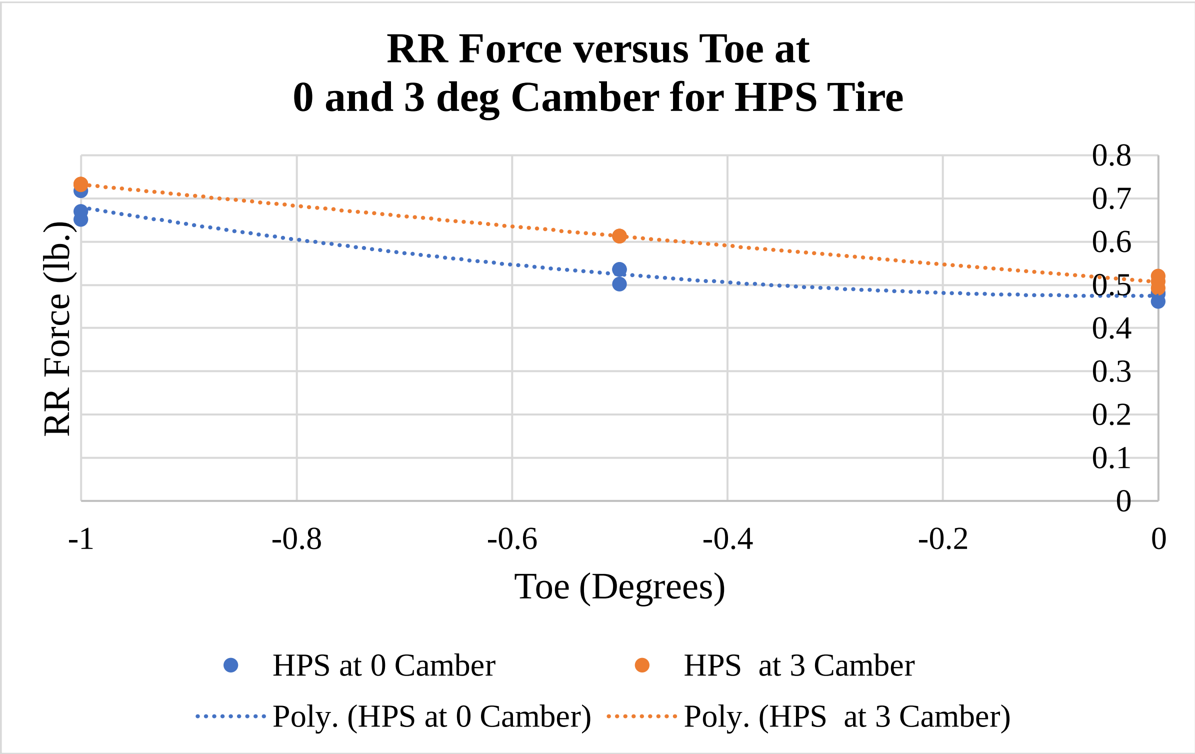


Appendix Figure 36 RR Force versus Pressure and High-pile Carpet

Appendix Table 20 RR Force versus Pressure and High-pile Carpet

	Coefficient (X^2)	Coefficient (X)	Constant	R^2
HPS	5E-05	-0.0069	0.8993	0.9165
HPP	7E-05	-0.0121	1.1933	0.9963
LPS	7E-05	-0.0129	1.3148	0.9962
KLS	7E-05	-0.0124	1.3440	0.9954

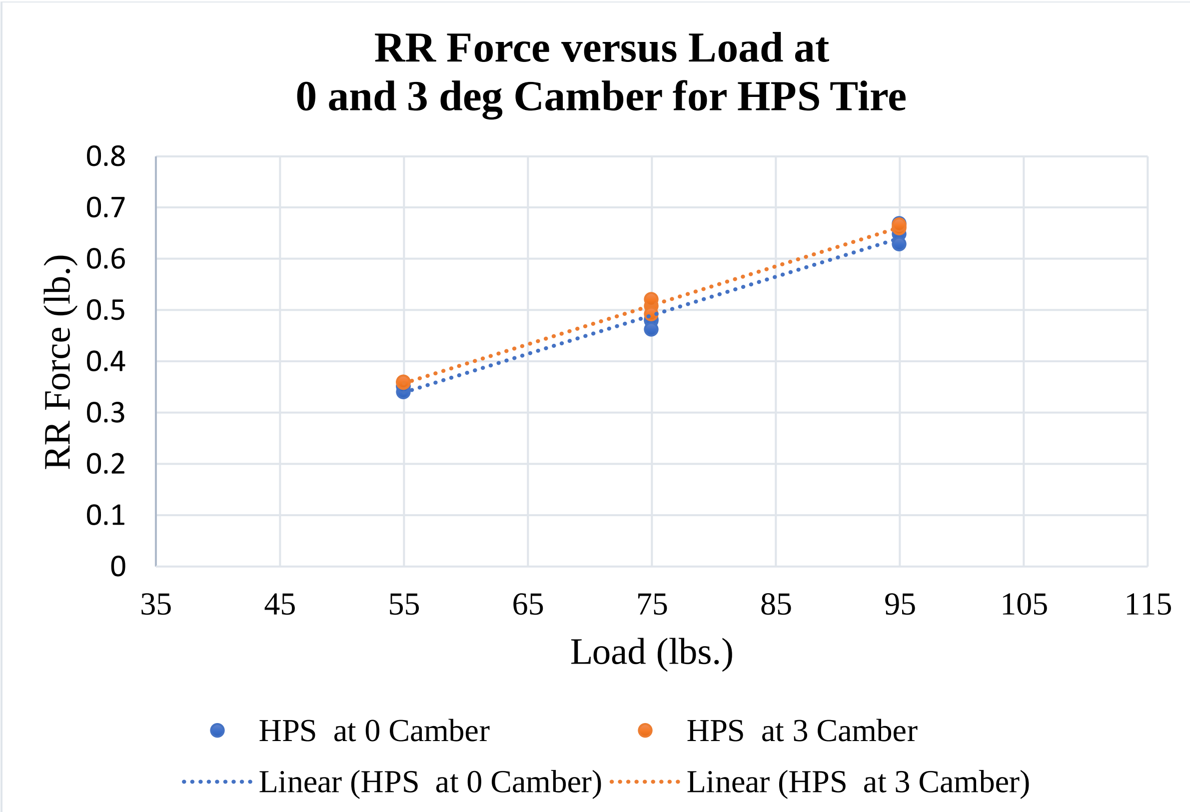
Appendix B.3 Combined Factors for HPS Tire



Appendix Figure 37 RR Force versus Toe Angle, 0 and 3 Camber, HPS Tire

Appendix Table 21 RR Force versus Toe Angle, 0 and 3 Camber, HPS Tire

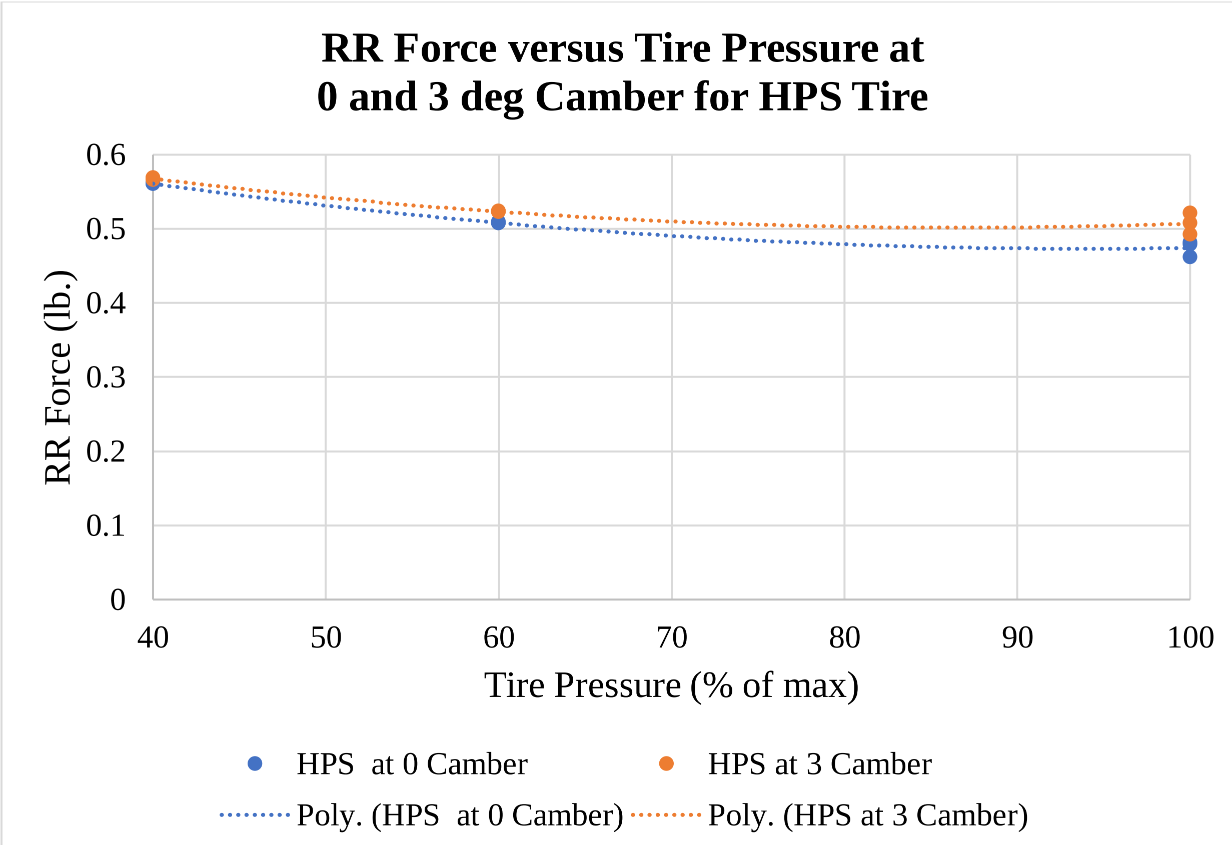
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
0 Camber	0.2098	0.0044	0.4742	0.9537
3 Camber	0.0278	-0.1974	0.5072	0.9948



Appendix Figure 38 RR Force versus Load, 0 and 3 Camber, HPS Tire

Appendix Table 22 RR Force versus Load, 0 and 3 Camber, HPS Tire

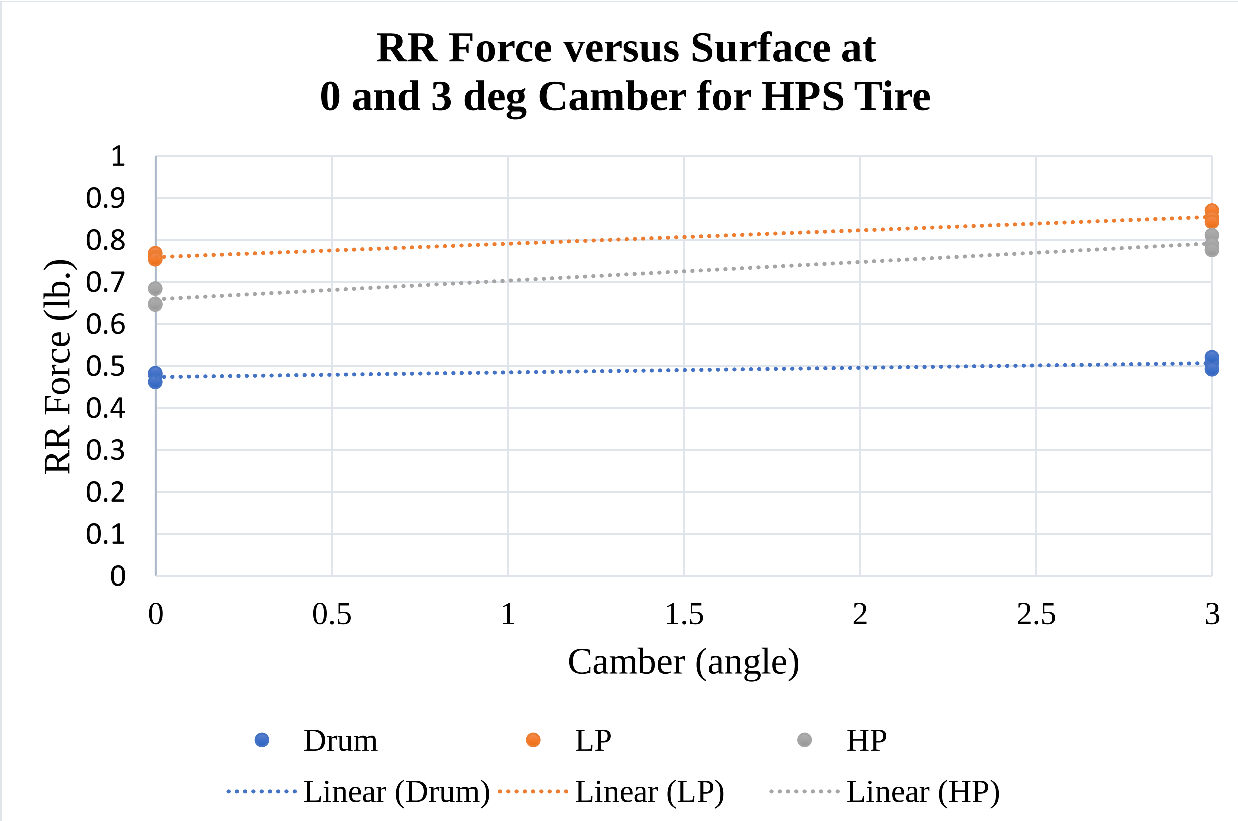
	Coefficient (X)	**Constant**	**R2**
0 Camber	0.0075	-0.0744	0.9837
3 Camber	0.0076	-0.0610	0.9967



Appendix Figure 39 RR Force versus Pressure, 0 and 3 Camber, HPS Tire

Appendix Table 23 RR Force versus Pressure, 0 and 3 Camber, HPS Tire

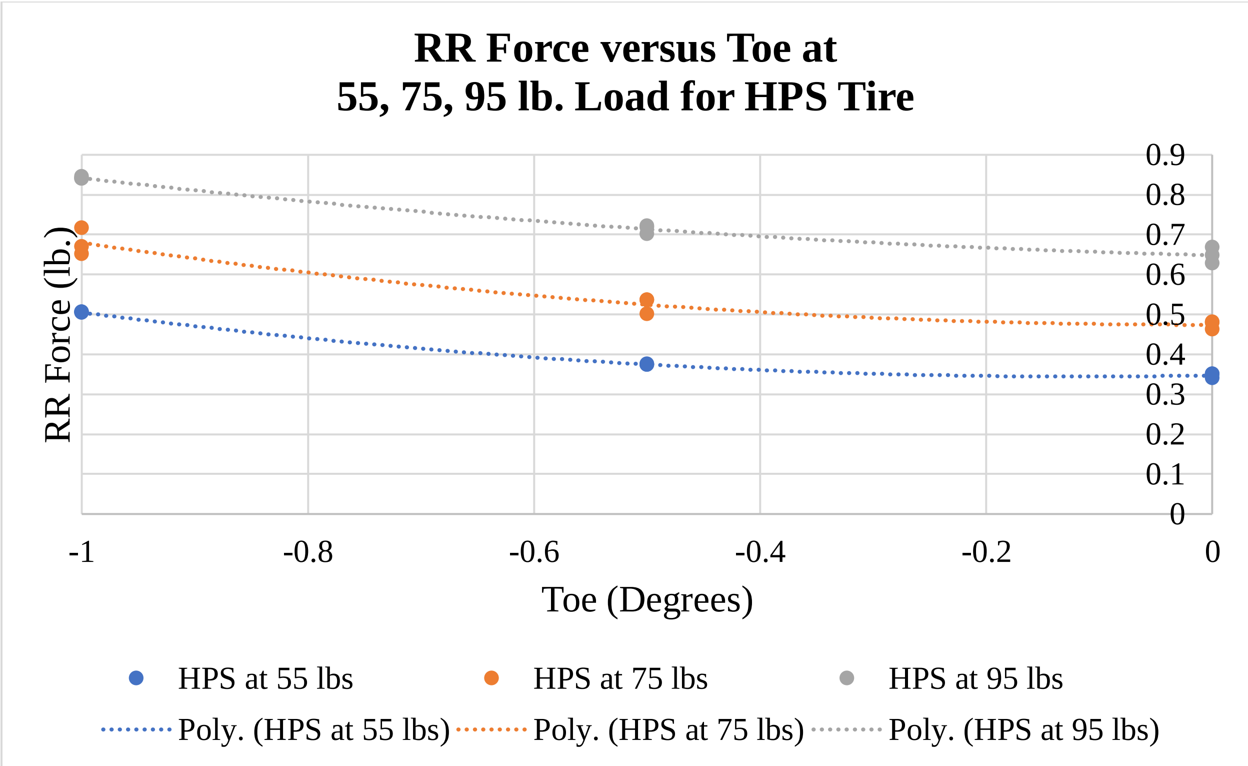
	Coefficient (X_2)	**Coefficient (X)**	**Constant**	**R_2**
0 Camber	3E-05	-0.0056	0.7388	0.9802
3 Camber	3E-05	-0.0053	0.7301	0.9359



Appendix Figure 40 RR Force versus Surface, 0 and 3 Camber, HPS Tire

Appendix Table 24 RR Force versus Surface, 0 and 3 Camber, HPS Tire

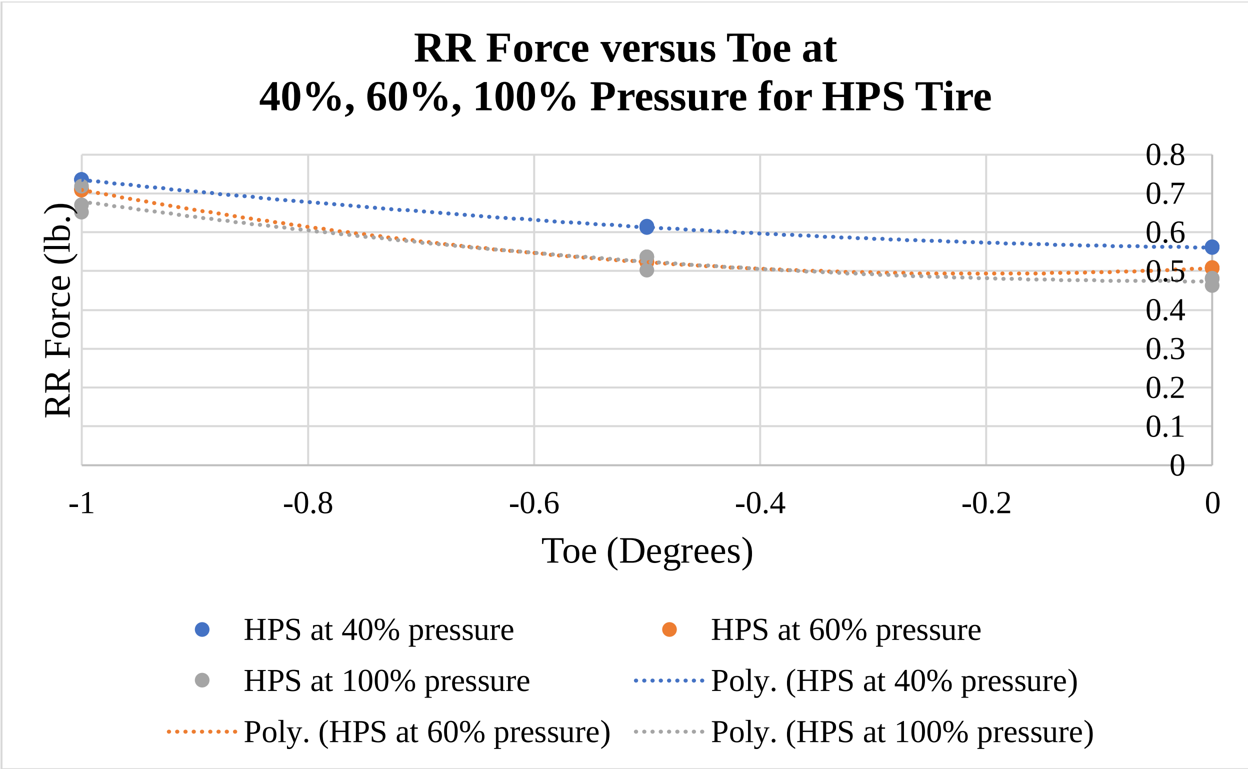
	Coefficient (X)	**Constant**	**R_2**
Drum	0.011	0.4742	0.7219
HP Carpet	0.0443	0.6593	0.9431
LP Carpet	0.0319	0.7597	0.9659



Appendix Figure 41 RR Force versus Toe Angle and Load, HPS Tire

Appendix Table 25 RR Force versus Toe Angle and Load, HPS Tire

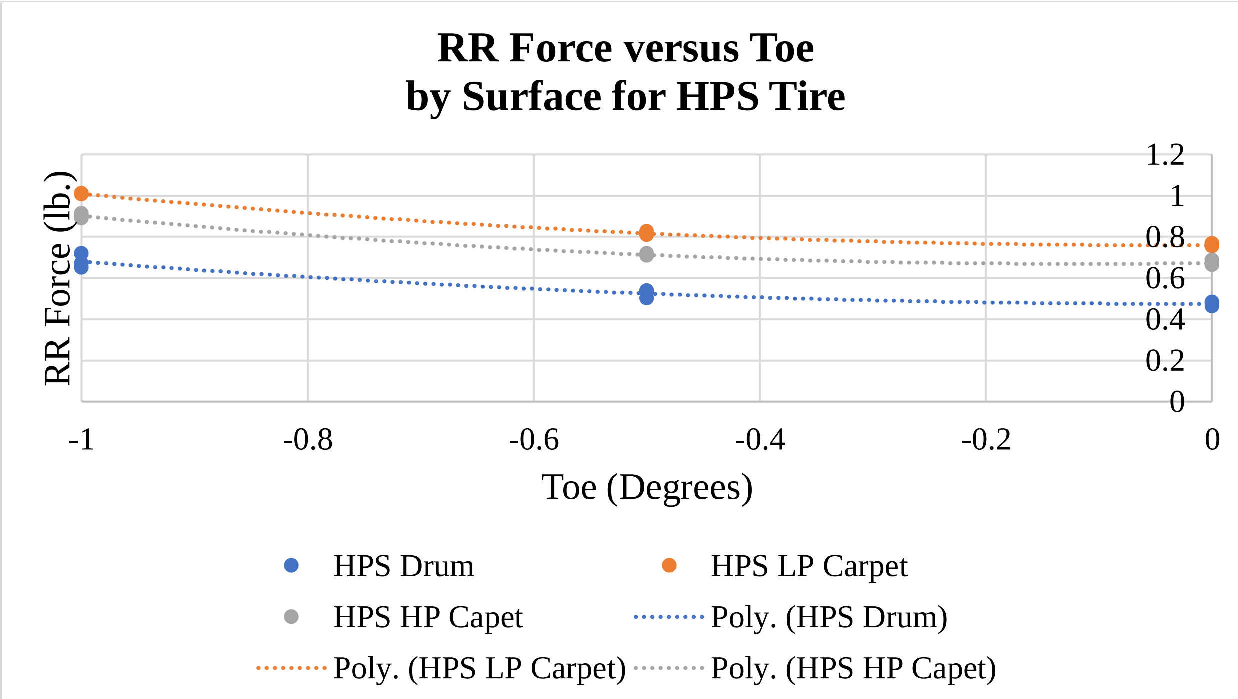
	Coefficient (X^2)	Coefficient (X)	Constant	R^2
55 lb.	0.2067	0.0490	0.3474	0.9983
75 lb.	0.2098	0.0044	0.4742	0.9537
95 lb.	0.1259	-0.0676	0.6484	0.9823



Appendix Figure 42 RR Force versus Toe Angle and Pressure, HPS Tire

Appendix Table 26 RR Force versus Toe Angle and Pressure, HPS Tire

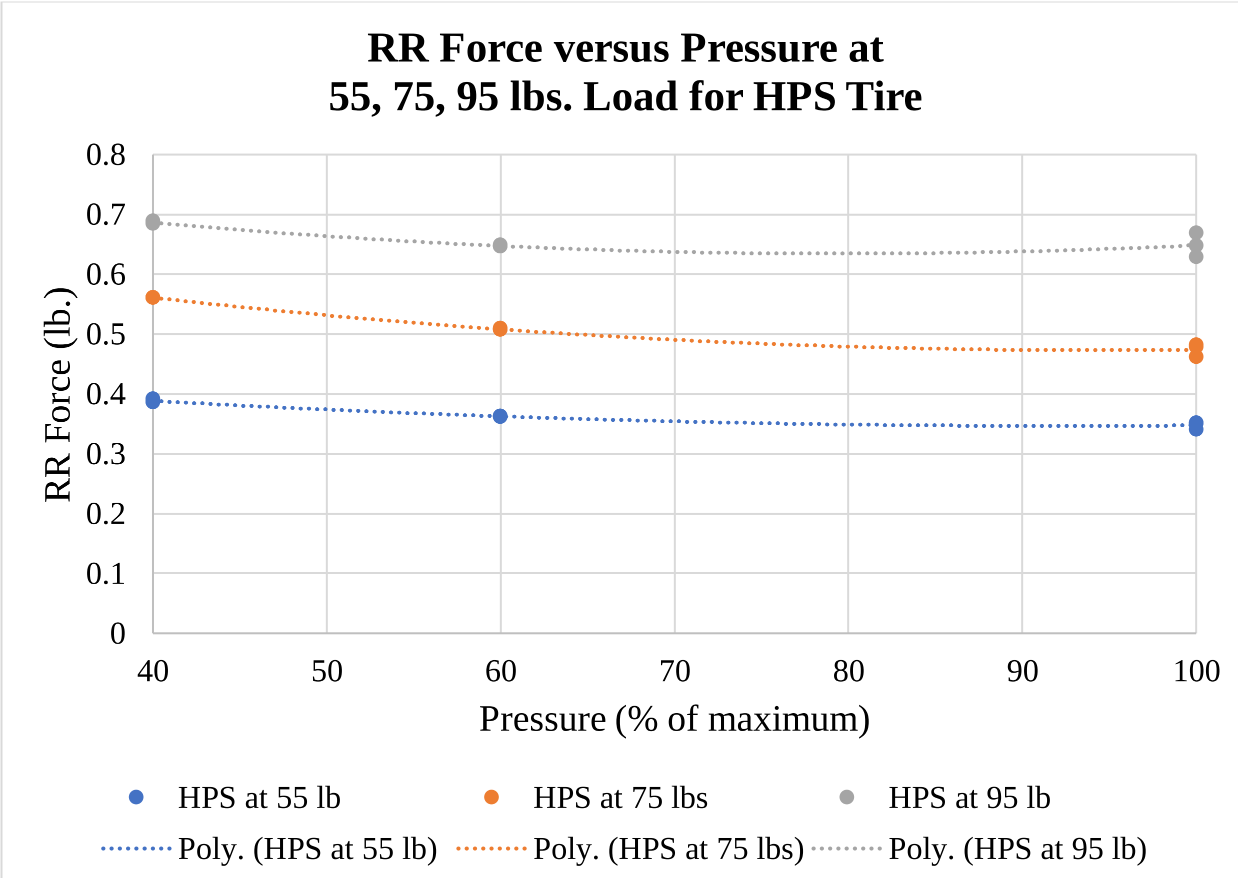
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
40%	0.1399	-0.0343	0.5610	0.9998
60%	0.3423	0.1412	0.5080	0.9999
100%	0.2098	0.0044	0.4742	0.9537



Appendix Figure 43 RR Force versus Toe Angle and Surfaces, HPS Tire

Appendix Table 27 RR Force versus Toe Angle and Surfaces, HPS Tire

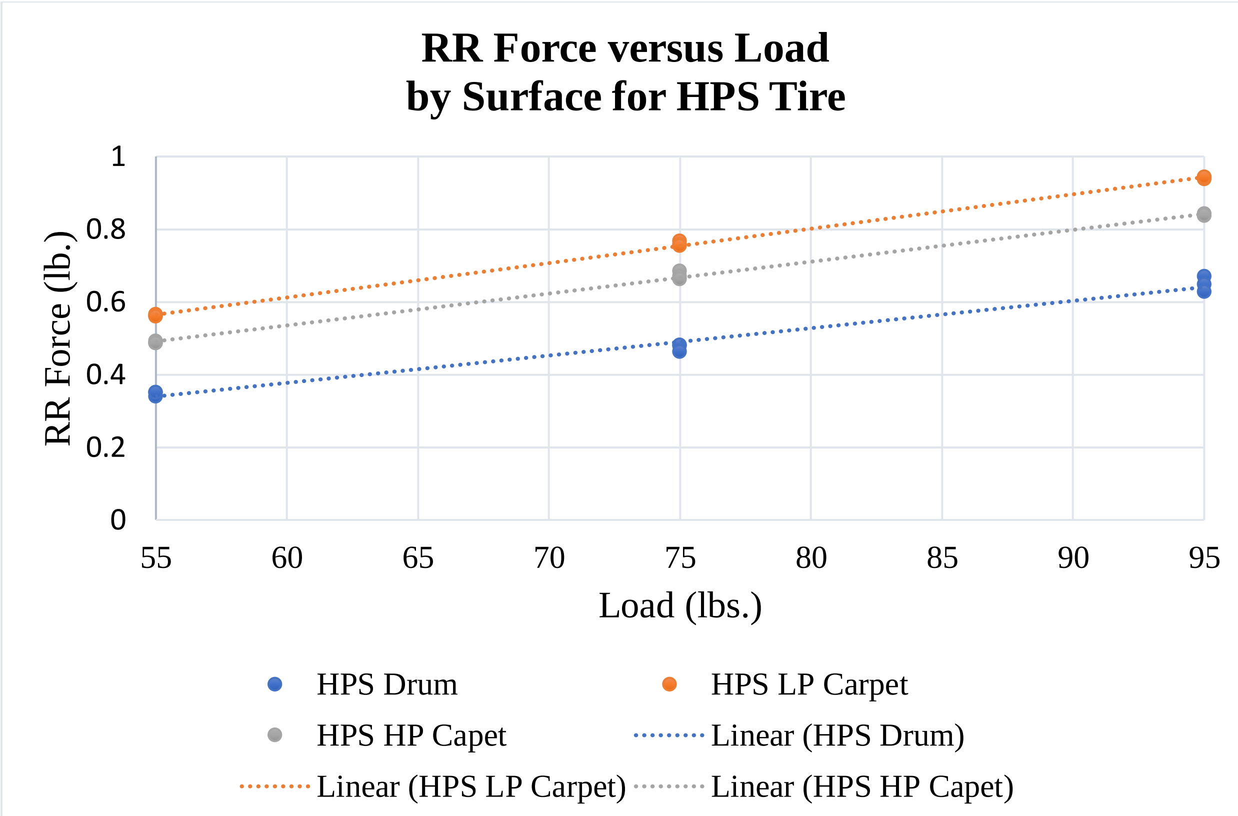
	Coefficient (X_2)	**Coefficient (X)**	**Constant**	**R_2**
Drum	0.2098	0.0044	0.4742	0.9537
LP	0.2705	0.0214	0.7597	0.9970
HP	0.2974	0.0685	0.6727	0.9941



Appendix Figure 44 RR Force versus Pressure and Load, HPS Tire

Appendix Table 28 RR Force versus Pressure and Load, HPS Tire

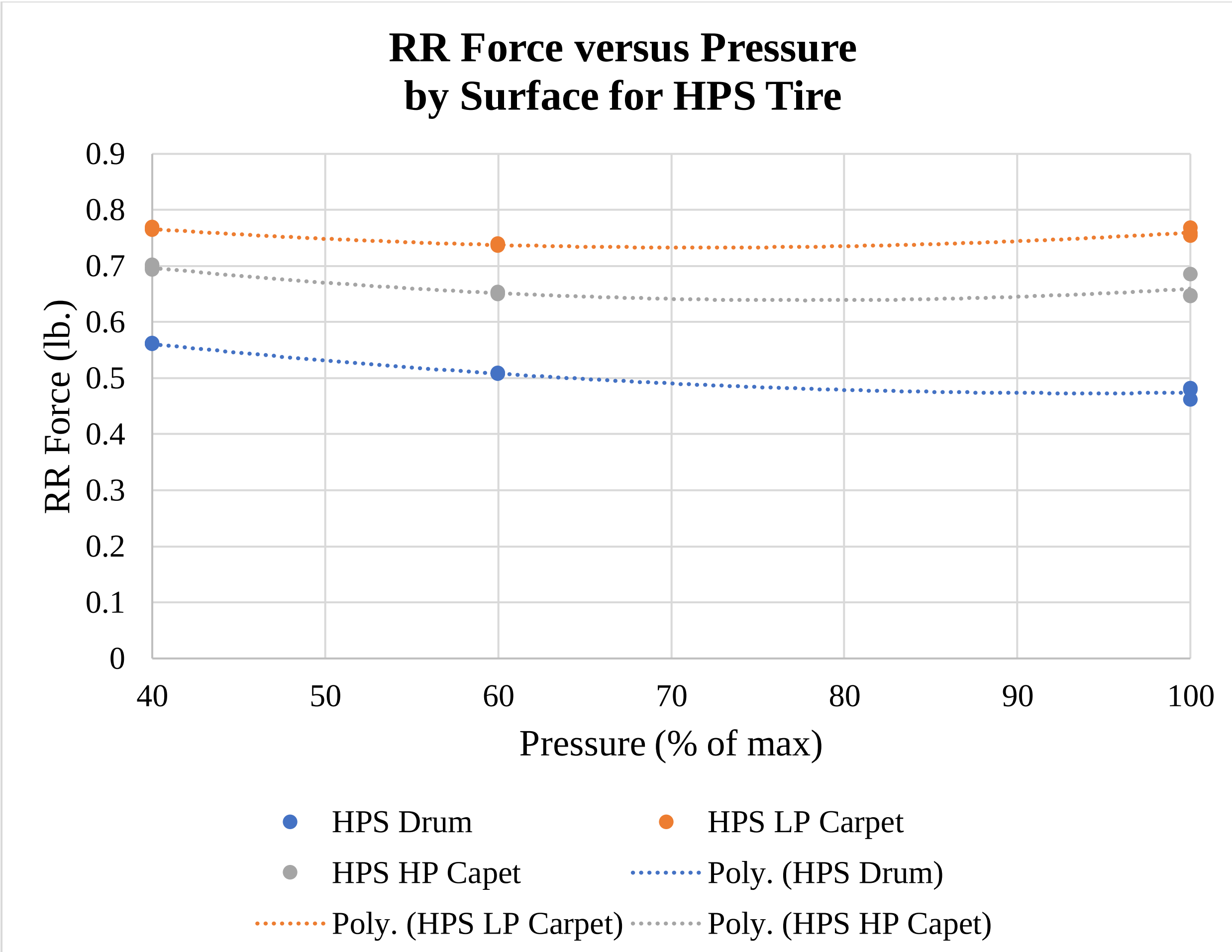
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
55 lb.	2E-05	-0.0028	0.4766	0.9653
75 lb.	3E-05	-0.0056	0.7388	0.9802
95 lb.	3E-05	-0.0053	0.8460	0.7838



