

**A Geometric Framework for Evaluating Compound Slopes  
Within the Wheelchair Footprint on a Curved Ramp**

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## **Abstract**

Existing accessibility guidelines such as the Americans with Disabilities Act (ADA) and ICC117.1 (ICC) are based on the slope of the running surface of a ramp and the cross-slope. This is usually measured along the side of the ramp. This is suitable for straight ramps but when used on curved ramps three-dimensional geometry must be considered. This is something that the current accessibility evaluation approaches do not sufficiently address. The ADA does not provide much help regarding these issues, even though the ADA does advise against the use of curved ramps, because there is the possibility of compound slopes and unreliable wheel performance at wheel contact points.

This thesis investigates the effect of the geometry of a curved ramp on the user's immediate slope of the ramp as experienced by the wheelchair user. Instead of considering the nominal running or cross slope, the proposed condition instead would be a diagonal compound slope between wheel contact points. This was done using a mixed method approach for the purpose of exploration. These methods included analysis of existing standards, geometrical analysis, construction of physical ramps models, in-situ observations of ramps, consulting disability experts and creating a basic spreadsheet tool to evaluate the ramps. The geometrical analysis served as the principal analysis method; physical and field models gave insights about the impact of different ramp designs on wheelchair movement. By analyzing the results of the research it is clear that the slope value, radius of the curve, ramp width and direction of the wheelchair are the significant factors that affect the amount of compound slope a ramp user might experience when using a curved ramp. Specifically, the study showed that enlarging the ramp would substantially reduce the degree of local diagonal slope of the wheelchair.

This study also shows that the interaction between asymmetric wheels and a ramp can be observed even if ramp slopes would fulfil the established requirements. The work does not indicate that curvilinear ramps are inaccessible in themselves. Rather, the work suggests a geometric approach to assessing curved

ramps as three-dimensional surfaces in a limited space. It outlines the start of a predictive approach that could be used for future design assessment, accessibility studies, and other related efforts in accessible design.

# **A Geometric Framework for Evaluating Compound Slopes Within the Wheelchair Footprint on a Curved Ramp**

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## **General Audience Abstract**

Typically, ramps used to traverse changes in level in a building or landscape and often used by people with disabilities are evaluated and regulated based on their slope (how steep a ramp is in the direction of travel) and cross slope (how much they slope from side to side). These measurements work well for straight ramps, but curved ramps, which landscape designers like to use for a variety of reasons, are more complicated. A sloped surface provided in conjunction with a curved path of travel can create uneven conditions under a wheelchair that are not adequately described in current standard accessibility standards. This thesis studies how a curving ramp affects the way a wheelchair sits and moves its surface. This study examines the ramp's overall slope experienced across the footprint of the wheelchair, especially between opposite wheel contact points which is not regularly studied when considering ramps that travel in one direction. This diagonal condition will help explain why some curved ramps may not be truly accessible even though they appear to meet basic accessibility requirements.

In this thesis, I used several research methods. These methods included a review of accessibility standards, geometric analysis, scaled ramp models, evaluation of existing ramps, consultation with disability experts, and a basic spreadsheet tool for evaluating ramp geometry. The findings indicate that ramp slope, curve radius, ramp width, and wheelchair orientation all affect the conditions experienced by a wheelchair user.

This work does not argue that curved ramps are inherently inaccessible. The work argues that they need to be evaluated more carefully as three-dimensional surfaces. The work offers the beginning of a practical method that could help designers, accessibility reviewers, and researchers better understand curved ramps before they are built.

## **Declaration**

I, Joseph Cooley, hereby declare that the work presented herein is original work done by me and has not been published or submitted elsewhere for the requirement of a degree program. Any literature or work done by others and cited within this thesis has given due acknowledgement and listed in the reference section.

Joseph Cooley

Virginia Polytechnic Institute and State University

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## Acknowledgements

This thesis has been nearly forty years in the making, spanning the completion of my bachelor's degree, decades of professional practice, my work at this university and a return to graduate study. I knew that I would someday complete this chapter of my education and the questions behind this work have never been far from my thoughts. There are many people who stood behind me as I undertook this project that deserve my gratitude.

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I am also grateful to the many friends and colleagues who offered a listening ear, offered suggestions and encouragement, and made seeking this degree possible in many other ways. Their support made this possible, kept me going and mattered more than they may realize.

Finally, I want to thank the love of my life, Robin Cooley, for her saintly patience, sage encouragement and steadfast support throughout this process. I am deeply grateful for the love and the space she gave me to complete something that has been so important to me a very long time.

*This work is dedicated to the belief that all people matter and that architecture is never neutral. To build is to shape the conditions of people's lives, an act that comes with the responsibility to serve with care, dignity and imagination.*

*Through design, professional service, and scholarship I hope to contribute to a more equitable world, one built to offer people greater access, dignity and  
belonging.*

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# **A Geometric Framework for Evaluating Accessibility Within the Wheelchair Footprint**

## **CHAPTER 1: Introduction and Problem Statement**

### **1.1 Introduction**

Current accessibility standards require that specifically designed inclined surfaces, henceforth called ramps, be employed at changes in grade exceeding six inches in height to facilitate the travel of that route for people using wheelchairs or having other disabilities affecting their motion. We have all seen, or possibly used ramps, because they are a common feature in architecture and site design. Curvilinear pathways are valued in environments where designers want to guide the movement of pedestrians, frame views, and have a design that is integrated in a broader, more natural design of the site. Curved ramps are particularly misunderstood by designers and are presented to users in the built form under the assumption that they have been designed correctly.

Accessibility standards in the United States mandate strict limits on the geometry of ramps. These limits include a maximum allowable slope of 8% (a 1 on 12 slope) and maximum allowable cross-slope of 2% (a 1 on 48 slope). These criteria are generally well understood and routinely applied to the design of ramps that travel in only one direction. Requirements for the design of curved ramps is not as well described. While not prohibited, the standards consistently recommend caution when using curved ramps due to the potential for dangerous conditions that might be presented due to compound slopes. This thesis is focused on that discrepancy.

The current design standards have been written to apply predominantly to straight ramps where the travel surface is uniform across the surface of the pathway. Curved ramps, however, introduce a warped plane that introduces conditions that are not fully addressed in the accessibility standards.

The central premise of this thesis is that evaluating the accessibility of a curved ramp must go beyond simple slopes and carefully address the complex slope conditions that are present within the area occupied by the wheelchair. By focusing on this geometry, this thesis proposes a more precise way to describe how compound slope conditions are generated and when they exceed the acceptable limits prescribed by the accessibility standards.

This study was completed using a combination of standards analysis, geometric modeling, physical prototyping, and consultation with people with disabilities. These approaches are used to develop a framework for evaluating curved ramp surfaces beyond everyday slopes. This work helps to clarify the conditions under which the standards are not sufficient to describe curved ramps leading to the blanket condemnation of them that has the potential to limit site design.

Three main contributions are presented in this thesis. First, an evaluation approach of curved ramps based on the condition of compound slope is suggested as a three-dimensional property that exists locally within the footprint of a wheelchair instead of an evaluation based solely on running slope and cross-slope alone. Second, the significance of ramp width as a geometric parameter in the formation of compound slopes is pointed out, alongside slope and ramp radius. Lastly, the start of a digital evaluation approach for determining compound slopes during the design phase is discussed. This research does not intend to replace existing accessible design standards; rather, it provides means of extending their approach of analyzing risks.

## 1.2 Problem Statement

Accessibility standards in the United States, such as the ADA and ICC, define ramps as compliant using the primary measures of slope (rise/run) and cross-slope evaluated on a straight ramp aligned with the path of travel.

