Pervious Concrete Accessible Pathways:

Usability for Individuals with Disabilities

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THESIS

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TABLE OF CONTENTS

CHAPTER PAGE

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ADA	Americans with Disabilities Act
ADAAG	Americans with Disabilities Act Accessibility Guidelines
ANSI	American National Satnadards Institute
ASTM	American Society for Testing and Materials
DOJ	Department of Justice
HAAT	Human, Activity, Assistive Technology Model
Hz	Hertz
IRI	International Roughness Index
ISO	International Organization for Standardization
PSD	Power Spectral Density
PVC	Polyvinyl Chloride
RESNA	Rehabilitation Engineering and Assistive Technology Society of North America
RMS	Root mean squared
SRC	Simulated road course
SRW	Single rear wheel
UFAS	Uniform Federal Accessibility Standards
VRI	Vehicle Response Index
WBV	Whole-Body Vibration
WPRI	Wheelchair Pathway Roughness Index
WT	Wavelet Theory

SUMMARY

A study regarding the usability for individuals with disabilities of accessible pathways constructed of pervious concrete was carried out examining two surface characteristics: slip-resistance and roughness. Coefficient of friction and roughness data was collected at 9 pervious concrete pathways, and an additional 3 pathways constructed of standard concrete for control. All sites were located in the community. Additionally, whole-body vibration data was taken via accelerometers placed on a manual wheelchair, at the footplate, between a standard polyurethane foam seat cushion and a metal mannequin, on the wheelchair backrest, and on a cross-member of the wheelchair's fixed frame.

Coefficient of friction data indicated that all pathways had values at or above the values recommended by the U.S. Access Board, except when recently treated with solutions to break down pollutants or when sealcoated.

Roughness data indicated that the surfaces compared favorably to roadway surfaces in good condition, with most pervious surfaces smoother than the standard concrete control surfaces.

Whole-body vibration data indicated that travel on pervious concrete surfaces by wheelchair users is safe regarding avoidance of health hazards, especially when research regarding actual daily travel in the community is taken into account.

1. INTRODUCTION

1.1 Background

Impairment and disability are not the same. To accurately describe which a person has is very much a function of the environment, and any Assistive Technology they utilize. If the environment does not support an individual's abilities, and there is no appropriate Assistive Technology to bridge the gap, impairment can become disability.

Under the medical model of disability, limitations in specific body functions (e.g., mobility) are described as impairments. Under the social model of disability, however, an impairment only becomes a disability if the environment is not designed such that the individual can use his or her range of abilities to take on required or chosen tasks. As noted in the "*World Health Organization's International Classification of Functioning, Disability, and Health"* (World Health Organization, 2001), a hybrid model is required to adequately portray the situation adequately.

Cook and Hussey (2002) present the Human-Activity-Assistive Technology (HAAT) conceptual model to describe the application of assistive technology devices to increase an individual's independence. The HAAT Model is an adaptation of Bailey's model human performance (1989), the adaptation necessary to allow for the use of Assistive Technology and to show that the context is relevant to all other aspects of the situation. The three central elements are the human (and what abilities he or she brings to the situation), the activity (e.g., movement within the community), and the Assistive

Technology utilized (e.g., cane, walker, manual or powered wheelchair). The interaction between the 3 elements occurs within several contexts (physical, social, cultural, and institutional). When considering the built environment as the physical context in which an individual with a disability travels, the accessible pathways become part of environment which either supports or inhibits independence, health, and safety.

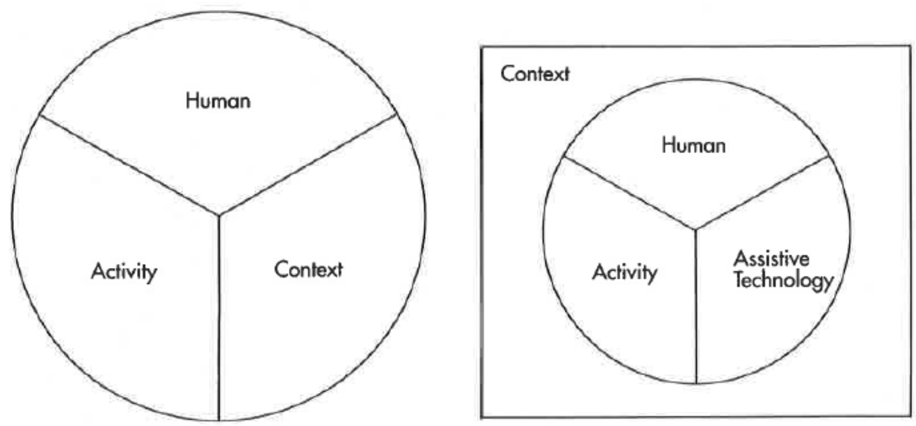


Figure 1. Bailey's model of human performance (left) and Cook & Hussey's HAAT Model (right).

With this framework in mind, this study is presented as a means of examining the usability of pervious concrete as an accessible pathway surface for individuals with disabilities.

1.2 Statement of the Problem

Accessible paths are required for access to public spaces, as well as to goods and services. Research is required on the materials and construction methods used to create these paths if independence of individuals with disabilities is to be achieved. One relatively new material used in the construction of outdoor accessible paths in the built environment is pervious concrete. Pervious concrete offers property owners and municipalities the opportunity to comply with the "*U.S. Environmental Protection Agency Storm Water Phase II Final Rule"* (U.S. Environmental Protection Agency, 2000) to control the amount of contaminants in waterways. Instead of auto-related fluids (e.g., oil, anti-freeze) washing into rivers and lakes with rainwater as they do at impervious surfaces, pervious surfaces allow the fluids to travel into the ground, where the chemistry of the soil and biology treat the polluted water naturally (Brown, 2003). This is especially true for the so-called "first-flush" of rainwater (first 30 minutes), where most of the contaminants are transported. For municipalities, pervious concrete roadway projects can be more affordable, since extensive drainage systems can be omitted from the designs.

While the use of standard concrete and brick pavers has received some attention from a disability research perspective, the use of pervious concrete has not. Since the material offers several advantages for use in public spaces, its inclusion in usability research is merited.

A comparison of key properties of standard and pervious concrete appears in Table I.

Table I. Comparison of key properties between standard concrete and pervious concrete (Engineering Properties, 2011; Kosmatka and Panarese, 1988; Nawy, 2000).

Property	**Concrete-Standard**	**Concrete-Pervious**
Density	2306 kg/m^3 (144 lb/ft^3)	1600-2000 kg/m^3 (100-125 lb/ft^3)
Compressive Strength	20-34.5 MPa (3000-5000 psi)	3.5-28 MPa (500-4000 psi)

Standard concrete is comprised of a mix of cement, coarse aggregate, fine aggregate, and water; pervious concrete is comprised of a mix of cement, coarse aggregate, and water only. For pervious concrete, use of smaller coarse aggregate produce a smoother surface, which makes this mix especially applicable for accessible pathways (Kerkhoff, 2004).

The lack of fine aggregate results in the material’s voids being connected, allowing water to pass through. Void ratio ranges from 15-25%, with 20% being typical (Engineering Properties, 2011). A pervious concrete layer is usually installed over a subbase having greater porosity, as shown in Figure 2. A geotextile material is typically installed below the subbase.

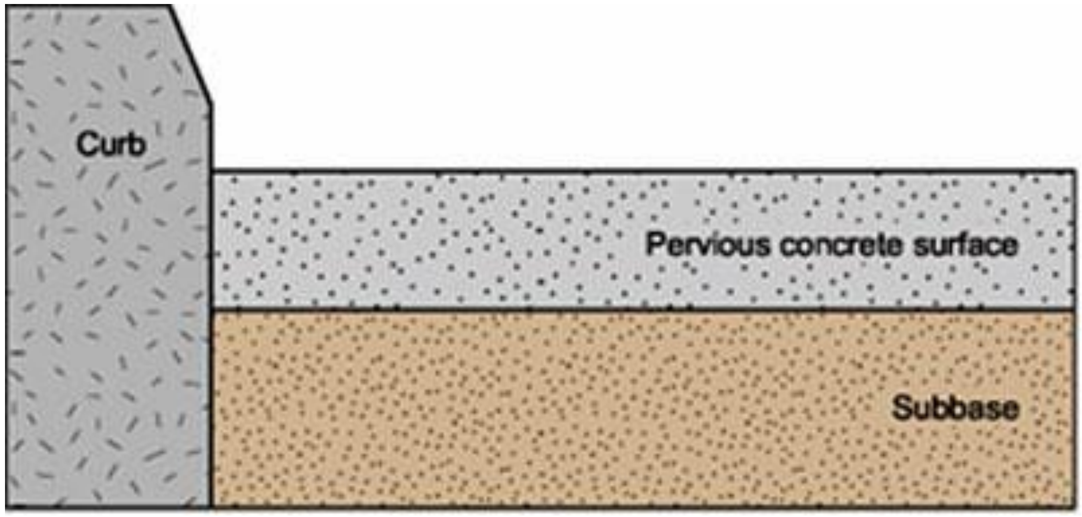


Figure 2. Cross section of typical pervious concrete construction (Engineering Properties, 2011).

Requirements regarding design and construction of pervious concrete are provided in *ACI 522.1-13, Specification for Pervious Concrete Pavement* (American Concrete Institute, 2013). Limited guidance is provided regarding the final surface texture (Section 3.7), and no specifications are present for installation as pathways.

The infiltration rate of pervious concrete is tested via *ASTM C1701/C1701M* (American Society for Testing and Materials, (2013). The test involves the positioning of a 300 mm (12 in) infiltration ring on the pervious surface, sealing the bottom edge with plumber's putty, filling the cylinder to specified marks 10 and 15 mm (0.40 and 0.60 in) from the bottom edge, and recording the time required for the water to drain. While there is no performance standard regarding a required infiltration rate to be considered pervious, the expected range is 7.5-68 L/min per 929 cm_2 (2-18 gallons/min per 1 ft_2 area). An infiltration rate below this range is an indicator for maintenance. The most effective maintenance plan consists of pressure washing followed by power vacuuming (Obla, 2007).