Appendix Figure 45 RR Force versus Load and Surfaces, HPS Tire

Appendix Table 29 RR Force versus Load and Surfaces, HPS Tire

	Coefficient (X)	**Constant**	**R2**
Drum	0.0075	-0.0744	0.9837
LP	0.0095	0.0442	0.9986
HP	0.0088	0.0094	0.9976



Appendix Figure 46 RR Force versus Pressure and Surfaces, HPS Tire

Appendix Table 30 RR Force versus Pressure and Surface, HPS Tire

	Coefficient (X_2)	**Coefficient (X)**	**Constant**	**R_2**
Drum	3E-05	-0.0056	0.7388	0.9802
LP	3E-05	-0.0047	0.9030	0.9137
HP	4E-05	-0.0064	0.8859	0.7800

Appendix B.4 Repeatability

Mean, Standard Deviation and Confidence Intervals for Wheels

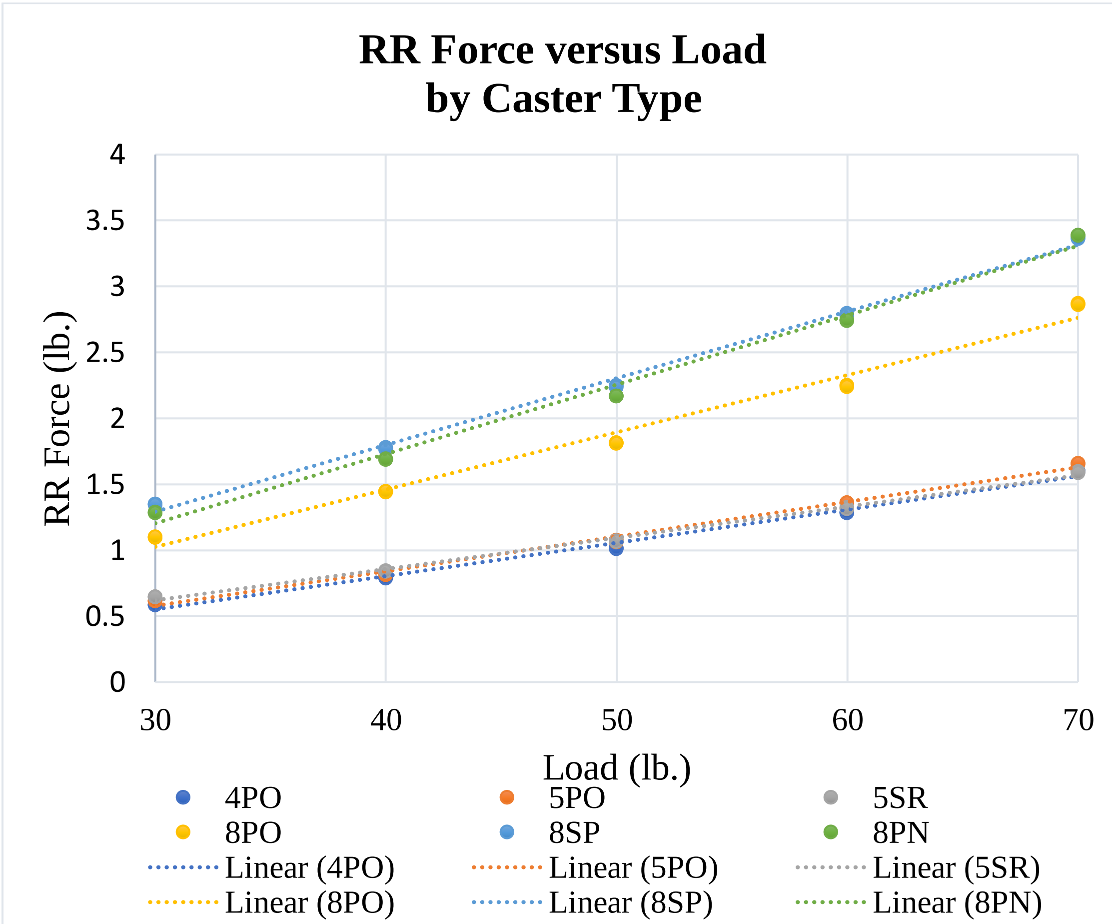
Appendix Table 31 Statistics for RR Forces from Wheels Tested on Drum

	HPS*	**HPP***	**LPS***	**AIS***	**KLS***	**SPM***
Mean RR Force (lbs.)	0.477	0.473	0.466	0.959	0.566	0.654
Standard deviation	0.013	0.010	0.012	0.018	0.015	0.010
Confidence level	0.008	0.005	0.006	0.012	0.008	0.005
Conf. interval low	0.469	0.468	0.460	0.947	0.557	0.648
Conf. interval high	0.484	0.478	0.473	0.971	0.574	0.659
Number of samples	13	16	16	12	15	15
*RR force in pounds						

Appendix C Caster Rolling Resistance Test Results and Analysis

This appendix contains all scatterplots from RR testing for casters. It is organized by single-factor and combined factor testing. Factors evaluated included load, speed, tire pressure, and a variety of surfaces. Standard testing conditions are 50 lb. load, 1 m/s speed, 100% tire pressure and drum surface. These conditions or subsets of them are assumed when not otherwise noted. Below each scatterplot will be a table showing the coefficient from lines of best fit in accordance with that chart.

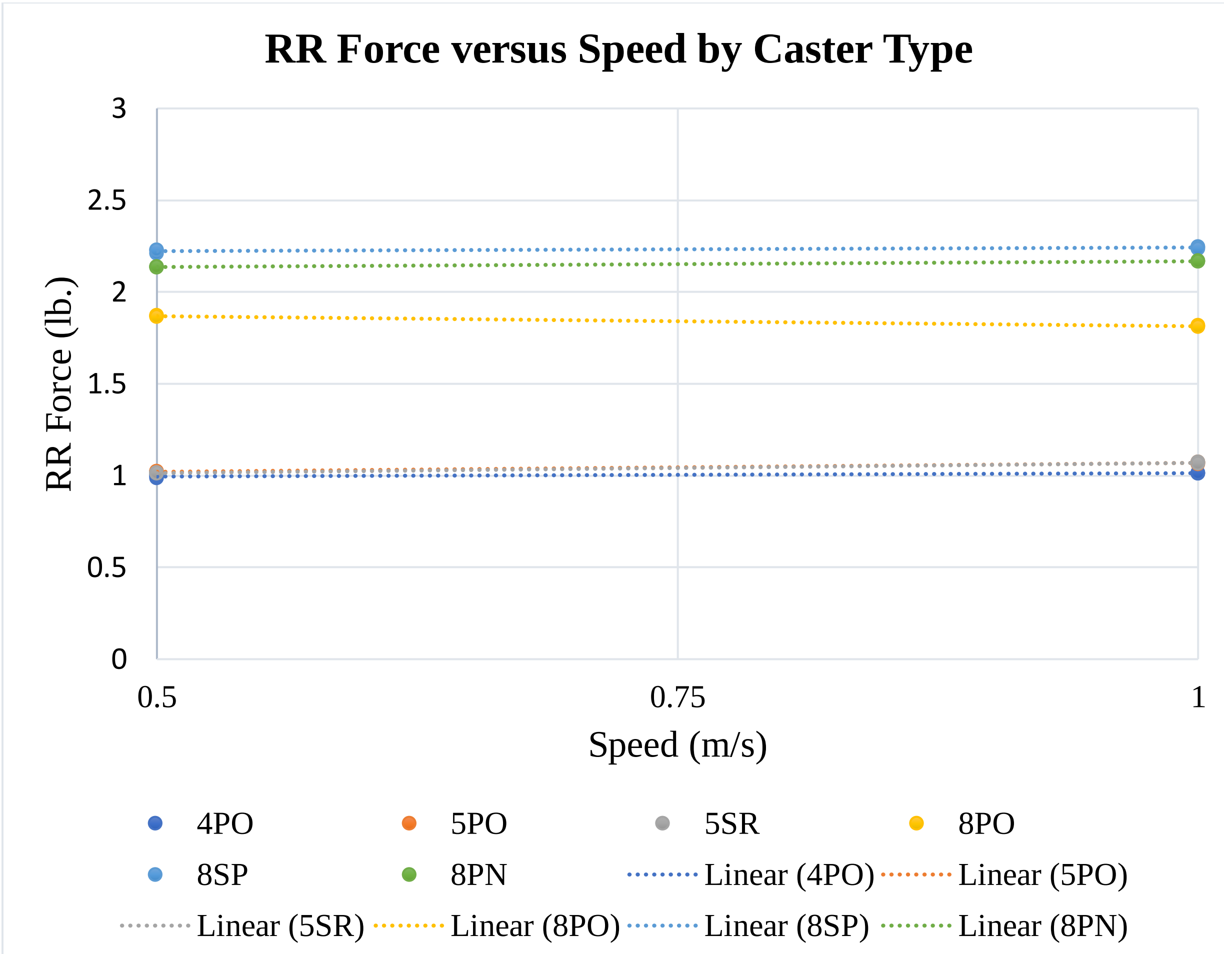
Appendix C.1 Single-factors



Appendix Figure 47 RR Force versus Load

Appendix Table 32 RR Force versus Load

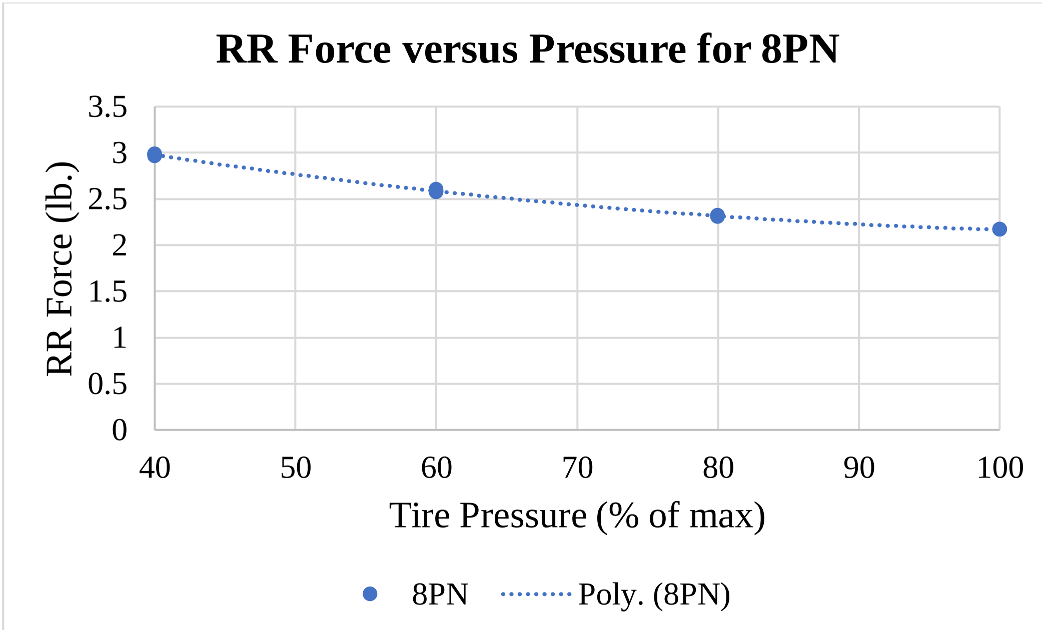
	Slope (m)	Intercept (b)	R_2
4PO	0.0252	-0.2053	0.9917
5PO	0.0263	-0.2102	0.9941
5SR	0.0237	-0.0905	0.996
8PO	0.0434	-0.2776	0.9846
8SP	0.0506	-0.2259	0.9956
8PN	0.0526	-0.3738	0.9914



Appendix Figure 48 RR Force versus Speed

Appendix Table 33 RR Force versus Speed

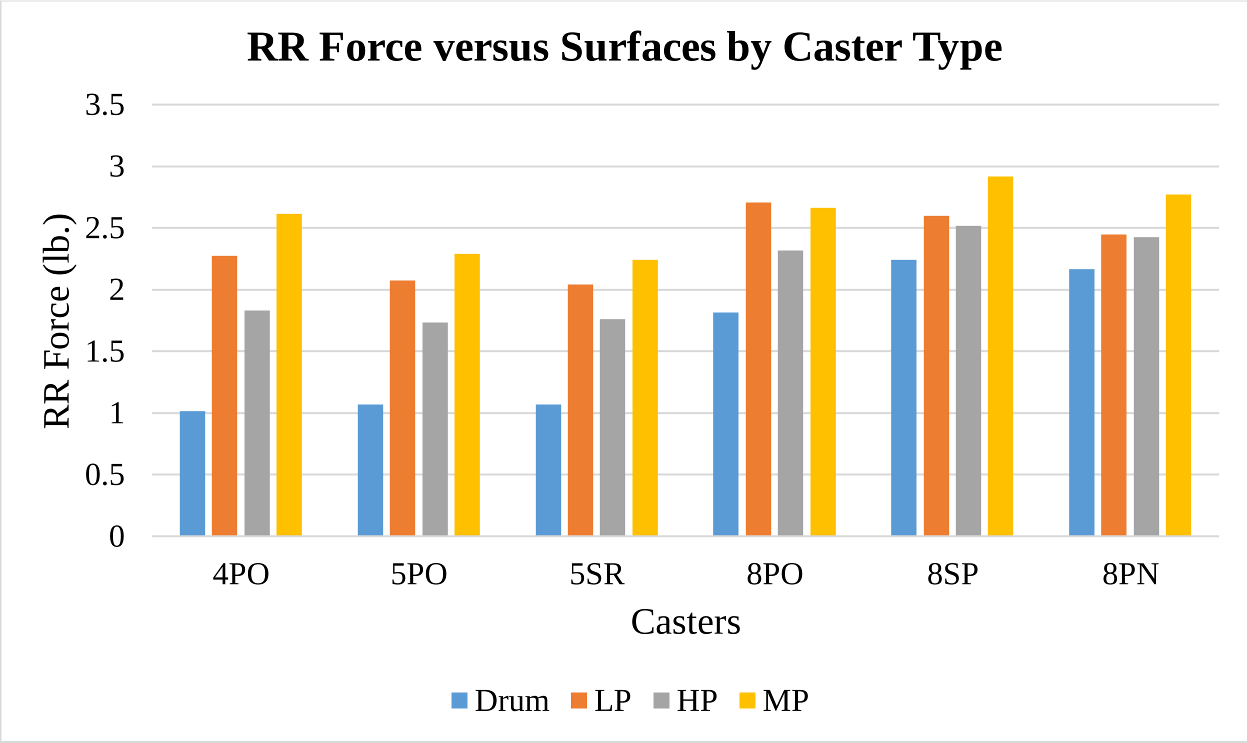
	Slope (m)	Intercept (b)	R_2
4PO	0.0368	0.9766	0.8242
5PO	0.0971	0.972	0.9767
5SR	0.1117	0.9576	0.9967
8PO	-0.1102	1.9235	0.9866
8SP	0.0397	2.2029	0.6961
8PN	0.0627	2.1048	0.9901



Appendix Figure 49 RR Force versus Pressure

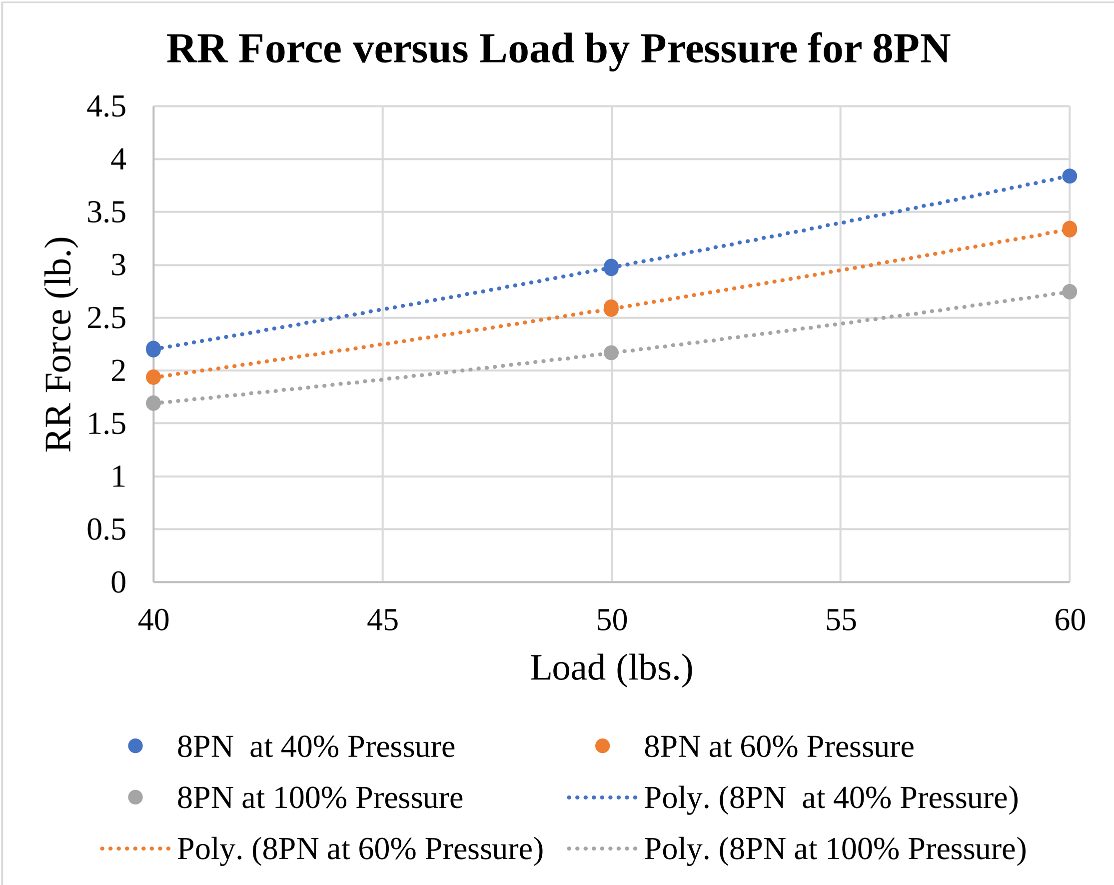
Appendix Table 34 RR Force versus Pressure

	Coefficient (X_2)	**Coefficient (X)**	**Intercept (b)**	**R_2**
8PN	0.0002	-0.0347	4.1215	0.9992



Appendix Figure 50 RR Force versus Surfaces

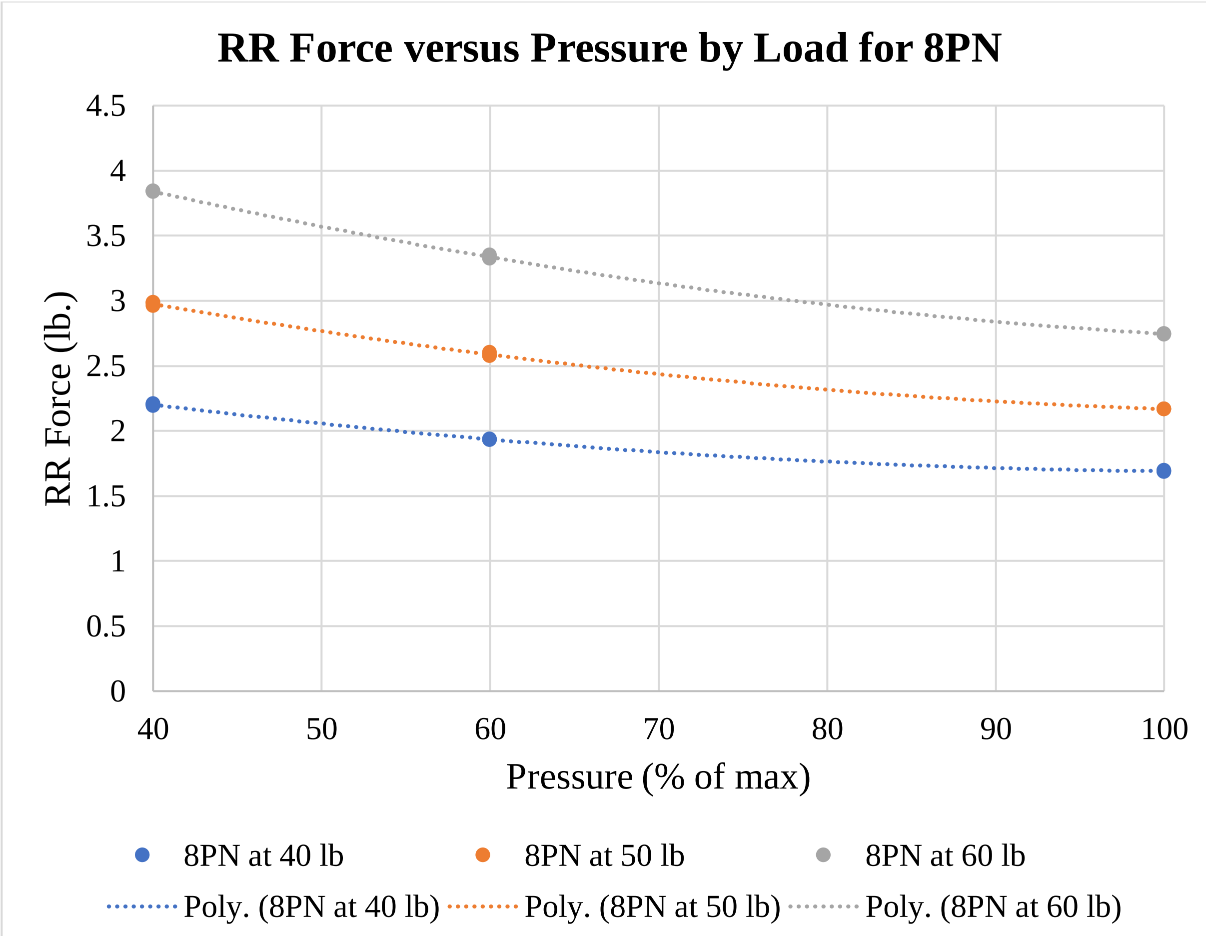
Appendix C.2 Combined Factors



Appendix Figure 51 RR Force versus Load and Pressure

Appendix Table 35 RR Force versus Load and Pressure

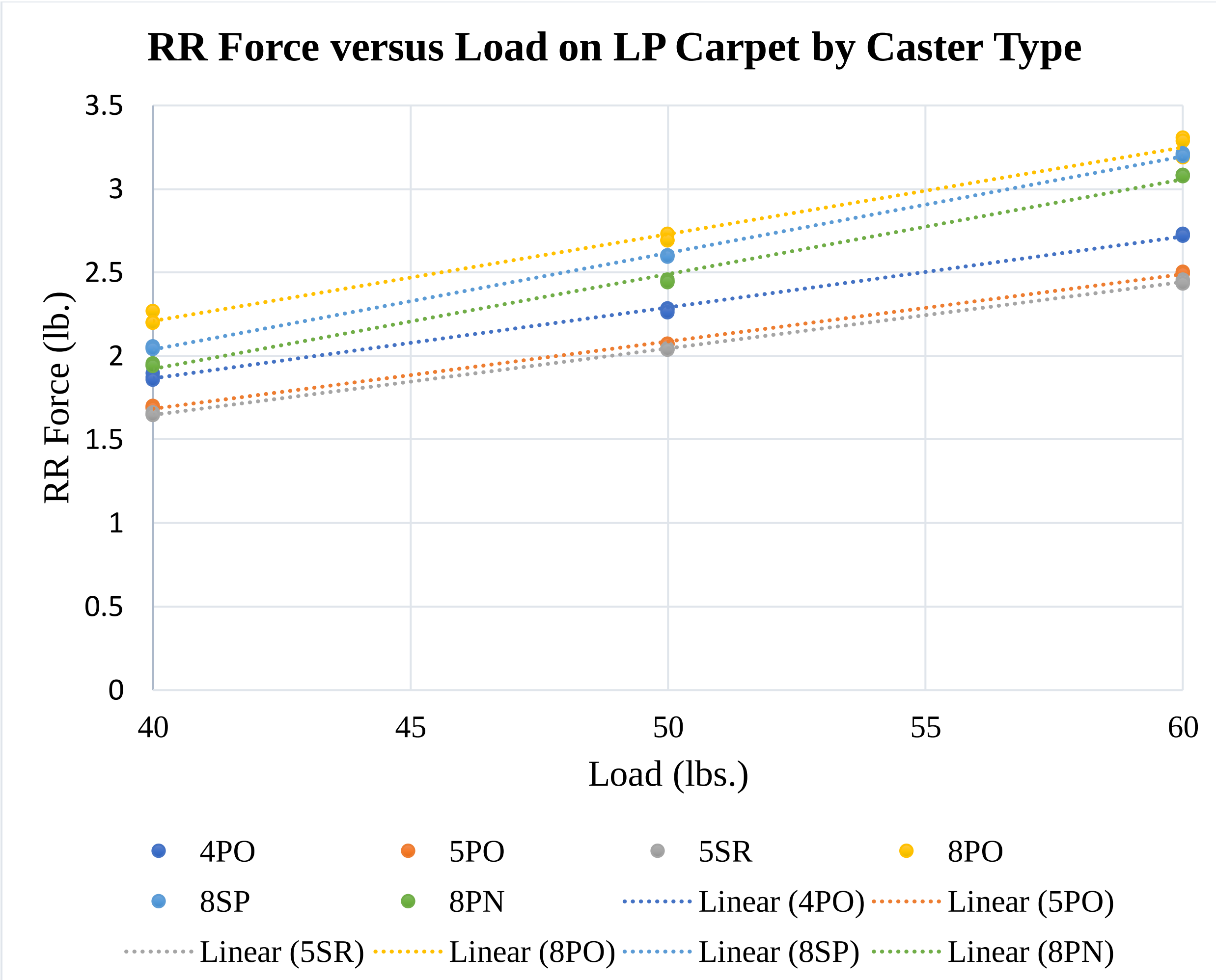
	Coefficient (X^2)	Coefficient (X)	Intercept (b)	R^2
8PN at 40%	0.0005	0.0368	0.0068	0.9999
8PN at 60%	0.0005	0.0216	0.2968	0.9997
8PN at 100%	0.0005	0.0025	0.7870	1



Appendix Figure 52 RR Force versus Load and Pressure

Appendix Table 36 RR Force versus Load and Pressure

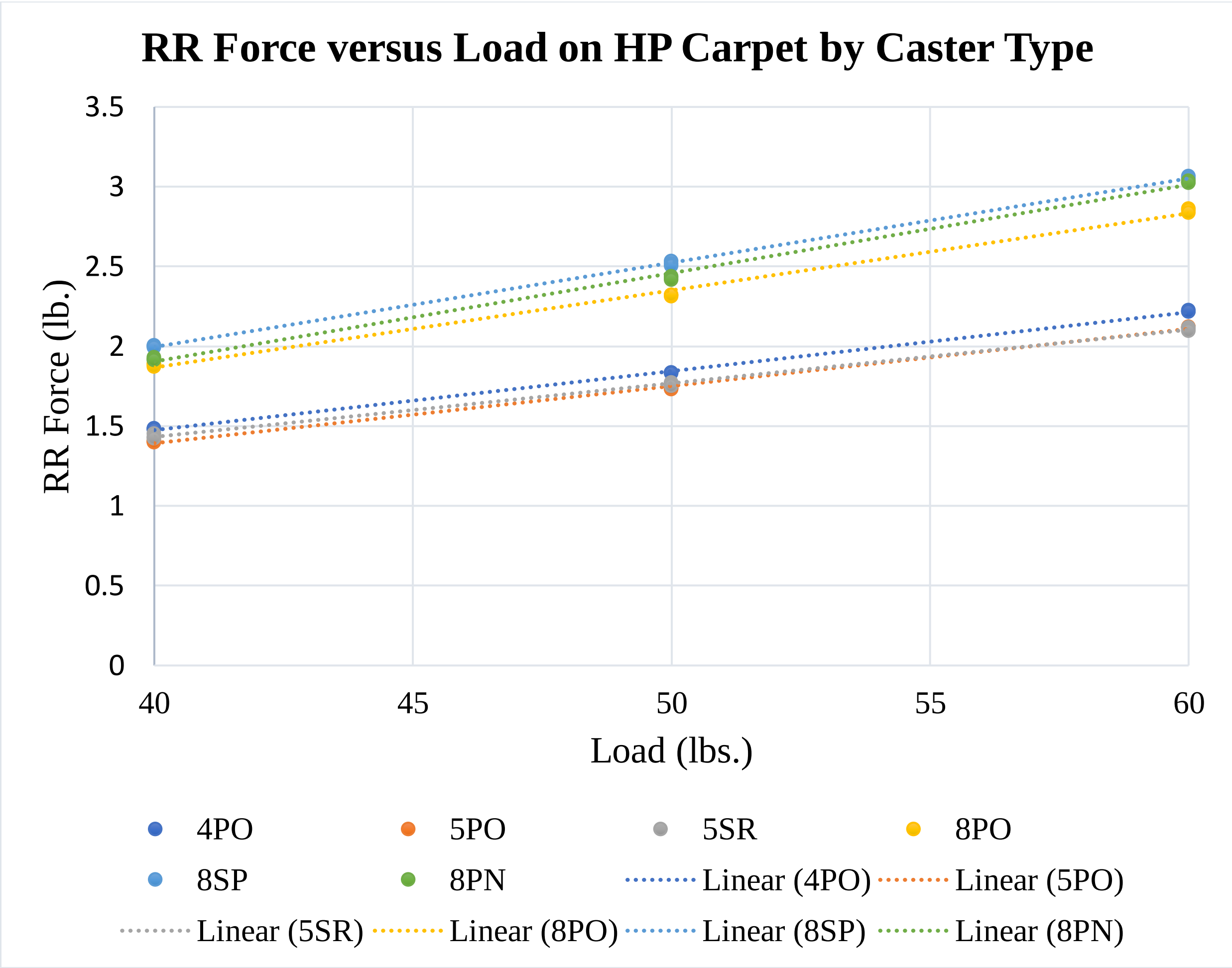
	Coefficient (X^2)	**Coefficient (X)**	**Intercept (b)**	**R^2**
8PN at 40 lb	0.0001	-0.0254	3.0261	0.9995
8PN at 50 lbs.	0.0002	-0.0345	4.1152	0.9991
8PN at 60 lbs.	0.0002	-0.0428	5.2712	0.9998



Appendix Figure 53 RR Force versus Load and Low-pile Carpet

Appendix Table 37 RR Force versus Load and Low-pile Carpet

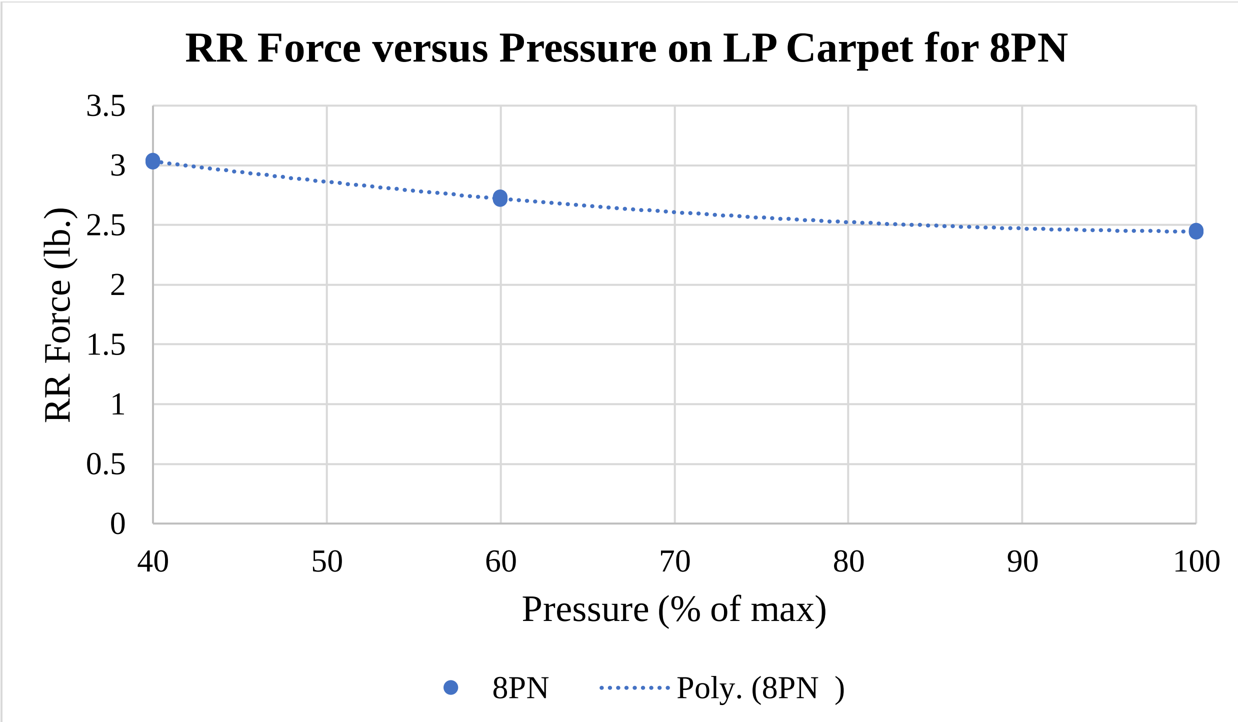
	Slope (m)	**Intercept (b)**	**R_2**
4PO	0.0424	0.1687	0.9977
5PO	0.0403	0.0738	0.9987
5SR	0.0398	0.0563	0.9994
8PO	0.0520	0.1312	0.9908
8SP	0.0578	-0.2718	0.9990
8PN	0.0567	-0.3457	0.9952