Curved ramps behave differently: a curved ramp creates a constant variation in elevation between the inside edge and outside edge of the path. When this is combined with longitudinal slope, a condition known as compound slope results. This is acknowledged in the advisory guidance published in various U.S. accessibility standards. This commentary states that curved ramps may produce compound slopes exceeding allowable limits and that this condition may result in un-even wheel contact. The guidance offers no methods for evaluating this condition. This leaves designers with a limited set of options: we can avoid curved ramps altogether or rely on conservative assumptions on the rise and radius without a clear understanding of how these variables interact. This uncertainty is not resolved by looking at international standards. Australian Standard AS 1428.1 permits curved ramps under specific ratios of slope and radius which suggests that compound slope conditions at curved ramps can be evaluated, but the lack of an equivalent framework in American standards highlights a lack of consensus on how curved ramp geometry can be understood. Curved ramps may not be inherently non-compliant, but there is not a widely adopted method for assessing how slope is experienced across the footprint of a wheelchair.

The problem is not simply that curved ramps may be difficult to design, but that current evaluation methods do not fully describe the localized three-dimensional slope condition experienced by the wheelchair footprint as it travels through a section of the curved path.

### **1.3 Hypothesis**

The hypothesis of this thesis is that the critical conditions governing accessibility on a curved ramp is in the three-dimensional slope experienced in the footprint of a wheelchair from opposite diagonal wheels, and not the nominal running slope and cross-slope measured along a standard X/Y axis. I hypothesize that this condition can be represented as a diagonal slope across the diagonal of the wheelchair as a result of the combined effects of the slope and radial elevation change. Under certain conditions, this diagonal slope may exceed the allowable limits of the accessibility standards even if the running slope and cross-slope each comply with the published standards. If this is the case, current evaluation methods might fail to recognize conditions that might be difficult or dangerous for a user. It may also be possible to design compliant curved ramps by adjusting various variables in a coordinated manner.

### **1.4 Research Questions**

The primary research question for this thesis is this:

*Under what geometric conditions does a curved ramp generate a compound slope across a wheelchair footprint that exceeds accessibility limits, even when nominal slope and cross-slope comply with ADA/ANSI criteria?*

### **1.5 Implications:**

The answer to this question will have implications for design practice and for the interpretation of the current accessibility standards.

First: The work helps to assess the geometry of curved ramps as three-dimensional surfaces as opposed to planar geometric designs with an assigned slope. The differentiation

enables the designers to understand the dynamics between the radius, width, slope and the users space position of the wheelchair.

Second: The study focuses on the possibility of ramp width to influence compound slope behavior. Although it is usually considered as a clearance dimension, my investigation indicates that width has an impact on the diagonal geometry of the wheelchair footprint. This may have an influence on the severity of compound slope conditions.

Third: A digital evaluation method was developed and begins to be used in the work through a spreadsheet-based tool. This is a proof-of-concept design tool, not a completed design application. Its importance is in showing that the conditions of compound slopes can be determined in a predictive manner and that these can be factored into early design decisions.

Fourth: The paper offers some insights into the problem of compliance and usability. While a ramp may meet all the nominal slope requirements, there may be some geometric characteristics of the ramp that need to be addressed on a local level. This does not deny that there are times when a curved ramp may be accessible. Instead, it suggests that the accessibility of such ramps depends on other factors beyond the dimensions.

## CHAPTER 2: Literature Review

This review begins with the existing research on curved pathways and their role in architectural design. The papers reviewed provide a basis for understanding the appeal of curved forms in landscape design. The literature review will then provide a detailed examination of the Americans with Disabilities Act (ADA) and the guidance it provides on curved ramps, as well as a comparative analysis of the Australian standard AS 1428.1 and the approach this foreign standard takes in addressing curved ramps. The review then explores the design of ramps and the physiological impact cross slopes has on users.

These studies provide important insights into the potential hazards posed by uneven surfaces and compound slopes, which are important in understanding the difficulties that might be associated with using curved ramps. The review of this body of research will identify several gaps in existing research and provide a solid basis for understanding of how to design these increasingly popular design elements.

In her paper “Basic Principles of Landscape Design”, author Gail Hansen suggests that the most common element in site design composition is the line, (Hansen, 2010). Hansen believes that curved lines can impart character that is associated more with nature and asymmetrical balance. As a site design element, curved lines move the eye at a slower pace and add mystery to the space by creating hidden views, (Hansen, 2010). Hansen states that lines “...are a powerful tool for the designer because they can be used to create an infinite variety of shapes and forms, and they control movement of the eye and the body.”, (Hansen, 2010). “Meandering lines work well for pathways” she says, “and can add interest and mystery to a garden by leading viewers around corners to discover new views and spaces” , (Hansen, 2010). In his essay on site design titled “The Future is Curved”, author Olafur Eliasson reiterates

Hansen's thoughts on how curved lines, when applied to walkways, can create a sense of anticipation and surprise because the continuous curve of the walkway "limits the viewer's sight to around 20 meters ahead, meaning they are constantly encountering new [experiences] as they progress", (Eliasson, 2003).

The paper "Students' And Landscape Designers' Perceptions Of The School Site Design" by Larry Robert Cates explores the perceptions of students and professional landscape designers regarding campus site design. The study focused on aesthetics, functionality, and maintenance. Cate's research revealed a preference for curved walkways among students and professional designers. Students reported that they found curvilinear walkways more enjoyable and felt they made the school grounds safer. Professional designers stressed the importance of curvilinear walkways for creating a sense of visual harmony, guiding pedestrian movement, and integrating the design with the surrounding landscape. The study suggests that incorporating curved walkways into campus site design enhances the aesthetic appeal and functionality of the environment, (Cates, 1981).

My professional experience in managing site design projects on the VT campus has included a noticeable increase in the use of curved pathways validating the literature claiming that curvilinear forms and non-linear lines are an important factor in landscape architecture and design. The significant inclined grade stretching across the VT campus requires the use of many banks of steps and alternative barrier-free routes are provided in the form of sloped walkways. The slope of many of these walkways is steep enough for them to be considered ramps as explained in literature reviewed below. Concern about the safety and ease of use of curved ramps by VT planning departments has sometimes thwarted the designer's vision of outdoor spaces as

VT insisted on using only straight ramps as part of a more conservative design approach intended to limit the University's liability for accidents or discrimination.

The Americans with Disabilities Act Standards for Accessible Design (ADA) was published by the United States Access Board in 1990 and provides the pertinent requirements for accessible routes including inclined surfaces and ramps. ADA section 303 details the requirements for floor and ground surfaces and the requirements for any changes in level. Under this section, changes in level greater than 1/2" or exceeding a slope of 1 foot of rise within 20 feet of run (1:20, or 5%) must be sloped in accordance with ADA Section 405. ADA section 405 provides the standards pertaining to this type of sloped surface known as a ramp. Under Section 405 a ramp must not exceed a slope of 1 foot of rise within 12 feet of run (1:12, or 8.333%). The cross-slope (also referred to as cross-fall or camber) is the slope of the ground surface perpendicular to the path of travel. Under ADA section 405, the cross slope of a ramp cannot exceed 1:48 (2%). This section offers an advisory section pertaining to curved ramps.

The US Access Board also offers a secondary publication known as "Guide to the ADA Accessibility Standards" (ADA Guide). The ADA Guide provides an illustrated narrative explaining many of the ADA requirements and explains the ADA advisory on curved ramps stating:

*"Ramps without level landings at changes in direction typically will not meet the Standards due to resulting compound slopes. This includes most circular or curved ramps, unless the radius is large enough so that the cross slope is compliant, and compound slopes are avoided. Otherwise, the curvature and slope result in uneven*

*surfaces that makes wheelchair maneuvering difficult because not all wheels rest evenly on the surface.”*

The US Access Board also offers a secondary manual known as the “Americans with Disability Act Accessibility Guideline Manual” (ADAAG Manual). The ADAAG Manual was offered as guidance to the ADA standards but still offers useful information pertaining to curved ramps. Section 4.8 of the ADAAG Manual states:

*“The cross slope (2% maximum) [on ramps] must be minimized because it makes wheelchair travel difficult by distributing more weight and required force to one side and causing front casters to veer.”*

Further, section 4.8.6 of the ADAAG Manual states:

*“Curved ramps, while not specifically addressed by ADAAG, are not considered suitable for wheelchair traffic unless the radius of curvature is large enough. The curvature and slope typically result in an uneven surface that makes wheelchair maneuvering difficult because not all wheels rest on the surface. An inner radius of curvature over 30 feet is considered necessary in order to minimize the slope differential.”*

Note that within all the ADA related documentation, the ADA does not outright prohibit the use of curved ramps, but it does warn designers in several ways that the use of curved ramps might result in conditions that are not compliant.