Performance in geographic areas with freeze-thaw cycles can be enhanced through the following strategies (Obla, 2007):

- Use of some fine aggregate to bring void content to 20%.
- Air entrainment of the cement paste.
- Use of 6-18 in aggregate base.
- Installation of perforated PVC in aggregate base.

However, with the connected void structure, the time spent in a saturated condition and at risk for damage via freeze-thaw, is greatly reduced.

1.3 Significance

There are over 2.7 million individuals in the United States who use a manual or powered wheelchair for mobility (Koontz et al, 2015). While the designs of those manual wheelchairs vary greatly, the surfaces that individuals travel across affect their health and well-being, both from the standpoint of mobility promoting improved health, and negative impacts on health from any risk factors associated with manual wheelchair use.

2. RELATED LITERATURE

2.1 Accessibility

The Americans with Disabilities Act (ADA, Public Law 101-336), while promoting access, is a piece of civil rights legislation, and is enforced by the U.S. Department of Justice (DOJ), designed to promote equal opportunity to employment, goods, and services. There are several aspects of the built environment, however, which involve the application of engineering expertise to document this access. The acceptability of pathways which comprise accessible routes is one example.

The Americans with Disabilities Act Accessibility Guidelines (ADAAG) were put in place following the signing of the ADA in 1990. The ADAAG were based on the Uniform Federal Accessibility Standards (UFAS), which since the 1970s have provided accessibility requirements for federal facilities, and entities which receive federal funding. The UFAS still exist, and are used in special circumstances, such as by the U.S. Department of Housing and Urban Development when determining the accessibility of public housing units.

The ADAAG are maintained by the U.S. Access Board, an independent federal agency which promotes accessible design. The Access Board is comprised of members from federal agencies and the public, including individuals with disabilities.

The current version of ADAAG used by the DOJ is termed the 2010 ADA Standards, and stipulates the following regarding pathway surfaces:

“302 – Floor or Ground Surfaces

302.1 – General. Floor and ground surfaces shall be stable, firm, and slip-resistant.”

And provides further information:

“Advisory 302.1 – General. A stable surface is one that remains unchanged by contaminants or applied force, so that when the contaminant or force is removed, the surface returns to its original condition. A firm surface resists deformation by either indentations or particles moving on its surface. A slip-resistant surface provides sufficient frictional counterforce to the force exerted in walking to permit safe ambulation.”

In its Guide to the ADA Standards (2010), the Access Board provides additional information specifically on the issue of surface smoothness:

“Regarding Section 302.1

The standards limit changes in level and openings in floor and ground surfaces, but they do not further address overall surface smoothness. Rough surfaces composed of cobblestones, Belgian blocks, and similar materials can be difficult and sometimes painful to negotiate with wheeled mobility aids due to the vibrations they cause.

Recommendation: Avoid materials or construction methods that create bumpy and uneven surfaces in areas and along routes required to be accessible.”

Ground surfaces of accessible paths within the built environment have been studied with respect to several of the abovementioned parameters.

2.2 Surface Stability

Stable surfaces are considered resistant to *movement* when forces are applied, such as individuals travelling across them. A rug which moves along a wood floor beneath it would not be considered stable. Common materials used for accessible pathways, such as concrete, asphalt, tile, and wood decking are considered to have sufficient stability to provide compliance regarding this aspect.

2.3 Surface Firmness

Firm surfaces are those that resist deformation when forces are applied. Again, common materials for accessible pathways are accepted as having sufficient firmness to provide compliance.

One device has been developed to measure surface firmness, the rotational penetrometer. Used on organic surfaces such as hiking trails, the device is used to measure the vertical travel by a common wheelchair caster as the axis is rotated back-and-forth. A compression spring provides a downward force on the caster as this rotation takes place.

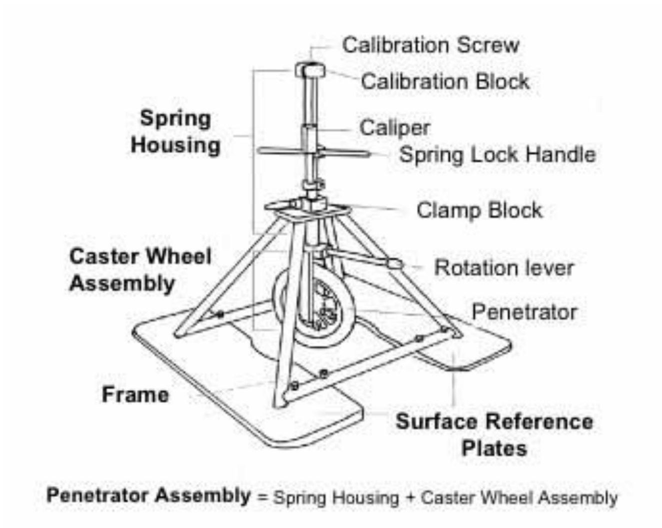


Figure 3. Rotating Penetrator used to gauge surface firmness (Beneficial Designs, Minden, NV).

2.4 Surface Slip-Resistance

Friction is needed as individuals travel along surfaces – individuals without disabilities, those that ambulate with mobility aids such as canes and walkers, and wheelchair or scooter users. The ADAAG does not stipulate a static coefficient of friction to indicate compliance regarding slip-resistance, the coefficient of friction being calculated as the ratio of frictional force required to move an object along a surface to the normal force of the mass on the surface (Figure 4):

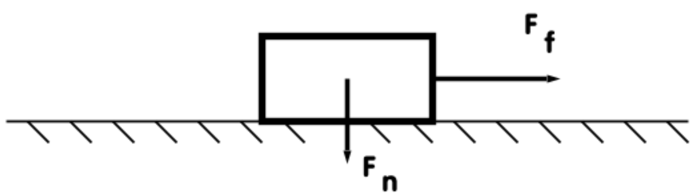
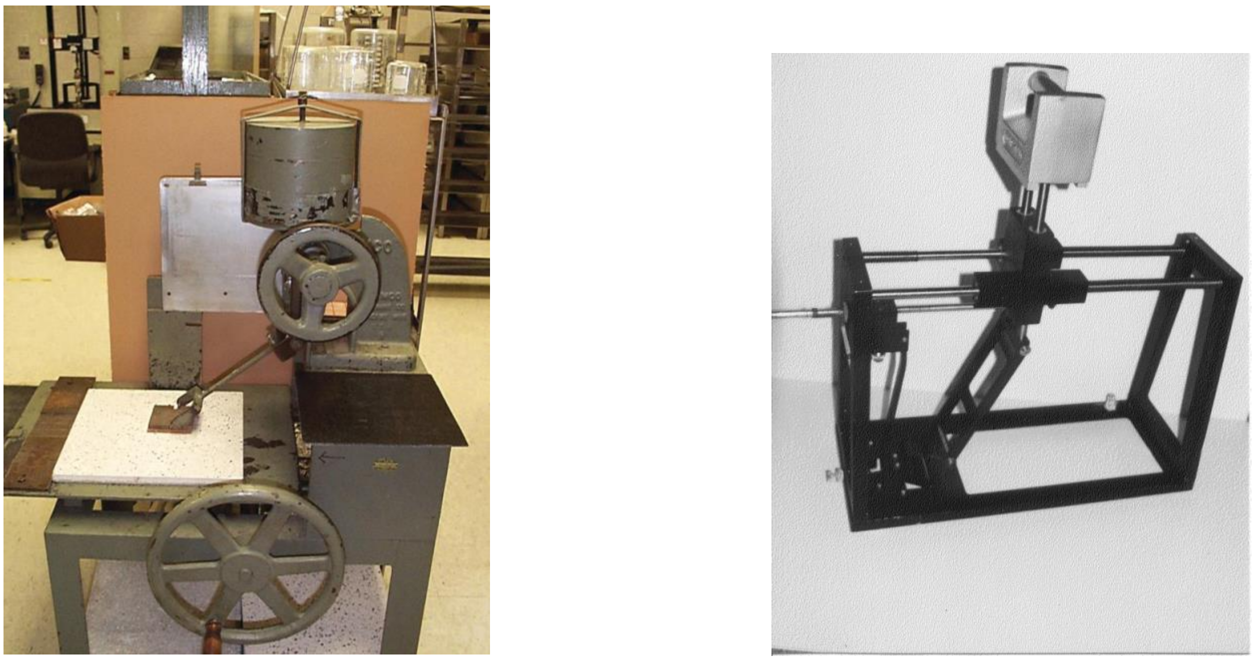


Figure 4. Force required to move a stationary object (frictional force) and the normal force of the object on a horizontal surface.

Coefficient of friction = Frictional force (F_f) / Normal force (F_n)

The Access Board provides background on the issue through Bulletin #4: Ground and Floor Surfaces (2004). The omission of a specified coefficient of friction to indicate compliance is due to the lack of an accepted measurement method which can be used in both laboratory and field locations, and the lack of correlation between the lab-based and field-based devices.

The James Machine, developed in the 1940s, is a device whose use is accepted in laboratory settings. The Brungraber series of slip-test devices has been used in field settings, and similar to the James Machine provides a coefficient of friction when the device's 7.6cm x 7.6cm (3in x 3in) leather pad is applied to a surface. A version of each is shown in Figure 5. The Access Board recommends that if the coefficient of friction of a surface is recorded, the instrument used for the measurement must be reported.



(a) (b)

Figure 5. Devices to measure the coefficient of friction, (a) James Machine; (b) Brungraber Mark I.

Although the ADAAG does not specify a *required* minimum value of the static coefficient of friction, a minimum value of 0.6 is *recommended* for level surfaces, and 0.8 for ramp surfaces.

The ADAAG is silent on surface smoothness, acknowledging that research is needed before even the establishment of non-mandatory recommendations can be considered.