Appendix Figure 54 RR Force versus Load and High-pile Carpet

Appendix Table 38 RR Force versus Load and High-pile Carpet

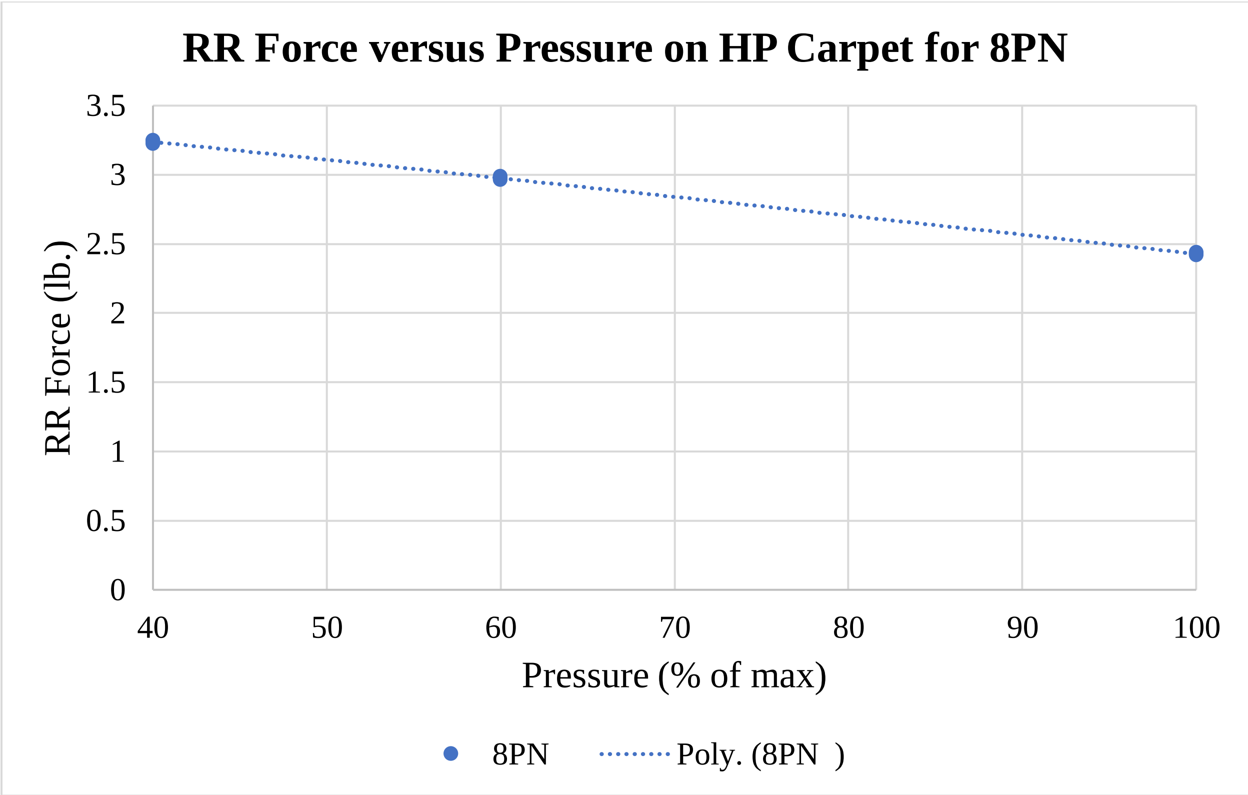
	Slope (m)	**Intercept (b)**	**R2**
4PO	0.0369	-0.0028	0.9991
5PO	0.0359	-0.0419	0.9982
5SR	0.0336	0.0894	0.9984
8PO	0.0483	-0.0653	0.9962
8SP	0.0528	-0.1163	0.9995
8PN	0.0554	-0.3107	0.9974



Appendix Figure 55 RR Force versus Pressure and Low-pile Carpet

Appendix Table 39 RR Force versus Pressure and Low-pile Carpet

	Coefficient (X_2)	**Coefficient (X)**	**Intercept (b)**	**R_2**
8PN	0.0001	-0.0303	4.0094	0.9991



Appendix Figure 56 RR Force versus Pressure and High-pile Carpet

Appendix Table 40 RR Force versus Pressure and High-pile Carpet

	Coefficient (X^2)	**Coefficient (X)**	**Intercept (b)**	**R^2**
8PN	-8E-06	-0.0124	3.7483	0.9993

Appendix C.3 Repeatability

Mean, Standard Deviation and Confidence Intervals for Wheels

Appendix Table 41 Statistics for RR Forces from Casters Tested on Drum

	4PO*	**5PO***	**5SR***	**8PO***	**8SP***	**8PN***
Mean	1.019	1.067	1.069	1.847	2.249	2.180
Standard Deviation	0.019	0.014	0.007	0.047	0.010	0.016
Confidence level	0.024	0.017	0.008	0.058	0.012	0.017
Confidence interval low	0.994	1.049	1.061	1.789	2.237	2.163
Confidence interval high	1.043	1.084	1.078	1.906	2.261	2.196
Number of samples	5	5	5	5	5	6
Variance (Std. Dev/Mean)	1.86%	1.31%	0.65%	2.54%	0.44%	0.73%
*RR force in pounds						

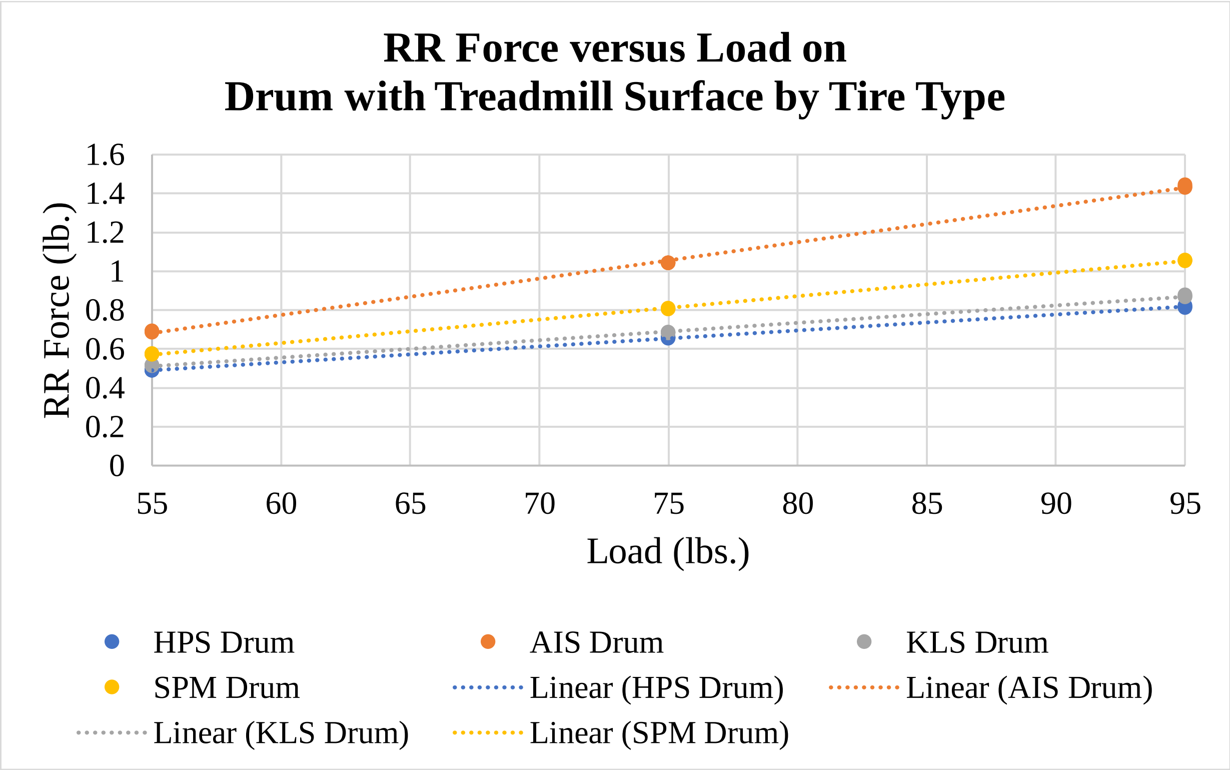
Appendix D External Validity

This Appendix contains all scatterplots from RR testing for drum versus overground testing using a treadmill surface. It is categorized by wheel and caster testing. Factors evaluated included load and toe angle. Standard testing conditions for wheels are 75 lb. load, 1 m/s speed, 0 toe angle, 0 camber angle and 100% tire pressure. Standard testing conditions for casters are 50 lb. load, 1 m/s speed and 100% tire pressure. These conditions or subsets of them are assumed when not otherwise noted. Below each scatterplot will be a table showing the coefficient from lines of best fit in accordance with that chart.

Appendix D.1 Single-factors

Treadmill Surface on Drum and Overground for tires

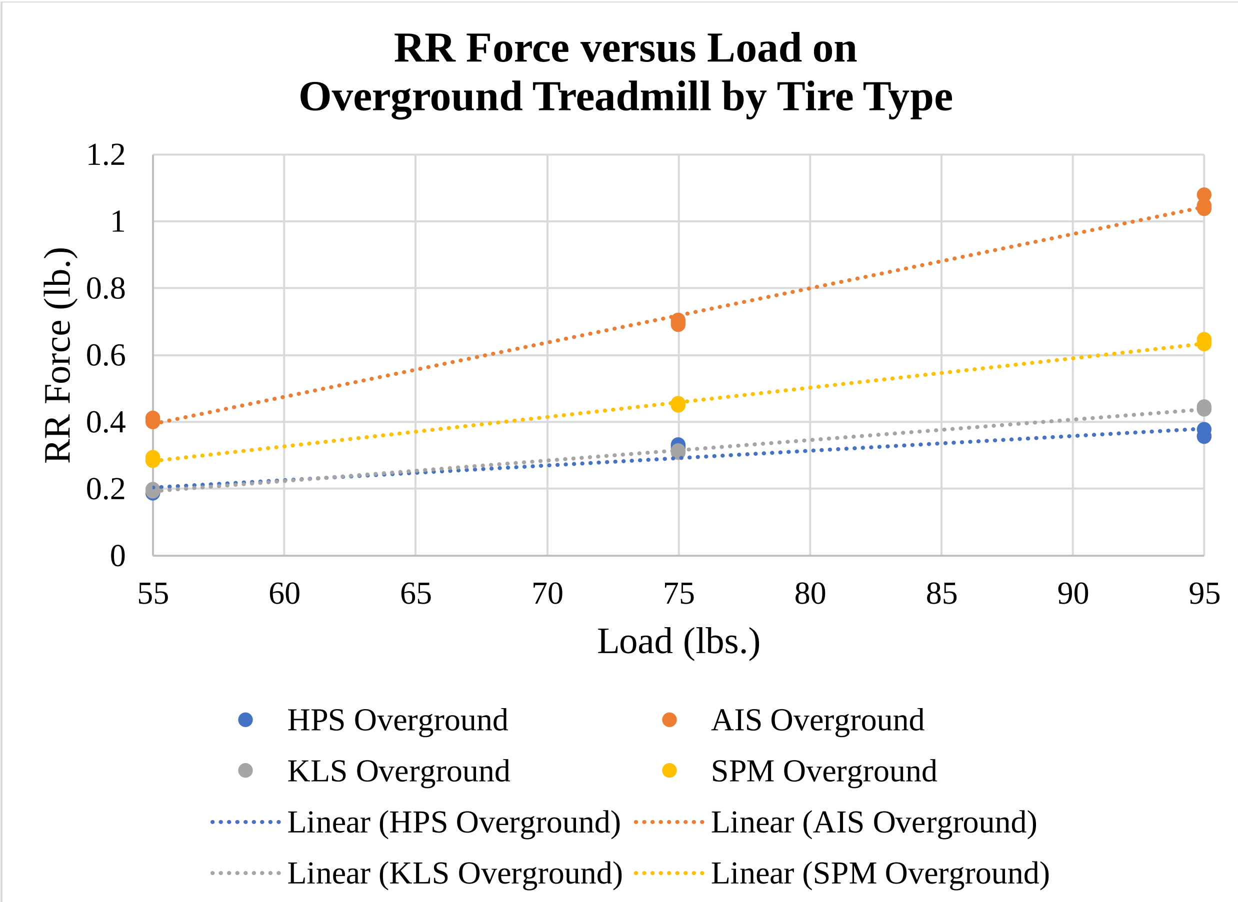
Appendix D.1.1 Load for Tires



Appendix Figure 57 RR Force versus Load, Drum Treadmill

Appendix Table 42 RR Force versus Load, Drum Treadmill

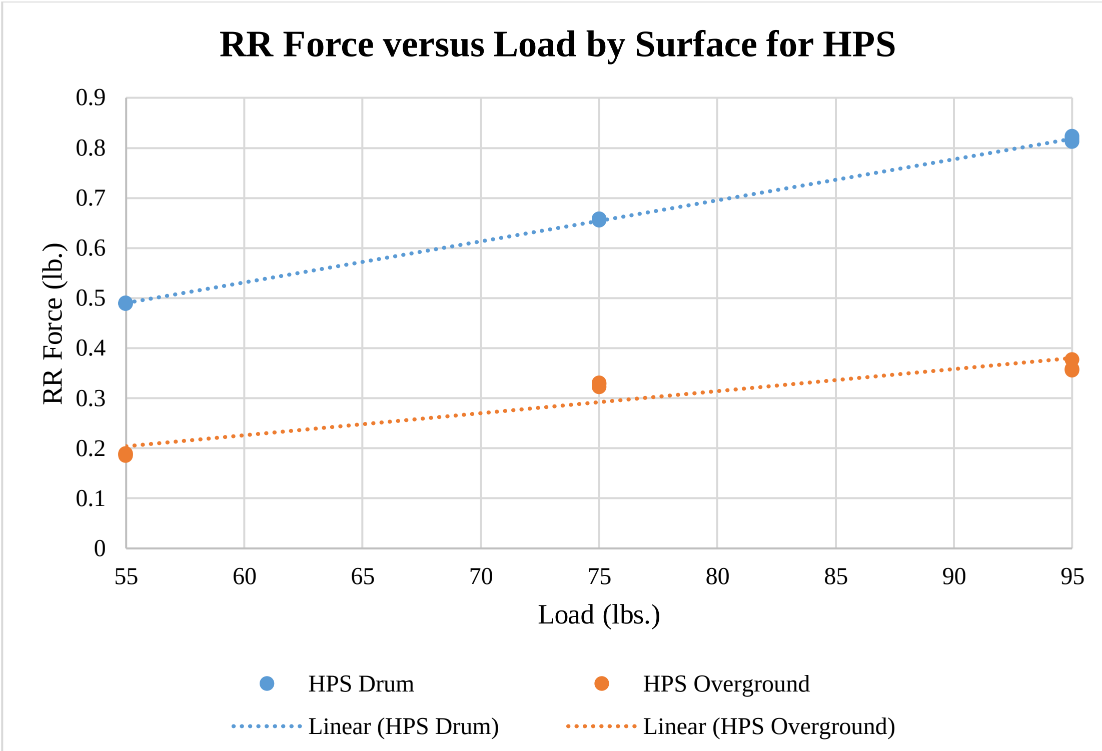
	Slope (m)	**Intercept (b)**	**R^2**
HPS	0.0082	0.0393	0.9994
AIS	0.0187	-0.3470	0.9989
KLS	0.0089	0.0193	0.9988
SPM	0.0121	-0.0927	0.9997



Appendix Figure 58 RR Force versus Load, Overground Treadmill

Appendix Table 43 RR Force versus Load, Overground Treadmill

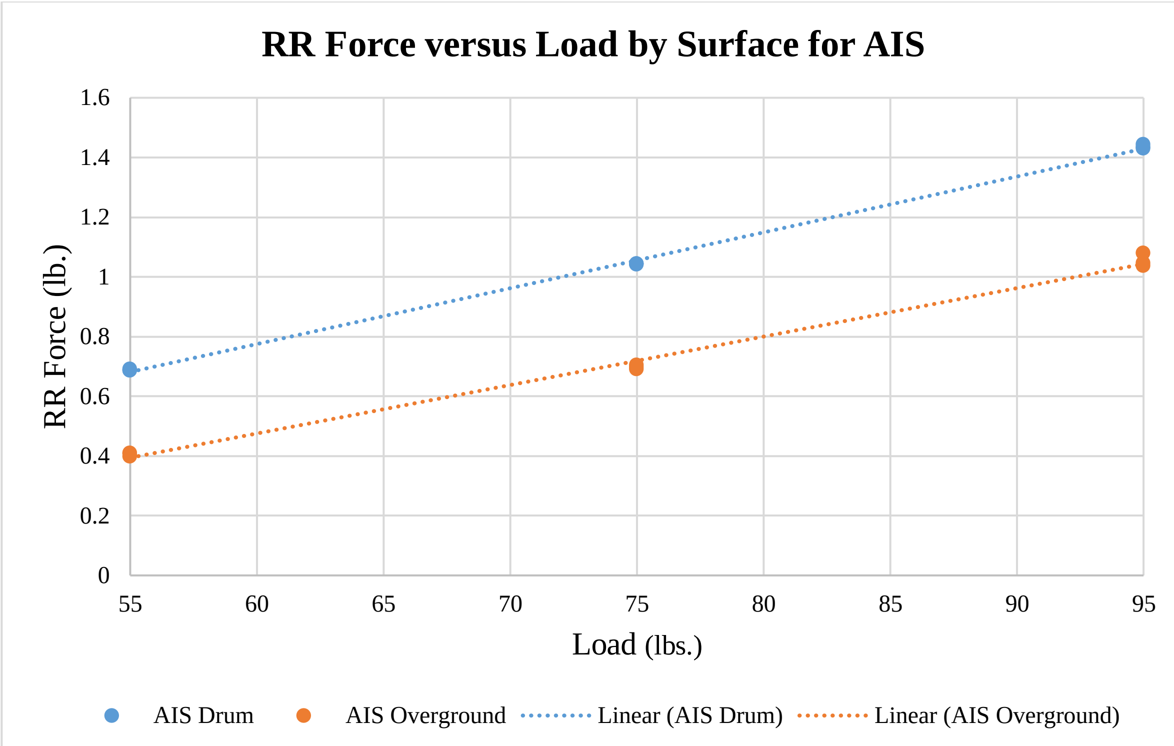
	Slope (m)	Intercept (b)	R_2
HPS	0.0044	-0.0382	0.8927
AIS	0.0162	-0.4982	0.9950
KLS	0.0061	-0.1436	0.9984
SPM	0.0088	-0.1996	0.9977



Appendix Figure 59 RR Force versus Load, Drum versus Overground, HPS Tire

Appendix Table 44 RR force versus Load, Drum versus Overground, HPS Tire

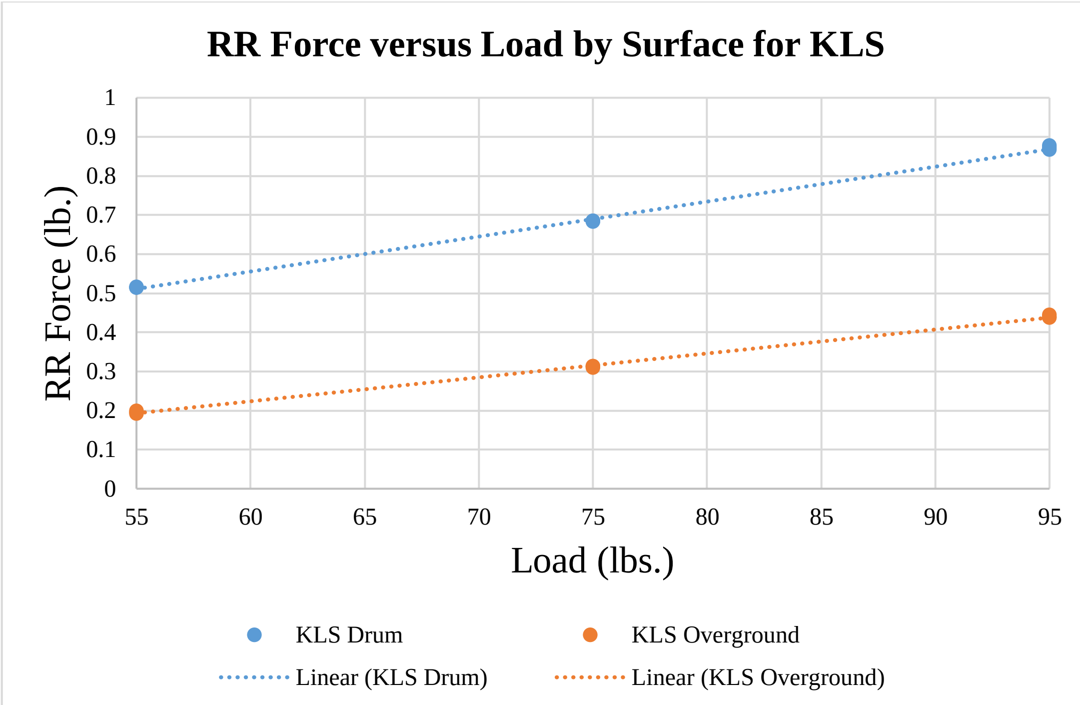
	Slope (m)	Intercept (b)	R_2
HPS Drum	0.0082	0.0393	0.9994
HPS Overground	0.0044	-0.0382	0.8927



Appendix Figure 60 RR Force versus Load, Drum versus Overground, AIS Tire

Appendix Table 45 RR Force versus Load, Drum versus Overground, AIS Tire

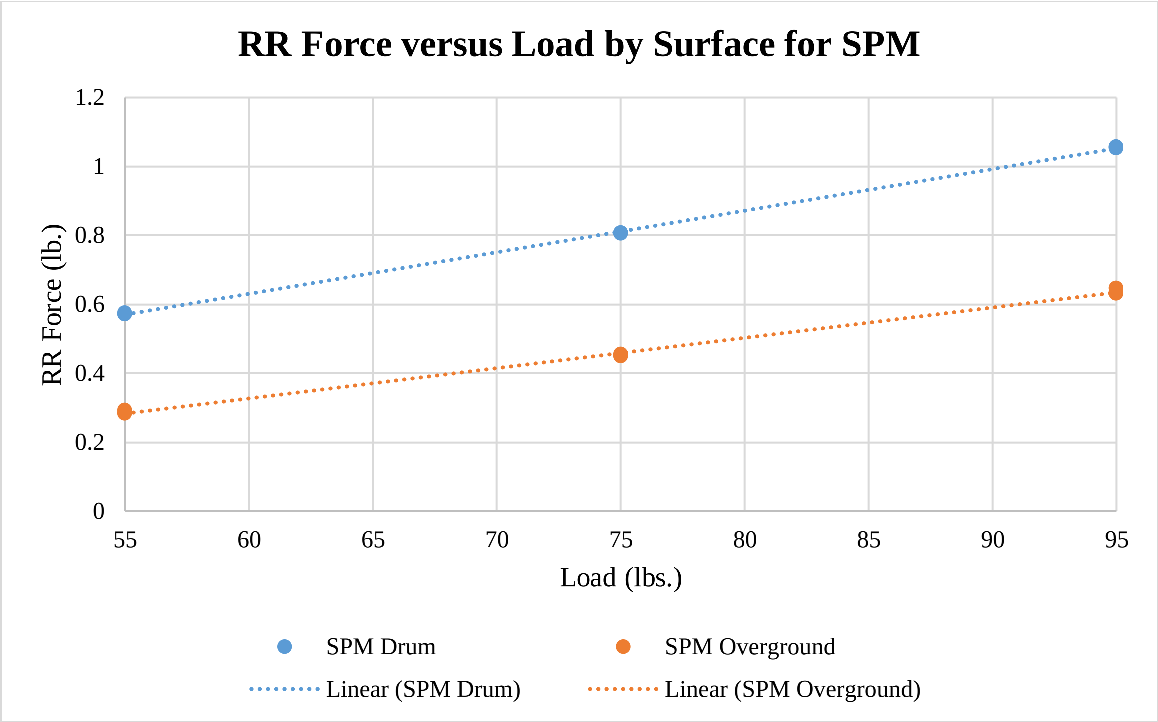
	Slope (m)	**Intercept (b)**	**R^2**
AIS Drum	0.0187	-0.3470	0.9989
AIS Overground	0.0162	-0.4982	0.9950



Appendix Figure 61 RR Force versus Load, Drum versus Overground, KLS Tire

Appendix Table 46 RR Force versus Load, Drum versus Overground, KLS Tire

	Slope (m)	**Intercept (b)**	**R2**
KLS Drum	0.0089	0.0193	0.9988
KLS Overground	0.0061	-0.1436	0.9984

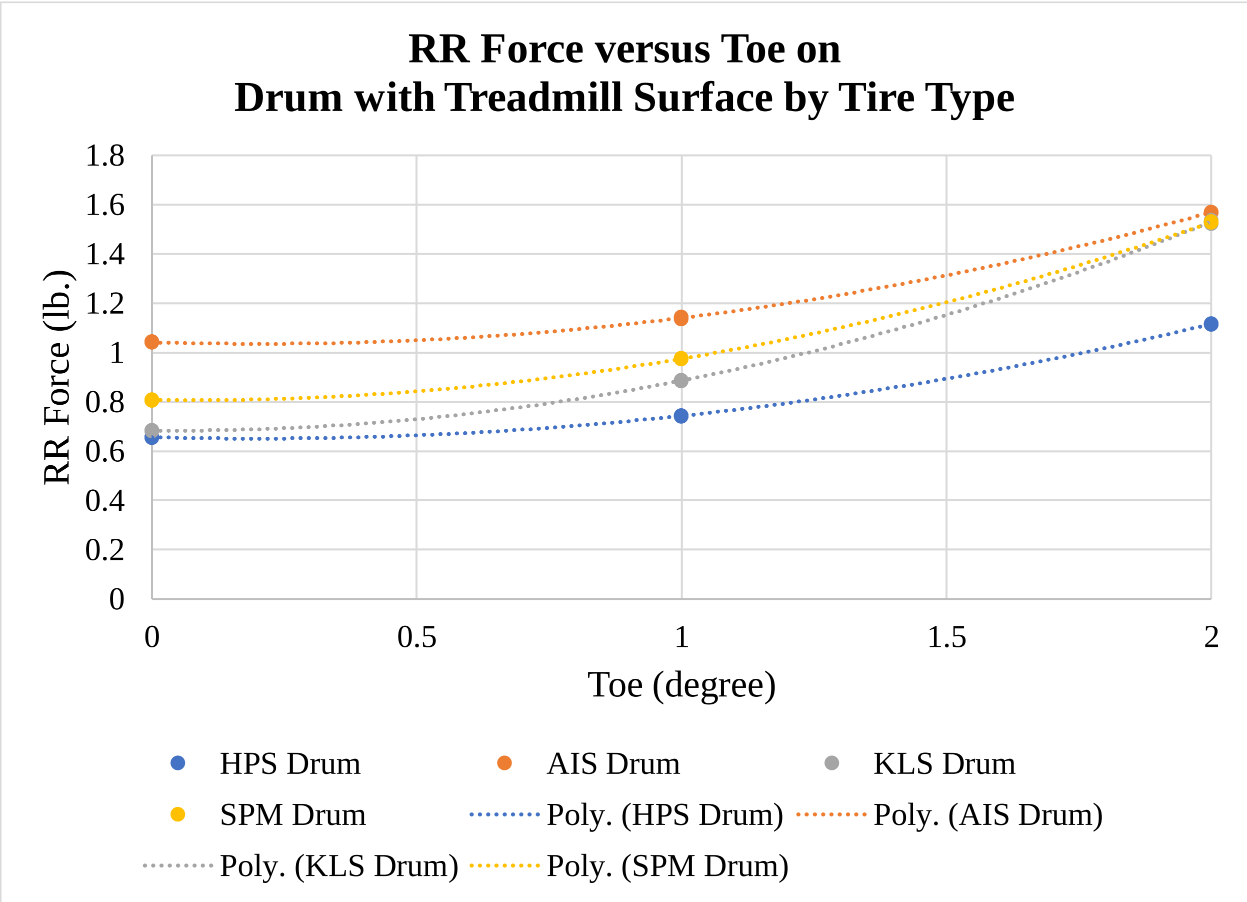


Appendix Figure 62 RR Force versus Load, Drum versus Overground, SPM Tire

Appendix Table 47 RR Force versus Load, Drum versus Overground, SPM Tire

	Slope (m)	**Intercept (b)**	**R^2**
SPM Drum	0.0121	-0.0927	0.9997
SPM Overground	0.0088	-0.1996	0.9977

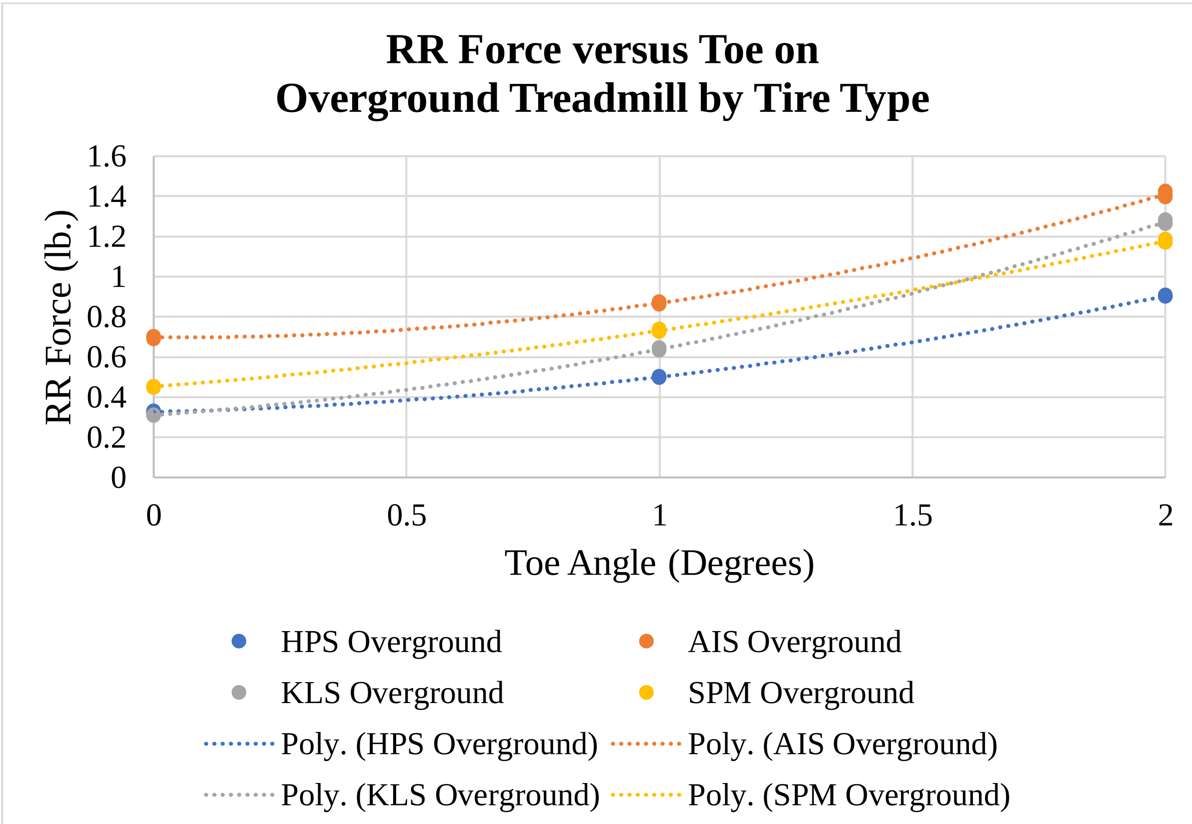
Appendix D.1.2 Toe for Tires



Appendix Figure 63 RR Force versus Toe, Drum Treadmill

Appendix Table 48 RR Force versus Toe, Drum Treadmill

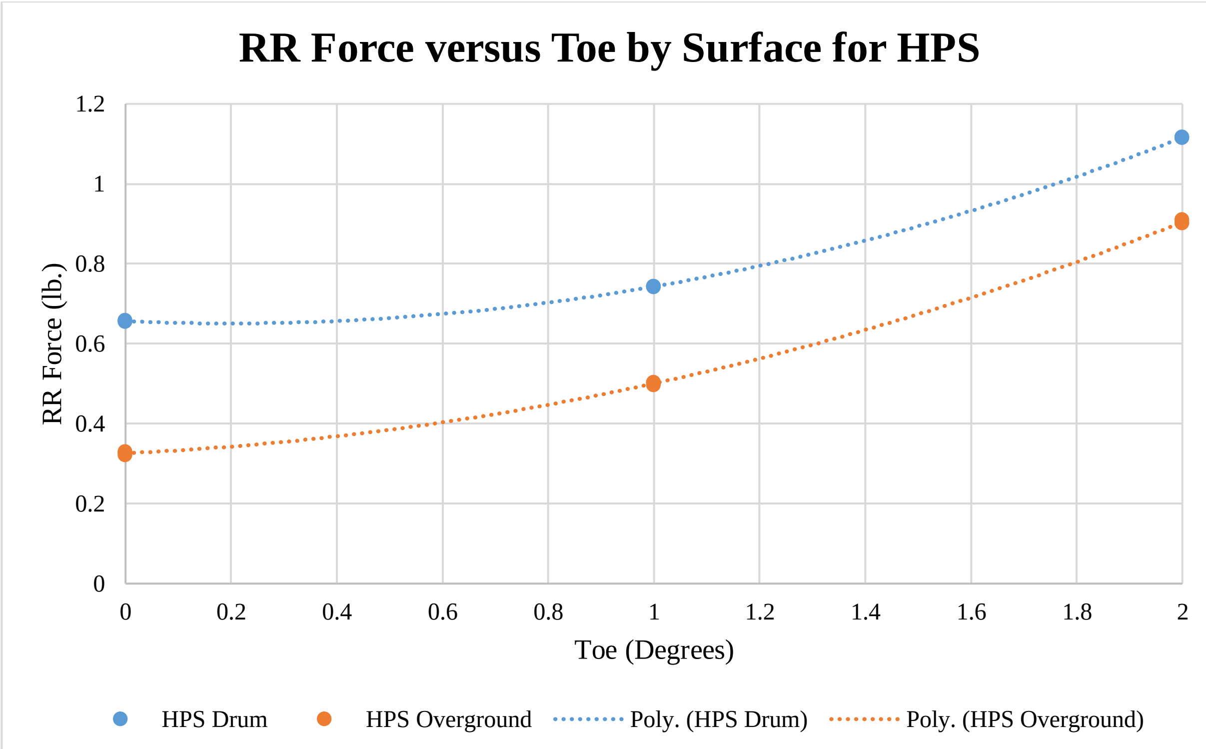
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
HPS	0.1428	-0.0561	0.6565	1
AIS	0.1654	-0.0673	1.0421	0.9999
KLS	0.2204	-0.0176	0.6835	0.9999
SPM	0.1926	-0.0242	0.8067	1