The American National Standard Institute (ANSI) is an organization that develops standards for products and systems in the United States. Section 405 of its publication “ICC/ANSI A117.1 2009” (ANSI

117.1) roughly parallels the ADA Standards for accessibility in buildings. It is this standard that is referenced and enforced by the International Building Code

(IBC). Like the US Access Board, ANSI offers a guide to these complex standards known as the “ICC/ANSI A117.1 – 2009 Standard and Commentary”. The commentary for Section 405.2 states:

*“Ramps should be straight, not curved, unless engineering analysis has been performed to ensure that the slope of the curved ramp is not steeper than 1:12 anywhere along the line of travel and the maximum cross slope in Section 405.3 is not exceeded. All four wheels of a wheelchair must remain in contact with the ramp surface at all times.”*

Additionally, the ANSI commentary for Section 405.3 states:

*“The cross slope of a curved ramp should be carefully designed and checked. A curved ramp is likely to have a difference in elevation from the inside to the outside of the curve, which creates a cross-slope steeper than 1:48 and a curved surface on which only three of the four wheels of a wheelchair rest at any one time. Dangerous handling problems are therefore created for the person using a wheelchair. It is not possible to maneuver a wheelchair to precisely follow the curvature of the ramp. A curved ramp is negotiated by a series of rectilinear movements, with intermittent corrections to compensate for the curvature of the ramp.”*

These American standards make it clear that curved ramps pose a substantial risk for noncompliance in comparison to straight ramps. A conservative design approach would be to avoid curved ramps altogether. This would help reduce the possibility of inadvertently building inaccessible features but presents severely limited design options. That curved ramps exist in

many landscape projects suggests that other more permissive standards exist and that further research to explain the effects compound slopes and how they affect the safety and ease of use on curved ramps is required.

Other countries have adopted accessibility laws and standards like the US. One such standard is “AS 1428.1-2021 Design for Access and Mobility” (AS 1428.1). AS 1428.1 is an Australian construction standard outlining the requirements that ensure accessibility for people with disabilities in new buildings. AS 1428.1 addresses ramps and walkways with notable differences from US standards. In general, Section 7.1 mandates a cross slope of 1:40 (2.5%). Section 7.3 states that the maximum slope of a ramp exceeding 1900mm (+/- 6’-3”) is 1:14 (7.14%). Curved ramps are specifically dealt with in Section 7.4. Under this section curved ramps are defined as ones with a maximum inside radius of 5 meters (+/- 16 feet). The required radius of the curved ramps is proportional to the slope of the ramp with the minimum radius decreasing in accordance with a graph offered in that section. For a maximum slope of 1:14, the minimum inside radius of a curved ramp is approximately 6 feet.

Several other differences exist, but the primary differences between the US and AU standards for curved ramps are, then, the AU disregards the potential for compound slopes that might be caused by the greatly reduced allowable radius of the curve which is 2.6 times smaller than the 30 feet approximated by the ANSI 117.1 standards. A search for literature that explained the rationale for the various design standards found many publications concerning the design of ramps in general, including several addressing the cross slopes of ramps in particular.

A technical report titled "Sidewalk Cross-Slope Design: Analysis of Accessibility for Persons with Disabilities," by Kara M. Kockelman, Lydia Heard, Young-Jun Kweon, and Thomas W. Rioux examines the accessibility of sidewalks for individuals with disabilities. This

study challenges the Americans with Disabilities Act (ADA) guidelines requiring a maximum cross-slope of 2 percent after finding that "...that there is essentially no research to support ADA's 2 percent cross-slope requirement", (Kockelman, et al, 2001). The research disputes the 2% standard, suggesting that this standard may be overly restrictive and lacking in scientific support. The study collected data from a diverse group of participants with disabilities that included people using canes, crutches, walkers, and manual and electric wheelchairs or scooters. Qualitative data pertaining to the participant's perception of comfort and qualitative data pertaining to their heart-rate changes were gathered while they traversed a variety of urban sidewalk sections selected for the survey. The key finding of the study was that cross slope may not be the biggest factor and that factors such as the primary slope of the surface and the length of the ramp were more important. Further, the researchers determined that cross-slopes exceeding the 2% standard were manageable for many individuals, especially when the primary slope was minimal. While this study calls the ADA requirement of 2% into question, other studies validate the standard.

The paper "Consequences of a Cross Slope on Wheelchair Handrim Biomechanics" details research in the area of cross-slopes that Kockelman et al states was missing. This study was made to understand specific biomechanical challenges presented by ramps with cross-slopes. In this study biomechanical data was acquired using instruments connected to the wheel of manual wheelchairs operated by people on an inclined treadmill with a cross slope of 3 and 6 degrees.

The data collected data included force, torque, push angle, cadence, distance, and power output. The physiological performance of the subject's body was also recorded using a motion capture system. The research concluded that pushing on a cross slope significantly increased

handrim (the outmost rim of a wheelchair wheel gripped by the user) loading. The researchers also found that users needed more pushes to cover the same distance which resulted in the user needing to compensate by adjusting their pushing technique. (Richter et al, 2007) The exertion required for propulsion increased substantially with increasing cross slope, reaching 2.3 times greater on the most severe cross slope compared to using the wheelchair on a level surface. (Richter et al, 2007). The research proved that excessive cross slope increased handrim loading that can put wheelchair at risk of injury due to fatigue and underscored the importance of reducing cross slopes in ramps with the built environments to make wheelchair use safer and more efficient.

The important effect that cross slope has on wheelchair users is reiterated in the paper “Effects of Cross Slopes and Varying Surface Characteristics on the Mobility of Manual Wheelchair Users”. This paper explored the challenges that manual wheelchair users face when traversing cross slopes. This paper details research conducted with manual wheelchair users who rated the difficulty of navigating cross slopes with varying attributes such as slope angle, weather conditions, and surface texture compared to other common obstacles. The key findings of this research were the following:

1. Severe cross-slope angles were consistently rated as more difficult to traverse.
2. Cross slopes combined with running slopes (compound angles) presented the greatest challenges.
3. Defective surface conditions and weather conditions like snow or ice exacerbated difficulties.
4. Participants expressed deep insecurities about ramps with excessive cross slopes and a strong inclination to avoid sloped routes with these challenging characteristics.

5. Cross slopes and compound slopes can increase propulsion effort and lead to injury, (Cooper, et al, 2012).

The study supports the importance of adhering to current ADA guidelines for cross slopes, and highlights the need for more comprehensive design considerations with respect to slopes, surface quality, and weather conditions.

Lastly, the paper titled “A Case Report Of A Severe Musculoskeletal Injury In A Wheelchair User Caused By An Incorrect Wheelchair Ramp Design” describes an incident involving the overturning of a wheelchair used by a person going down an inaccessible ramp in the garage of a hospital. The accident resulted in a severe injury involving the fracture of the wheelchair user’s femur that required extensive surgery to repair. It was discovered that the ramps in the hospital garage did not comply with the guidelines of the ADA. The case study showed the importance of ensuring that hospital ramps comply with accessible guidelines and the very real physical dangers of not doing so, (Eldich et al., 2001)

Several key findings emerge from the literature reviewed herein. Curves in pathways have been shown to be valuable in the field of architecture and landscape design. Accessibility codes state that curves in ramps could give rise to diagonal or compound slopes and varying contact points on wheels. Biomechanical studies demonstrate that cross slopes as well as compound slopes might pose greater challenges for people using wheelchairs because they result in higher energy expenditures and difficulties associated with instability. The problem is that there is no established method for assessing three-dimensional local slopes generated in the area of a wheelchair's footprint when the wheelchair is navigating a curved ramp. It is this problem that this thesis will address.