2.5 Pathways

Methods to evaluate sidewalk pathways have been proposed. Axelson (1999) proposed an assessment process to determine the accessibility of sidewalks, but it focused on parameters such as grade, cross-slope, and ramping at intersections. Sidewalk roughness was not addressed.

Ishida et al (2006) studied the effect of uneven sidewalk surfaces on the rear wheel torque required for propulsion of a manual wheelchair, and wheelchair user ratings of discomfort. The researchers found that increased unevenness resulted in increased torque requirements, and increased wheelchair user ratings of discomfort. The study analyzed the pathway surfaces from the perspectives of slope and changes in level, rather than surface roughness. Slope was allowed to vary between 0 and 10%. Changes in level were present, as data was collected on pathways which had boundaries between the pathway surface and driveways. No limit or range of the changes in level was provided.

Pearlman et al (2013) provided a survey of road roughness measurement procedures, and discussed the merits of each in relation to the measurement of sidewalk roughness. The IRI, Power Spectral Density (PSD), Wavelet Theory (WT) methods were cited as viable to consider for the analysis of wheelchair user travel. All three approaches would be performed using profile data collected via profilometer – a device which takes the longitudinal profile of a wheelpath as it travels along the surface. Use of the IRI, Pearlman indicated, would benefit from existing extensive use by state and municipal departments of transportation, as they measure road serviceability.

Pearlman also summarized a study performed by Yamanaka and Namerikawa (2006), where researchers used the IRI method to analyze data as 10 subjects propelled manual wheelchairs over 19 different surfaces. Vertical profile data was collected at 10 mm intervals, and vibration data was taken at one of the front caster wheels. Results indicated a strong relationship between user road ratings and vibration, but not between the IRI and user road ratings. The researchers stated that the 10 mm interval used was likely not frequent enough to detect small imperfections in the pathway.

Pearlman noted that the PSD method may be useful since it provides measures of frequencies and amplitudes. This would permit the description of roughness based on profile variance as a function of wavelength. He notes that the IRI and PSD need a relatively long sample size, however. For this reason, he notes that profile data analyzed using WT may have value, as it would take a signal and break it down based on frequency components. He also cited the work of Loizos and Plati (2008a, b), which found that irregularities can be categorized by wavelengths, with top layer irregularities having shorter wavelengths (less than 3 m (19.84 ft)). That research team also proposed another method of pavement roughness measurement, the Vehicle Response Index (VRI), but its use as an alternative to the IRI and PSD was considered appropriate for data collection at passenger vehicle speeds (e.g., 60 km/hr (37.3 miles/hr)) – not achievable for the vast majority of accessible pathways.

In general, Pearlman made three recommendations regarding pathway roughness measurement: (1) Profiles need to be collected with an accuracy level relevant for wheelchair users, on the order of mm.; (2) Subjective comfort ratings need to be collected from wheelchair users.; (3) WBV measurements should be collected as the wheelchair user is travelling across the pathways.

Pearlman's work has formed the basis for a new ASTM Standard, "ASTM E3028-16, Standard Practice for Computing Wheelchair Pathway Roughness Index as Related to Comfort, Passability, and Whole-Body Vibrations from Longitudinal Profile Measurements" (American Society for Testing and Materials, 2016). The standard provides a suggested method for providing an estimate of pathway roughness for pedestrian surfaces, and provides a sample program for the computation of a Wheelchair Pathway Roughness Index (WPRI) using longitudinal profile measurements.

2.6 Wheelchair Use and Whole-Body Vibration

Dupuis (1986) compared vibration exposure (kind, intensity, duration) to the engineering concept of stress, and the body's reaction to vibration (biodynamic, psychological, physiological, damage) as the corresponding strain produced. Further, he suggests specific vibration characteristics and effects:

"Characteristics	amplitudes, frequencies, shocks, directions
Contributing factors	body posture, seat belts, active and passive support
Acute effects	subjective discomfort, pain perception, biomechanical reactions, physiological reactions, decrease in performance
Chronic effects	injury to health"

Users of both manual and powered wheelchairs experience whole-body vibration (WBV) during the course of travel. WBV is defined by Mansfield (2005) as vibration that "affects the whole of the person, that is, affecting every part of the body, noting that it is "usually transmitted through the seat surface, backrest, and through the floor," WBV puts the wheelchair user at risk for the development of secondary conditions, such as fatigue, back pain, and neck pain.

Hansson et al (1991) studied the effect of whole-body vibration on erector spinae (lumbar area) muscle activity, as six seated subjects supported a weight in front of their chest. The researchers found that the introduction of whole-body vibration caused the muscle fatigue to occur quicker, and to a greater extent, as compared to when there was no vibration present.

Boninger (2003) surveyed 68 wheelchair users, and found that 60.3% reported upper back / neck pain during the previous month, with 55.9% reporting pain during the previous 24 hours. Of those that reported pain, 60% had visited their doctor regarding the issue, and 40% reported a limitation in activity due to the pain.

In a review of studies on low back pain of seated individuals and whole-body vibration, Pope et al (1999) noted that resonance of the back is 4-5 Hz, and resulting vibration increases produce increased muscle activity, muscle fatigue, disc pressure, and decreased spinal height. Suggested practices to reduce risk include vibration dampening, improved ergonomic design, reduction in exposure, and reduction in lifting requirements.

Garcia-Mendez et al (2013) studied the travel of 37 wheelchair users over a 2 week period, and learned that all were exposed to WBV levels that ISO 2631 classifies as within or above a health caution zone. The measurement location was beneath the seat cushion, and participants used their own seat cushions. This result is of concern, especially since some of the participants utilized wheelchairs with suspension systems designed to dampen vibration transmitted to the user.

Van Sickle et al (2001) studied the accelerations present for 16 wheelchair users, as they traversed a simulated road course (SRC), followed by data collection during regular travel over a minimum duration of 4 hours. During the lab-based SRC travel, data was collected via accelerometers on the wheelchair frame and on a bite plate held by the user. The SRC contained a 5 cm drop, rumble strips, sine wave sections, detectable warning strips (i.e., detectable warning strips found at intersections), carpet, and a simulated door threshold. Study results indicated that acceleration levels were present during travel on the SRC at both the wheelchair frame and bite plate that would likely produce fatigue-decreased performance, according to ISO 2631. The author noted that a standardized seat cushion could not be used, as the wheelchair user's cushion was required to ensure that no negative effects such as pressure sores or abrasion from participation would be encountered.

DiGiovine et al (2003) analyzed the performance of different seat cushion and backrest supports when 32 wheelchair users travelled across the simulated surfaces established by the Van Sickle study. Four types of seat cushions were used (contoured foam, air bladder with foam base, viscoelastic material with foam base, and air-filled), and four types of backrest support (nylon upholstery, nylon upholstery plus supplemental foam, foam with rigid base and rigid attachment hardware, and a foam / air bladder / rigid base / Velcro attachment straps). Acceleration data was collected at two locations, via an accelerometer on a bite bar and an accelerometer positioned on an aluminum seat pan, positioned beneath the seat cushion. The latter accelerometer was positioned midway between the ischial tuberocities. While the results did not show a clear difference in the effectiveness of each seat or backrest in reducing vibration, it did show that vibrations may be amplified as they travel from the seat area to the head. Reasons proposed for the amplification included the seating system, voluntary movement of the individual during propulsion, physical properties of the individual, and ability / inability of the individual's muscles to dampen the vibrations.

Additional analysis of sidewalks was performed by Cooper et al (2004), where wheelchair travel across one poured concrete sidewalk (as a control) and 5 different types of concrete / brick pavers and installation patterns was studied. Ten individuals without disabilities participated in the study, using powered and manual wheelchairs. Regarding peak vibrations experienced by the manual wheelchair users, values were lower than those for the control surface except for one concrete paver design with an 8 mm chamfer. Other chamfers were smaller, at 0, 2, or 4 mm. The authors note that limitations of the study included the positioning of the seat accelerometer between the seat pan and the bottom of the seat cushion (since a plate present at the seat cushion – wheelchair user interface would put the user at risk for injury) and the use of instrumented handrims to measure the work required for propulsion (heavier than standard handrims). Also noted was the need for more research, to possibly use a standardized wheelchair and seat cushion, and to test surfaces in the field, long after installation to learn the effects of weathering on the surface and resulting vibrations produced. The study was repeated by Wolf et al (2005), and the results were verified.

Additionally, the authors of the follow-up study noted that paver patterns with edges at 45-degrees to the path of travel resulted in higher WBV, as compared to a 90-degree orientation.

Duvall et al (2013) studied the use of nine indoor wood pathways simulating different roughnesses, and of a mix of six outdoor pathway surfaces of different materials. In a similar attempt at using the IRI system, roughness was measured using an instrumented powered wheelchair base, travelling longitudinally along 2 flat boards to the sides of the test surface. Measurement of vertical distances along the surface were taken via laser, at a sampling rate of 2000 Hz. Acceleration data was taken at the foot, seat, and backrest surfaces of consumers travelled along the surfaces while using their own wheelchairs. Additionally, survey data was taken regarding consumer ratings of acceptability of each surface.

Results from the Duvall study indicated that for roughness indexes 1.5 in/ft (12.5 cm/m) and greater, average RMS accelerations of 1.5 m/sec_2 were experienced, indicating that the participants were at risk. Consumer ratings of acceptability decreased with increasing surface roughness.

The authors acknowledged limitations of the study, including the sole use of wood for the indoor simulated surfaces and any visual bias of consumer ratings, given that the participants could see the surfaces on which they were travelling.

There is precedent regarding the use of the ANSI/RESNA WC-1 Mannequin for vibration data collection during simulated wheelchair use. Cooper et al (2003) used both the WC-1 Mannequin and the Hybrid III Test Mannequin (automotive crash test mannequin, First Technology Safety Systems, Plymouth, MI), measuring vibration at the footrest and seat support surface, as 6 different wheelchair models were positioned on the ANSI/RESNA Double Drum Test Machine. This test station positions both front casters on one drum, and rear wheels on another drum, each having a transverse metal strip to simulate a small obstacle on the pathway. The wheelchair models represented mobility bases which were of fixed frame design, and those which had either rear suspension or shock-absorbing front casters.