Appendix Figure 64 RR Force versus Toe, Overground Treadmill

Appendix Table 49 RR Force versus To, Overground Treadmill

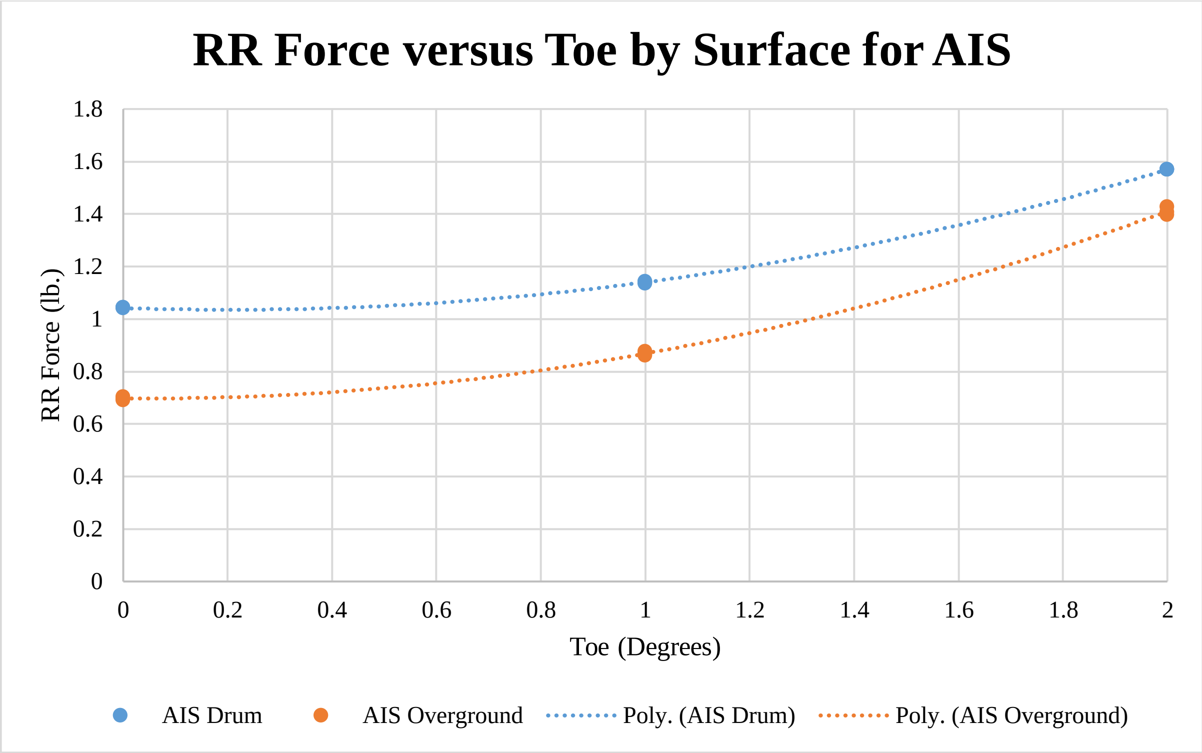
	Coefficient (X_2)	Coefficient (X)	Constant	R_2
HPS	0.1145	0.0600	0.3263	0.9998
AIS	0.1857	-0.0149	0.6974	0.9992
KLS	0.1533	0.1742	0.3111	0.9998
SPM	0.0836	0.1957	0.4518	0.9996



Appendix Figure 65 RR Force versus Toe, Drum versus Overground, HPS Tire

Appendix Table 50 RR Force versus Toe, Drum versus Overground, HPS Tire

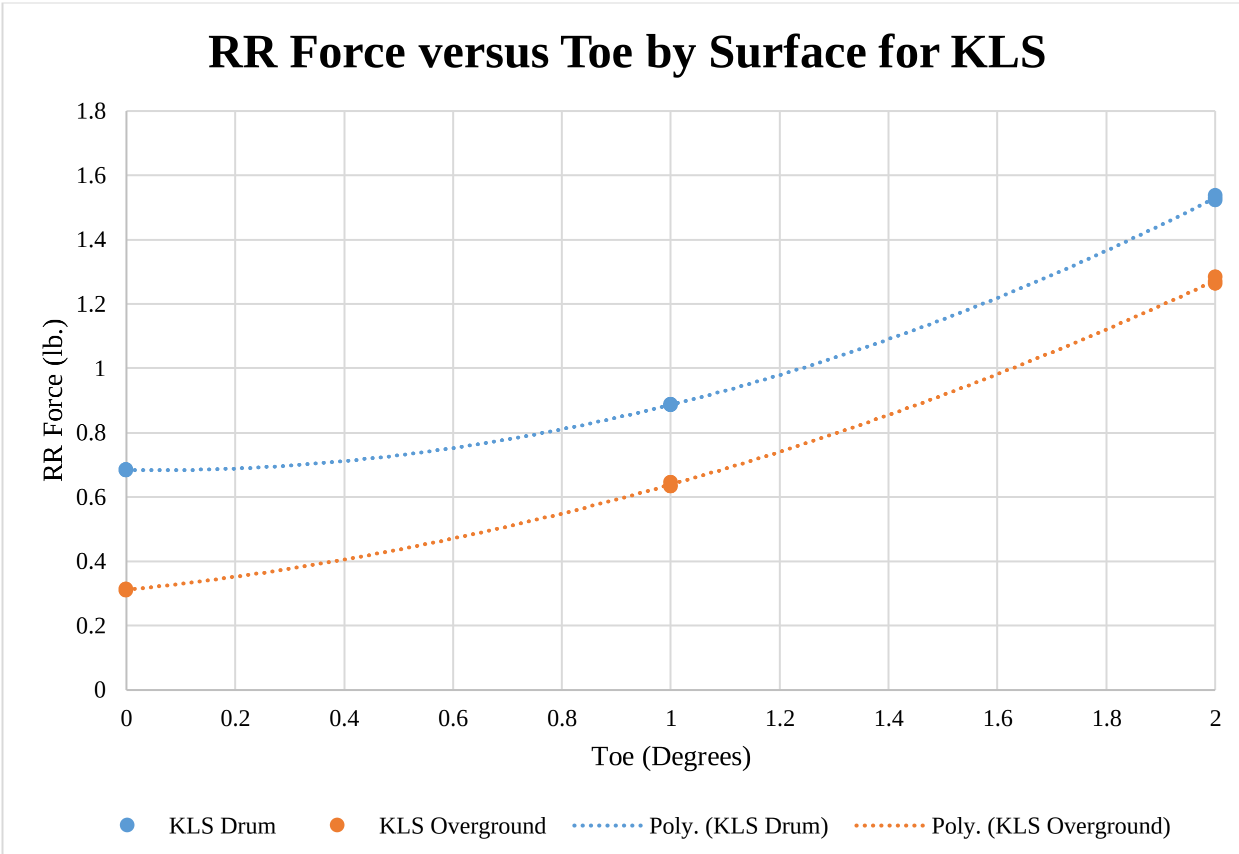
	Coefficient (X2)	**Coefficient (X)**	**Constant**	**R2**
HPS Drum	0.1428	-0.0561	0.6565	1.0
HPS Overground	0.1145	0.0600	0.3263	0.9998



Appendix Figure 66 RR Force versus Toe, Drum versus Overground, AIS Tire

Appendix Table 51 RR Force versus Toe, Drum versus Overground, AIS Tire

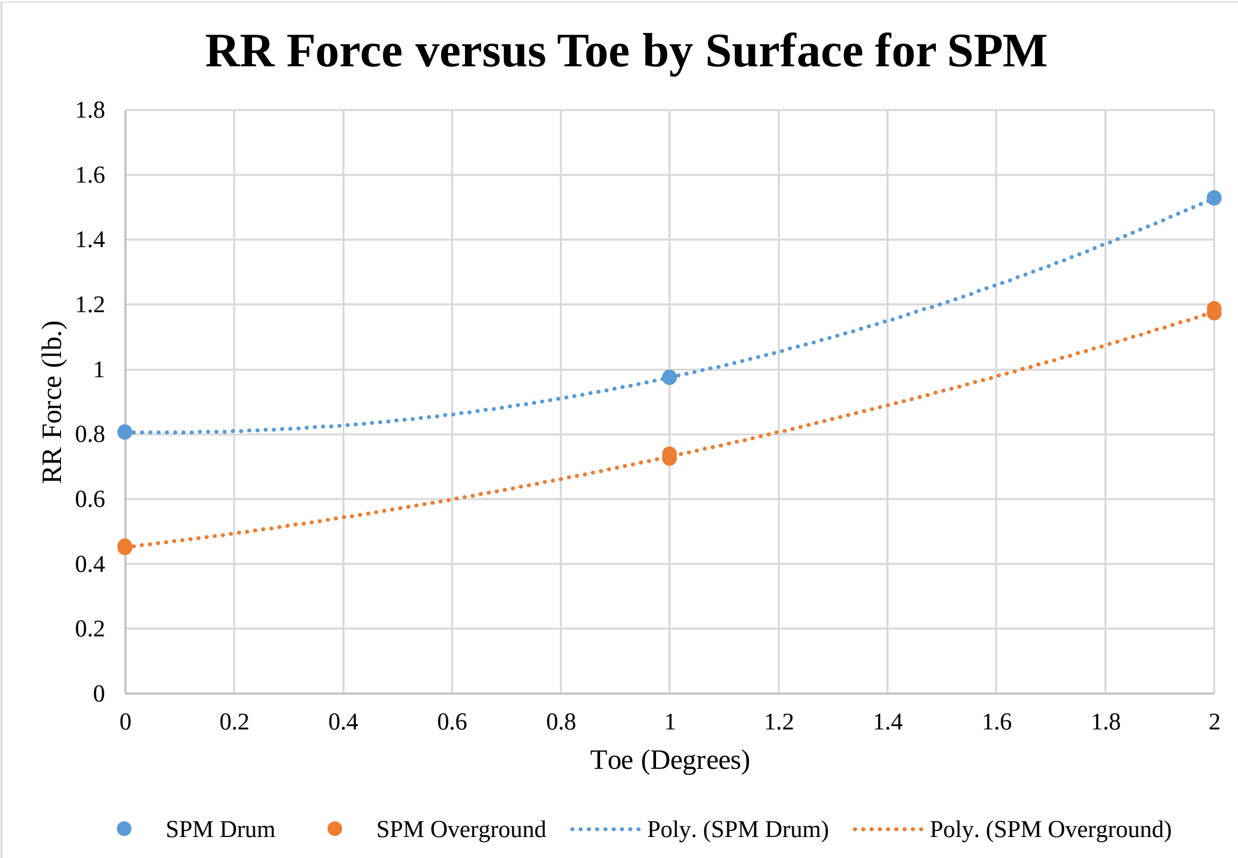
	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
AIS Drum	0.1654	-0.0673	1.0421	0.9999
AIS Overground	0.1857	-0.0149	0.6974	0.9992



Appendix Figure 67 RR Force versus Toe, Drum versus Overground, KLS Tire

Appendix Table 52 RR Force versus Toe, Drum versus Overground, KLS Tire

	Coefficient (X2)	**Coefficient (X)**	**Constant**	**R2**
KLS Drum	0.2204	-0.0176	0.6835	0.9999
KLS Overground	0.1533	0.1742	0.3111	0.9998

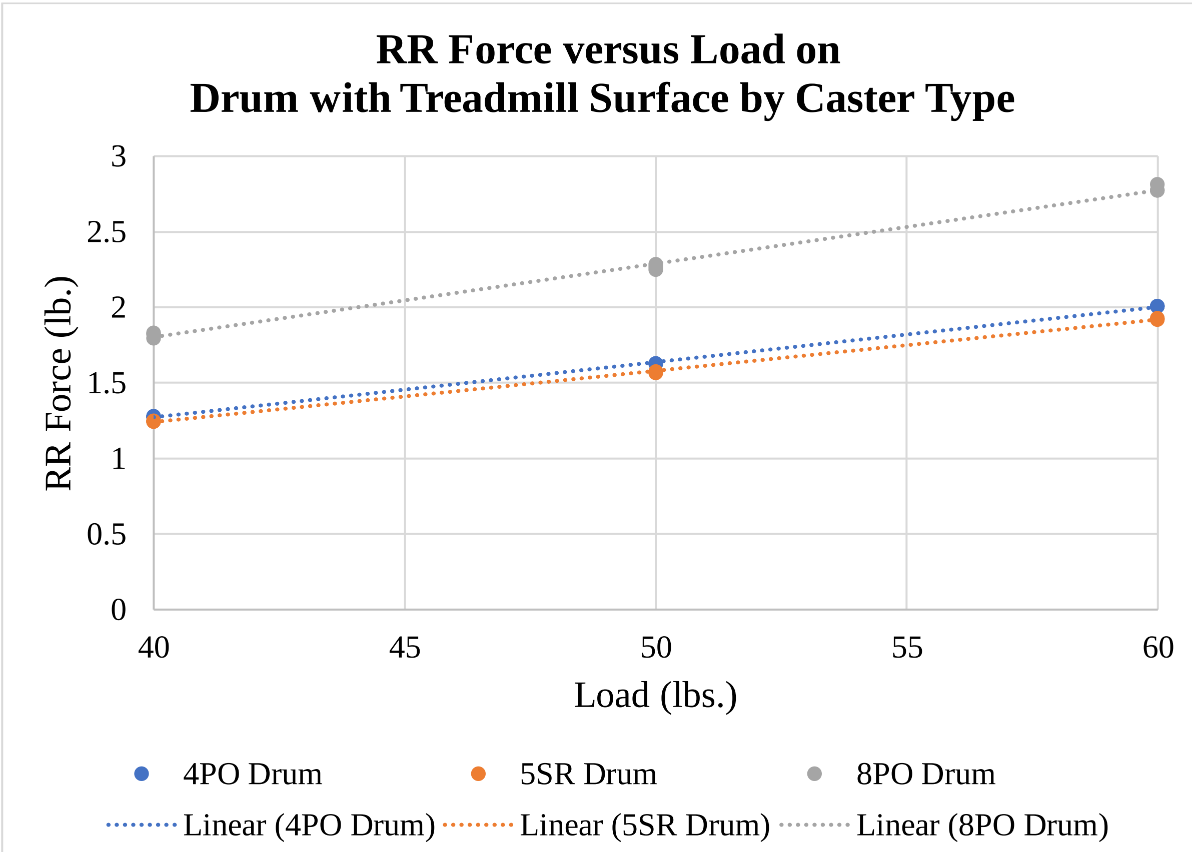


Appendix Figure 68 RR Force versus Toe, Drum versus Overground, SPM Tire

Appendix Table 53 RR Force versus Toe, Drum versus Overground, SPM Tire

	Coefficient (X^2)	**Coefficient (X)**	**Constant**	**R^2**
SPM Drum	0.1926	-0.0242	0.8067	1.0
SPM Overground	0.0836	0.1957	0.4518	0.9996

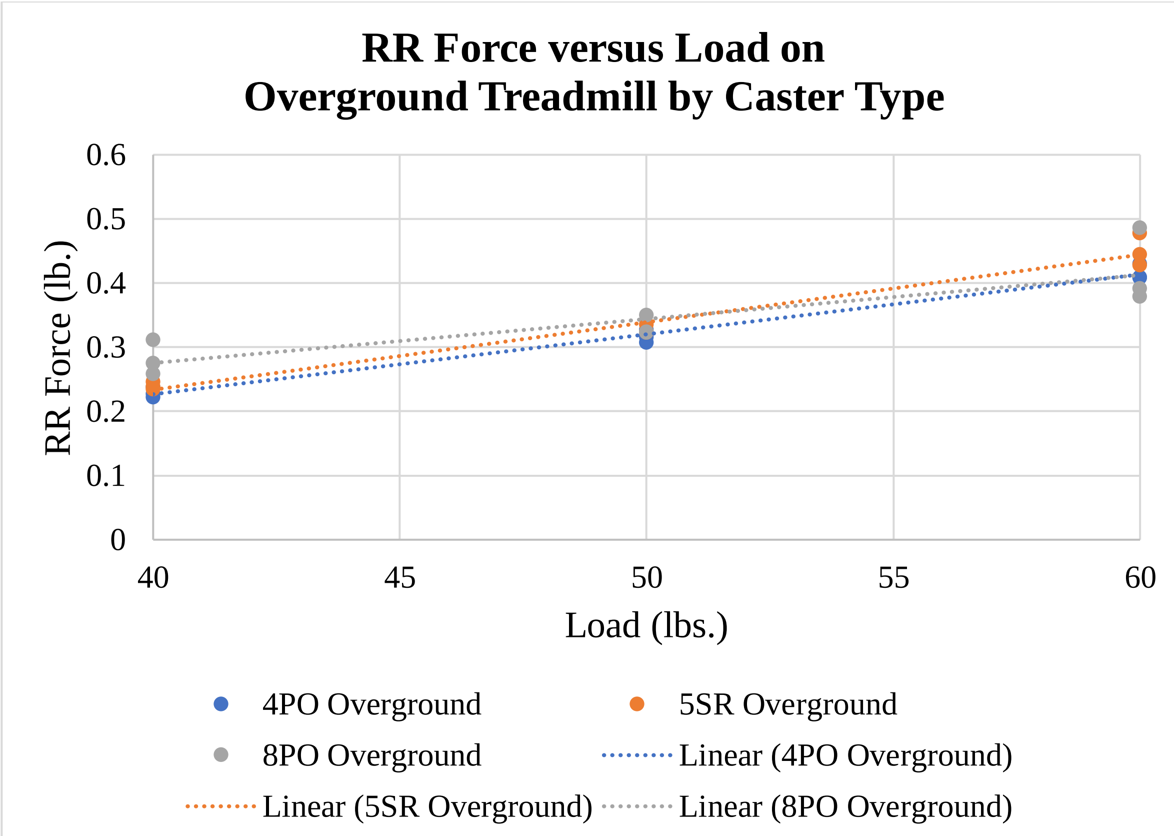
Appendix D.1.3 Load for Casters



Appendix Figure 69 RR Force versus Load, Drum Treadmill

Appendix Table 54 RR Force versus Load, Drum Treadmill

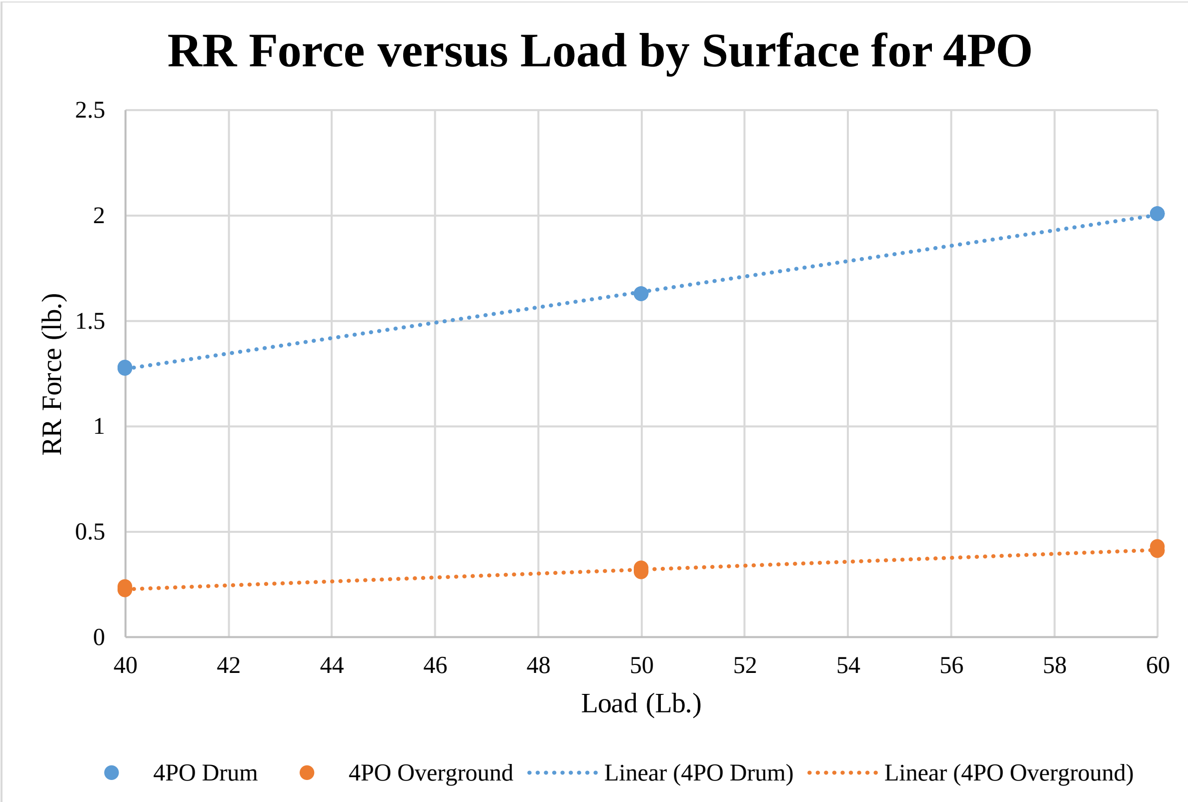
	Slope (m)	**Intercept (b)**	**R_2**
4PO	0.0365	-0.1873	0.9995
5SR	0.0486	-0.1409	0.9968
8PO	0.0339	-0.1166	0.9992



Appendix Figure 70 RR Force versus Load, Drum versus Overground

Appendix Table 55 RR Force versus Load, Drum versus Overground

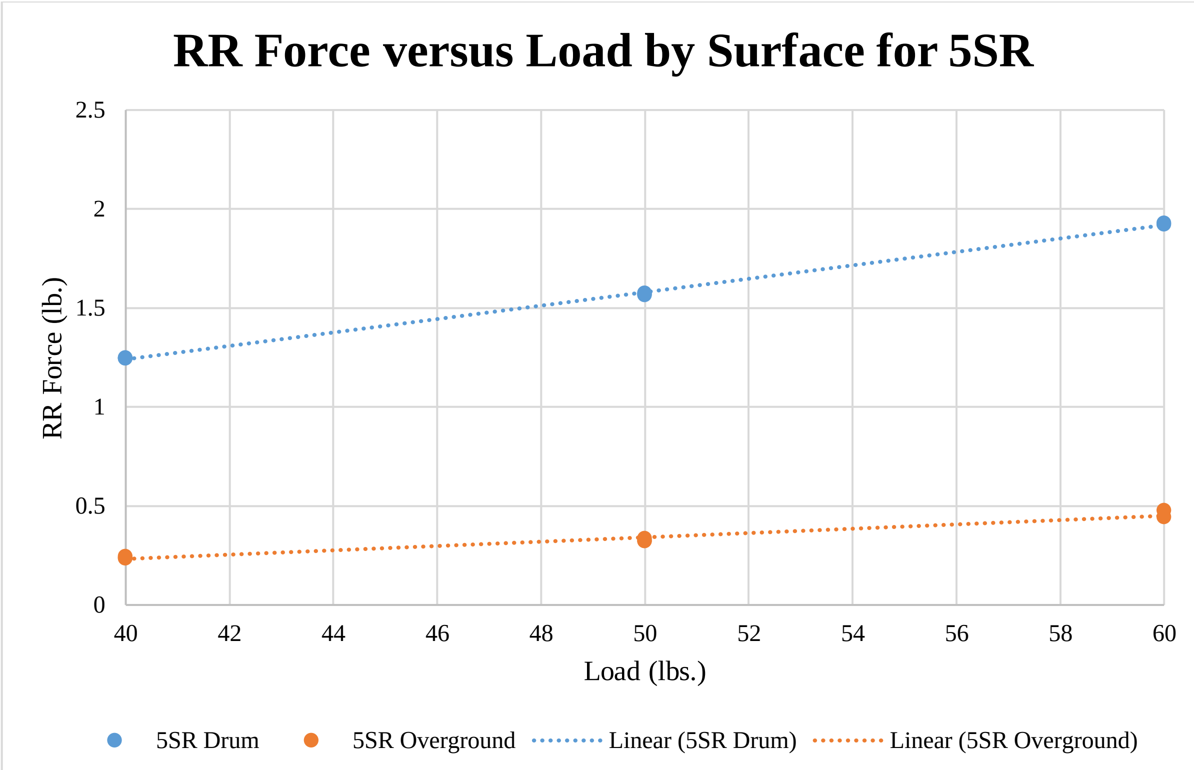
	Slope (m)	Intercept (b)	R_2
4PO	0.0093	-0.1469	0.9875
5SR	0.0069	0.0011	0.7486
8PO	0.0105	-0.1874	0.9693



Appendix Figure 71 RR Force versus Load, Drum versus Overground, 4PO Caster

Appendix Table 56 RR Force versus Load, Drum versus Overground, 4PO Caster

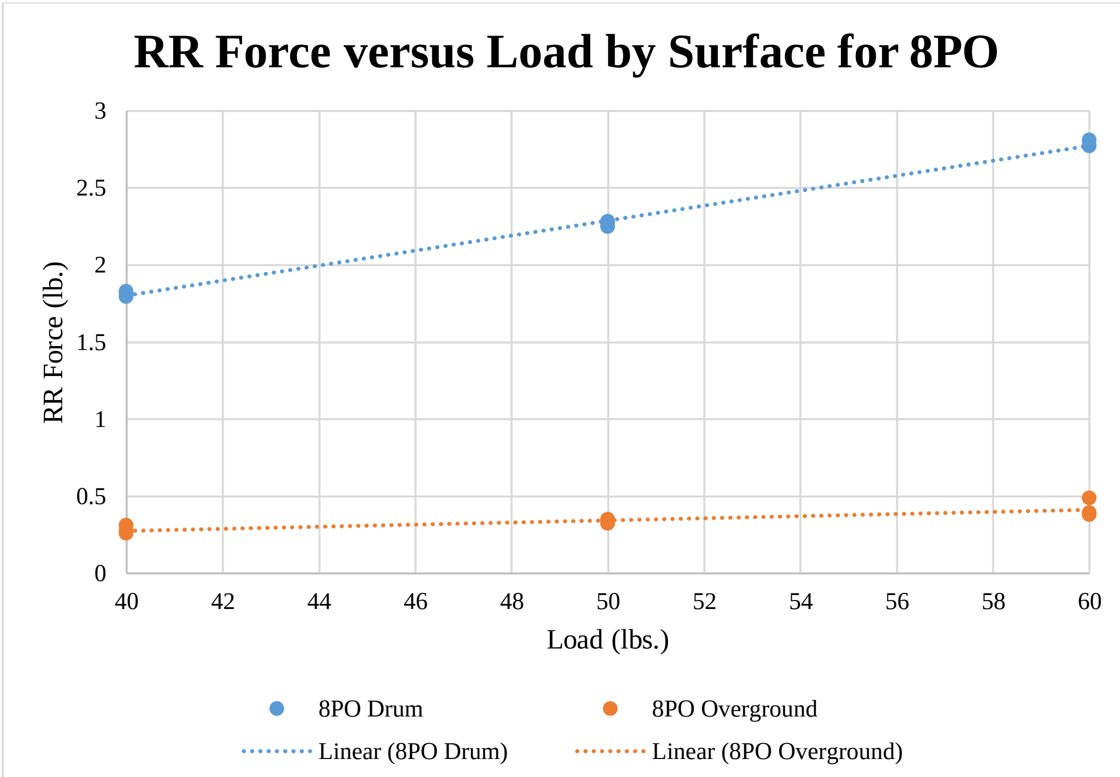
	Slope (m)	**Intercept (b)**	**R^2**
4PO Drum	0.0365	-0.1873	0.9995
4PO Overground	0.0093	-0.1469	0.9875



Appendix Figure 72 RR Force versus Load, Drum versus Overground, 5SR Caster

Appendix Table 57 RR Force versus Load, Drum versus Floor, 5SR Caster

	Slope (m)	**Intercept (b)**	**R_2**
5SR Drum	0.0339	-0.1156	0.9990
5SR Overground	0.0109	-0.2040	0.9711



Appendix Figure 73 RR Force versus Load, Drum versus Overground, 8PO Caster

Appendix Table 58 RR Force versus Load, Drum versus Overground, 8PO Caster

	Slope (m)	Intercept (b)	R_2
8PO Drum	0.0486	-0.1409	0.9968
8PO Overground	0.0069	0.0011	0.7486

Appendix D.2 Descriptive Statistics

The descriptive analysis below provides mean, standard deviation and confidence intervals for RR forces for wheels testing. Wheels (Appendix Table 59) tested were a subset of the larger study and included the high-pressure (HPS), airless insert (AIS), knobby (KLS) and solid (SPM). Appendix Table 60 shows the caster results. DTM represents the Drum with the treadmill surface attached and OTM represents the Overground-Treadmill surface.

Appendix Table 59 Statistics for Drum versus Overground, Treadmill Surface, Wheels

	HPS DTM*	HPS OTM*	AIS DTM*	AIS OTM*	KLS DTM*	KLS OTM*	SPM DTM*	SPM OTM*
Mean	0.6591	0.3263	1.0422	0.6974	0.6841	0.3111	0.8099	0.4518
Standard Deviation	0.0047	0.0045	0.0058	0.0069	0.0024	0.0024	0.0078	0.0034
Confidence level	0.0059	0.0112	0.0072	0.0171	0.0030	0.0059	0.0097	0.0084
Confidence interval low	0.6532	0.3151	1.0349	0.6804	0.6811	0.3053	0.8002	0.4434
Confidence interval high	0.6650	0.3375	1.0494	0.7145	0.6870	0.3170	0.8196	0.4601
Variance (Std. Dev/Mean)	0.71%	1.38%	0.56%	0.99%	0.35%	0.77%	0.96%	0.75%
Number of samples	5	3	5	3	5	3	5	3
*RR force in pounds								

Appendix Table 60 Caster Drum versus Overground Treadmill Statistical Results

	4PO DTM*	4PO OTM*	5SR DTM*	5SR OTM*	8PO DTM*	8PO OTM*
Mean	1.6274	0.3163	1.5718	0.3272	2.2901	0.3321
Standard Deviation	0.0020	0.0097	0.0138	0.0071	0.0588	0.0150
Confidence Level	0.0024	0.0241	0.0171	0.0176	0.0731	0.0372
Confidence Interval Low	1.6249	0.2922	1.5547	0.3096	2.2171	0.2949
Confidence Interval High	1.6298	0.3404	1.5890	0.3448	2.3632	0.3692
Variance (Std. Dev/Mean)	0.12%	3.07%	0.88%	2.17%	2.57%	4.52%
Number of Samples	5	3	5	3	5	3
*RR force in pounds						

Appendix E Community-based Study

This section provides a summary of the survey, the data collected, and the data analysis from the community-based study. This study focused on measuring the prevalence and severity of rear-wheel misalignment, measured as toe and slop, in MWCs. Descriptive data tables summarize the responses and provide averages and the number of responses per category. Data representation for each potential predictive factor is presented in a series of box and whisker plots and a table summarizing the average, standard deviation and total responses for each potential predictor.

Appendix E.1 Questionnaire

The questionnaire that was utilized in this study, from Qualtrics, is listed below. It was utilized for the majority of the study by researchers. Participants were asked the questions as they are written.

Community Based Study: Toe, Slop

Start of Block: Descriptive Questions

Recruitment Event Type

- ○ Adaptive Sports (1)
- ○ Assistive Living (2)
- ○ Education & Training (3)
- ○ Research Lab (4)
- ○ Seating Clinic (5)

Approximately how many years have you had this wheelchair?

- ○ Less than 1 year (1)
- ○ 1-2 years (2)
- ○ 3-4 years (3)
- ○ Greater than 4 years (4)

Have you ever replaced the rear wheels or tires?

- ☐ Yes- Tires only (1)
- ☐ Yes- Wheels and tires (2)
- ☐ No (3)

Skip next question If "Have you ever replaced the rear wheels or tires?" = No

If you replaced the rear wheels or tires, how long ago was it?

- ○ Less than 1 year (1)
- ○ 1-2 years (2)
- ○ 3-4 years (3)
- ○ Greater than 4 years (4)

Approximately how many hours per day do you use your wheelchair?

- ○ < 5 hours (1)
- ○ 5-10 hours (2)
- ○ 11-15 hours (3)
- ○ > 15 hours (4)

Page 1 of 4

Appendix Figure 74 Qualtrics Questionnaire Page 1

Approximately how many days per week do you use your wheelchair?

- ○ 1 day (1)
- ○ 2-3 days (2)
- ○ 4-5 days (3)
- ○ > 5 days (4)

Is this your primary means of mobility?

- ○ Yes (1)
- ○ No (2)

Where do your primarily use your device? (check all that apply)

- ☐ Home (1)
- ☐ Work (2)
- ☐ School (3)
- ☐ Urban Environment (4)
- ☐ Rural Environment (5)

What is your primary source of propulsion?

- ○ Yourself (1)
- ○ Caregiver (2)

End of Block: Descriptive Questions

Start of Block: Device Questions

What is the make of your wheelchair? ________________________________

What is the model of your wheelchair? ________________________________

What type of tires do you have? ________________________________

What is the max pressure capable in your tires? ________________________________

What type of wheels do you have? ________________________________

End of Block: Device Questions

Start of Block: Measurement Block

BEGIN GROUND LEVEL MEASUREMENTS

Page 2 of 4

Appendix Figure 75 Qualtrics Questionnaire Page 2

MEASUREMENT- Caster Diameter (in.) ________________

MEASUREMENT- Overall wheel and Tire Diameter (nominal on sidewall) (in.) ________________

MEASUREMENT- Tire Width (in.) ________________

MEASUREMENT- Wheel Rim Diameter (in.) ________________

Tire Pressure - Left side (0 if non-pneumatic) ________________

Tire Pressure - Right side (0 if non-pneumatic) ________________

MEASUREMENT- Slope of Floor (left to right) (°) ________________

Which side of the level does the arrow point up on?