## **CHAPTER 3: Methods and Research Design**

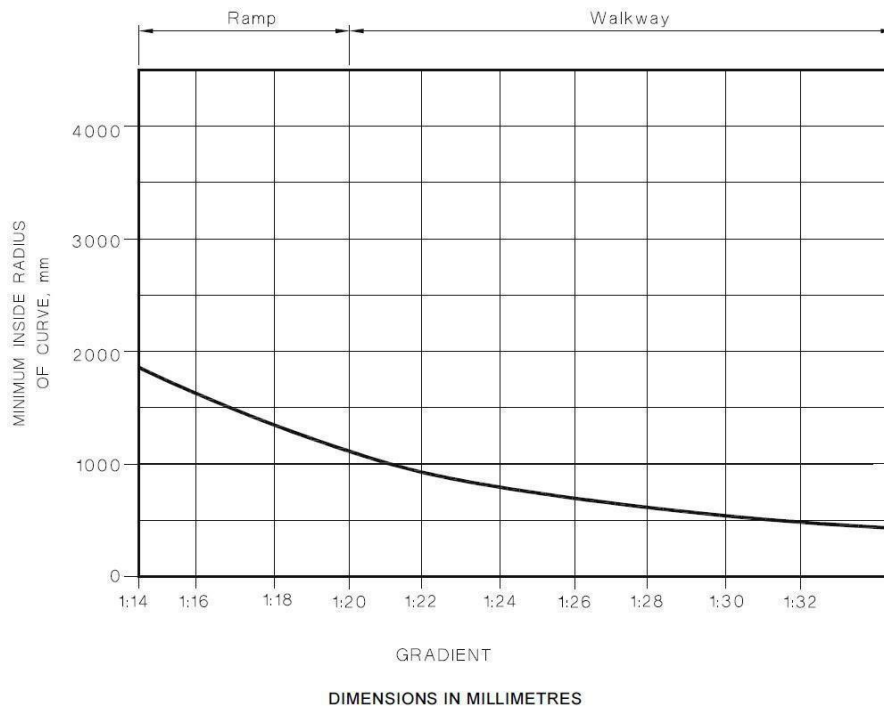
### **3.0 Introduction to Methods**

For this thesis, I used an exploratory mixed-method approach that scrutinized curved ramps in terms of analytical, physical, observational, and experiential approaches. This combination of approaches was important because none of these methods could have individually answered the research questions on their own. The geometric analysis gave the core of the analytical approach. Physical models allowed for the comparison of wheelchairs on different types of ramps. Observations on-site linked this project to actual conditions on campus. Input from the disability consultant informed this project with practical experience of ramps regarding effort, orientation, and stability. The digital tool showed how the framework can be used.

Thus, the methods have to be perceived hierarchically. The geometric analysis forms the core of the work done here. Physical modeling and the on-site observations are exploratory and supplementary. Input from the disability consultant gives experiential validity to this study.

### **3.1 Curved Ramp Gradient Analysis**

The Australian accessibility standards offer a solution to curved ramps shown in the table below.



### Australian Accessibility Standards Ramp Curve/Gradients

Under the Australian accessibility standards, curved ramps are allowed with a radius having a proportionate but non-linear relationship with the slope of the ramp: as the slope increases, the required curve radius increases. The maximum slope allowed for a ramp in the Australian standards is 1:14 versus the ADA standard of 1:12. Predicting what curve radius would be allowed for the ADA standard would align the graph with ADA design standards. The precise mathematical relationship will be explored using mathematical modeling tools. To do this we will carefully consider which type of linear or non-linear models' mathematical models could be employed to model this trend.

Notice that the ramp slope decreases as the radius increases. The Australian standard links curved-ramp geometry to gradient by requiring larger inside radii as ramps become steeper, while permitting tighter curves only at gentler gradients. This relationship provides a useful

comparative framework for examining how curvature might need to be treated if a ramp were designed at the steeper 1:12 maximum slope permitted under the ADA..

To interpolate turning radii for intermediate slope values—especially near the ADA relevant slope of 1:12—I evaluated both linear and quadratic regression models using the full dataset. While a linear fit is simpler, it failed to capture the increasing curvature evident in the lower slope range. A second-degree polynomial provided a better representation of the observed data trend, matching the natural increase in required turning radius as slope decreases. The quadratic model was chosen for its balance of mathematical simplicity, geometric realism, and visual fit. Unlike higher-degree polynomials, which risk overfitting and erratic behavior, the second-degree fit remained stable and interpretable across the full domain of interest. This model was used to estimate the turning radius at slope = 12, yielding a value of approximately 7.35 units.

## **3.2 Physical Models and Testing**

### **3.2.1 Model Ramps**

Careful observation of the physical behavior of wheeled mobility devices was essential in determining the safety of ramps proposed. I modeled my initial testing plans after the types of apparatus I observed being used by my colleagues at the IDEA Lab which conducts similar accessibility research at the University of Buffalo. Building full-scale versions of ramps of various configurations as they do at the IDEA center would have been optimal, but doing so would have been burdensome in terms of space and material. A space in which to build the various ramp configurations we would have liked to test would be costly to rent and impossible to find. The construction materials and the construction methods required to make each ramp

structurally adequate for users' safety would be cost prohibitive. To overcome these challenges, I conducted the observation with physical models constructed at a scale to allow as equivalent operation and behavior as at full scale. The use of the models was intended to give preliminary data about the behavior of the chairs on the slope and to refine the study methods for full scale testing in subsequent phases of this study.

A scale of 3" = 1'-0" is a large enough scale to manage these practical matters. A total of 6 large-scale models were built to represent the various ramp configurations as follows:

1. Basic ADA compliant straight run ramp at slope of 1 foot of rise over 12 feet of run (1:12).
2. AS 1428.1-2009 Ramp for ramp with curve radius of 3.6 (minimum) at a slope of 1:20.
3. AS 1428.1-2009 Ramp with curve radius of 4. (median radius) at a slope of 1:17
4. AS 1428.1-2009 Ramp with curve radius of 6. At a slope of 1:14

Construction of the ramps using a scaled down version of real-world construction methods was attempted using formwork and cast in place concrete. Forms were fashioned using 3mm cardboard cut to the slopes required slopes and affixed to Masonite boards using removable tape. Foam blocking was used to reduce the amount of concrete needed to fill the forms. The cardboard was coated on the interior with packaging tape to act as a bond break between the concrete and form surfaces. Wire mesh was used as reinforcement and as a mechanical attachment to the Masonite substrate and was secured to the Masonite using screws. "Rocktite", a cementitious mixture used for patching concrete but favored by architecture students for

modeling, was then mixed and placed into the concrete forms. A thick plexi-glass screed was used to smooth the surface. This method was not satisfactory as it cured fast and resulted in an uneven surface. The irregularities were filled using gypsum joint compound which was then sanded smooth.

For the testing a model wheelchair was guided down the ramp models manually using a rear handle, traveling along the centerline of the ramp with the wheelchair slope angle measured and recorded at each quarter-point. Additionally, the wheel positions, caster wheel positions and behavior and the attitude and behavior of the mannequin were also observed. Similar observations were made with the wheelchair model positioned at a 45 degree angle from the center path of the ramp.

Physical models did not aim to be conclusive biomechanical simulations. They were meant to act as comparative instruments used to observe general trends in wheelchair movement over various ramp geometries. The lack of accuracy in surface modeling, size, friction effects, and caster movement rendered the models unreliable for exact measurement. But the models were able to show how conditions on the surface of interaction between the wheelchair and the ramps varied depending on factors such as radius, slope, and orientation. This necessitated a geometric approach that would not rely purely on physical simulations.