Accelerometers collected data on a specially-designed metal plate affixed to the wheelchair footrest, and on a metal plate placed on the wheelchair seat. A layer of foam and the mannequin were positioned on top of the data collection plate.

Results indicated no significant difference between the vibration recorded based on which mannequin was used. The authors indicate that the cost of the ANSI/RESNA WC-1 Mannequin is approximately 10% the cost of the Hybrid III, so continued use of the WC-1 Mannequin was considered justified. The study also found that the rear suspension systems were effective in reducing vibration at the seat, and shock-absorbing front casters were effective in reducing the vibration at the footrest. The use of shock-absorbing front casters had mixed results regarding reduction of vibration at the seat.

Limitations of the study included the location of the seat vibration accelerometer, noted above as not at the seat cushion – user interface, and that travel did not occur over real pathway surfaces. It should also be pointed out that third-party payer funding policies do not usually allow for the provision of the rear suspension and shock-absorbing front caster components for most wheelchair users.

2.7 Measurement of Whole-Body Vibration

"ISO 2631 – *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements"* establishes the experimental method for the measurement of whole-body vibration in a seated position. The development of ISO 2631 began in 1966, and the standard was first published in 1974. As noted by Griffin (1990), the standard was developed to provide "numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1-80 Hz."

3. OBJECTIVES

The study attempted to address the usability of pervious concrete for individuals with disabilities through the engineering, ergonomics, and disability perspectives. To achieve this, the following questions to investigate, specific aims, and hypotheses can be cited.

Question 1

Are standard concrete and pervious concrete pathway surfaces in the community compliant with ADAAG with respect to slip-resistance guidelines?

Specific Aim 1

To quantify the slip-resistance of standard concrete and pervious concrete pathway surfaces, to determine if the surfaces are in compliance with ADAAG recommendations.

Hypothesis 1.1

Both standard concrete and pervious concrete pathway surfaces are in compliance with the slip-resistance guideline in ADAAG.

Question 2

Can we use existing engineering tools to adequately describe standard concrete and pervious concrete surface pathway roughness?

Specific Aim 2

To quantify the surface roughness of standard concrete and pervious concrete pathways, to determine how they compare with each other, and other concrete surfaces in the community.

Hypothesis 2.1

There will be a range of roughness values associated with pervious concrete pathway surfaces, as quantified by the International Roughness Index.

Hypothesis 2.2

There will be a range of roughness values associated with pervious concrete pathway surfaces, as quantified by the Wheelchair Pathway Roughness Index.

Question 3

Given that excessive whole-body vibration has several potential negative health effects on seated individuals, including wheelchair users, can the risk be quantified?

Specific Aim 3

To quantify the whole-body vibration transmitted to a simulated wheelchair user travelling across standard concrete and pervious concrete surfaces in the community.

Hypothesis 3.1

A range of whole-body vibration levels exist, based on the type of pathway in the community (lowest for sidewalks, higher for parking lot pathways, highest for alley pathways).

Hypothesis 3.2

For travel across pervious concrete pathway surfaces, greater wheelchair velocities result in higher levels of whole-body vibration transmitted to the wheelchair user.

<u>Question 4:</u>

Do rougher pathways bring more risk to the wheelchair user?

<u>Specific Aim 4</u>

To determine the usefulness of existing road roughness measurement devices in indicating the whole-body vibration a wheelchair user is likely to experience when travelling across the surface in the community.

<u>Hypothesis 4.1</u>

Higher International Roughness Index ratings result in higher levels of whole-body vibration.

<u>Hypothesis 4.2</u>

Higher Wheelchair Pathway Roughness Index ratings result in higher levels of whole-body vibration.

<u>Question 5:</u>

What factors other than roughness affect the level of risk to wheelchair users when travelling in the community?

<u>Specific Aim 5</u>

To determine the health risk for wheelchair users travelling on pervious concrete pathway surfaces, based on study data and likely daily exposure.

<u>Hypothesis 5.1</u>

Travel across pervious concrete pathway surfaces for anticipated daily exposure levels is safe for wheelchair users.

4. METHODS

4.1 Approach

This effort attempts to address the usability of pervious pathway surfaces, through the study of two surface characteristics: slip-resistance and pathway roughness. The study employed the following:

- a combination of guidelines and accepted standards for slip-resistance, smoothness, and whole-body vibration.
- commercially-available measurement devices.
- a custom-designed data collection apparatus which simulated typical travel in a manual wheelchair.

The relationship of the different aspects of the study is shown in Figure 6.

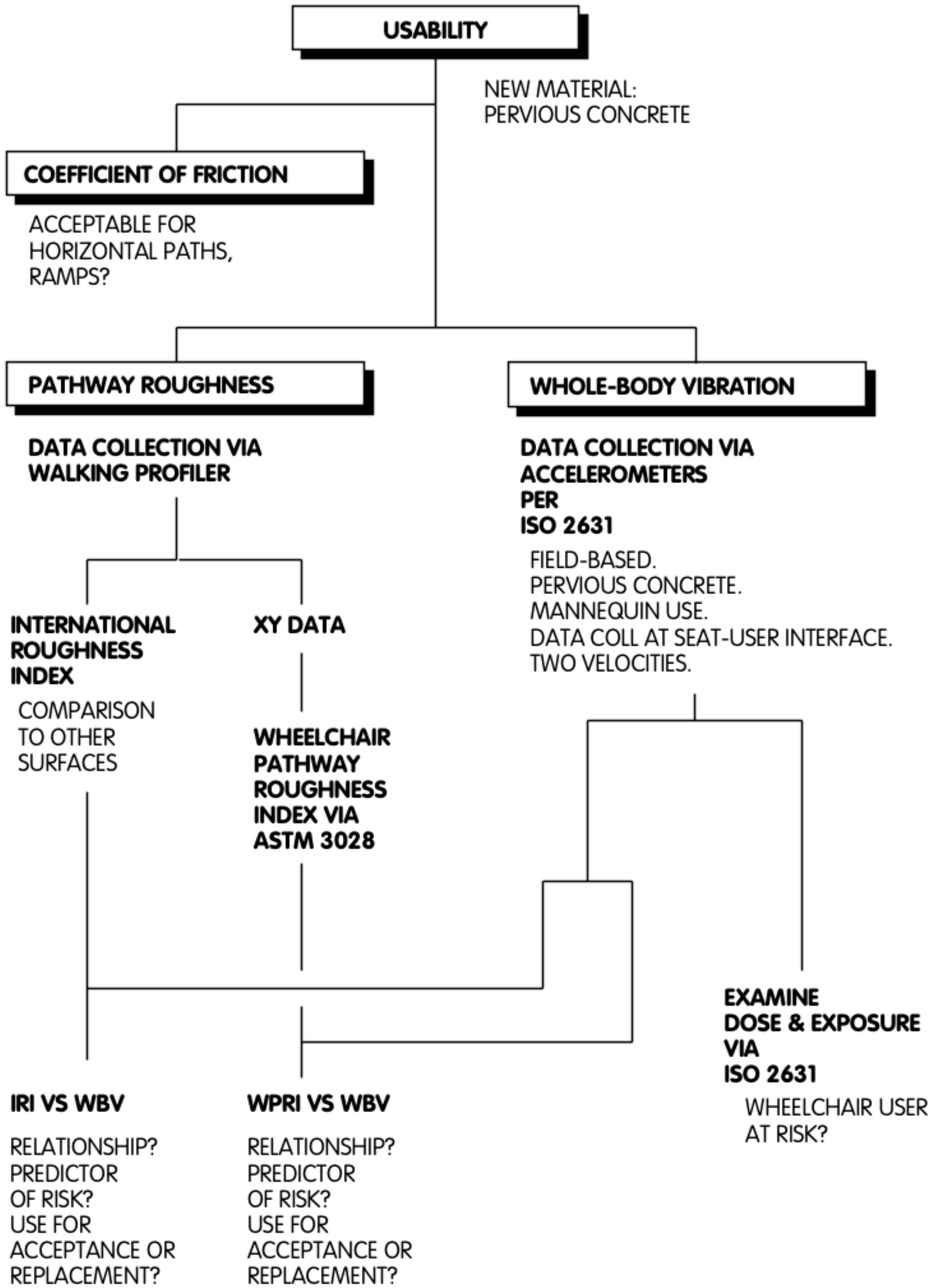


Figure 6. Overview of study approach.

Regarding slip-resistance, is it safe to assume that pervious concrete pathway surfaces are in compliance with the ADAAG guidelines? Although there is no single device or set of procedures recognized for use in the field, can we look at empirical data? We can use the Brungraber Mark IV, the current version of this device.

Regarding pathway roughness, what is the range for pervious concrete when the traditional IRI and recently-developed WPRI measurement systems are applied? We can use a device recognized by the roadway construction and inspection communities, the SurPRO 4000. If a relationship exists between the IRI and whole-body vibration, or between the WPRI and whole-body vibration, to indicate acceptance of a pathway surface for use by individuals with disabilities, or to indicate deterioration such that replacement is necessary, perhaps the construction and inspection communities can use an existing tool.

Regarding whole-body vibration, how does travel across pervious concrete pathways compare with travel across other surfaces which have been studied? At what risk is a manual wheelchair user regarding the vibration experienced, when it is paired with estimates on the duration of daily exposure that are in the literature.

As we examine whole-body vibration, we will examine how wheelchair velocity affects the user. Since there is disagreement on the typical wheelchair velocity by manual wheelchair users, we can examine how much of a difference the assumptions make.

The study also adds to the science by being the first to study pervious concrete, and the first to be 100% field-based. The experimental design and protocol may serve to investigate other combinations of the HAAT Model's Assistive Technology (wheelchair and wheelchair components) and Context components (different ground surfaces in the community).