- ○ Left (1)
- ○ Right (2)

End of Block: Measurement Block

Start of Block: Ground Measurements

AT THIS TIME ASK SUBJECT TO PUT THE BRAKES ON FOR CONTINUED MEASUREMENTS

MEASUREMENT- Camber Left Side (°) (Level must be vertical, not touching the ground) ____

MEASUREMENT- Camber Right Side (°) ________________

Which measurement device are you using?

- ○ Device 1 Pitt (1)
- ○ Device 2 (2)

Level to the Axel Height

Measurement: Laser of Front w/o being raised Left (mm) ________________

MEASUREMENT: Laser of Front w/o being raised Right (mm) ________________

Page 3 of 4

Appendix Figure 76 Qualtrics Questionnaire Page 3

MEASUREMENT: Laser of Rear w/o being raised Left (mm) ________________

MEASUREMENT: Laser of Rear w/o being raised Right (mm) ________________

End of Block: Ground Measurements

Start of Block: Lifted Measurements

AT THIS TIME, TELL THE PARTICIPANT THEY ARE GOING TO BE LIFTED PLEASE ASK PARTICIPANT TO REMOVE THE BRAKES ONCE THEY ARE LIFTED

PLACE CONSTANT FORCE SPRINGS/HOOKS ON THE WHEELS FROM BESIDE THE LASERS

MEASUREMENT: Laser with toe in induced Left (mm) ________________

MEASUREMENT: Laser with toe in induced Right (mm) ________________

REMOVE SPRINGS FROM WHEELS

PLEASE POSITION TENSIONER BETWEEN THE WHEELS AND PLACE CONSTANT FORCE SPRINGS/HOOKS ON WHEELS FROM THE TENSIONER

MEASUREMENT: Laser with toe out induced Left (mm) ________________

MEASUREMENT: Laser with toe out induced Right (mm) ________________

AT THIS TIME TELL PARTICIPANT THAT THEY WILL BE LOWERED AND THEY SHOULD APPLY THEIR BRAKES TO THE WHEEL TO PREVENT ROLLING

THANK PARTICIPANT AND GIVE THEM THEIR GIFT CARD

End of Block: Lifted Measurements

Page 4 of 4

Appendix Figure 77 Qualtrics Questionnaire Page 4

Appendix E.2 Descriptive Tables

Below are the descriptive tables summarizing the data collected from the Community based study of the prevalence of toe and slop. These tables summarize the questions asked in the survey and groups the responses, providing N, the number of responses and the percentage this response represents. The total number of responses for each question is listed at the bottom of the table.

Appendix Table 61 Age of Device

Manual Wheelchair Community-based Study

Wheelchair Information	N	(%)
Approximately how many years have you had this wheelchair?		
<1 year	27	(13.5)
1-2 years	42	(21.0)
3-4 years	50	(25.0)
>4 years	79	(39.5)
No response	2	(1.0)
Have you ever replaced the rear-wheels or tires?		
Yes - Wheels and Tires	62	(31.0)
Yes - Tires Only	63	(31.5)
No	68	(34.0)
No response *	7	(3.5)
If you replaced both the rear-wheels or tires, how long ago was it?**		
< 1 year	44	(71.0)
1-2 years	14	(22.6)
3-4 years	2	(3.2)
>4 years	1	(1.6)
No response	1	(1.6)
**Note. Total, N=62		
If you replaced only the rear tires, how long ago was it?***		
< 1 year	46	(73.0)
1-2 years	15	(23.8)
3-4 years	0	(0.0)
>4 years	1	(1.6)
No response	1	(1.6)
***Note. Total, N=63		

Note. Total, N=200
*seven responses lost
**N=62 for rear-wheel and tires
***N=63 for rear tires only

Appendix Table 62 Wheelchair Use Frequency

Manual Wheelchair Community-based Study

Wheelchair Use Frequency	N	(%)
Is this your primary means of mobility?		
Yes	186	(93.0)
No	12	(6.0)
No response	2	(1.0)
What is your primary source of propulsion?		
Yourself	193	(96.5)
Caregiver	5	(2.5)
No response	2	(1.0)

Note. Total, N=200

Appendix Table 63 Wheelchair Location Use

Manual Wheelchair Community-based Study

Wheelchair Use Frequency	N	(%)
Where do you primarily use your device? (check all that apply)		
Home	174	(87.0)
Work	135	(67.5)
School	77	(38.5)
Urban Environment	159	(79.5)
Rural Environment	97	(48.5)

Note. Total, N=200; Participants selected multiple categories for wheelchair use

Appendix Table 64 Wheel and Caster Measurements

Manual Wheelchair Community-based Study

Wheel and Caster Measurements	N	(%)
Overall Wheel and Tire Diameter (in.)		
22	7	(3.5)
24	117	(58.5)
25	53	(26.5)
26	23	(11.5)
Wheel Rim Diameter (in.)		
20*	8	(4.0)
21.75	115	(57.5)
22.5	55	(27.5)
23**	2	(1.0)
23.75	20	(10.0)
*includes 20, 20.25- and 20.5-inch rims		
** includes 23- and 23.5-inch rims		
Tire Width (in.)		
1.0	136	(68.0)
1.25*	9	(4.5)
1.375	48	(24.0)
1.5**	7	(3.5)
*includes 1.125-inch tire		
**includes 1.5, 2, 2.25 and 2.375 tires		
Caster Diameter (in.)		
3	5	(2.5)
3.5	2	(1.0)
4	77	(38.5)
4.5	33	(16.5)
5	62	(31.0)
5.5	2	(1.0)
6	13	(6.5)
7	1	(0.5)
8	5	(2.5)

Note. Total, N=200

Appendix Table 65 Tire Pressure Measurements

Manual Wheelchair Community-based Study

Tire Pressure Measurements	N	(%)
Wheel Tire Pressure		
Solid or Non-Pneumatic	21	(10.5)
Numerical Value listed	29	(14.5)
Not recorded	150	(75.0)
Distribution of left tire pressure (%)*		
Less than 20 % inflated	3	(10.3)
20 % to 40 % inflated	12	(41.4)
40 % to 60% inflated	10	(34.5)
60% to 80% inflated	4	(13.8)
80% to 100% inflated	0	(0.0)
Average pressure, left (psi)		(41.6)
Distribution of right tire pressure (%)*		
Less than 20 % inflated	4	(13.8)
20 % to 40 % inflated	11	(37.9)
40 % to 60% inflated	7	(24.1)
60% to 80% inflated	7	(24.1)
80% to 100% inflated	0	(0.0)
Average pressure, right (%)		(40.0)

Note. Total, N=200

*N=29

Appendix Table 66 Tire Pressure Comparison – Left and Right

Manual Wheelchair Community-based Study

Comparison of Left and Right Pressure Difference (% of max)	N	(%)	N	(%)	N	(%)
	Overall		Left		Right	
Equal	1	(3)	-	-	-	-
Less than 5%	16	(55)	9	(56)	7	(58)
5 to 10%	6	(21)	3	(19)	3	(25)
More than 10%	6	(21)	4	(25)	2	(17)

Note. Total, N=29

Appendix Table 67 Toe Measurements

Manual Wheelchair Community-based Study Calculations

Toe Measurements	N	(%)
Total difference (mm)		
0 degrees	7	(3.5)
Less than 5 mm	84	(42)
Between 5 and 10 mm	53	(26.5)
Between 10 and 15 mm	26	(13)
Over 15 mm	30	(15)
Toe Measured on Ground		
0 degrees	7	(3.5)
Less than 0.5 degree	71	(35.5)
Between 0.5 and 1.0 degree	56	(28)
Between 1.0 and 1.5 degree	32	(16)
More than 1.5 degree	34	(17)
Average Toe Angle	0.92	
Direction of Toe		
Toe-out	124	(62)
Toe-in	76	(38)

Note. Total, N=200

Appendix Table 68 Slop Measurements

Manual Wheelchair Community-based Study Calculations

Slop Measurements	N	(%)
Toe Measured with Wheelchair Raised Rear Difference (mm)		
0 degrees	9	(4.5)
Less than 5 mm	119	(59.5)
Between 5 and 10 mm	54	(27)
Between 10 and 15 mm	11	(5.5)
Over 15 mm	7	(3.5)
Toe Measured with Wheelchair Raised		
0 degrees	9	(4.5)
Less than 0.5 degree	103	(51.5)
Between 0.5 and 1.0 degree	66	(33)
Between 1.0 and 1.5 degree	13	(6.5)
More than 1.5 degree	9	(4.5)
Average slop	0.60	

Note. Total, N=200

Appendix Table 69 Camber Measurements

Manual Wheelchair Community-based Study Calculations

Camber Measurements	N	(%)
Left Wheel Camber Angle (Degrees)	N	(%)
Less than 0	3	(1.5)
0 to 1	20	(10.1)
1 to 2	17	(8.5)
2 to 3	53	(26.6)
3 to 4	65	(32.7)
4 to 5	27	(13.6)
Over 5	14	(7.0)
Average Camber, Left	2.95	
Right Wheel Camber Angle (Degrees)	N	(%)
Less than 0	1	(0.5)
0 to 1	21	(10.6)
1 to 2	22	(11)
2 to 3	44	(22.1)
3 to 4	65	(32.7)
4 to 5	31	(15.6)
Over 5	15	(7.5)
Average Camber, Right	3.05	

Note. Total, N=199*
*one camber measurement was lost due to application recording error

Appendix Table 70 Camber Comparison – Left and Right

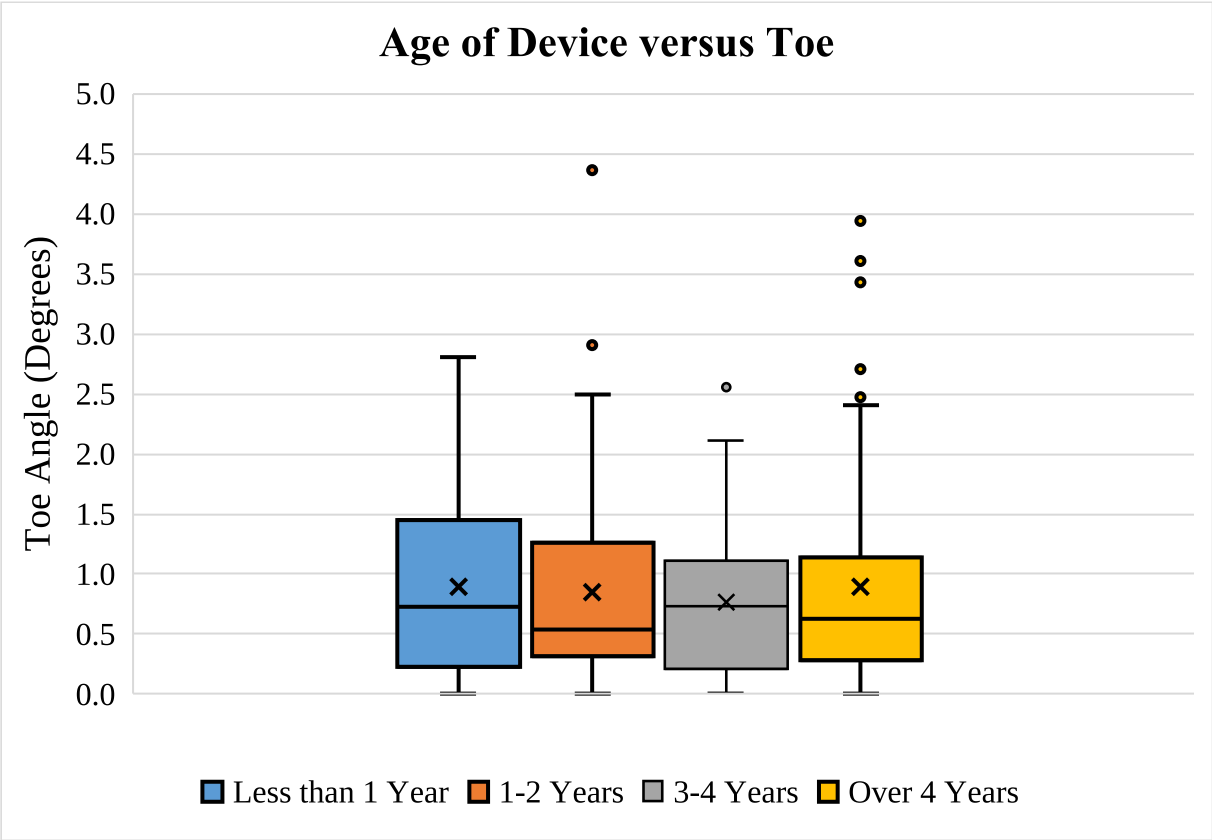
Manual Wheelchair Community-based Study

Left and Right Camber Difference (degrees)	N	(%)	N	(%)	N	(%)
	Overall		Left		Right	
Equal	8	(4)	-	-	-	-
0 to 0.5	110	(55)	44	(61)	66	(56)
0.5 to 1	51	(26)	12	(17)	39	(32)
1 to 1.5	16	(8)	9	(12)	7	(6)
Over 1.5	14	(7)	7	(10)	7	(6)

Note. Total, N=199

Appendix E.3 Box and Whisker Plots

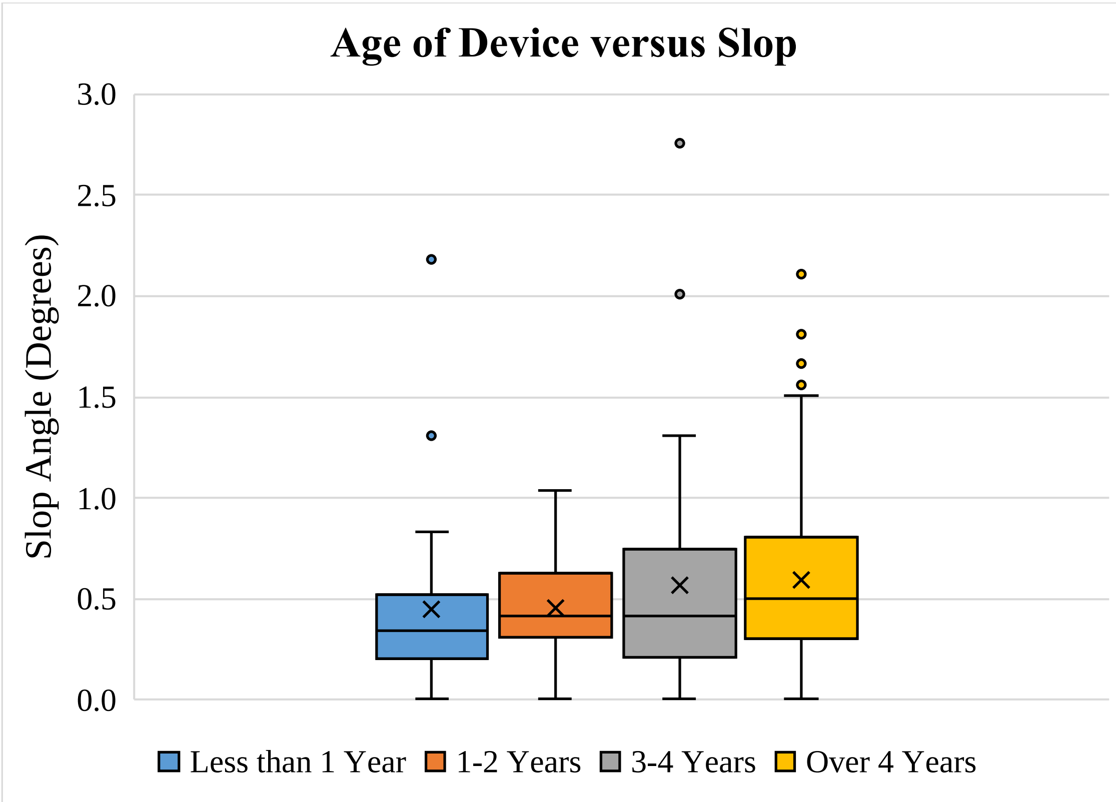
The MWC community-based study results are outlined below in a series of box and whisker plots with specific statistics for these charts outlined in the table below. The full analysis with all box and whisker charts is included in the appendix to give the reader a broader understanding of the results of this study. The results are organized to provide the respective toe and slop for each question and measurement taken.



Appendix Figure 78 Device Age versus Toe

Appendix Table 71 Device Age versus Toe

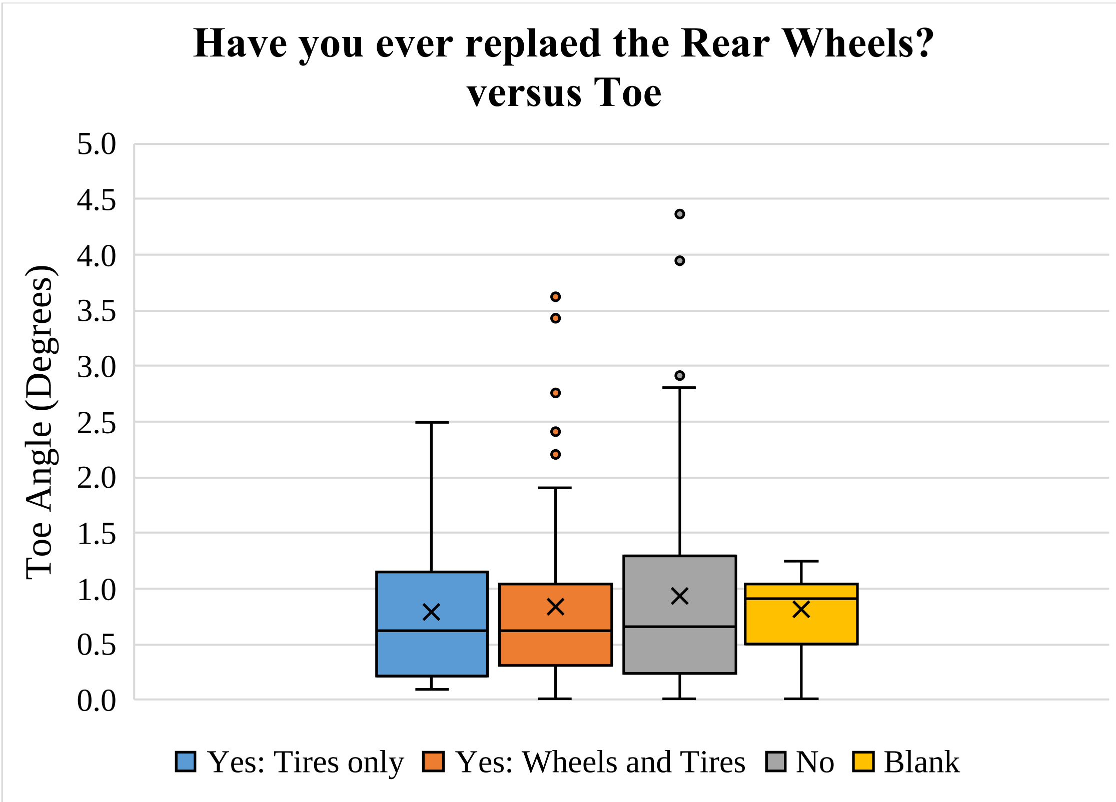
`	Less than 1 Year	1-2 Years	3-4 Years	Over 4 Years	Blank
Average (deg)	0.89	0.85	0.78	0.89	0.88
Std Dev (deg)	0.81	0.85	0.60	0.86	0.22
N (qty)	27	42	50	79	2



Appendix Figure 79 Device Age versus Slop

Appendix Table 72 Device Age versus Slop

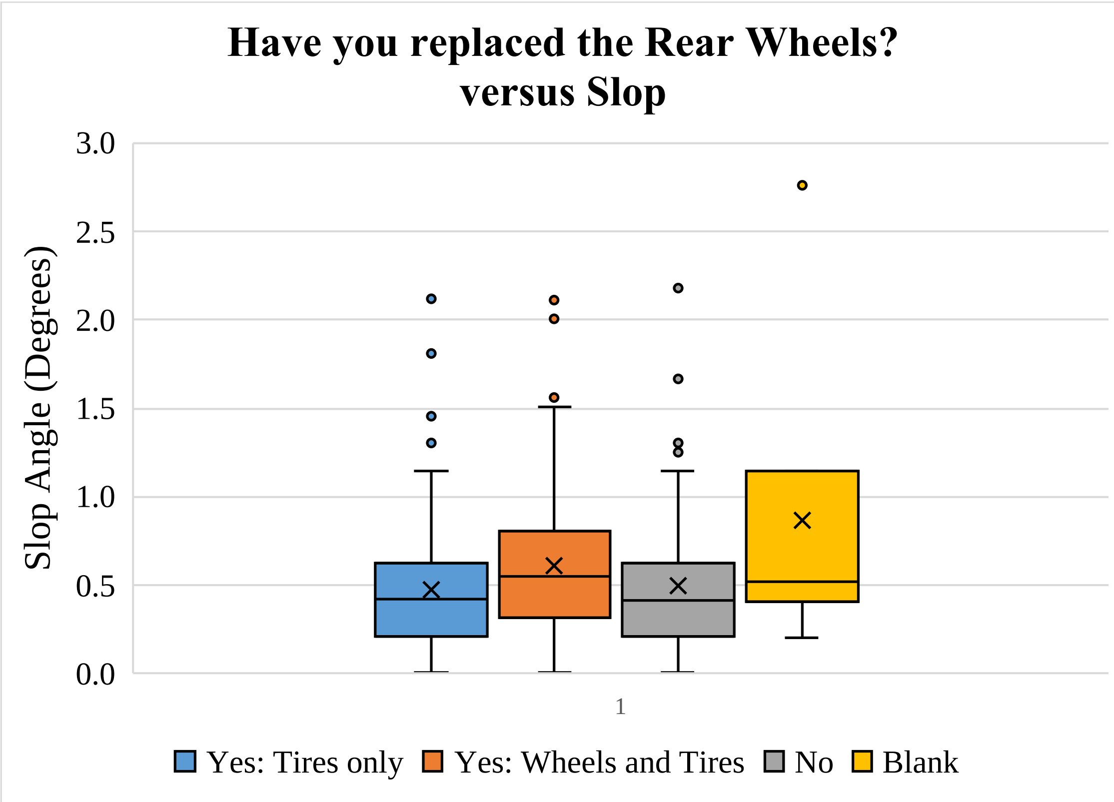
	Less than 1 Year	1-2 Years	3-4 Years	Over 4 Years	Blank
Average (deg)	0.44	0.45	0.58	0.60	0.52
Std Dev (deg)	0.44	0.25	0.51	0.46	0.15
N (qty)	27	42	50	79	2



Appendix Figure 80 Rear-wheel Replacement veresus Toe

Appendix Table 73 Rear-wheel Replacement versus Toe

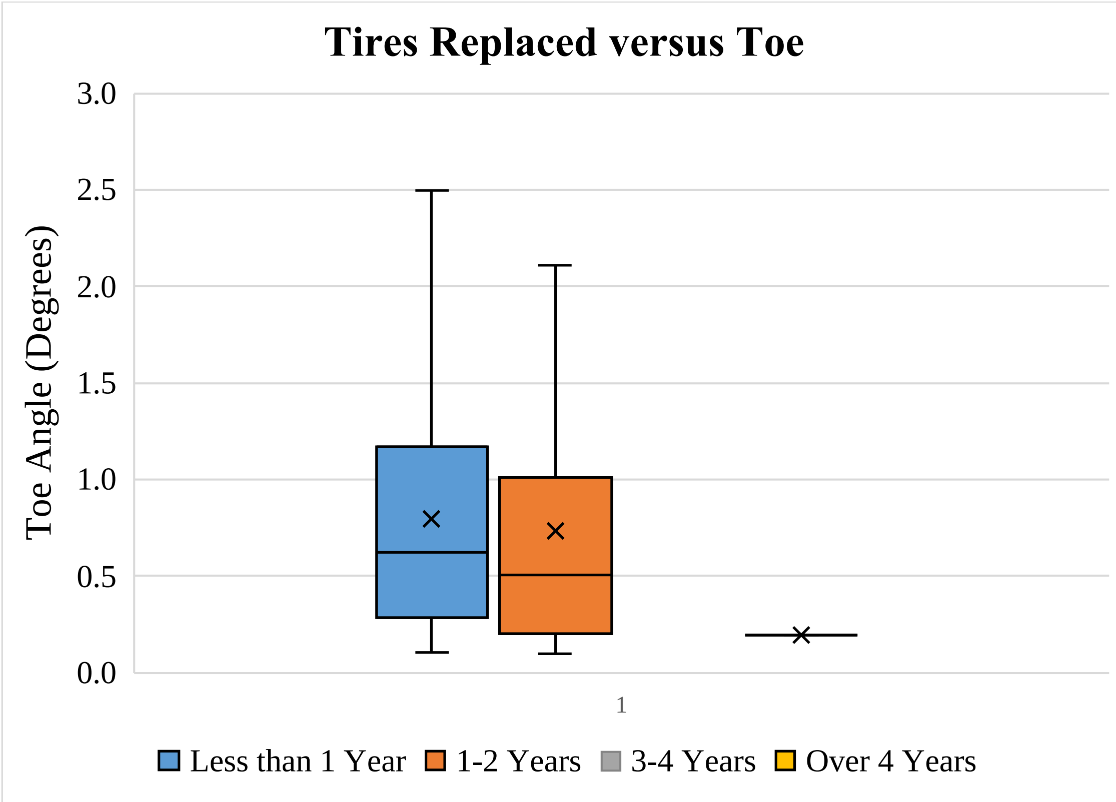
	Yes: Tires only	Yes: Wheels and Tires	No	Blank
Average (deg)	0.79	0.83	0.93	0.94
Std Dev (deg)	0.62	0.77	0.96	0.25
N (qty)	63	62	68	7



Appendix Figure 81 Rear-wheel Replacement versus Slop

Appendix Table 74 Rear-wheel Replacement versus Slop

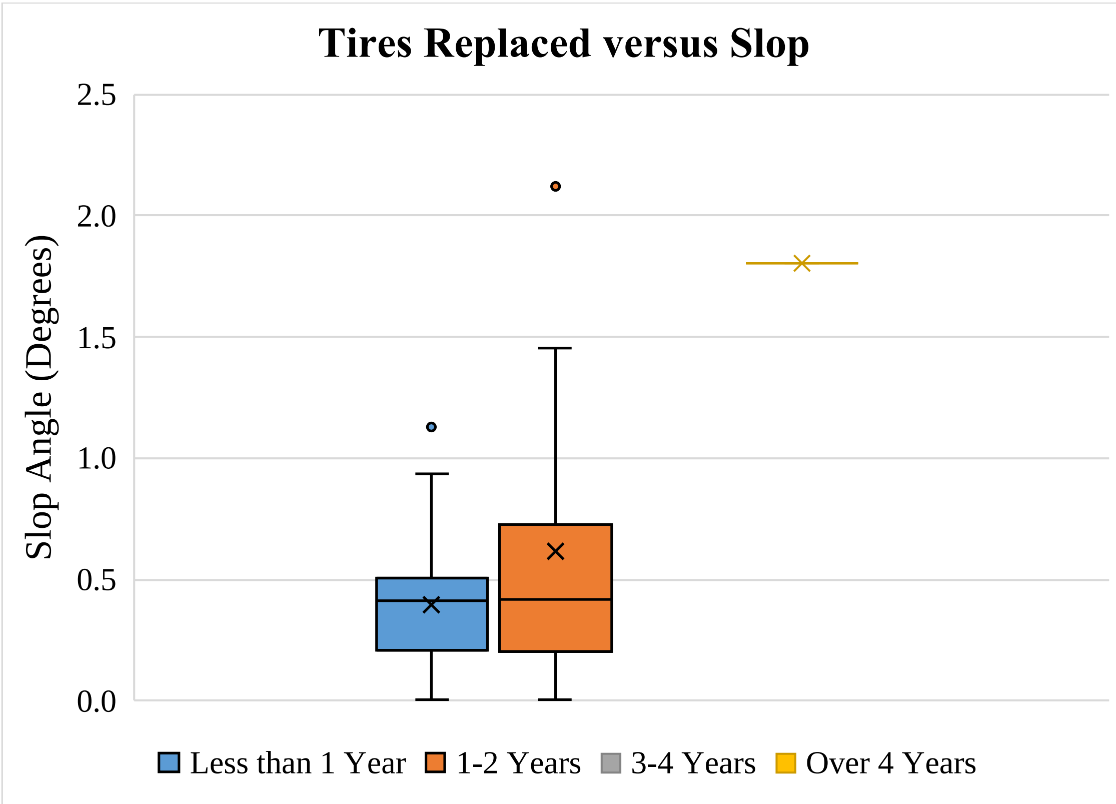
	Yes: Tires only	**Yes: Wheels and Tires**	**No**	**Blank**
Average (deg)	0.48	0.62	0.49	0.86
Std Dev (deg)	0.41	0.43	0.38	0.89
N (qty)	63	62	68	7



Appendix Figure 82 Tire Replacement versus Toe

Appendix Table 75 Tire Replacement versus Toe

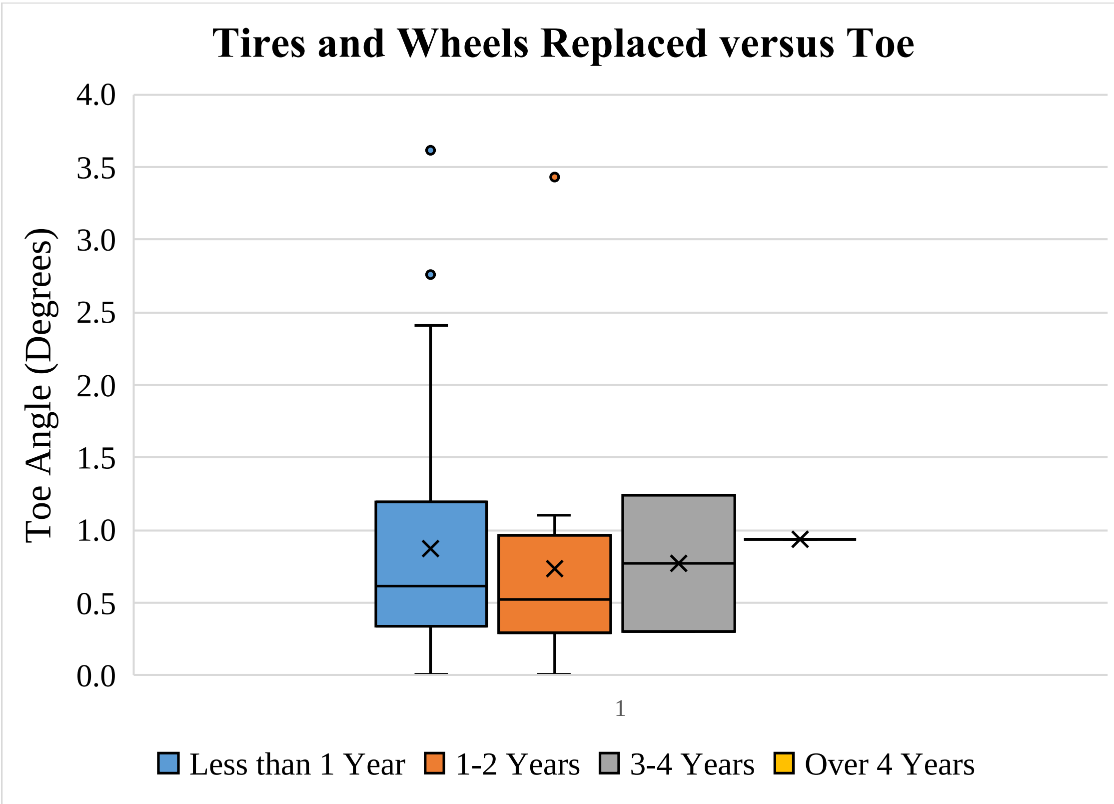
	Less than 1 Year	**1-2 Years**	**3-4 Years**	**Over 4 Years**	**Blank**
Average (deg)	0.80	0.73		0.19	1.91
Std Dev (deg)	0.58	0.71			
N (qty)	46	15	0	1	1



Appendix Figure 83 Tire Replacement versus Slop

Appendix Table 76 Tire Replacement versus Slop

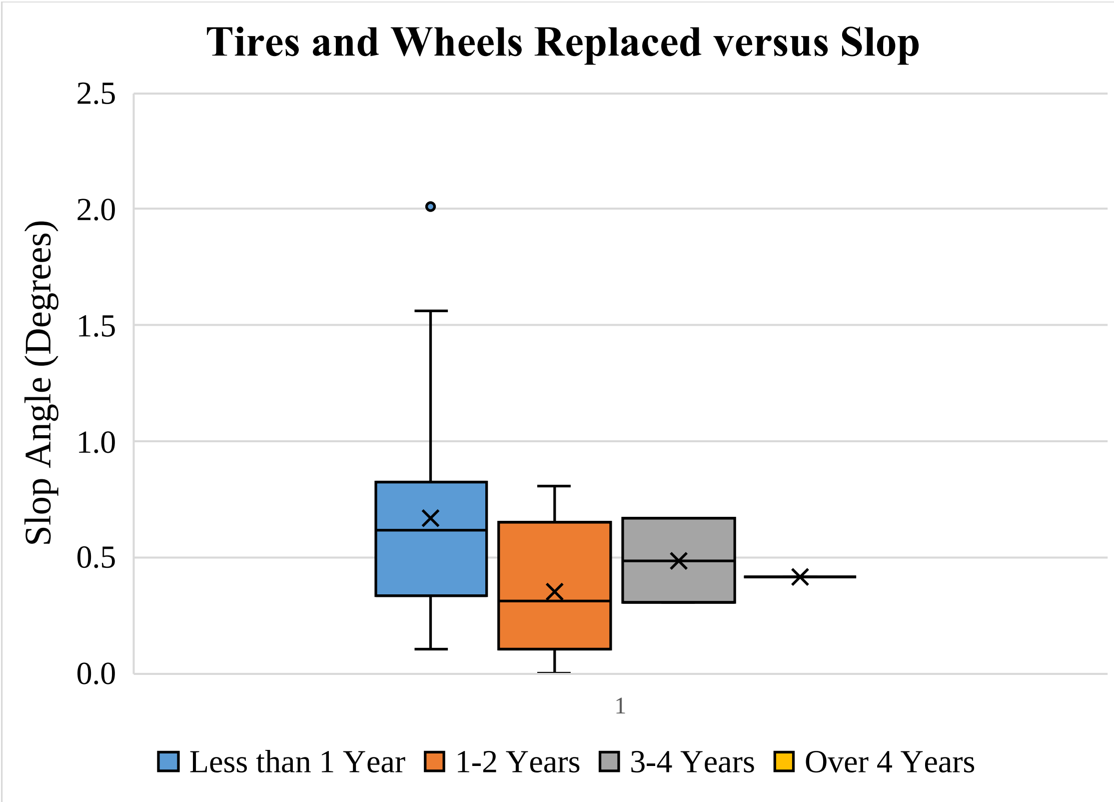
	Less than 1 Year	**1-2 Years**	**3-4 Years**	**Over 4 Years**	**Blank**
Average (deg)	0.40	0.61		1.80	0.40
Std Dev (deg)	0.27	0.59			
N (qty)	46	15	0	1	1