Cast concrete ramp apparatus



Cast concrete ramp apparatus

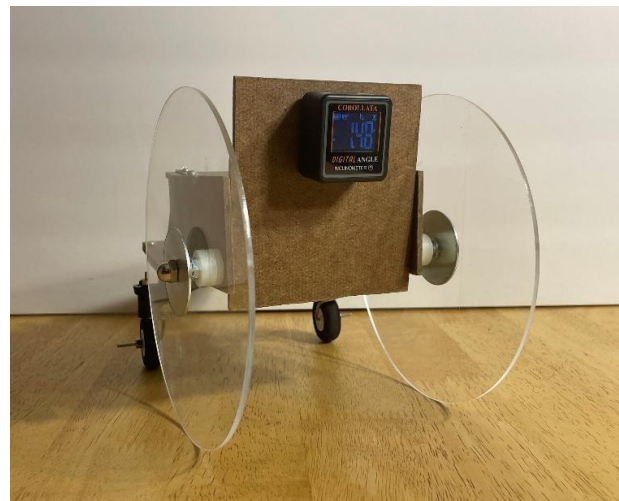
### 3.2.2 Model Devices

Testing involved evaluating the ramp surfaces using a model of a wheeled assistive device constructed to the same scale and detailed to provide accurate representation of actual products. Accuracy of the models was ensured by fabricating it utilizing reference materials obtained from manufacturers of these assistive or the average dimensions published in “Types of Wheel Chairs” from “Wheelchairs: A Prescription Guide” by Wilson and McFarland. The use of scaled models increased the number of research opportunities by allowing us to study a greater number of this large apparatus than if it were built at full scale because of efficiencies in time, material, cost, and space. The model was not constructed to simulate the actual construction techniques of an actual wheelchair. Using meticulously crafted scaled models allowed the study of simulated wheel contact conditions to assess the performance of the various ramp configurations. Prefabricated components were chosen to prevent glitches and to make the operable parts operate as smoothly and as realistically as possible. The rear wheels were

constructed of pre-fabricated acrylic discs. The front wheels are model aircraft parts that simulate the front casters of a wheelchair. Small digital levels were attached to the back and sides. This will provide data about the physical interactions between the model devices and the ramp surfaces in various configurations and will contribute to a more nuanced understanding of how assistive devices interact with compound slopes. It is known that there are limitations to the use of models for this application: the center of gravity may not be equal to a full-sized wheel chair.



Front View of Wheelchair Model



Rear View of Wheelchair Model

### 3.2.3 Mannequin

An anthropometric mannequin was also included in the testing apparatus to approximate realistic body positioning, center of gravity, and wheelchair turning behavior. The mannequin was constructed to represent average adult human proportions based on standardized anthropometric data obtained from Architectural Graphic Standards. Average measurements

excluded many potential body types, but a standard set of average dimensions was required given the limited scope of this study, The mannequin consists of fabric fashioned into stylized geometric body parts in three sections: Head and torso, upper legs, lower legs and feet. The body segments are hinged at typical bending points to allow the mannequin to “sit” in the wheelchair model realistically.

A realistically proportioned mass was an important factor for the mannequin. Mass depends on volume and volume scales with the cube of other linear dimensions. Therefore, the mass scale is  $(1/4)^3 = 1/64$ . Using an average human mass of 185 pounds based on data from the CDC, an accurately scaled mannequin will weigh 2.9 pounds. The mannequin was filled with 2.9 pounds of crushed stone distributed throughout the mannequin. The mannequin was not affixed to the chair but was allowed to be able to tip, slide, and be ejected from the model wheelchair to simulate instability realistically. While the mannequin did not behave exactly as a human subject would, its use enabled repeatable, comparative analysis across a range of ramp geometries. During testing on the ramp, the position of the mannequin was observed. Instances where the mannequin leaned, slid, or ejected from the model wheelchair was recorded.



Patterning for Mannequin



Finished Mannequin



Mannequin seated in Model Wheelchair

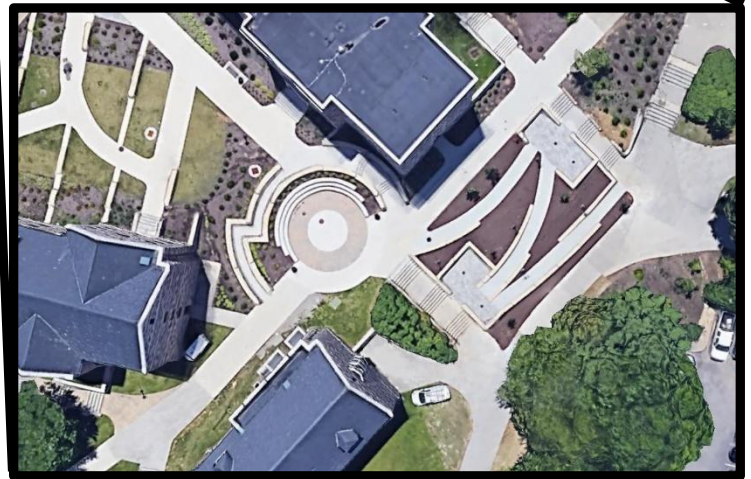
### **3.3 Analysis and Testing of Existing Ramps In-Situ**

#### **3.3.1 Existing Ramp Analysis**

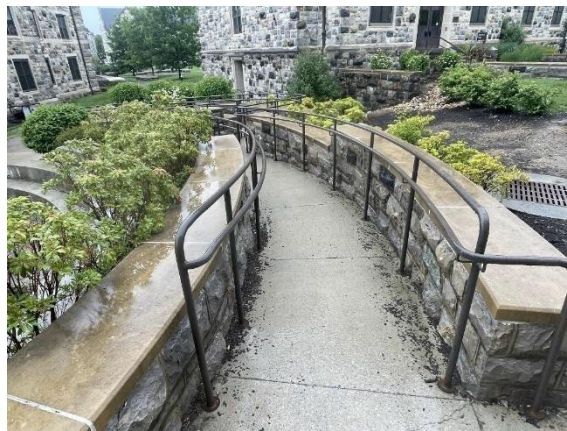
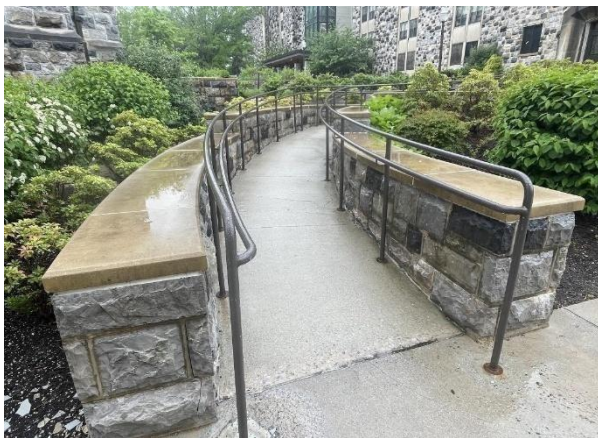
There are existing ramps on campus that were selected for study in lieu of constructing full-scale test ramps. These ramps were evaluated against applicable ADA and ANSI accessibility criteria, including running slope, cross-slope, landings, handrails, and related dimensional requirements. The results of this evaluation are presented in the Findings section.



Partial Campus Map



Configuration of Curved Ramps Studied



Upper-most Ramp Segment 1



Upper-most Ramp Segment 2

Lower-most Ramp Segment 1 (of 3)

### 3.3.2 Existing Ramp Testing

Qualitative data about the behavior of full-sized wheelchairs was desired using actual wheelchairs operated by people with disabilities on the in-situ ramps in the next phase of research. Disability simulations are sometimes conducted by disability researchers include activities like using a wheelchair or wearing goggles to mimic blindness, intended to help participants “*experience*” disability. Since the ramps chosen to study exist in-situ and are deemed ADA compliant and fit for use by the campus community few safety concerns about the use of these ramps (as opposed to constructing sample ramps in a lab) exist but to limit the process of IRB review I decided to forgo using human subjects. Therefore, we used a manual wheelchair loaded with 70 pounds of mass to observe how the device behaved on the inclined surfaces in being studied.

The observations of these ramps focused on several key items. First, the path of travel was observed to determine whether the wheelchair maintained its intended trajectory or drifted laterally toward the inside or outside edge of the ramp. Second, the front caster wheels were observed for rotation, flutter, pivoting, resistance, or loss of contact with the ramp surface. Third,

the rear wheels were observed for consistent surface contact and evidence of uneven loading. Fourth, the frame of the wheelchair was observed for tilt, rocking, or torsional movement as it traveled through curved or sloped portions of the route. The behavior of this is described in the findings section.