4.2 Experimental Design

4.2.1 Slip-Resistance

As noted above, there is no agreed-upon device or method to measure the slip-resistance of a pathway surface in the community. The study, however, affords the opportunity to gather data on the coefficient of friction of each trial pathway. Results are reported with the caveat that the empirical data is offered without the benefit of an accepted standard or measurement device.

The device used to measure the coefficient of friction is the Brungraber Mark IV, shown in Figure 7, a more mobile version of the Mark I referred to earlier. The device allows a mass to be dropped in a controlled manner, producing contact between a 7.6 cm x 7.6 cm (3 in x 3 in) leather "shoe" and pathway surface. A graduated scale along the arc of angle of approach indicates the coefficient of friction of the surface, and is recorded at the first instance of the shoe slipping on the surface when contact is made.

Figure 7. Brungraber Mark IV device (Slip-Test, Inc., Spring Lake, NJ).

4.2.2 Surface Roughness

The roughness of the pathway was measured using a commercially-available roadway/flooring roughness measurement device, the SurPRO 4000 walking profiler (International Cybernetics, Largo, FL).

Use of the current SurPRO 4000 offered several advantages. The device is accepted by the concrete industry and inspection professionals for use on roadways (to measure road roughness for acceptance upon construction completion or the need for replacement when service life is at an end) and warehouse flooring. The device also allows variation in the sampling frequency (1, 5.08, or 10 mm), 1mm was used for the smoothness data collection. The device is also intended to be used by a worker walking along the roadway or floor at a velocity comparable with wheelchair travel, as opposed to devices used on moving data collection vehicles at much higher speeds.

Figure 8. SurPRO 4000 device in use (International Cybernetics, Largo, FL).

Figure 9. SurPRO 4000 in custom-fabricated cart, allowing transport to sites.

4.3 Whole-Body Vibration

4.3.1 Data Collection Manual Wheelchair

Since the whole-body vibration aspect of the study would examine from the dose of vibration and take into account the duration of exposure during a typical day, the wheelchair to be instrumented needed to be a relatively lightweight wheelchair which promotes activity in the community. It also needed to have positioning features a user in this category would likely have.

The wheelchair was selected in consultation with the UIC Assistive Technology Unit Seating and Wheeled Mobility Group Leader. The specific model, a Sunrise Medical Quickie GPV, weighs 11.2 kg (23.6 lbs), and is shown in Figure 10. It is comprised of a rigid frame, single footplate, sling seat with 5.08 cm (2 in) polyurethane seat cushion, and sling backrest. A tall backrest cane was retrofitted onto the wheelchair, to better support the torso of the ANSI/RESNA WC-1 mannequin. The wheelchair has 61.0 cm (24 in) pneumatic rear tires and 12.7 cm (5 in) diameter solid polyurethane front casters. No shock-absorbing front caster hardware was present.

(a) (b)

Figure 10. Sunrise Quickie GPV manual wheelchair used for whole-body vibration data collection: (a), standard configuration, (b), study configuration, with armrests removed and taller backrest.

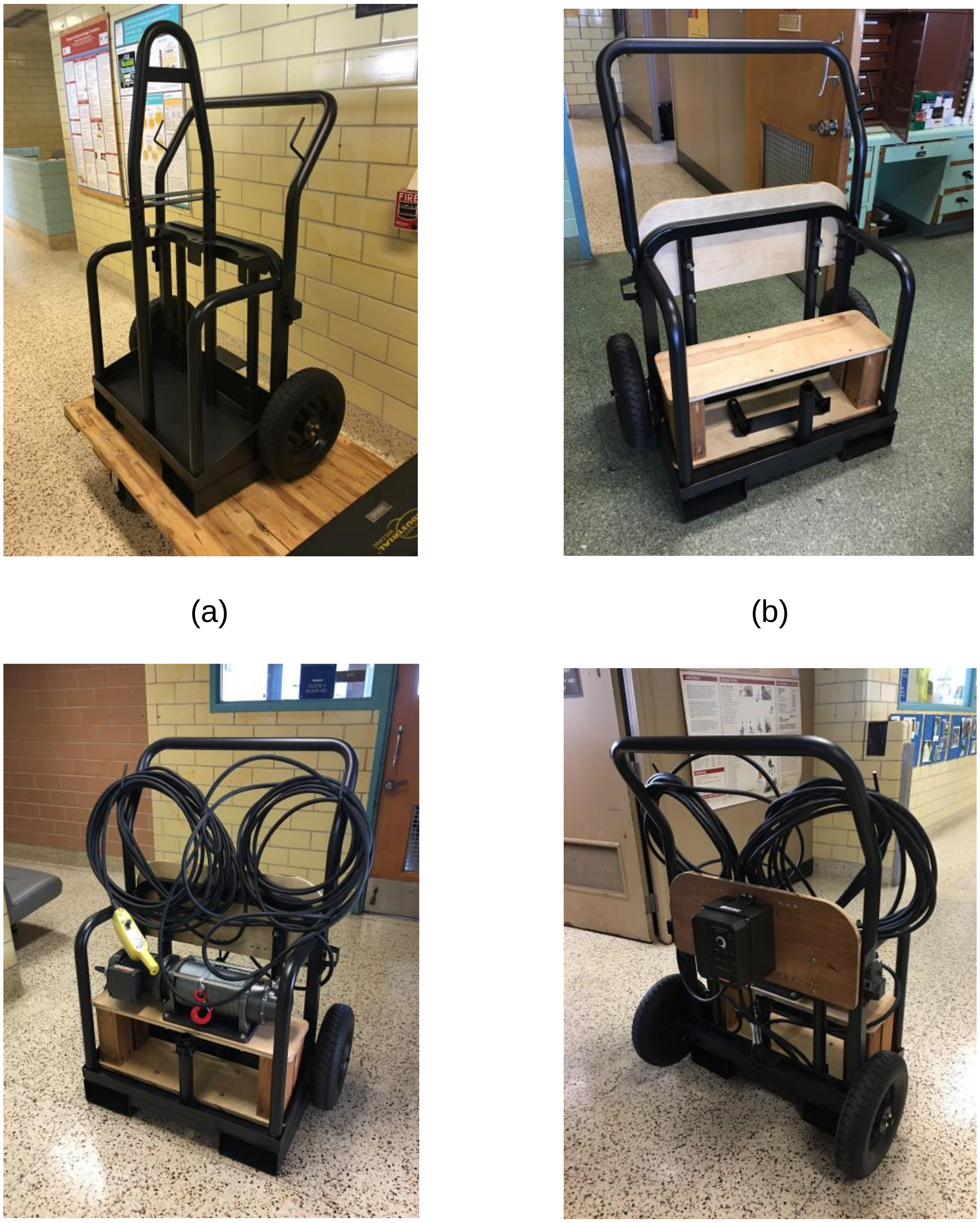
Key specifications of the wheelchair are provided in Table II.

Table II. Data collection manual wheelchair specifications.

Specification	Dimension
Frame width	45.7 cm (18 in)
Seat depth	40.6 cm (16 in)
Frame length	56.5 cm (22-1/4 in)
Frame height (front)	25.4 cm (10 in)
Frame height (rear)	22.9 cm (9 in)
Rear wheels	61.0 cm (24 in) pneumatic
Front casters	12.7 cm (5 in) solid polyurethane

4.3.2 Wheelchair Velocity

The initial experimental design included propulsion of the data collection manual wheelchair via the researcher pushing at a constant velocity. To increase the likelihood of a constant velocity which did not fluctuate with the investigator's gait, consideration was given to the use of a winch to pull the data collection manual wheelchair for the entire length of the trial path. An adapted welding tank cart and winch involved in the set up are shown in Figure 11.



(a) (b)

(c) (d)

Figure 11. Welding tank cart and winch assembly, from top left: (a) un-adapted welding tank cart, (b) adapted welding tank cart, (c) adapted welding tank cart and winch-front, (d) adapted welding tank cart and winch-rear.

Two issues emerged when this design concept was investigated. First, the trial path length, at 30 m, would result in the winch cable being prone to sagging under its own weight. Second, the relatively low force required to pull the data collection wheelchair, measured at approximately 44 N (10 lb) during simulated trial runs, was not constant. During trial runs, this produced periods of intermittent slack in the cable, and fluctuating velocity. An attempt was made to introduce an opposing force to ensure that the cable would remain taught via a following walker with spring connection (Figure 12), but this had limited effectiveness. As such, this method of propelling the data collection manual wheelchair was abandoned.

(a) (b)

Figure 12. (a) Adapted welding tank cart-winch assembly shown during trial data collection; (b) Assembly with walker providing following force. Note that method of providing force at rear of data collection manual wheelchair and the use of a portable generator had to be introduced.

To produce a constant velocity scenario, the concept of towing the data collection manual wheelchair with a powered wheelchair was investigated. Use of a powered wheelchair would have the advantage of being able to be used on any trial path where the data collection manual wheelchair was used, straight or slightly curved. Most importantly, by using a powered wheelchair with programmable circuitry, the required data collection manual wheelchair velocity could be achieved in the lab and merely verified in the field at each site. The powered wheelchair selected was an Invacare TDX SP model, with MK circuitry. Drive modes were set to match with the required data collection manual wheelchair run velocities, with the ability to fine-tune the velocity in the field if necessary. Figure 13 shows the wheelchair, programmer, and drive mode display.

(a)

(b)

(c)

(d)

Figure 13. Powered wheelchair used to tow the data collection manual wheelchair: (a) Invacare TDX-SP wheelchair, (b) programmer for MK circuitry, (c) drive mode for 0.75 m/s travel, (d) drive mode for 1.00 m/s travel).

For the connection between the powered wheelchair and the data collection manual wheelchair, a custom tow bar was constructed using tubing and fittings from a modular materials handling system manufacturer. With a vertical tube attached to the powered wheelchair, tube attached as the horizontal connection (free to rotate in the XY plane via slip-fit sleeve), and 3-D printed flexible link attachment point to the data collection manual wheelchair, towing could occur without introducing any restriction in movement of the data collection manual wheelchair. Figure 14 shows the arrangement of these components. Figure 15 shows the flexible link.