Appendix Figure 84 Tire and WheelsReplacement versus Toe

Appendix Table 77 Tire and Wheel Replacement versus Toe

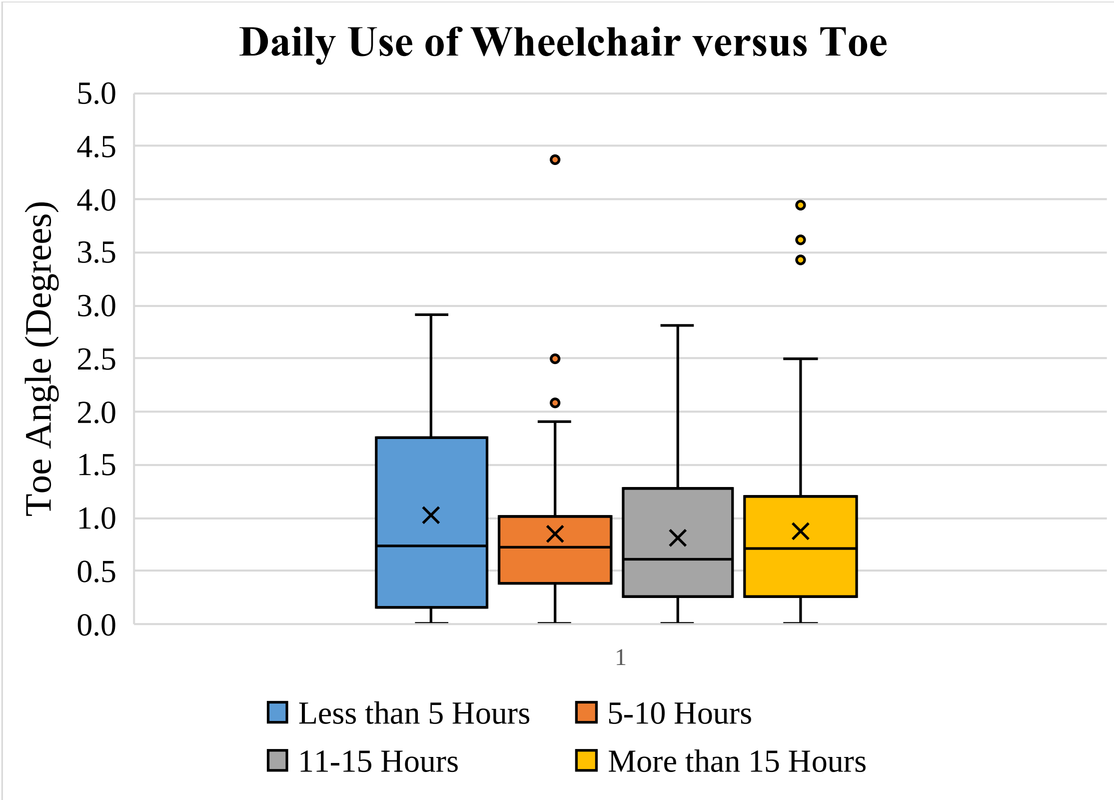
	Less than 1 Year	1-2 Years	3-4 Years	Over 4 Years	Blank
Average (deg)	0.87	0.73	0.77	0.93	0.80
Std Dev (deg)	0.78	0.85	0.66		
N (qty)	44	14	2	1	1



Appendix Figure 85 Tire and Wheel Replacement versus Slop

Appendix Table 78 Tire and Wheel Replacement versus Slop

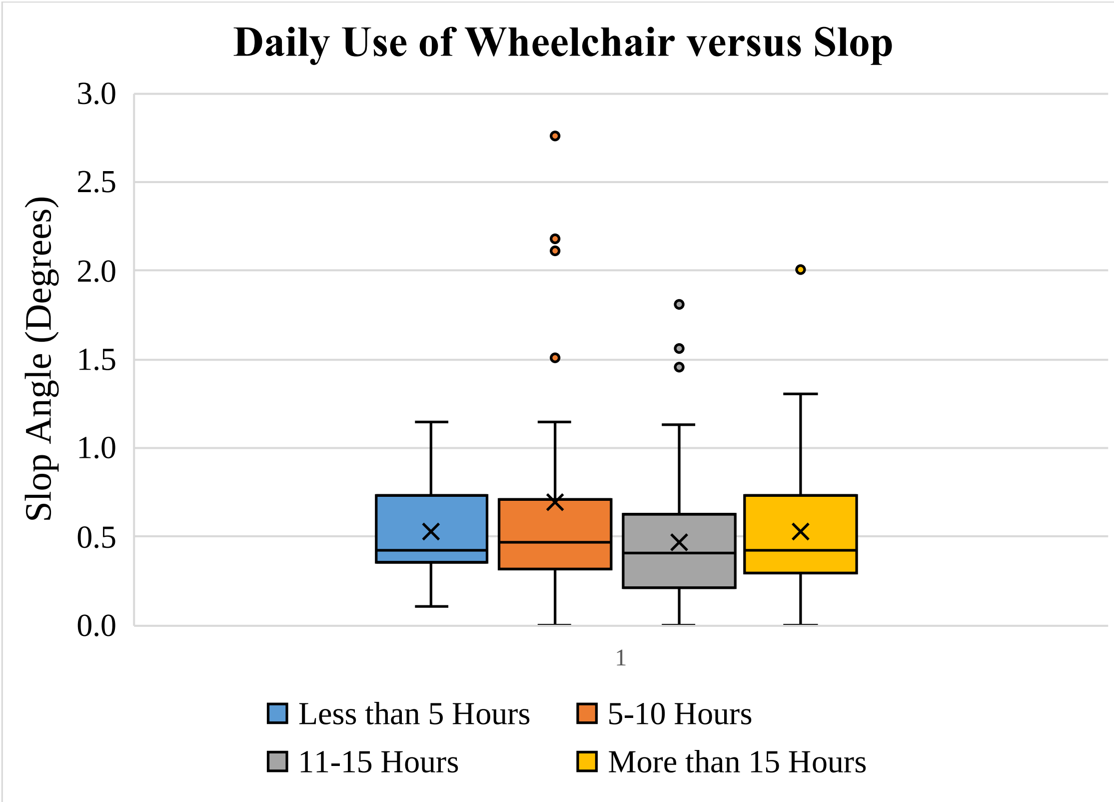
	Less than 1 Year	**1-2 Years**	**3-4 Years**	**Over 4 Years**	**Blank**
Average (deg)	0.66	0.37	0.48	0.41	2.11
Std Dev (deg)	0.40	0.27	0.26		
N (qty)	44	14	2	1	1



Appendix Figure 86 Wheelchair Use per Day versus Toe

Appendix Table 79 Wheelchair Use per Day versus Toe

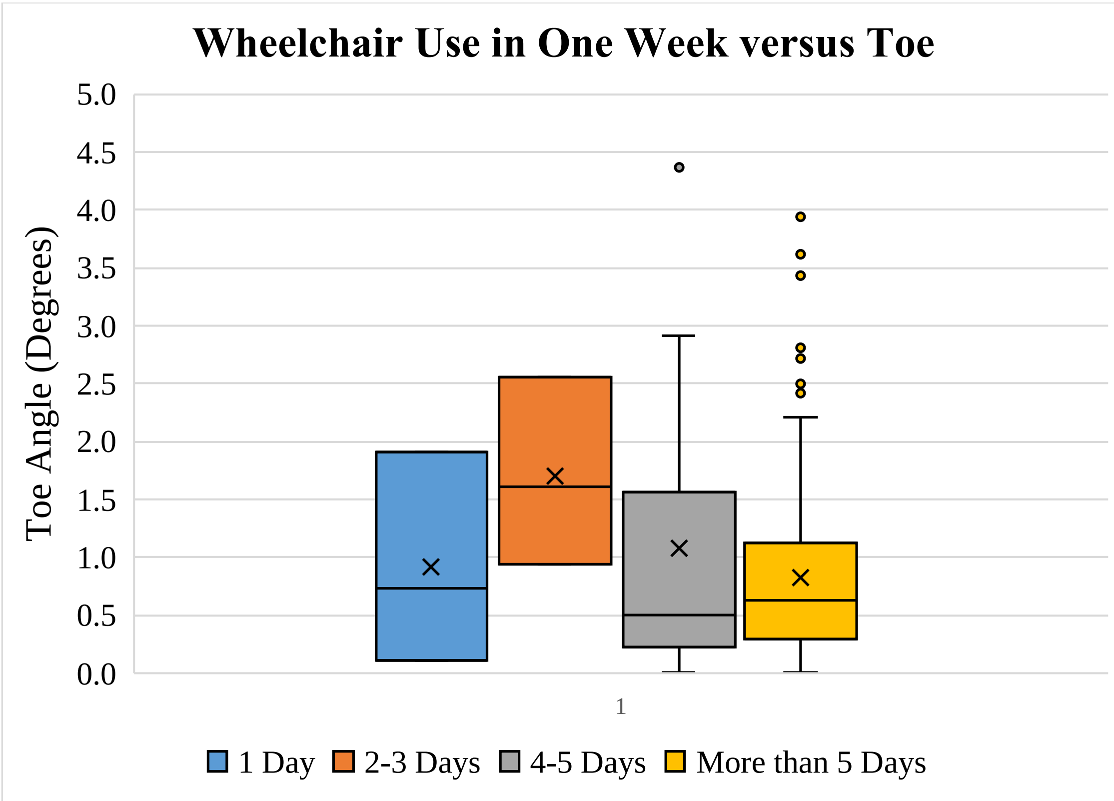
	Less than 5 Hours	5-10 Hours	11-15 Hours	More than 15 Hours	Blank
Average (deg)	1.02	0.87	0.81	0.87	0.69
Std Dev (deg)	0.96	0.84	0.72	0.82	0.30
N (qty)	13	34	73	77	3



Appendix Figure 87 Wheelchair Use per Day versus Slop

Appendix Table 80 Wheelchair Use per Day versus Slop

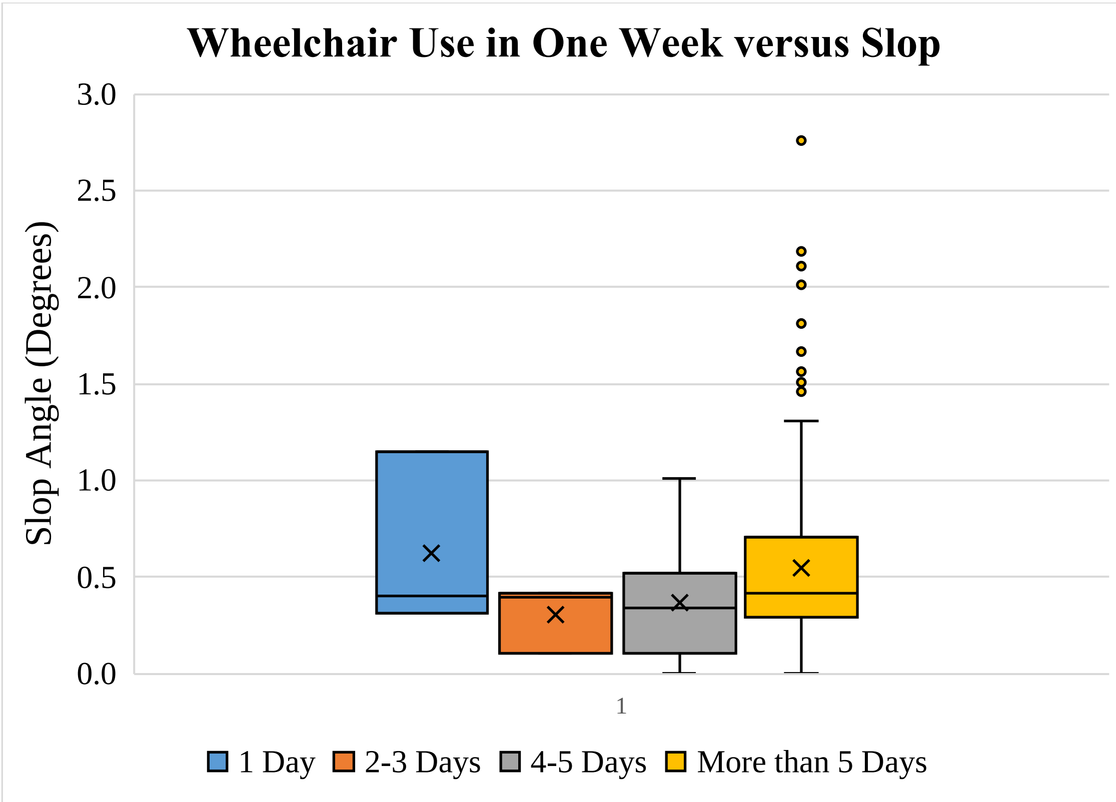
	Less than 5 Hours	5-10 Hours	11-15 Hours	More than 15 Hours	Blank
Average (deg)	0.52	0.69	0.46	0.53	0.90
Std Dev (deg)	0.31	0.67	0.36	0.36	0.67
N (qty)	13	34	73	77	3



Appendix Figure 88 Wheelchair Use per Week versus Toe

Appendix Table 81 Wheelchair Use per Week versus Toe

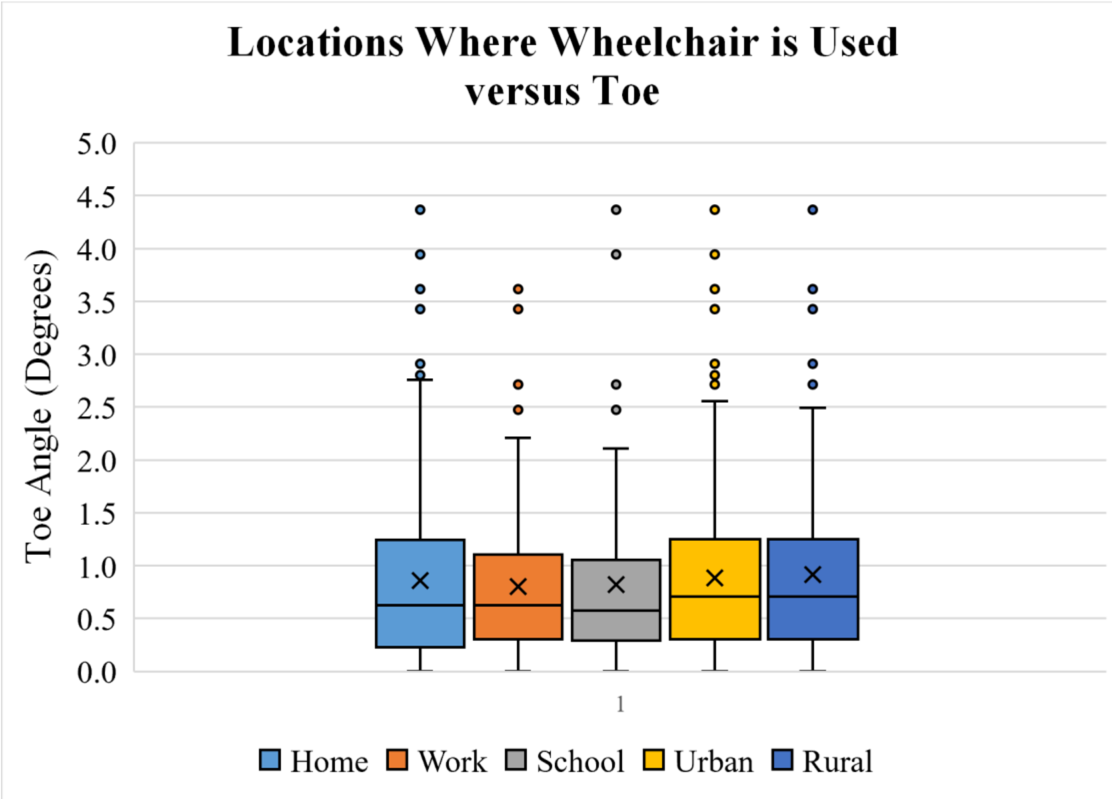
	1 Day	**2-3 Days**	**4-5 Days**	**More than 5 Days**	**Blank**
Average (deg)	0.91	1.70	1.07	0.83	0.67
Std Dev (deg)	0.91	0.81	1.38	0.74	0.51
N (qty)	3	3	11	181	2



Appendix Figure 89 Wheelchair Use per Week versus Slop

Appendix Table 82 Wheelchair Use per Week versus Slop

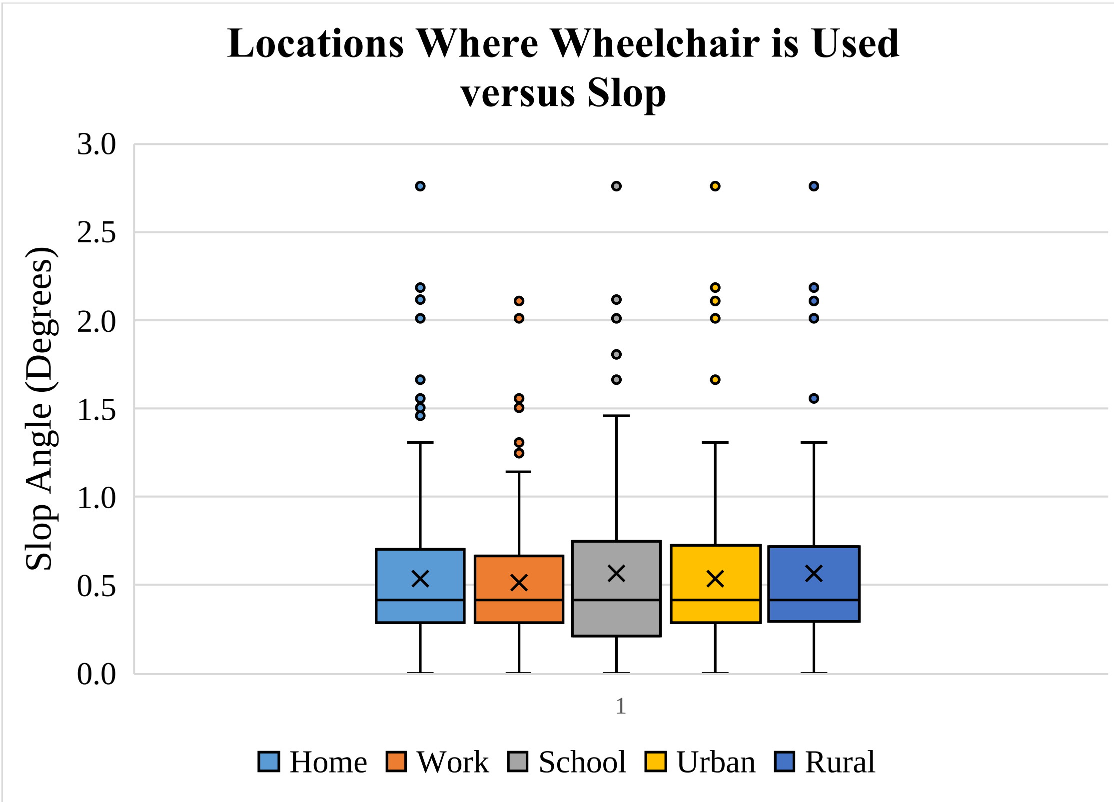
	1 Day	2-3 Days	4-5 Days	More than 5 Days	Blank
Average (deg)	0.62	0.30	0.36	0.55	0.67
Std Dev (deg)	0.46	0.18	0.28	0.45	0.07
N (qty)	3	3	11	181	2



Appendix Figure 90 Locations Where Wheelchair is Used versus Toe

Appendix Table 83 Locations Where Wheelchair is Used versus Toe

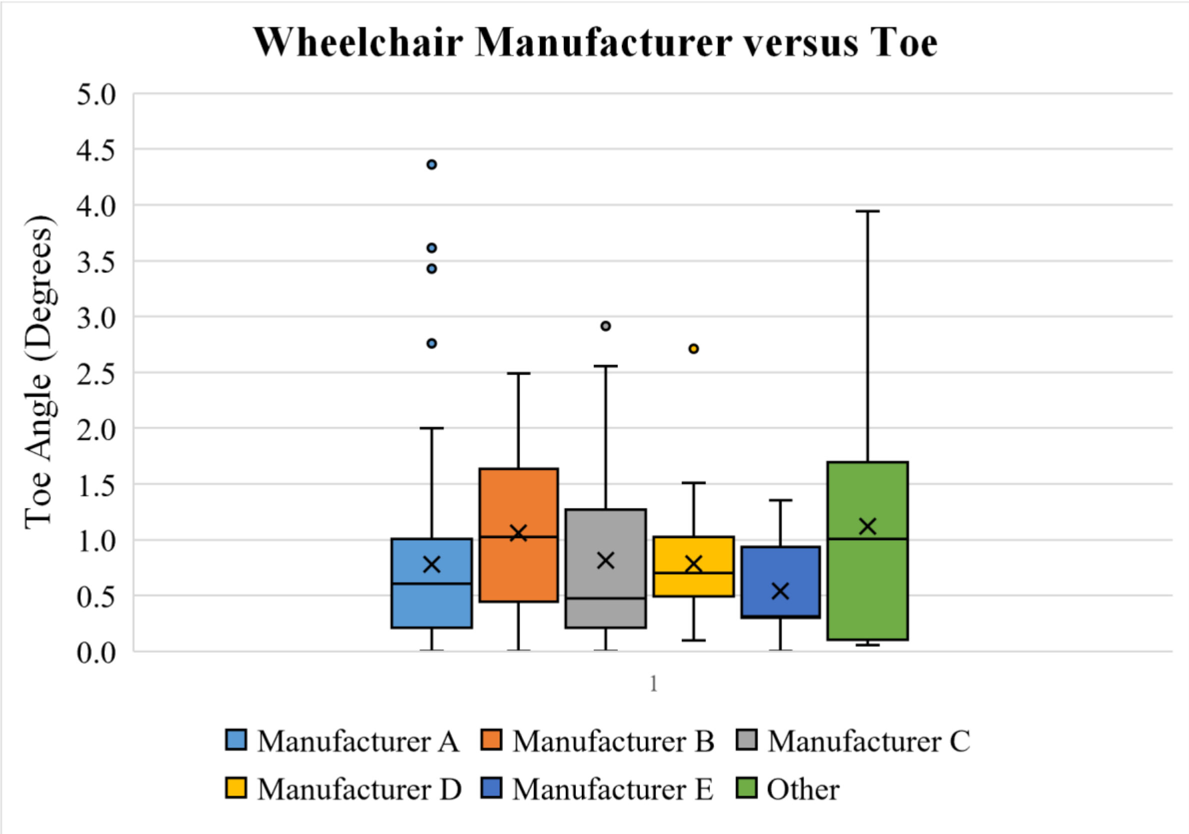
	Home	**Work**	**School**	**Urban**	**Rural**
Average (deg)	0.86	0.80	0.83	0.89	0.92
Std Dev (deg)	0.81	0.69	0.83	0.82	0.87
N (qty)	174	135	77	159	97



Appendix Figure 91 Locations Where Wheelchair is Used versus Slop

Appendix Table 84 Locations Where Wheelchair is Used versus Slop

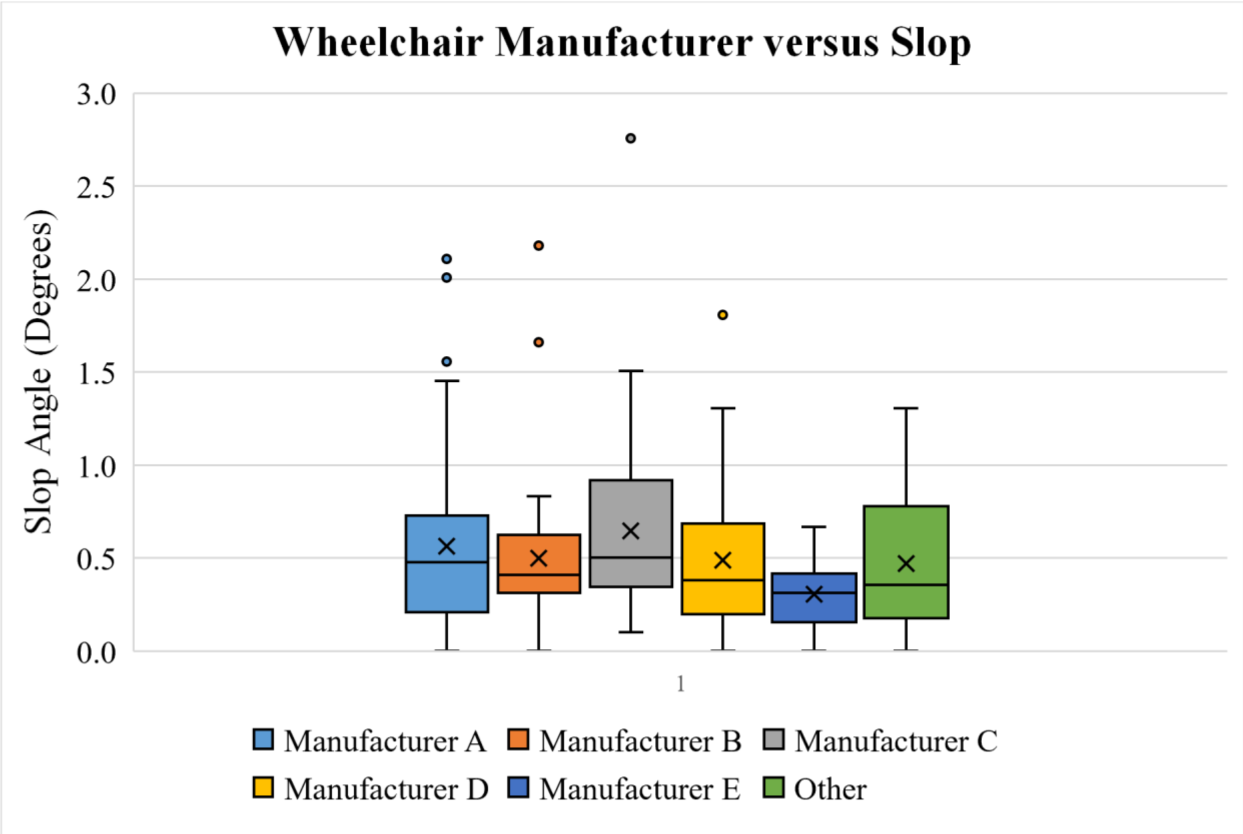
	Home	**Work**	**School**	**Urban**	**Rural**
Average (deg)	0.54	0.52	0.57	0.53	0.57
Std Dev (deg)	0.43	0.40	0.52	0.45	0.50
N (qty)	174	135	77	159	97



Appendix Figure 92 Wheelchair Manufacturer versus Toe

Appendix Table 85 Wheelchair Manufacturer versus Toe

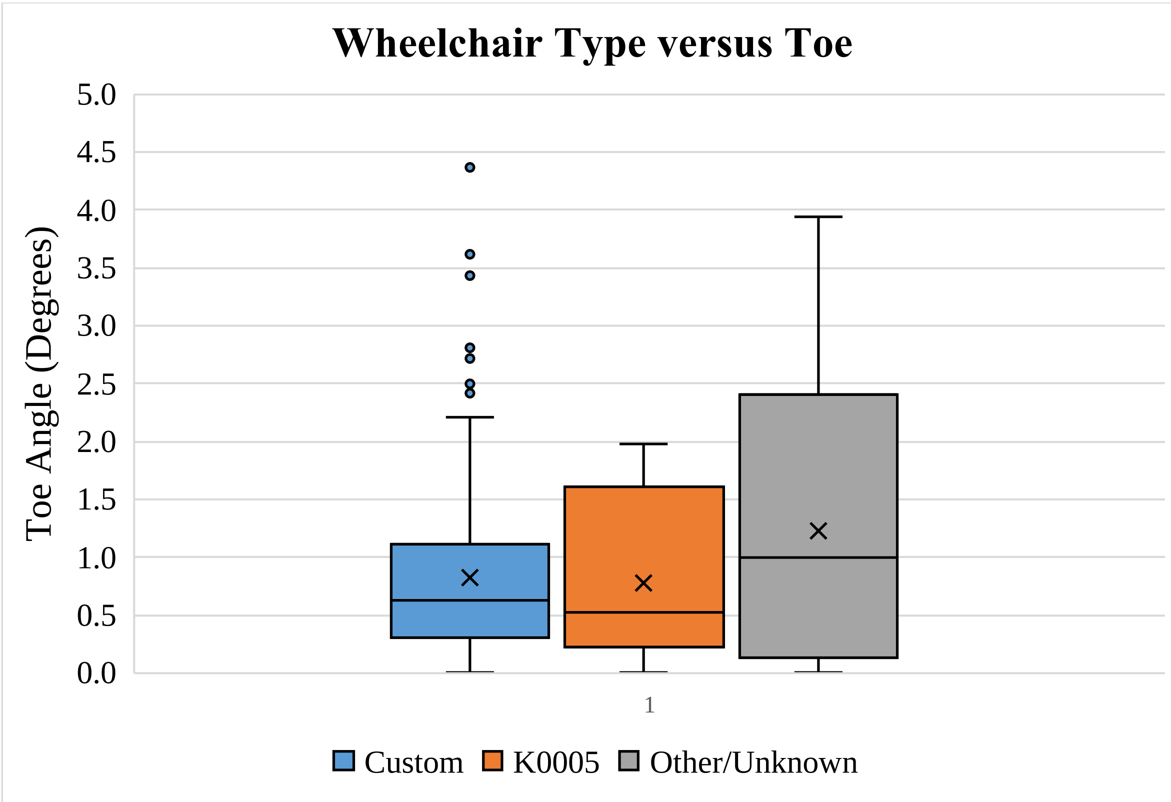
	Mfr. A	Mfr. B	Mfr. C	Mfr. D	Mfr. E	Other
Average (deg)	0.78	1.06	0.85	0.79	0.54	1.12
Std Dev (deg)	0.80	0.69	0.89	0.58	0.46	1.12
N (qty)	91	40	25	21	9	14



Appendix Figure 93 Wheelchair Manfacturer versus Slop

Appendix Table 86 Wheelchair Manufacturer versus Slop

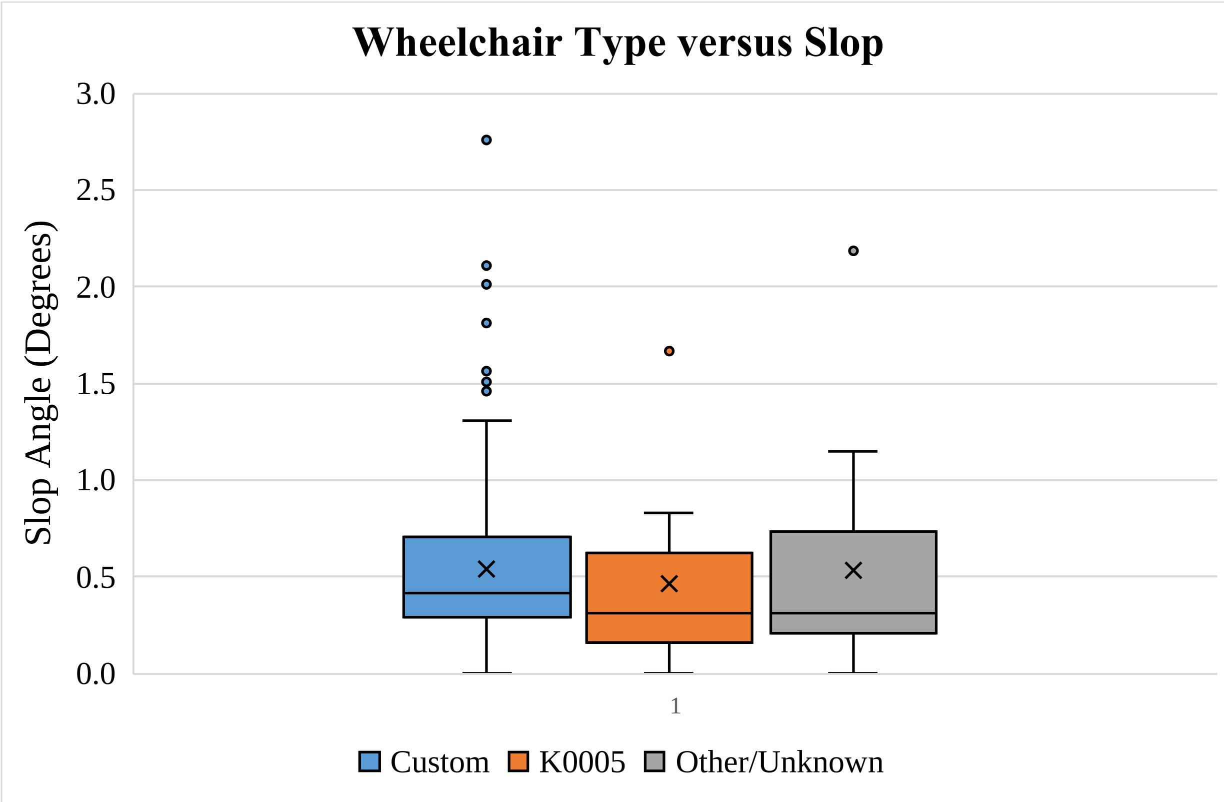
	Mfr. A	Mfr. B	Mfr. C	Mfr. D	Mfr. E	Other
Average (deg)	0.57	0.51	0.64	0.49	0.30	0.47
Std Dev (deg)	0.44	0.39	0.56	0.43	0.19	0.41
N (qty)	91	40	25	21	9	14