### **3.4 Digital Tool**

The beginning of a digital tool was developed to evaluate ramp geometry based on user inputs. After inputting the desired ramp radius, the intended ramp angle for the controlling surface (interior), the tool provides additional information about the ramp's opposite surface and the resultant compound slopes. The output is discussed in the finding section.

### **3.5 Disability Consultant Group**

“Nothing for us without us” is a phrase having meaning across several social justice movements including the disability rights movement. It means that policies should be decided or enacted for a group without full and direct consultation or participation of the members of the group that will be affected by the proposed policy. Disability scholarship stresses that purposeful and meaningful engagement with people with disabilities is crucial to designing environments that actually work for them highlighting that expertise gained by lived experience is a necessary form of knowledge that must inform professional design practice and research. (Bigby 2020). Proceeding with research or making designs for people with disabilities without this knowledge and input risks the making of assumptions that could lead to errors or tokenistic outcomes. The worst outcome would be a solution that is compliant but functionally

To obtain this knowledge we sought the opinion of panel of people having experience using assistive devices. The process was evaluated by the Virginia Tech IRB. Because data leading to generalized knowledge about the participants was not being collected, the IRB determined that it was not research but an exercise in informing this study. 5 Participants recruited from people with disabilities registered as consultants with a disability research group associated with Virginia Tech were asked semi-structured interview questions.

## **CHAPTER 4: Findings**

### **4.1 Ramp Model Findings**

The physical ramp models were used to observe relative differences in wheelchair behavior across a range of geometric conditions. Substantial limitations in measuring accuracy were found. This was due to the quality of the modeled surfaces and model inconsistencies. Consistent patterns were observed, however, that help illustrate how curvature and slope interact.

#### **4.1.1. Wheelchair Traversing Centerline of Ramp**

As the wheelchair model was guided along the centerline of each ramp, the following consistent trends were observed:

**Axle Tilt:** Axle tilt increased with steeper slopes, as expected, but was also influenced by curvature.

Ramp 1 (1:20, 3.6' radius) produced a maximum tilt of approximately  $2.5^\circ$  at the lower portion of the ramp.

Ramp 2 (1:14, 6' radius) showed lower overall tilt, peaking at approximately  $0.6^\circ$ .

The straight control ramp (Ramp 3, 1:12) maintained a consistent and minimal tilt of approximately  $0.25^\circ$  throughout.

The 30' radius ramp (Ramp 4, 1:12) showed increasing tilt along the run, reaching approximately  $1.6^\circ$  at the bottom.

These results suggest that while slope is the primary driver of tilt, curvature introduces variation along the length of the ramp that is not present in straight conditions.

**B: Wheel Contact:** The rear wheels of the wheelchair model maintained consistent contact with the surface on all ramps. This indicates that, under centerline conditions, the modeled surfaces did not produce complete loss of rear-wheel support.

**C: Caster Behavior:** Caster behavior varied more significantly:

- On tighter-radius ramps (Ramps 1 and 2), casters remained free throughout, suggesting continuous adjustment to the changing surface condition.
- On the straight control ramp, both casters maintained full contact at all points.
- On the 30' radius ramp, the inner caster remained engaged while the outer caster frequently lost contact.

This indicates that even at larger radii, curvature introduces asymmetrical contact conditions not present in straight ramps.

### 4.1.2 Off-Axis Traversal

When the wheelchair was positioned at the midpoint of each ramp and rotated  $\pm 45^\circ$ , the effects of compound geometry became more pronounced.

#### A: Axle Tilt

- Ramps with tighter radii (Ramps 1 and 2) produced the highest tilt values, ranging from approximately  $3.5^\circ$  to  $4.65^\circ$ .
- The straight control ramp produced moderate tilt, between approximately  $2.2^\circ$  and  $2.75^\circ$ .
- The 30' radius ramp produced tilt values comparable to the straight ramp, reaching approximately  $3.5^\circ$ .

These results indicate that orientation relative to the ramp surface significantly affects stability.

Even in straight ramps, off-axis positioning introduces measurable tilt, but this effect is amplified in curved geometries.

#### B: Caster Behavior Under Rotation

- The straight control ramp exhibited unexpected caster instability, with pivot engagement and “loose” contact conditions.
- The 30' radius ramp showed mixed behavior, with inner casters maintaining contact while outer casters exhibited intermittent or loose engagement.

- The tighter-radius ramps maintained free caster movement across all angles.

These observations suggest that compound surface conditions are not limited to curved ramps alone, but are intensified by curvature and user orientation.

#### **4.1.3 Summary of Model Findings**

Results from the modeling exercise demonstrate three key tendencies:

1. Variation in surface condition introduced additional slope and cross slope anomalies that is not captured by measurement of the known ramp geometries.
2. Wheelchair behavior is sensitive to orientation relative to the ramp surface, not just alignment with the path of travel.
3. Even large-radius curves produce asymmetrical contact conditions, particularly at the casters.

The limitations of the models must be acknowledged here. Surface irregularities and scaling effects definitely reduced my confidence in having obtained precise measurements. Because of this, these findings are best understood to be indicative rather than definitive and support the need for a more rigorous geometric method of evaluation.

#### **4.2 In-Situ Ramp Observations**

Observations of wheelchair movement on existing ramps were made to provide additional data given the measuring difficulties experienced with the scale models.

**4.2.1 Trajectory and Path Control:** On flat surfaces and straight ramps, the wheelchair maintained a consistent path with minimal correction required. On curved ramps, the wheelchair was able to follow the intended path but required continuous adjustment to maintain alignment.

**4.2.2 Path Deviation:** On curved ramps, the wheelchair consistently drifted toward the edge of the path, requiring frequent corrective input. This behavior was not observed on straight ramps, where movement remained aligned with the direction of travel.

**4.2.3 Effort and Maneuverability:** Effort increased in all sloped conditions relative to flat surfaces. However, curved ramps introduced an additional lateral component of effort, as a user would be required to resist drift while also overcoming gravity.

These observations reinforce that curved ramps introduce a compound condition combining vertical and lateral forces, even when nominal slope values remain within acceptable limits.

### **4.3 Interview with Disabilities Consultant Findings**

#### **4.3.1. Engagement with Ramps and Curved Ramps**

The consultants reported encountering ramps relatively often in daily life but seldomly a curved ramp. The consultants described the negative aspects of ramps in general as ones that were narrow or constrictive, difficult to ascend, and confusing to navigate, particularly where runs connected to landings and transitioned back into segments that changed direction. That well designed curved ramps are not regularly designed and implemented indicates a gap in design practice and a corresponding lack of user-informed evaluation. This absence of precedent directly supports the need for a more precise geometric framework to guide the design of nonlinear ramps.

### **4.3.2. Cross-Slope and Stability**

Manual wheelchair users described increased instability on nonlinear ramps. This instability included the risk of rolling backwards, drifting to one side or the other of the intended path, and a consistent need to exert effort to correct the path of travel. One participant reported the necessity of gripping both handrails simultaneously to maintain forward motion in certain conditions. Participants with blind and low vision noted that nonlinear paths present the potential to interrupt linear navigation cues creating an unpredictable path of travel for the user. These observations show that nonlinear paths, including sloped paths and ramps, change the expected experience of users and introduce complex conditions not addressed by standard accessibility guidelines.

### **4.3.3. Manual and Powered Wheelchair Performance**

The consultants traveled to a location on campus to observe existing curved ramps. One of the users, using a manual wheelchair and having an attendant, was unable to travel to the site citing fatigue. Upon reaching the site, powered mobility users elected to try the ramp and traversed the entire length of the ramp with no observed or reported difficulty. Despite this, the consultants did have negative comments concerning the inconsistent slope, tight turning radii, and insufficient landing space. This contrast underscores the inadequacy of slope-based compliance alone: ramps that satisfy numerical requirements may remain unusable by significant segments of the disability community, particularly those relying on human propulsion.