Figure 14. Custom tow bar between powered wheelchair and data collection manual wheelchair (Creform Material Handling Systems, Greer, SC).

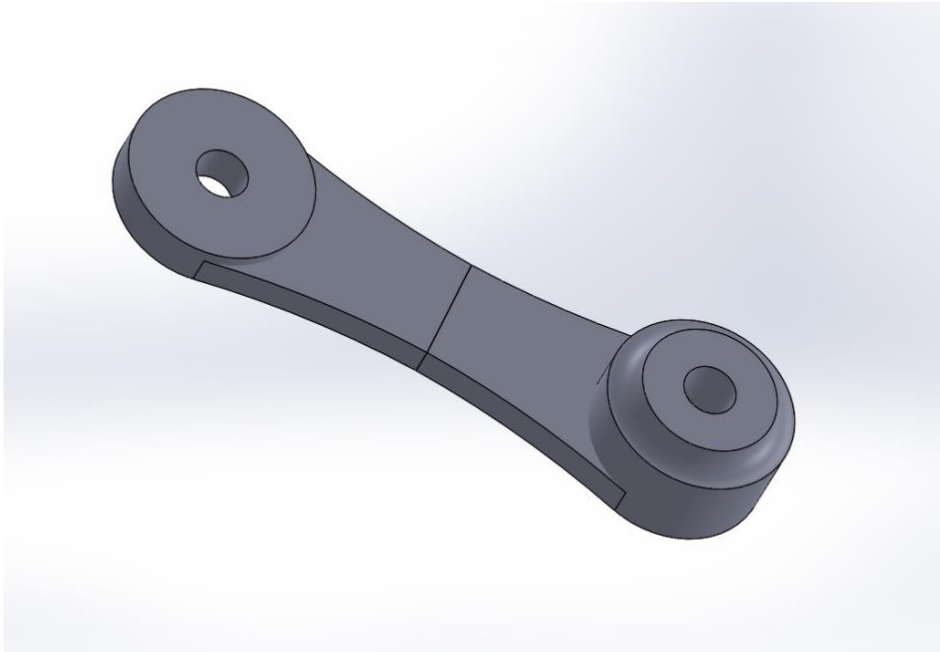


Figure 15. Flexible link, connecting horizontal tube to data collection manual wheelchair.

4.3.3 Accelerometers

Commercially-available accelerometers were used for data collection at points on the support surface-simulated user interface as stipulated by ISO 2631-1:1997 between the WC-1 Mannequin and the foot, seat, and backrest surfaces (Figure 16). Holders were fabricated for the seat and backrest accelerometers, adapted from specifications in ISO 10326-1:1992, *Mechanical vibration - Laboratory method for evaluating seat vibration – Part 1: Basic requirements* (International Organization for Standardization, 1992; Figure 17).

Dimensions in millimetres

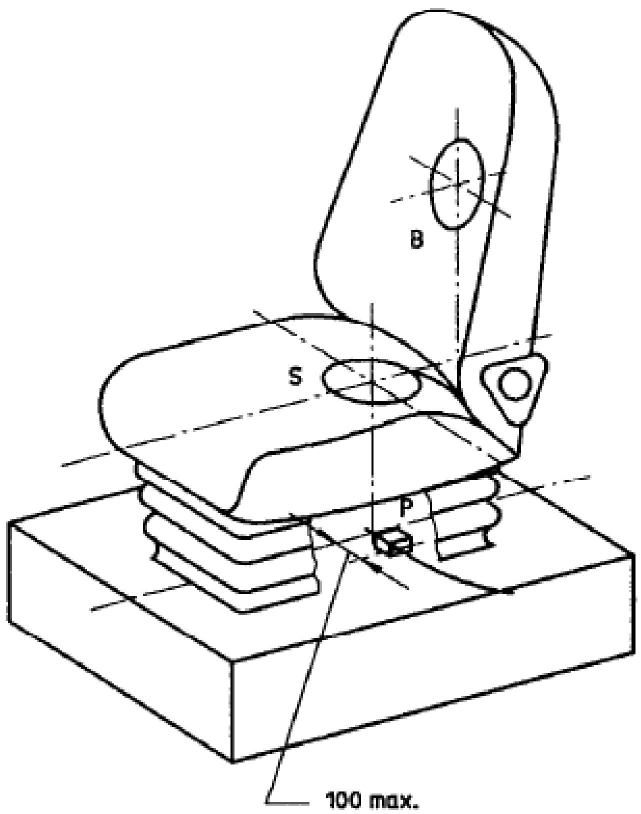


Figure 16. ISO 10326-1:1992 – specified data collection locations for seat and backrest.

Dimensions in millimetres

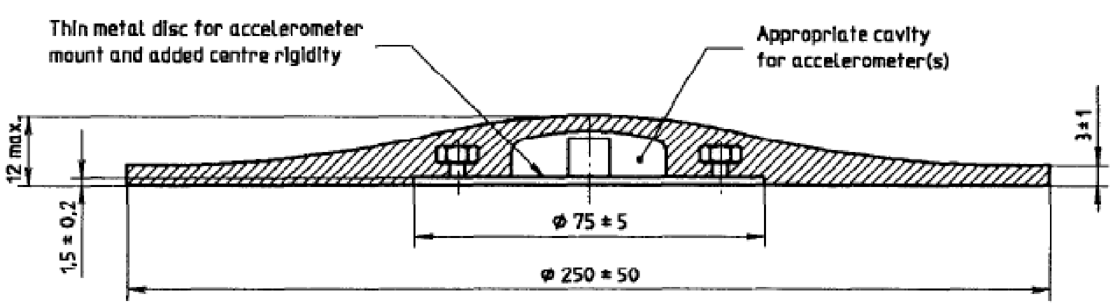
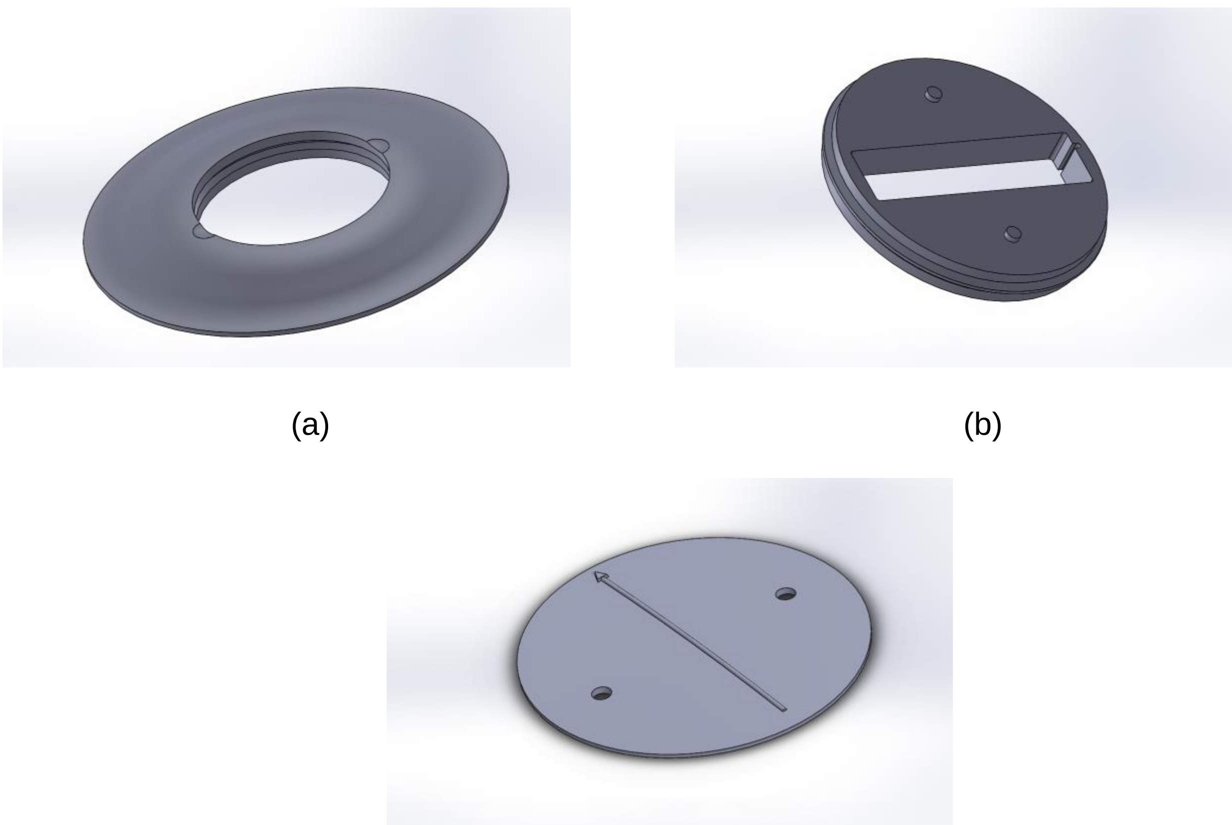


Figure 17. ISO 10326-1:1992 – specified accelerometer holder.

To achieve the specified size and shape of the accelerometer holders for the seat and backrest locations, the holder was broken out into 4 components: aluminum plate to affix the accelerometer, conical base, puck-shaped filler piece, and thin lid. Fabrication of the base, filler, and lid was achieved in the UIC Assistive Technology Unit shop using a Lulzbot Taz 6 3D printer (Loveland, CO). The polymer used resulted in the ISO 10326-1:1992 – specified 80 durometer hardness. Figure 18 shows the CAD drawings for these components.



(a) (b)

(c)

Figure 18. Pictorial images of 3D-printed accelerometer holder (a) base, (b) filler, and (c) lid.

The final assembly of the base, filler, lid, and accelerometer provided the specified overall size and shape of the holder, and protection of the accelerometer (Figure 19).