Appendix Figure 94 Wheelchair Type versus Toe

Appendix Table 87 Wheelchair Type versus Toe

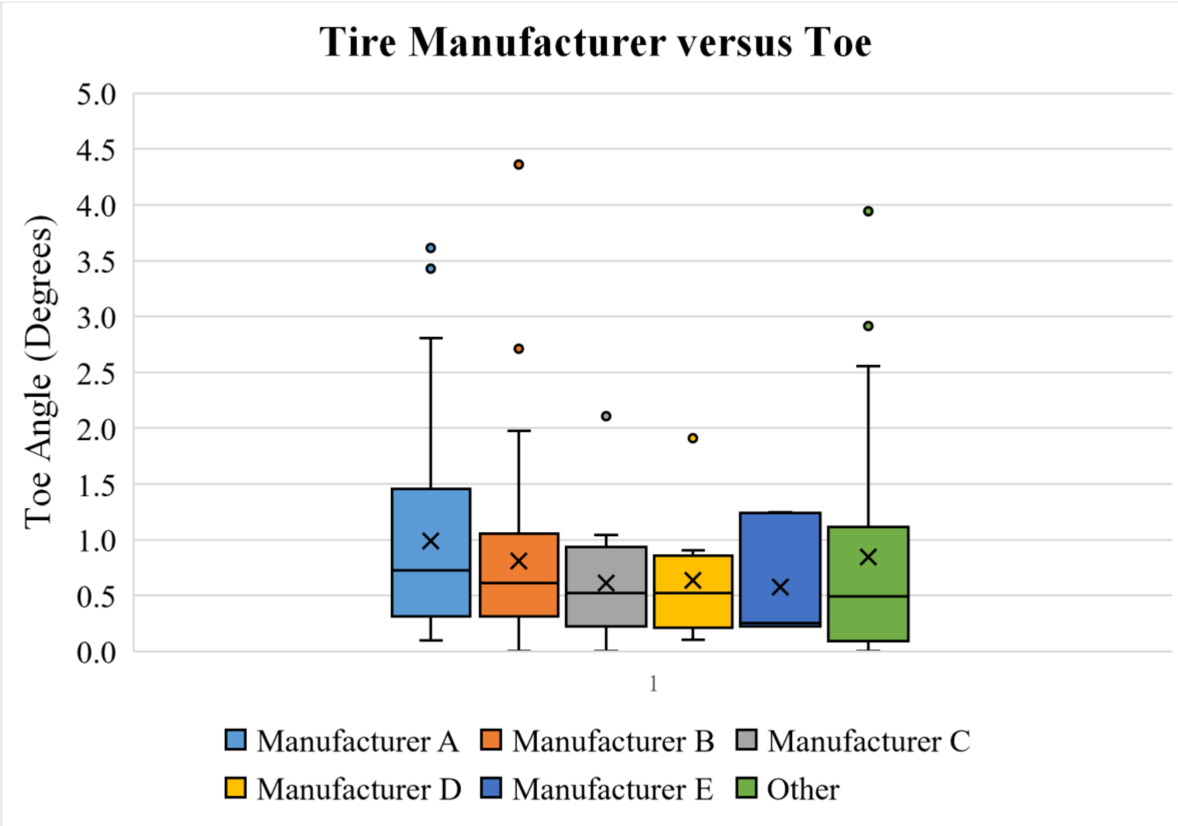
	Custom	**K0005**	**Other**
Average (deg)	0.83	0.77	1.23
Std Dev (deg)	0.74	0.71	1.22
N (qty)	171	13	16



Appendix Figure 95 Wheelchair Type versus Slop

Appendix Table 88 Wheelchair Type versus Slop

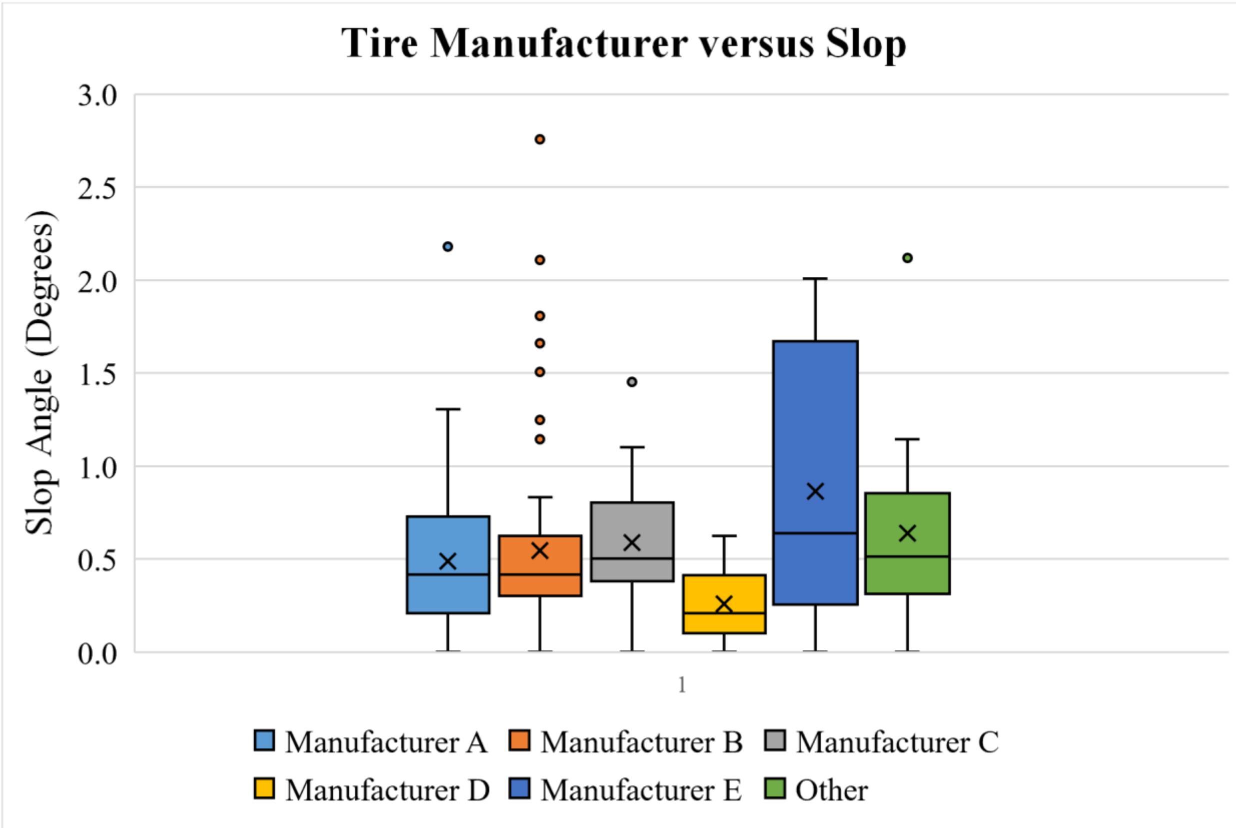
	Custom	K0005	Other
Average (deg)	0.54	0.50	0.53
Std Dev (deg)	0.43	0.43	0.55
N (qty)	171	13	16



Appendix Figure 96 Tire Manufacturer versus Toe

Appendix Table 89 Tire Manufacturer versus Toe

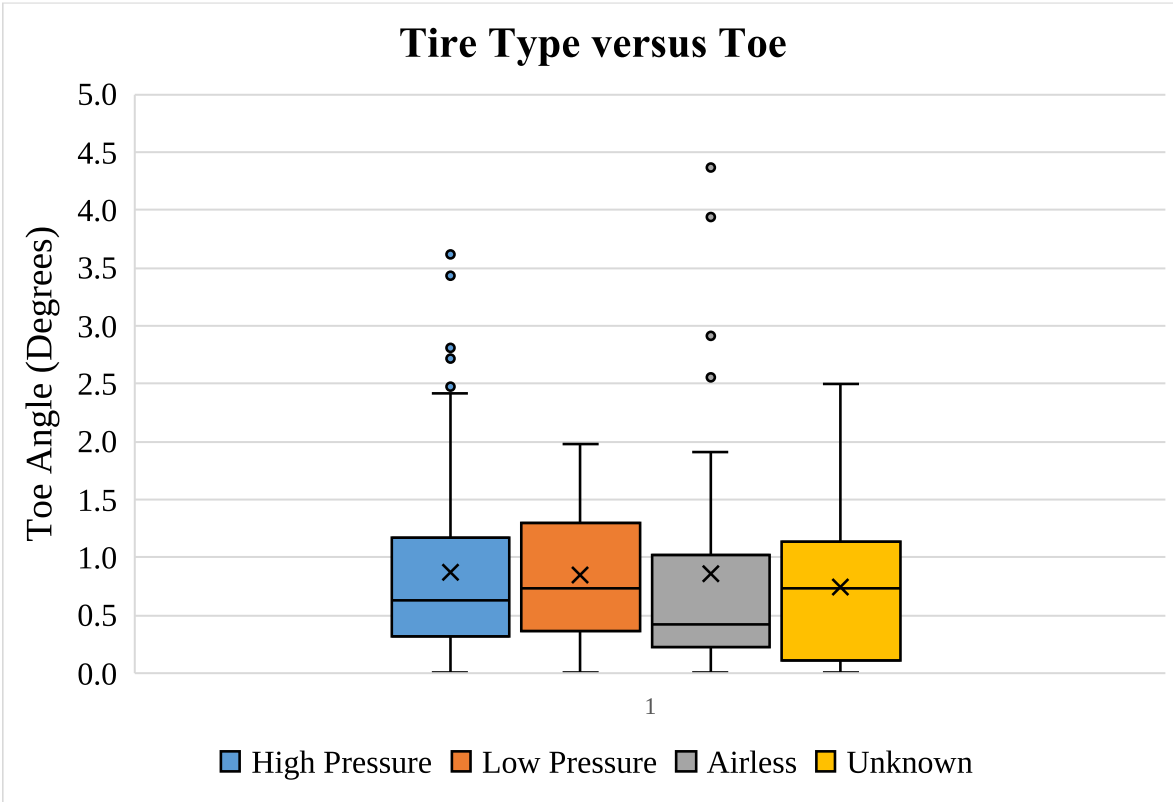
	Mfr. A	**Mfr. B**	**Mfr. C**	**Mfr. D**	**Mfr. E**	**Other**
Average (deg)	0.98	0.82	0.61	0.63	0.57	0.84
Std Dev (deg)	0.84	0.71	0.53	0.58	0.52	1.05
N (qty)	79	70	15	8	6	22



Appendix Figure 97 Tire Manufacturer versus Slop

Appendix Table 90 Tire Manufacturer versus Slop

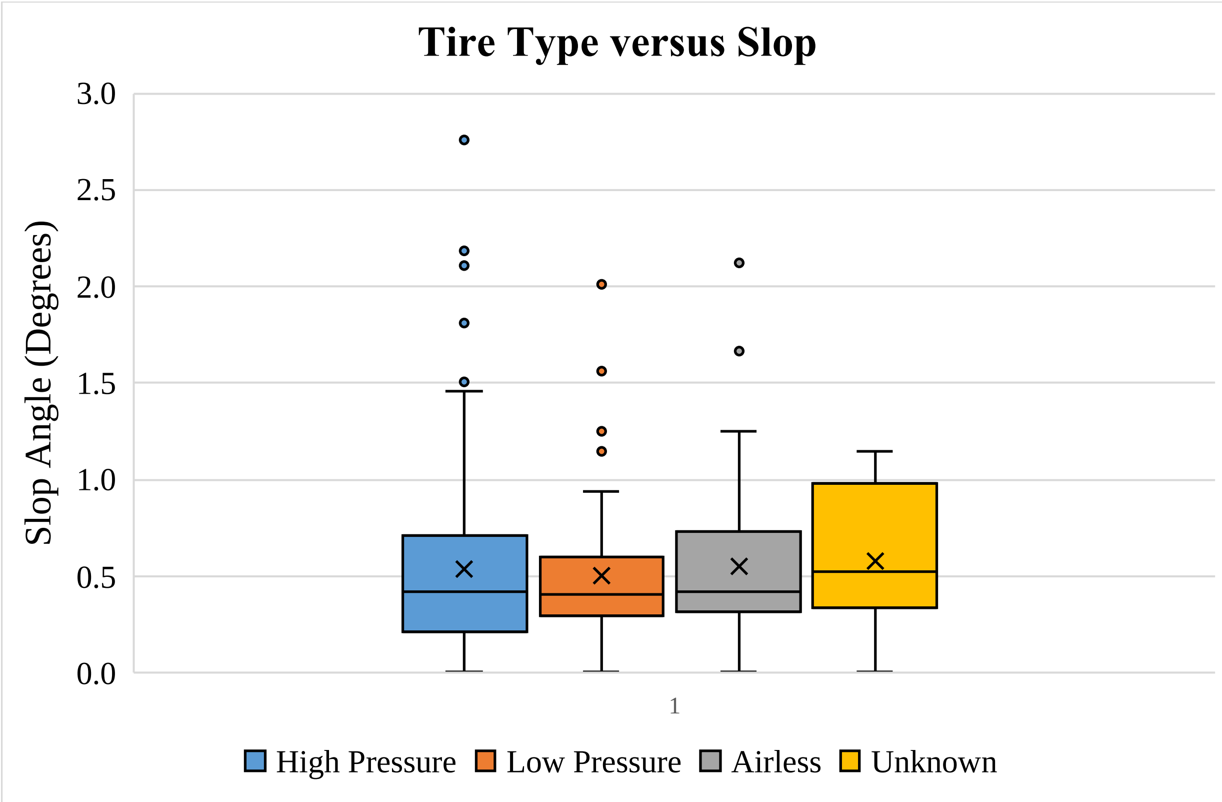
	Mfr. A	Mfr. B	Mfr. C	Mfr. D	Mfr. E	Other
Average (deg)	0.49	0.54	0.59	0.26	1.04	0.64
Std Dev (deg)	0.37	0.49	0.36	0.21	0.71	0.46
N (qty)	79	70	15	8	6	22



Appendix Figure 98 Tire Type versus Toe

Appendix Table 91 Tire Type versus Toe

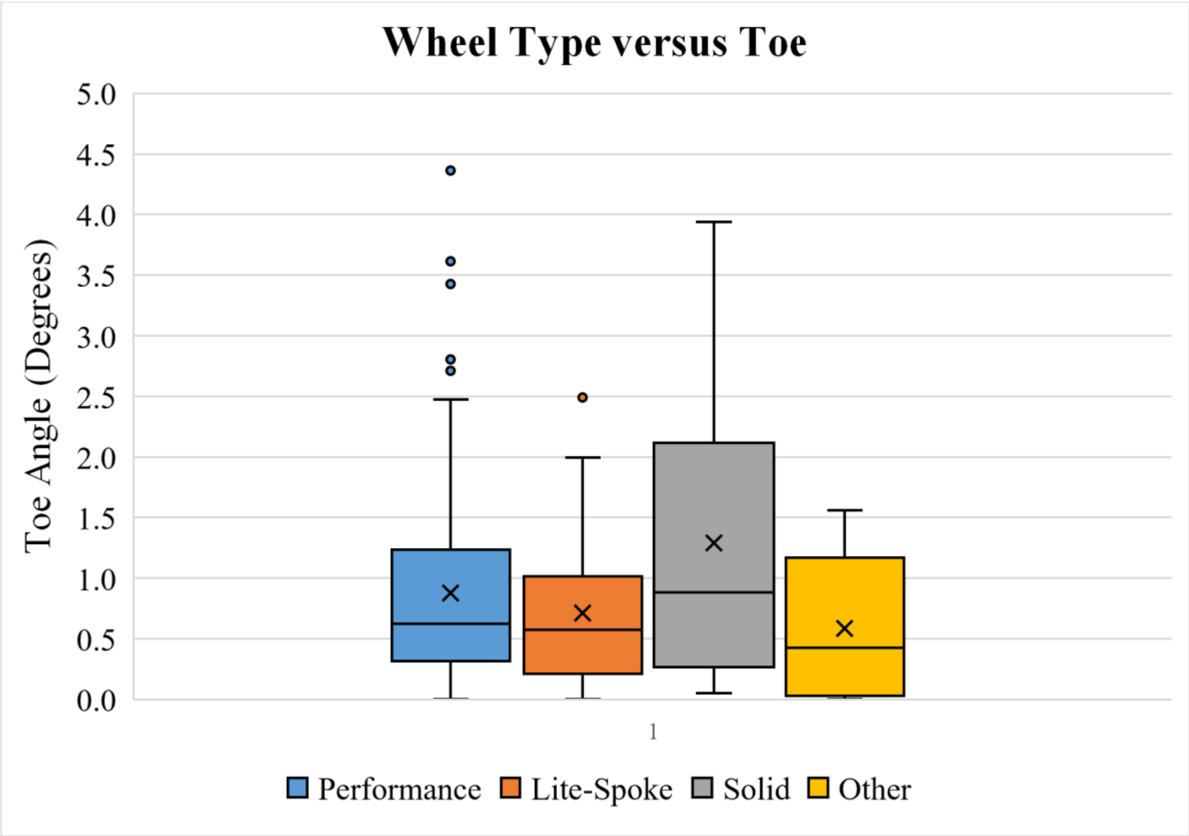
	High-pressure	**Low-pressure**	**Airless**	**Unknown**
Average (deg)	0.88	0.84	0.86	0.74
Std Dev (deg)	0.77	0.57	1.05	0.70
N (qty)	110	37	37	16



Appendix Figure 99 Tire Type versus Slop

Appendix Table 92 Tire Type versus Slop

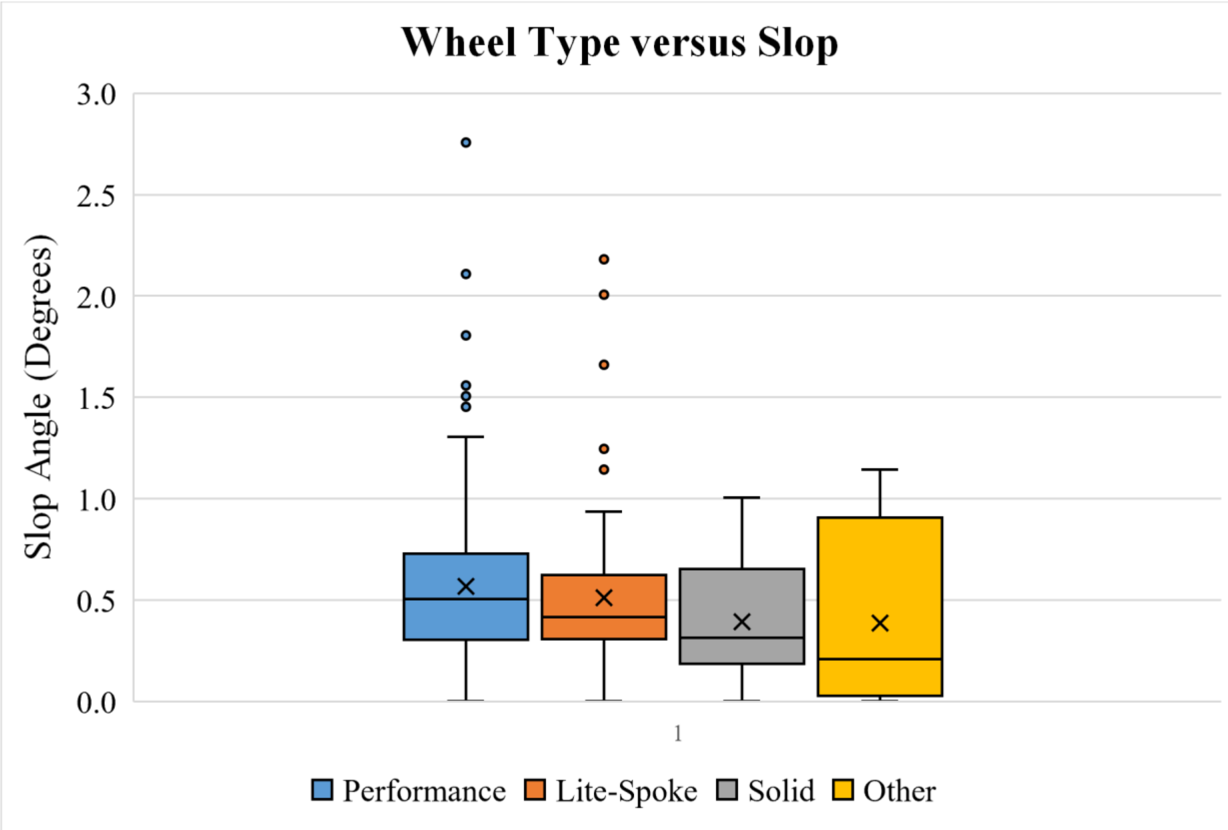
	High-pressure	**Low-pressure**	**Airless**	**Unknown**
Average (deg)	0.54	0.50	0.56	0.58
Std Dev (deg)	0.46	0.41	0.44	0.38
N (qty)	110	37	37	16



Appendix Figure 100 Wheel Type versus Toe

Appendix Table 93 Wheel Type versus Toe

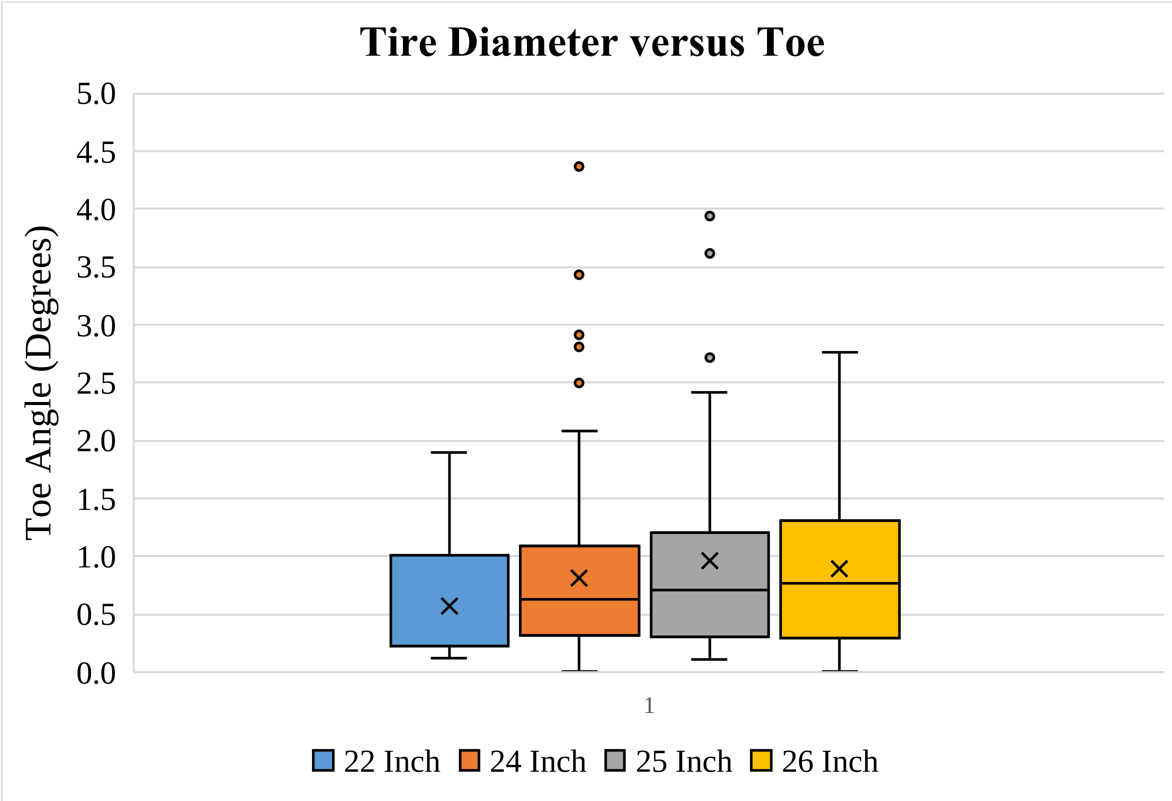
	Performance	**Lite-Spoke**	**Solid**	**Other**
Average (deg)	0.88	0.71	1.29	0.67
Std Dev (deg)	0.80	0.61	1.21	0.60
N (qty)	123	56	14	7



Appendix Figure 101 Wheel Type versus Slop

Appendix Table 94 Wheel Type versus Slop

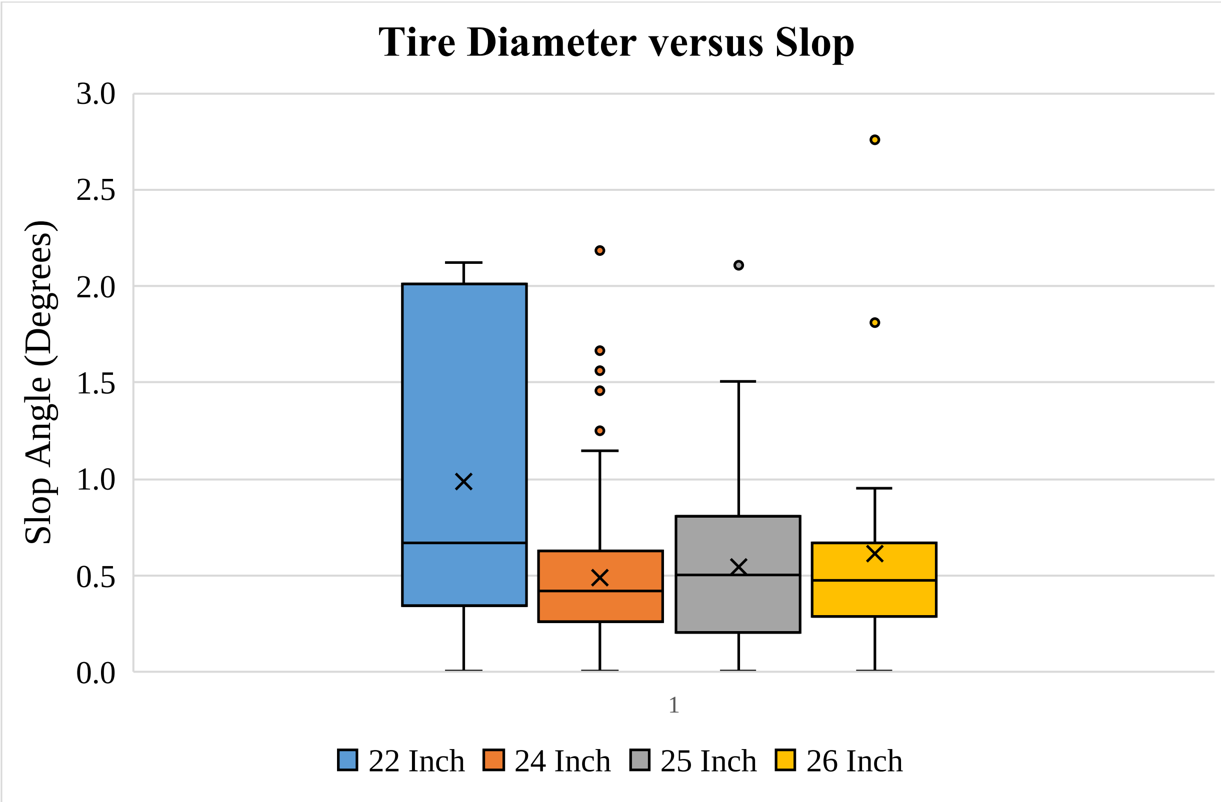
	Performance	Lite-Spoke	Solid	Other
Average (deg)	0.57	0.52	0.42	0.44
Std Dev (deg)	0.45	0.43	0.29	0.48
N (qty)	123	56	14	7



Appendix Figure 102 Tire Diameter versus Toe

Appendix Table 95 Tire Diameter versus Toe

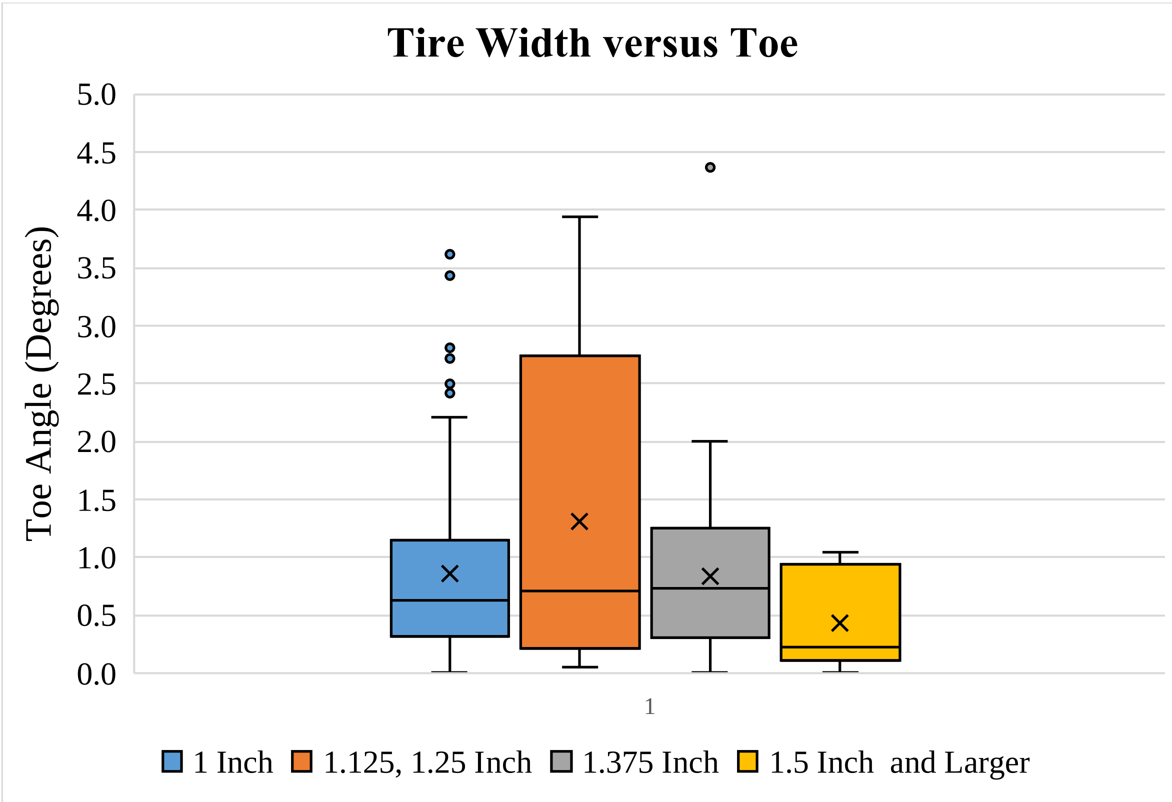
	22 Inch	**24 Inch**	**25 Inch**	**26 Inch**
Average (deg)	0.57	0.81	0.96	0.93
Std Dev (deg)	0.66	0.76	0.87	0.75
N (qty)	7	117	53	23



Appendix Figure 103 Tire Diameter versus Slop

Appendix Table 96 Tire Diameter versus Slop

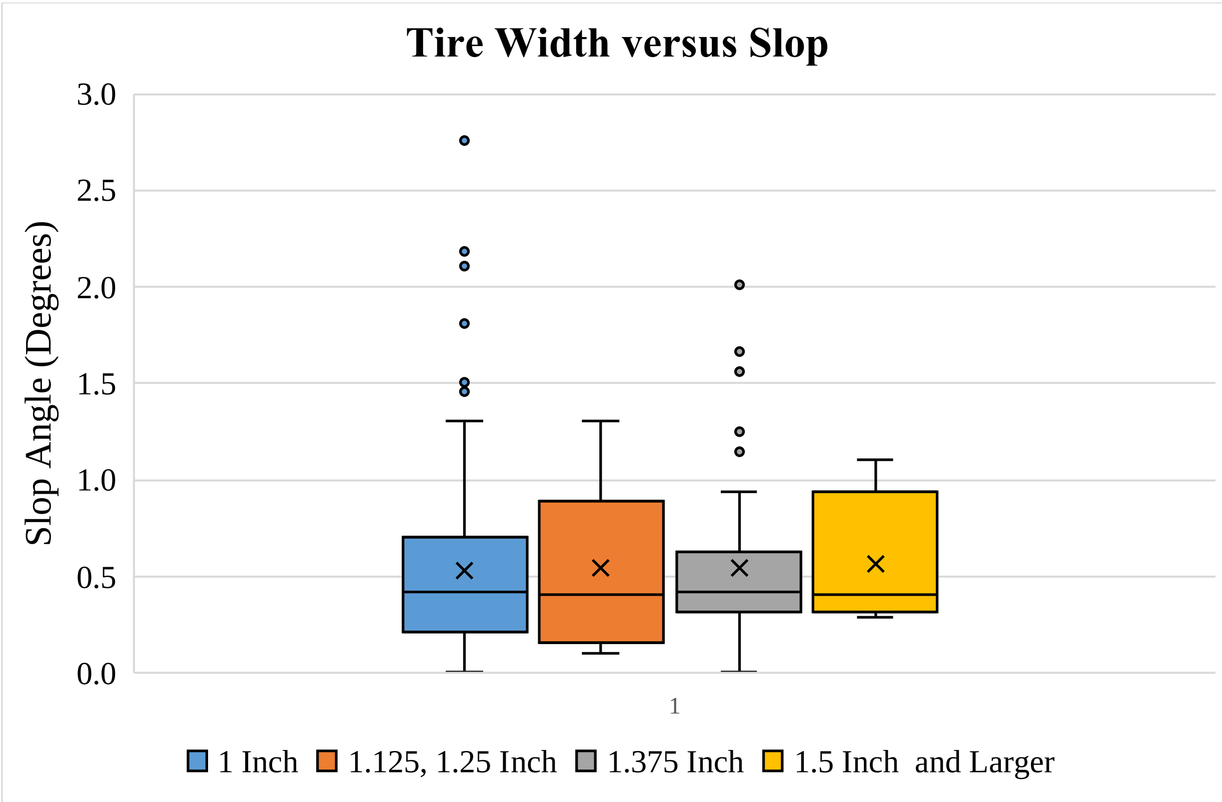
	22 Inch	**24 Inch**	**25 Inch**	**26 Inch**
Average (deg)	1.14	0.49	0.54	0.64
Std Dev (deg)	0.75	0.37	0.40	0.59
N (qty)	7	117	53	23