#### **4.3.4. Wayfinding and Destination Clarity Influence Usability**

Participants stressed that the usability of a ramp depends on the clarity of its destination as much as the ramp geometry itself. They noted that non-linear ramps can obscure sightlines thus reducing the advanced preview. This lack of preview prevented users from knowing if the route led to an accessible entrance, a set of stairs, a dead end or other barrier. Blind participants pointed out the need for tactile and auditory cues along routes. These comments reinforce that fact that in addition to assisting in the change of elevation ramps have a secondary function as navigational elements. Changes in linearity introduces complexity in way finding that requires careful design consideration.

#### **4.3.5. Surface Conditions**

Participants noted that hazardous conditions can be introduced in ramps by surface texture, color contrast, and winter maintenance practices. Slippery coatings, inadequate color differentiation for users with depth-perception issues, and improper snow removal (such as depositing snow piles in accessible routes) create dynamic hazards. Environmental performance must therefore be considered an intrinsic design criterion rather than an operational afterthought.

#### **4.3.6. Handrails**

The consultants described handrails as crucial aspects of useful ramps. They described handrails as essential tools for stability, directional control, and propulsion. Differences in handedness, cane use, and gripping strategies highlight that handrails perform biomechanical functions beyond the assumed use.

### **4.3.7. Accessibility Depends on the Entire Travel Chain**

Participants emphasized that a ramp's usability cannot be separated from its context: door approach zones, placement of push-plate actuators, alignment with parking spaces, cross-slopes at curb ramps, and the continuity of accessible pathways. This reinforces the need to evaluate ramps as integrated components of an access network rather than isolated objects.

The workshop demonstrate that curved ramps introduce challenges not adequately addressed by existing accessibility standards or design thinking. The users confirm that curved ramp would introduce a variety of challenges including cross-slope effects, destabilizing, disruption in blind navigation, complicated transitions. These findings show that our thesis claim that the field requires careful three-dimensional study and a design framework to predict and mitigate the impacts of non-linear ramp surfaces.

## **4.4 Digital Tool Findings**

The digital tool created for this thesis serves as an initial approach to analyze compound slope situations based on wheelchair footprint dimensions. The tool analyzes the diagonal slope condition that will arise from the interaction of ramp radius, ramp width, rise height of each segment, and the geometry of the wheelchair footprint using spreadsheet technology. This tool does not represent a full design application, nor is it meant to serve as a replacement to accessibility regulations.

For the first test scenario, a ramp with a 30-foot interior radius, a width of 3 feet, and a nominal slope of 1:12 resulted in a calculated diagonal compound slope of 6.5 percent. For the second test scenario, increasing the width of the ramp to 6 feet brought down the calculated

diagonal compound slope to 4.5 percent. It appears that width, which is often seen solely as a clearance issue, has a considerable effect on compound slopes.

These results demonstrate two critical points:

1. A ramp can meet nominal ADA slope requirements while producing a localized compound condition that exceeds acceptable limits.
2. Ramp width, often treated as a secondary parameter, plays a significant role in controlling compound slope conditions.

This analysis supports the central premise of the thesis: that accessibility on curved ramps is governed by three-dimensional geometric relationships within the wheelchair footprint, and that these conditions are not fully captured by conventional slope metrics.

# RAMP SLOPE CALCULATION TOOL

<b>Input</b>		
	Interior Ramp Surface	Exterior Ramp Surface
Interior Ramp Radius	30.000	33.000
Interior Ramp Angle	22.500	22.500
Ramp Width	3.000	3.000
Intended Rise	1.000	1.000
<b>Output</b>		
	Interior Ramp Surface	Exterior Ramp Surface
Length	11.781	12.959
Slope	0.085	0.077
Slope	1:12	1:13
% Grade	8.488	7.717
<b>Compound slope Analysis</b>		
Curve Segments (Input)	3.000	
Segment Angle	7.500	
Interior Chord Length	3.933	
Exterior Chord Length	4.326	
Sides	3.006	
Overhang	0.197	
Segment Rise	0.333	
Bottom Angle	86.250	
Diagonal	5.104	
Compound Slope	0.065	
Compound Slope	1:15	
<b>% Grade</b>	<b>6.531</b>	

# RAMP SLOPE CALCULATION TOOL

Input		
	Interior Ramp Surface	Exterior Ramp Surface
Interior Ramp Radius	30.000	36.000
Interior Ramp Angle	22.500	22.500
Ramp Width	6.000	6.000
Intended Rise	1.000	1.000
Output		
	Interior Ramp Surface	Exterior Ramp Surface
Length	11.781	14.137
Slope	0.085	0.071
Slope	1:12	1:14
% Grade	8.488	7.074
<b>Compound slope Analysis</b>		
Curve Segments (Input)	3.000	
Segment Angle	7.500	
Interior Chord Length	3.933	
Exterior Chord Length	4.719	
Sides	6.013	
Overhang	0.393	
Segment Rise	0.333	
Bottom Angle	86.250	
Diagonal	7.397	
Compound Slope	0.045	
Compound Slope	1:22	
<b>% Grade</b>	<b>4.506</b>	

#### 4.4.1 Digital Tool Validation

Validation of the spreadsheet was achieved by comparing the results produced from its spreadsheet with independently calculated results from the same input geometric parameters. The validation process aimed at validating the mathematical correctness of the calculation rather than the biomechanical validity of the wheelchair. The spreadsheet computes the diagonal distance between two corners of the wheelchair footprint and divides the rise in elevation by the diagonal distance to obtain a localized compound diagonal slope.

In the case of a ramp with a radius of curvature of 30 feet and width of 3 feet, the program determines a diagonal distance of 5.104 feet. When the rise is 0.333 feet, the localized compound slope will be:  $0.333 / 5.104 = 0.0653$ , or 6.53 percent.

With respect to the 30-foot-radius and 6-foot-wide ramp configuration, the calculator returned a diagonal measurement of 7.397 feet. Using the same rise per segment of 0.333 feet, the compound slope produced is:  $0.333/7.397 = 0.0450$ , or 4.50 percent. This corresponds with the spreadsheet calculations as well.

The validation process confirms that the digital tool is calculating the geometry of interest correctly with respect to each test case scenario. This does not provide proof that the calculation will serve as an accurate predictor of user effort, instability, or potential injuries. Full-scale biomechanical testing is required to prove these claims. Nevertheless, the validation serves to validate the tool for use as an initial screening process.

## CHAPTER 5: Discussion

This study demonstrates that curved ramps should be evaluated as localized three-dimensional surfaces rather than as simple inclined planes. The biggest issue how curvature interacts with slope, radius, width, and wheelchair orientation within the footprint of the mobility device.

The physical model testing suggested that ramp curve radii below 6 feet produced increased axle tilt and more variable caster behavior, especially when the wheelchair was rotated off-axis. In Ramps 1 and 2, tilt reached values as high as 4.65 degrees under off-axis conditions, compared to substantially lower values when the wheelchair was aligned with the centerline. These results should be interpreted cautiously because the physical models had limitations related to surface quality, scale, friction, and caster mechanics. They are best understood as exploratory findings rather than definitive biomechanical evidence.

The behavior of the straight ramp was stable during use along the centerline path, but the performance of the ramp in terms of caster behavior proved to be rather unpredictable during use on the basis of rotation around the axis of the wheelchair itself. Therefore, it becomes clear that the orientation of the person using the ramp plays an important role. A wheelchair user doesn't always stay straight when passing the ramp; turning, drifting, correcting positions and approach angles will likely influence the slope condition at which the wheelchair is.

The results showed that the 30-foot radius ramp operated in a more consistent way compared to the other two. This conclusion confirms the current recommendation regarding the effect of radius on compound slopes. The data received proves that the radius should not be considered as an absolute parameter in assessing the compound slope condition of a ramp since this element works together with other parameters including slope, width and position of the wheelchair itself.

A major contribution made by this thesis is the relationship between ramp width and the diagonal slope criterion. Width has been usually considered a clearance issue, the digital model indicates that width is a major influence the calculation of diagonal slopes in a wheelchair footprint. When the 30-foot-radius condition was analyzed, it was determined that the diagonal slope in a wheelchair footprint decreased from about 6.5% to about 4.5% when ramp width changed from 3 feet to 6 feet. This conclusion shows that width can be treated as a dynamic geometric parameter rather than just a dimension.