Figure 19. Accelerometer holder components, assembled.

Additionally, an accelerometer was mounted on the wheelchair frame itself, on a cross-member in line with the rear wheel axles, to determine the vibration coming into the main portion of the wheelchair.

Accelerometer designations and locations can be summarized as follows (Table III):

Table III. Accelerometer designations and locations.

Accelerometer	Location	Holder / Attachment
A1	Wheelchair footplate, between mannequin footplates	Accelerometer case / Snap-together fastener
A2	Seat cushion – Mannequin interface	3D-printed mounting disc assembly / Velcro
A3	Backrest – Spacer / Mannequin backrest	3D-printed mounting disc assembly / Velcro
A4	Wheelchair cross-member, at rear wheel axles	Steel plate & shaft collars / Snap-together fastener

Figure 20 shows the location of each accelerometer.

Figure 20. (a) A1 at footplate, (b) A2 at seat and A3 at backrest, (c) A4 at wheelchair frame cross member.

Turning on and off of the accelerometers at the beginning and end of the trial path proved to be challenging. While each accelerometer is equipped with a recessed push-on, push-off switch to being and end data collection, the position of each of the 4 accelerometers made them inaccessible. This was especially true for A2 and A3, which are covered by the mannequin. Also, data collection start and stop had to be synchronized across all 4 accelerometers.

A check with the accelerometer manufacturer indicated that no models were available which had remote access to begin or end data collection. Modification of the accelerometers was necessary, in the form of hard-wiring a lead and jack to the circuit board at the point of the on-off button contacts. This was achieved by the University of Illinois at Chicago Civil and Materials Engineering Electronics Shop. The manufacturer recommended a compatible on-off switch to use for this modification (E-Switch LPOA1ARL1 Series SPST Momentary Red LED Panel Mount Illuminated Pushbutton Switch, Minneapolis, MN). Figure 21 shows the modified A1 and A2 accelerometers.

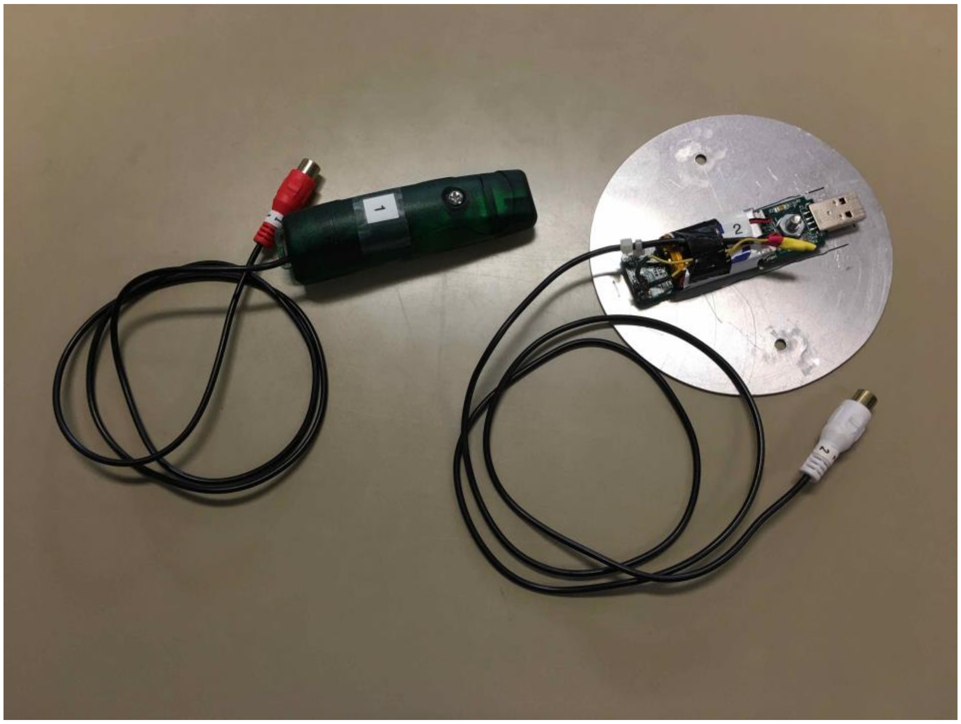


Figure 21. Modified accelerometers A1 and A2.

Custom wiring to the on/off switches proved challenging as well. The ideal configuration of a cable that would provide control of all 4 accelerometers via one switch was attempted, but due to high sensitivity of the accelerometers to slight changes in voltage, and durations of the switch closures, consistent simultaneous control of all 4 was not achieved. Instead, a custom 3D-printed holder and hinged lid was fabricated, to allow control of the 4 switches simultaneously (Figure 22).

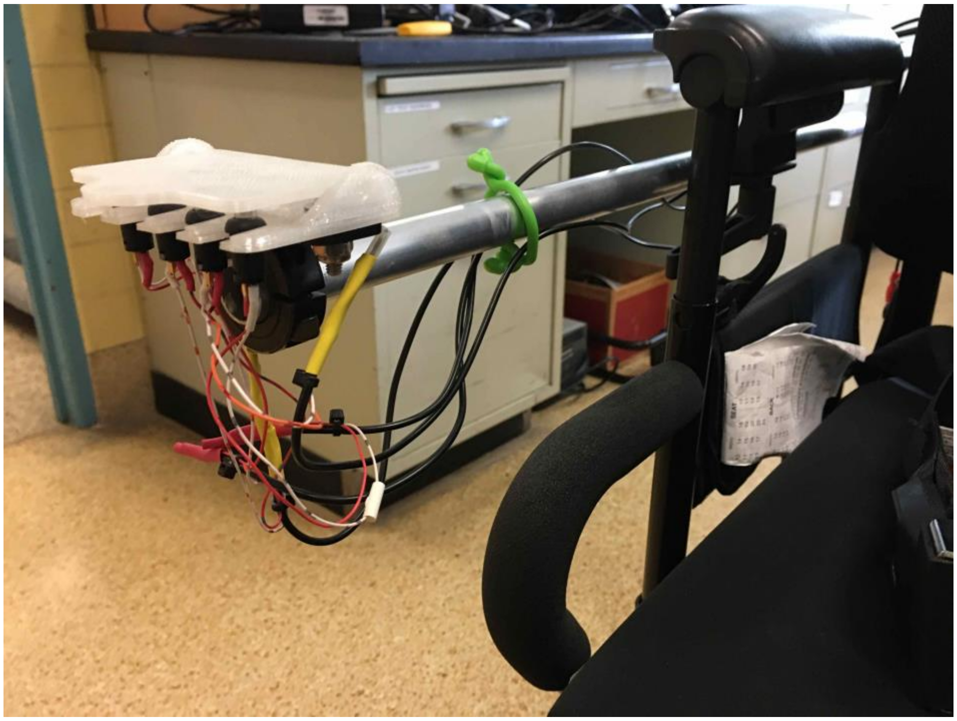


Figure 22. 3D-printed switch holder and activation lid.

4.4 Fabrication Capability

Assembly or modification of commercially-available equipment, or custom-design and fabrication of components was achieved at the UIC Assistive Technology Unit Fabrication Shop, within the Disability, Health, and Social Policy Building (Figure 23). The shop has general stations for assembly / fabrication, and stations equipped with equipment including a band saw, belt sander, disc sander, welding station, milling machine, machine lathe, electronics bench, and 3D printing station.

Figure 23. UIC Disability, Health, and Social Policy Building (location of UIC Assistive Technology Unit Fabrication Shop).

4.5 Mobile Capability

Field-based data collection was made possible through the allocation of one Mobile Unit operated by the UIC Assistive Technology Unit. The vehicle used was a Dodge Promaster 3500, single rear wheel (SRW), cargo van. The van was adapted with a fold-out, 2-section aluminum ramp with hydraulic assist, and wheelchair tie-downs to enable 2 wheelchairs to be safely transported. The vehicle enabled all experimental equipment to be transported to a data collection sites, and unloaded / loaded by one individual. The vehicle used is shown in Figure 24.

(a)

(b)

Figure 24. (a) UIC Assistive Technology Unit vehicle used in the study (Dodge Promaster 3500, single rear wheel, Auburn Hills, MI), (b) study-related equipment loaded.

4.6 Site Inclusion Criteria

To be considered for inclusion in the study, a concrete accessible path had to meet the following criteria:

- Large enough to permit data collection over a straight-line path of 30 m (98 ft 5 in), with additional approach and departure space.
- Level surface with respect to running slope and side slope.
- No changes in level greater than 6 mm (0.25 in)
- Part of a path that could be taken by an individual with a disability using a wheelchair. This could be in the form of a recognized path of travel, or required path (e.g., from an accessible parking space through the parking lot to the front door of a place of business). Residential streets constructed of pervious concrete would not qualify.

Potential site locations were gathered via communication with a senior official of the major concrete contractor in the Chicago area and trade publications which highlighted pervious concrete projects. Table IV lists the 9 pervious concrete and 3 standard concrete locations which were included in the study.

Table IV. Study Locations

Address	City	State	ZIP	Designation	Function
Concrete-Standard					
1101 W Harrison	Chicago	IL	60607	CS1	Parking lot path
1640 W Roosevelt	Chicago	IL	60608	CS2	Sidewalk
1200 Sibley Blvd	Calumet City	IL	60409	CS3	Sidewalk
Concrete-Pervious					
1101 W Harrison	Chicago	IL	60607	CP1	Parking lot path
2535 S King Dr	Chicago	IL	60616	CP2	Sidewalk
2100 Ridge	Evanston	IL	60201	CP3	Parking lot path
1200 Sibley Blvd	Calumet City	IL	60409	CP4	Parking lot path
484 Lee St	Des Plaines	IL	60016	CP5	Alley
721 E 112th St	Chicago	IL	60628	CP6	Parking lot path
862 E Algonquin Rd	Des Plaines	IL	60016	CP7	Alley
1631 Sheridan Road	Evanston	IL	60201	CP8	Sidewalk
2754 S Eleanor	Chicago	IL	60608	CP9	Sidewalk

Figures 25 shows mapped study locations.