Appendix Figure 104 Tire Width versus Toe

Appendix Table 97 Tire Width versus Toe

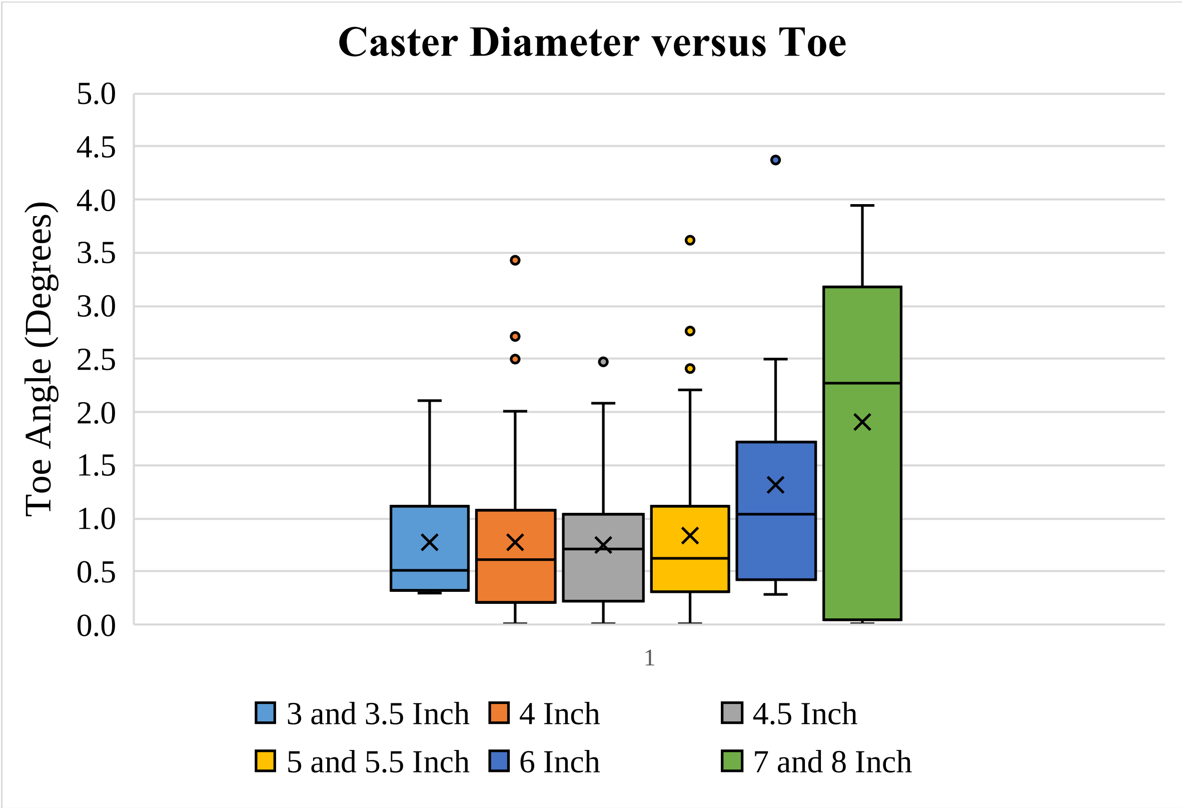
	1 Inch	**1.125, 1.25 Inch**	**1.375 Inch**	**1.5 Inch and Larger**
Average (deg)	0.86	1.31	0.83	0.42
Std Dev (deg)	0.75	1.44	0.76	0.41
N (qty)	136	9	48	7



Appendix Figure 105 Tire Width versus Slop

Appendix Table 98 Tire Width versus Slop

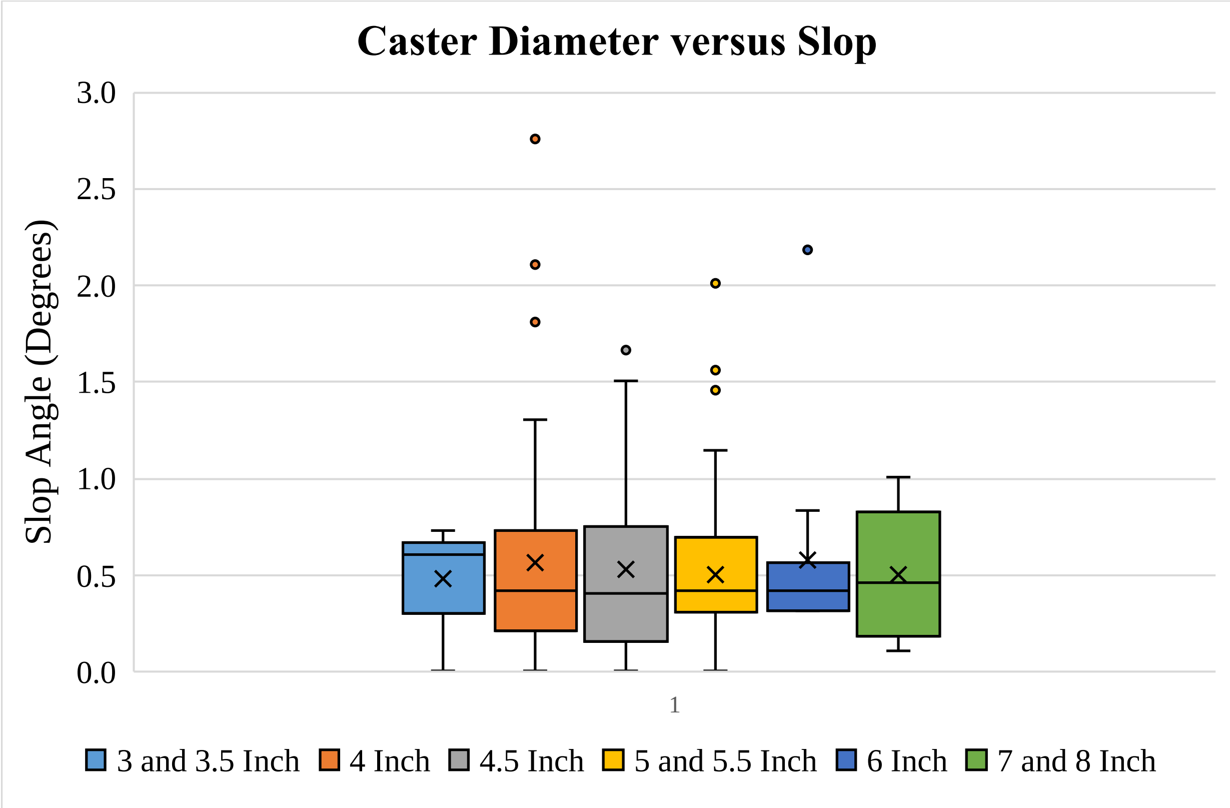
	1 Inch	**1.125, 1.25 Inch**	**1.375 Inch**	**1.5 Inch and Larger**
Average (deg)	0.53	0.54	0.55	0.56
Std Dev (deg)	0.45	0.42	0.42	0.32
N (qty)	136	9	48	7



Appendix Figure 106 Caster Diameter versus Toe

Appendix Table 99 Caster Diameter versus Toe

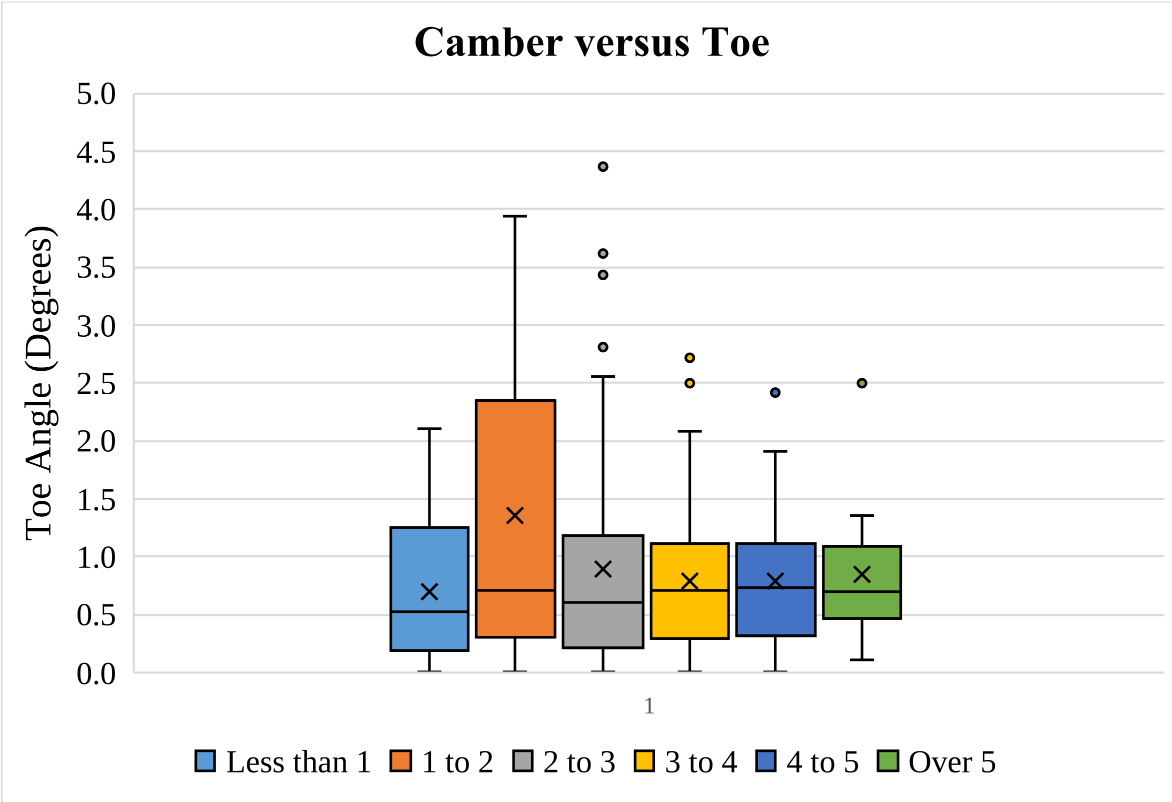
	3 and 3.5 Inch	4 Inch	4.5 Inch	5 and 5.5 Inch	6 Inch	7 and 8 Inch
Average (deg)	0.76	0.78	0.74	0.83	1.31	1.90
Std Dev (deg)	0.65	0.68	0.59	0.76	1.13	1.59
N (qty)	7	77	33	64	13	6



Appendix Figure 107 Caster Diameter versus Slop

Appendix Table 100 Caster Diameter versus Slop

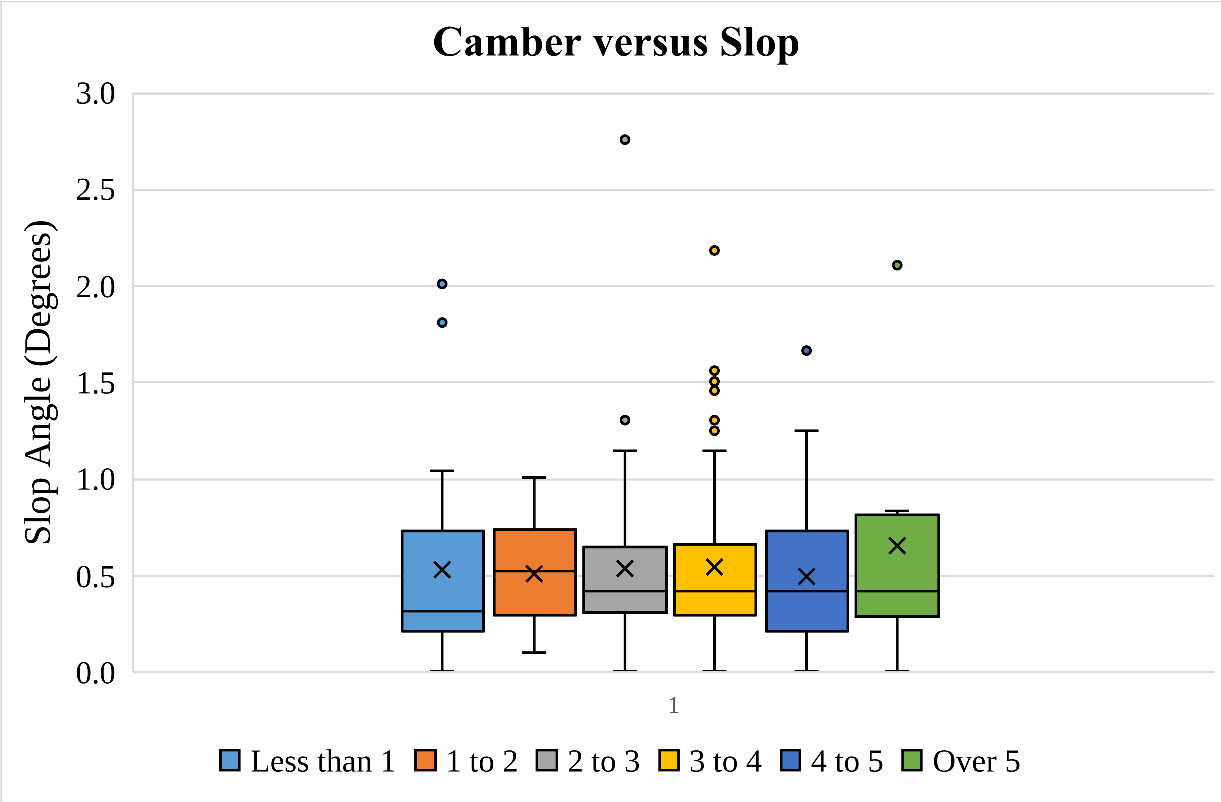
	3 and 3.5 Inch	**4 Inch**	**4.5 Inch**	**5 and 5.5 Inch**	**6 Inch**	**7 and 8 Inch**
Average (deg)	0.48	0.56	0.55	0.51	0.57	0.50
Std Dev (deg)	0.26	0.50	0.45	0.36	0.51	0.34
N (qty)	7	77	33	64	13	6



Appendix Figure 108 Camber Angle Versus Toe

Appendix Table 101 Camber Angle versus Toe

	Less than 1	**1 to 2**	**2 to 3**	**3 to 4**	**4 to 5**	**Over 5**
Average (deg)	0.69	1.35	0.91	0.78	0.79	0.84
Std Dev (deg)	0.63	1.21	0.98	0.59	0.60	0.59
N (qty)	23	17	53	65	27	14



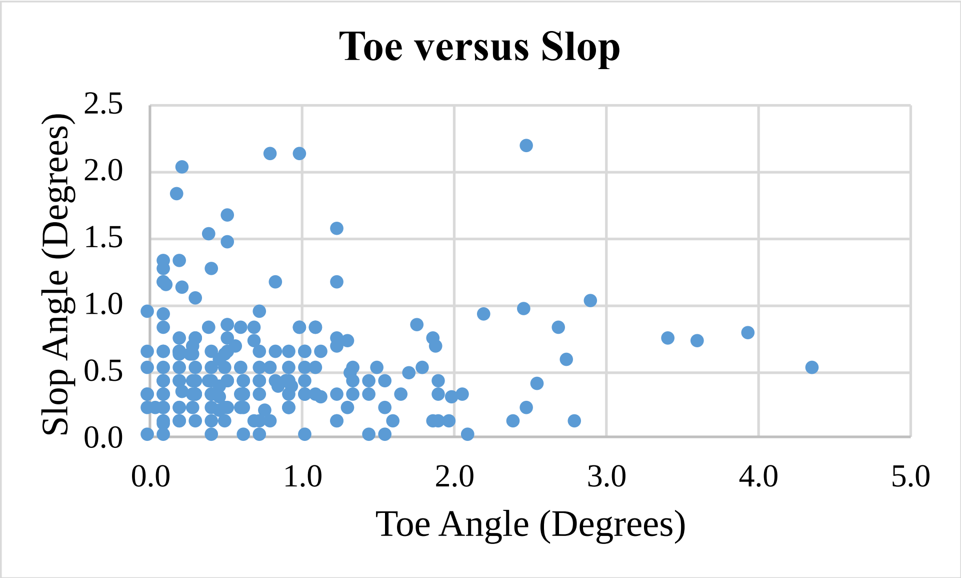
Appendix Figure 109 Camber Angle versus Slop

Appendix Table 102 Camber Angle versus Slop

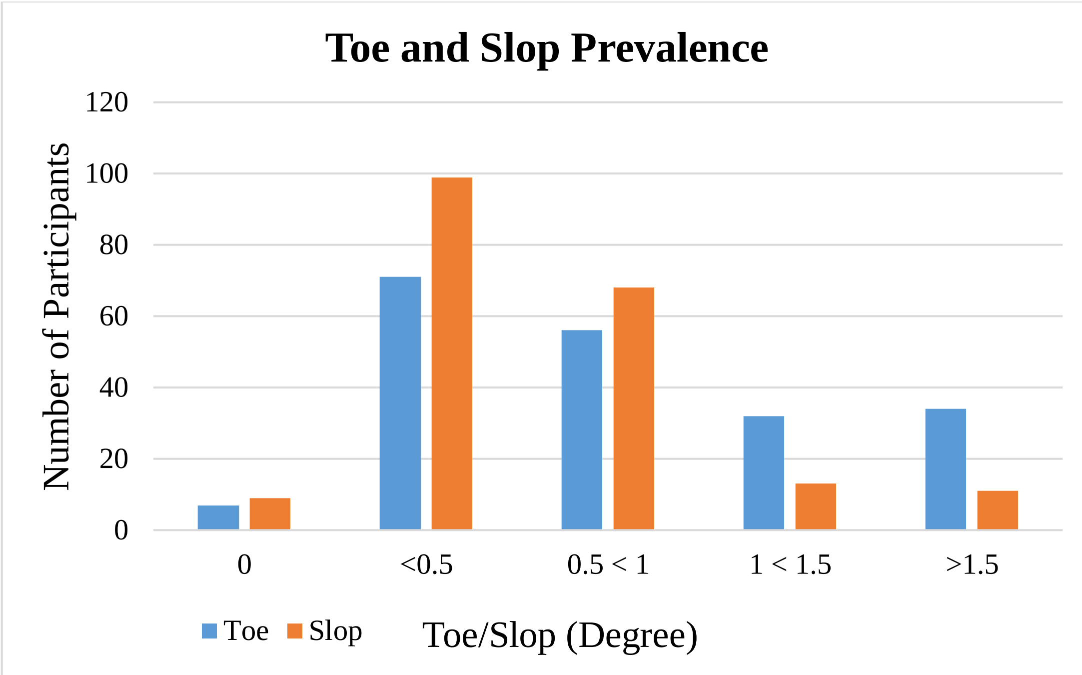
	Less than 1	**1 to 2**	**2 to 3**	**3 to 4**	**4 to 5**	**Over 5**
Average (deg)	0.53	0.51	0.53	0.55	0.49	0.70
Std Dev (deg)	0.52	0.30	0.44	0.41	0.40	0.66
N (qty)	23	17	53	65	27	14

Appendix E.4 Toe and Slop Statistics

No correlation was found between toe and slop as shown in Appendix Figure 110.



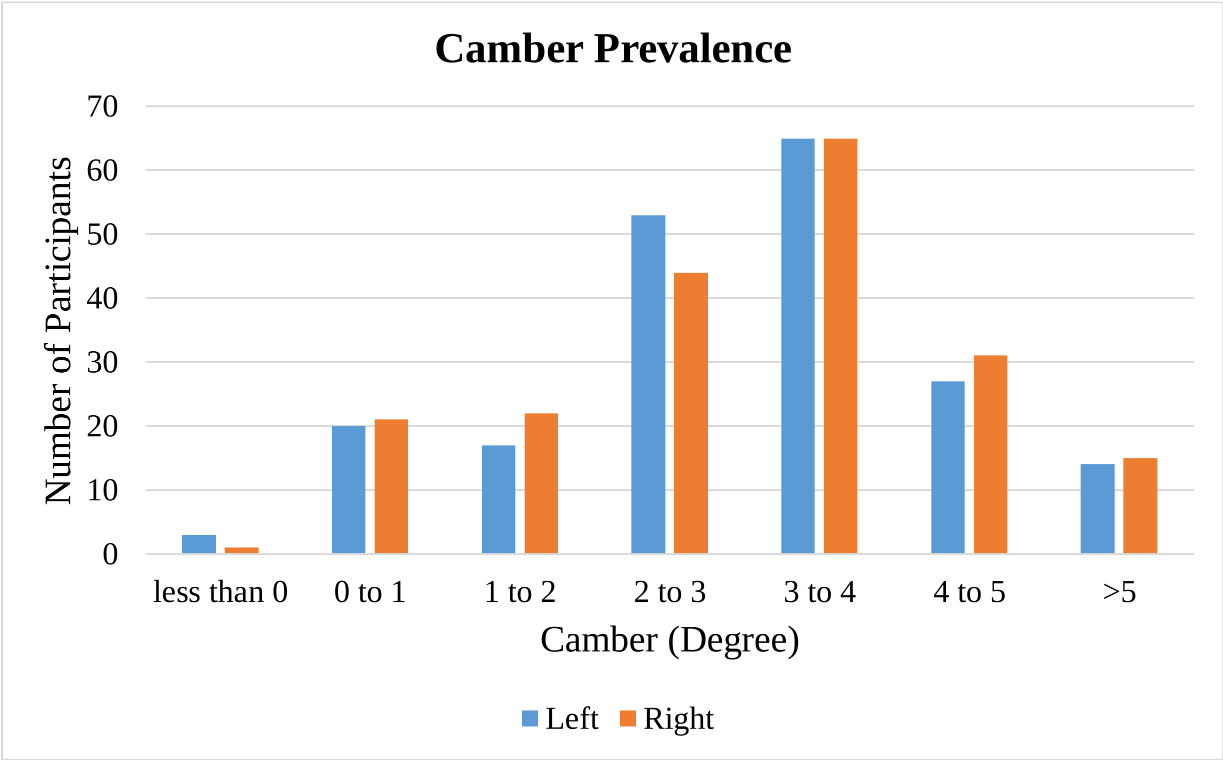
Appendix Figure 110 Toe versus Slop Scatterplot



Appendix Figure 111 Toe and Slop Prevalence

Appendix Table 103 Toe and Slop Prevalence

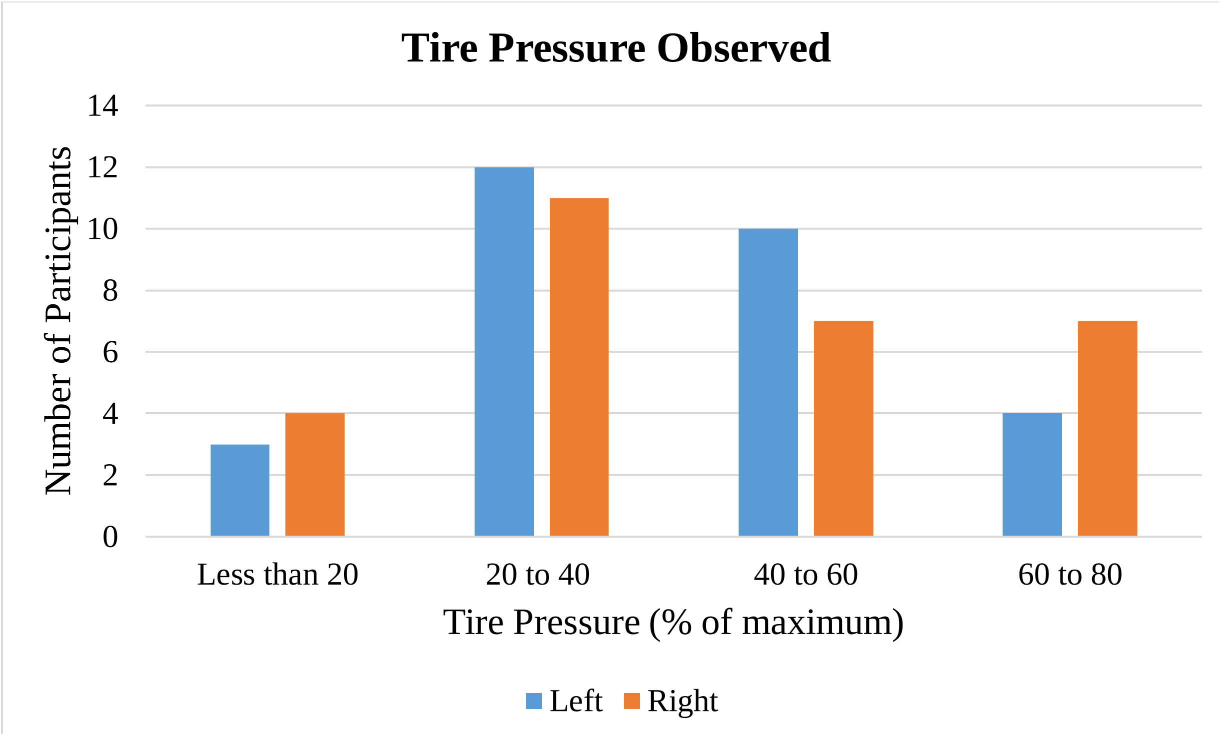
Toe (Degree)	**Toe**	**Slop**
0	7	9
<0.5	71	99
0.5 < 1	56	68
1 < 1.5	32	13
=>1.5	34	11
Total	**200**	**200**



Appendix Figure 112 Camber Angle Prevalence – Left and Right

Appendix Table 104 Camber Angle Prevalence – Left and Right

Camber (Degrees)	**Left**	**Right**
less than 0	3	1
0 to 1	20	21
1 to 2	17	22
2 to 3	53	44
3 to 4	65	65
4 to 5	27	31
>5	14	15
Total	**199**	**199**



Appendix Figure 113 Tire Pressure Observed – Left and Right

Appendix Table 105 Tire Pressure Observed – Left and Right

% of Max Pressure	Left	Right
Less than 20	3	4
20 to 40	12	11
40 to 60	10	7
60 to 80	4	7
80 to 100	0	0
Total	**29**	**29**

Appendix F Perceived Weight Equivalent Conversion

This appendix provides an overview of the perceived weight equivalent (PWE) conversion, how it works, and some examples using this tool. The conversion allows the user to select a specific tire from a drop-down menu and requires input of RR forces for baseline and comparison scenario. In addition, the estimated weight of the user (MWC load) divided by 2 and is entered as the test load. The weight distribution (% load on rear-wheels) is also entered. The PWE conversion uses RR force data and loading equations to estimate the effect of factors in terms of what the equivalent additional load would be.

The first example (Appendix Figure 114) compares the HPS tire at 0 and 3 camber at a MWU weight of 150 lbs. and 80% load distribution. The PWE conversion estimates the total increase in RR as 7.9 pounds of additional weight over wheels and casters.

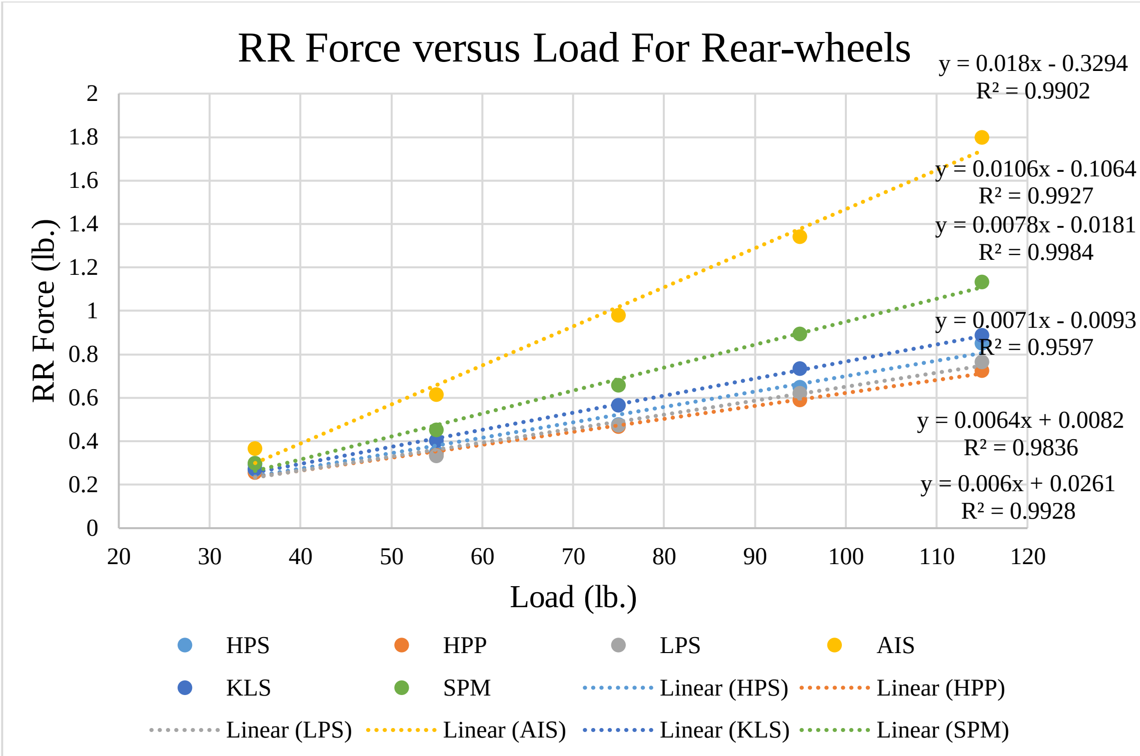
Perceived Weight Equivalent Calculator					
Choose tire or caster		**HPS Tire**			Click in box for drop down
Inputs			Ouputs		
Starting Force	0.474	Lbs	Increase Load - Front	1.6	Lbs
Ending Force	0.507	Lbs	Increase Load - Rear	6.3	Lbs
Testing Load	75.00	Lbs	Total Increase	7.9	Lbs
% load on rear	80%				
Toe Related value?	No	Click in box for drop down	Original Weight	187.5	Lbs
			New Weight	195.4	Lbs

Appendix Figure 114 Weight Conversion Example 1

The second example (Appendix Figure 115) compares the HPS high-pressure pneumatic tire with AIS, at a MWU load of 150 lbs. and 80% weight distribution. The RR force for the LPS was 0.978 compared to the HPS tire with a RR force of 0.474. The conversion uses the loading equations shown in Appendix Figure 116 to calculate the additional weight, which in this case is 120 lbs. over both wheels and casters.

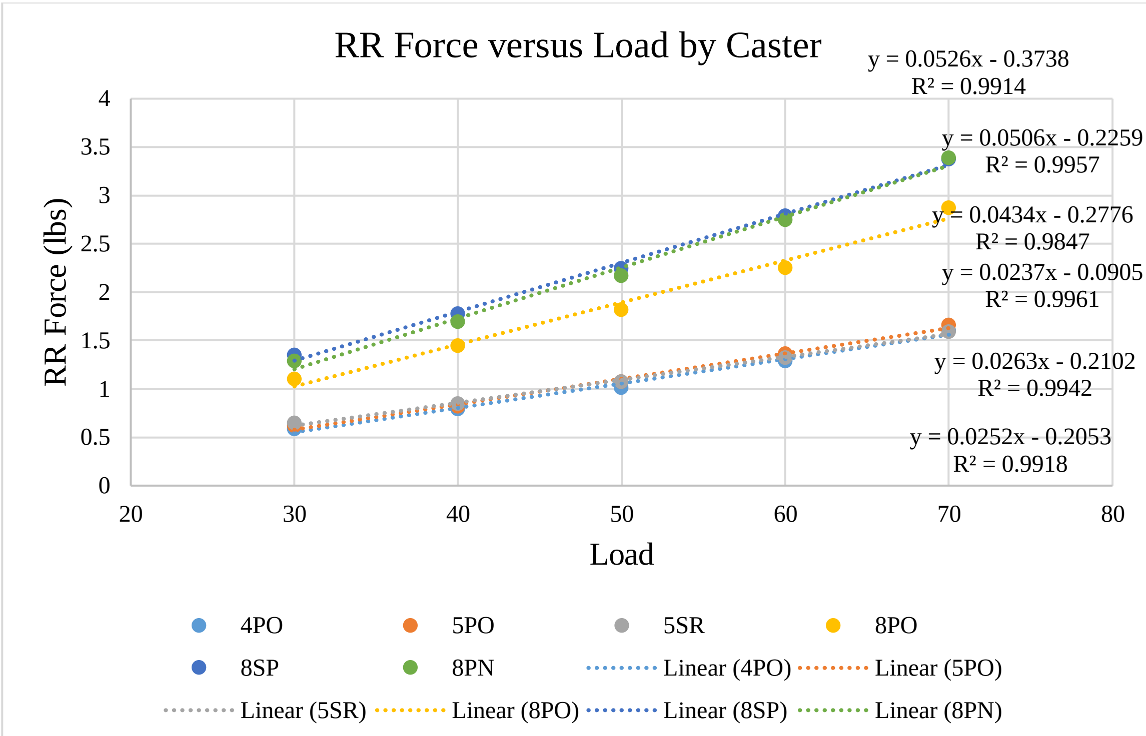
Perceived Weight Equivalent Calculator					
Choose tire or caster		**HPS Tire**			Click in box for drop down
Inputs			Ouputs		
Starting Force	0.474	Lbs	Increase Load - Front	24.0	Lbs
Ending Force	0.978	Lbs	Increase Load - Rear	96.0	Lbs
Testing Load	75.00	Lbs	Total Increase	120.0	Lbs
% load on rear	80%				
Toe Related value?	No	Click in box for drop down	Original Weight	187.5	Lbs
			New Weight	307.5	Lbs

Appendix Figure 115 Weight Conversion Example 2



Appendix Figure 116 Weight Conversion Loading Equations

The graph in Appendix Figure 116 shows the loading equations used in the conversion to estimate the increased load for rear-wheels.



Appendix Figure 117 Weight Conversion Loading Equations for Casters

The graph in Appendix Figure 117 shows the loading equations used in the conversion to estimate the increased load for casters.

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