Because of this, the wheelchair footprint becomes the key object of investigation. Traditionally, accessibility standards calculate the running slope and cross-slope at conventional coordinates, but those parameters may not capture the details of the diagonal slope created inside a wheelchair footprint, especially when the wheelchair is placed on a sloped curved path and rotated relative to its primary direction of motion.

The input from the disability consultants highlighted the need for integrating geometric analysis with the experience of the user. In the discussion, the consultants noted issues ranging from instability to fatigue, steering correction, handrails, wayfinding, surface condition, and continuity of the accessible route. These statements show that ramp usability cannot be quantified in terms of geometric measurements alone. Even so, the remarks also help to prove the broader theory of this thesis; that access is dependent upon the interaction of physical geometry with mobility in space.

This research does not imply that curved ramps are inaccessible by default. This research also does not imply that aesthetics should no longer play a role in accessible designs. Instead, this research implies that the presence of aesthetic site geometries requires closer examination when included in an accessible route. Accessibility and beauty should not be seen as competing interests, but accessibility should always have more weight than aesthetics when evaluating a ramp; a

curved ramp cannot be considered truly accessible or compliant until this responsibility is met.

The tool that has been created through this research can be classified as a prototype of a digital tool which proves that compound slopes are calculated in such a way that it might become useful for designing. The further iterations of such a tool might make it possible for designers to evaluate their assumptions on radii, widths, slopes, and wheelchair footprints without having to build it.

The conclusions that have been made because conducting this research must be regarded as somewhat preliminary because of the exploratory character of creating physical prototypes and making the observations. Nevertheless, they helped to realize the role of local geometry as well as contributed to creation of the digital framework. Thus, the greatest value of this research can be attributed to the digital framework created.

## **CHAPTER 6: Conclusion**

The purpose of this thesis was to gain insight in how the curved ramp is evaluated in current accessibility protocols and if slope measurement reflects the real situation of how wheelchair users use a curved ramp. This type of research was motivated by the real-world problem of designing a usable curved ramp which must also satisfy the requirements outlined in the accessibility guidelines, where curved ramps are regarded with suspicion because of compound slope possibilities and the lack of even wheel contact.

The main conclusion of this thesis is that access should be considered with respect to the wheelchair footprint on the ramp. The assessment of the slope and cross slope still needs to be completed, but it doesn't tell the whole story. The diagonal condition is the relationship between the position of two wheels at any given point and provides a better understanding of slope and curvature interaction.

There are four contributions that this thesis makes to accessibility research and design. First, it gives a geometric assessment of the slope of a compound slope within the reach of the wheelchair. Secondly, it indicates the significance of the width of the ramp in either developing or narrowing diagonal compound slopes. Thirdly, it shows the way of calculation in a preliminary digital application. Third, it shows the way of calculation in a preliminary digital application. Lastly, it makes user-defined issues of stability, fatigue, steering and navigation corrections, usage of handrail and route continuity visible and relevant using geometric analysis.

This thesis also highlights the fact that there is nothing wrong with using curved ramps. It's quite feasible that a curved ramp may be the best option, provided the radius, slope, width, landings, handrails, surfaces and destination are all considered in the design. The question is not

whether curved ramps should be provided. The problem is whether or not designers have the means with which to evaluate them.

The physical modeling stage was not as accurate. Surface anomalies, scaling effect, friction, and simplified modelling of the wheelchair had an impact on the results accuracy. So the physical model is not a definitive model, but rather a model for exploration. It is important in pointing out tendencies, in demonstrating behavior of certain shapes and in introducing geometric modeling.

The software tool, developed in the context of this thesis, remains very rudimentary. It is not an application that has been completed and should not be considered an accessible ramps standard. Rather, its significance is in showing the potential for predictive evaluation. In the early design phases, tools like these can be used by architects, landscape architects, accessibility evaluators and code officials to evaluate the geometry of curved ramps. The digital tool was tested internally by comparing the result in the spreadsheet to hand calculation, which proved that the tool can do the intended geometric calculations under the tested conditions.

This thesis needs to be substantiated by extensive experimentation and measurement. Factors that could be measured would include wheel forces, axle tilt angles, caster action, effort levels, steering adjustments, and difficulty ratings using instrumented wheelchairs, different ramp configurations and different wheelchairs.

Additionally, future research might be useful for conducting multidisciplinary research with centers that specialize in accessibility, anthropometrics and universal design, such as the IDEA Center at the University at Buffalo. The opportunity for future research could be enhanced through collaboration among architects, biomechanical engineers, disability studies researchers and people with disabilities.

On a larger scale this thesis suggests that reaching accessibility cannot only be done by dimensional requirement and consideration. Accessibility is made possible by the geometry, kinematics, perception, effort and variability of the human body. By concentrating on the footprint of the wheelchair a new and more realistic assessment of the efficacy of a curved ramp is possible and a design approach that supports accessibility and spatial imagination can be adopted.

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## Appendix 1

### Questions for Accessibility Consultant Group

#### Demographic Information

1. **Age:** What is your age?
2. **Gender:** What is your gender?
3. **Type of Disability:** What is the nature of your disability?
4. **Usage Frequency:** How often do you use ramps (daily, weekly, monthly)?
5. **Primary Location:** In what types of locations do you most frequently use ramps? (e.g., public buildings, private residences, workplaces)

#### General Ramp Usage

6. **Ramp Preference:** Do you have a preference between curved ramps and straight ramps?  
Why?
7. **Accessibility Ease:** How would you rate the overall accessibility of curved ramps compared to straight ramps?
8. **Safety Perception:** Do you feel safer using curved ramps or straight ramps? Please explain your reasoning.
9. **Ease of Navigation:** Which type of ramp do you find easier to navigate? Curved or straight?
10. **Comfort Level:** How comfortable do you feel using curved ramps versus straight ramps?

#### Design and Functionality

11. **Space Utilization:** How does the design (curved vs. straight) affect the amount of space required for the ramp?

12. **Aesthetic Appeal:** Which ramp design do you find more aesthetically pleasing? Curved or straight?
13. **Slope Consistency:** Do you find the slope consistency of curved ramps to be adequate compared to straight ramps?
14. **Turn Radius:** Is the turning radius of curved ramps sufficient for your needs?
15. **Handrail Availability:** How important are handrails on ramps, and do you find them more effective on curved or straight ramps?

### **Usability and Maintenance**

16. **Maintenance Needs:** How do the maintenance requirements of curved ramps compare to those of straight ramps?
17. **Ease of Installation:** Which type of ramp is easier to install in your opinion? Curved or straight?
18. **Durability:** Do you perceive any differences in durability between curved ramps and straight ramps?
19. **Mobility Device Compatibility:** How well do curved ramps accommodate your mobility devices compared to straight ramps?
20. **Weather Impact:** How do curved ramps perform in various weather conditions relative to straight ramps?

### **User Experience**

21. **Confidence Level:** How does your confidence in navigating a ramp change when using a curved ramp versus a straight ramp?
22. **Fatigue Levels:** Do you experience different levels of fatigue when using curved ramps compared to straight ramps?

23. **Incident Frequency:** Have you experienced any incidents or difficulties on curved ramps that you haven't on straight ramps, or vice versa?
24. **Skill Requirement:** Do curved ramps require different or additional skills to navigate compared to straight ramps?
25. **Preference in Specific Settings:** In which settings (e.g., indoor vs. outdoor) do you prefer curved ramps over straight ramps, or vice versa?

### **Overall Satisfaction and Suggestions**

26. **Overall Satisfaction:** How satisfied are you with the current ramp designs available to you?
27. **Improvement Suggestions:** What improvements would you suggest for curved ramps to better meet your needs?
28. **Comparative Satisfaction:** On a scale of 1 to 10, how would you rate your satisfaction with curved ramps compared to straight ramps?
29. **Future Preferences:** Would you prefer more curved ramps to be installed in your community? Why or why not?
30. **Additional Comments:** Do you have any additional comments or experiences you'd like to share regarding curved and straight ramps?