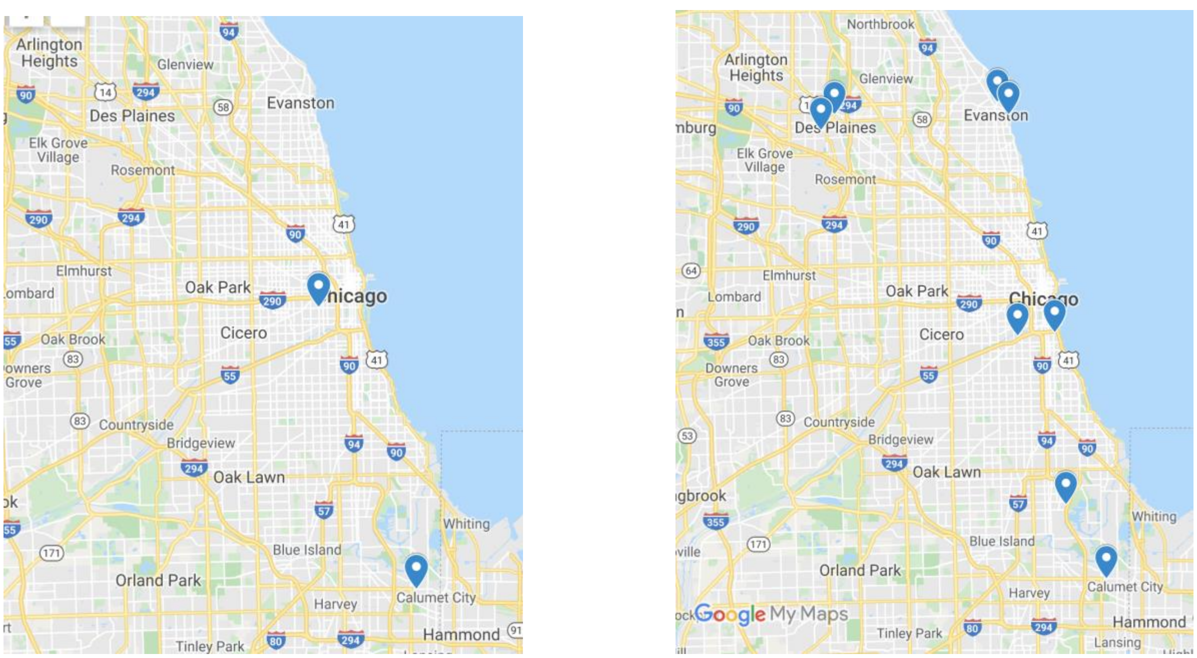


Figure 52. Mapped study locations for (a) Concrete-Standard and (b) Concrete-Pervious.

Most data collection occurred from September 2018 through January 2019, with site CP9 data collection occurring in September 2019. Ambient temperature was required to be at least 4.4 degrees Celsius (40 degrees Fahrenheit), dry surface with no precipitation during the previous 24 hours.

4.7 Experimental Procedures

Step 1

The approximate position of the trial path is identified, and inspected for gaps and changes in level.

Step 2

Orange safety cones are placed along the trial path and required approach and departure spaces.

Step 3

The trial path is swept with a manual sweeper (Hoover Commercial SpinSweep 18-inch Pro Outdoor Sweeper) via overlapping straight runs.

Step 4

The running slope and side slope are checked for ADAAG compliance (1:20, 1:48, maximum, respectively).

Step 5

A chalk line is laid down to indicate the line of travel of the center of the data collection wheelchair. The trial path is 30 m (98 ft 5 in) in length, and the chalk line denotes approach and departure sections which are approximately 2 m (6 ft 6 in) in length each.

Step 6

The coefficient of friction measurement is taken at approximate 6 m (20 ft) intervals along the approximate wheelpath of the data collection manual wheelchair (Brungraber Mark IV, Philadelphia, PA).

Step 7

The walking profilometer is used to measure the IRI and take the profile of the wheelpath of the data collection manual wheelchair (SurPRO 4000, International Cybernetics, Largo, FL).

Step 8

Accelerometers are placed at 4 locations: footrest, in between the feet of the ANSI/RESNA EC-1 mannequin; on the seat cushion, in between the areas of the ischial tuberosities; on the backrest, in midline, at the highest point possible with the ISO 10326 holder still supported; on a plate on the frame of the data collection wheelchair, on a cross member near the line of the rear axles (Gulf Coast Data Concepts, Model X2-2, Waveland, MS). Each accelerometer is attached to the activation switches via patch cables.

Step 9

The ANSI/RESNA WC-1 mannequin is placed on the data collection manual wheelchair.

Step 10

The powered wheelchair and the data collection manual wheelchair are connected via the custom tow bar.

Step 11

The powered wheelchair is driven along the wheelpath of the data collection wheelchair to verify that the powered wheelchair settings produce a constant velocity of 0.75 m/s (2.5 ft/s) and 1.00 m/s (3.3 ft/s), (+/-10%).

Step 12

Vibration data is taken for 10 runs: 5 at 0.75 m/s, 5 at 1.00 m/s. Runs are straight line travel for 30 m (98 ft 5 in). Travel begins in the approach area, with the powered wheelchair achieving the constant velocity associated with that trial before the trial section. The start time of each run is recorded, to match with specific accelerometer data files later.

5. RESULTS

5.1 Slip-Resistance

The Brungraber Mark IV device was used to take 5 readings along the trial path and averaged, per manufacturer instructions, to determine a coefficient of friction for each trial path. Results are shown in Table V and Figure 26.

Table V. Coefficient of friction by location.

Location	COF
CS1	0.964
CS2	0.874
CS3	0.972
CP1	0.424
CP2	0.698
CP3	0.854
CP4	0.964
CP5	0.906
CP6	0.962
CP7	0.894
CP8	0.870
CP9	0.908

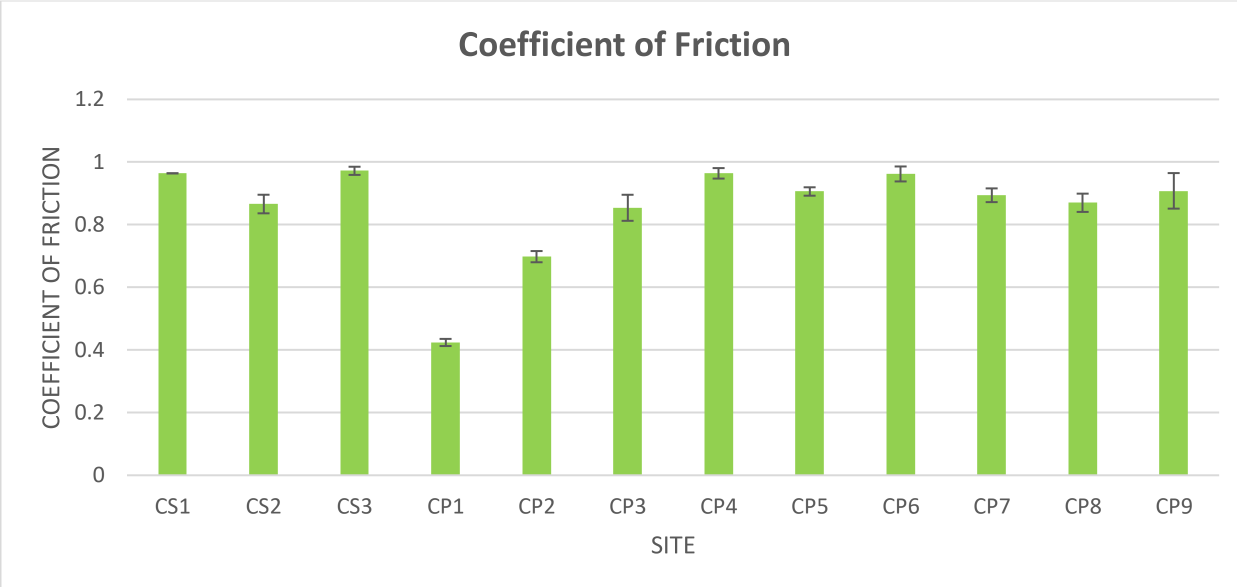


Figure 26. Graphical representation of coefficient of friction by location. The first three entries are for Concrete-Standard locations, the remainder are for Concrete-Pervious locations. CP1 has a coefficient of friction which is below the ADAAG guideline for horizontal surfaces (0.60).

The results indicate expected high coefficients of friction for both concrete-standard and concrete-pervious locations, except for location CP1. Upon completion of all data collection for the study, a return visit was made to location CP1 to double-check measurements. More typical measurements were found to exist at that return visit. Since CP1 and CS1 measurements were taken on the same day, yielding significantly different results, possible reasons for the low CP1 coefficient of friction readings were considered.

After discussion with a local concrete company official, it was determined that a contractor may have sprayed a microbial solution on the surface to break down oil and grease (Lutey, 2019). The CP1 results indicate that attention should be given to the cleaning and sealant schedule at a given location, as a recent application of sealant or microbial solution may produce a surface coefficient of friction, for a period of time, which brings the pathway out of compliance regarding slip-resistance. Figure 27 shows a contractor applying sealant at the CP1 site.

Figure 27. Sealcoating crew at location CP1.

5.2 Surface Roughness

5.2.1 International Roughness Index

Per standard practice in road roughness measurement, six IRI measurements were taken along the data collection manual wheelchair assumed wheelpath. Results of the average IRI values for the Concrete-Standard and Concrete-Pervious trials are summarized in Table VI.

Table VI. Average IRI values by Site.

SITE	**IRI**
	(mm/km)
CS1	3.26
CS2	5.07
CS3	5.94
CP1	3.57
CP2	5.15
CP3	5.07
CP4	6.82
CP5	2.66
CP6	5.54
CP7	2.10
CP8	4.05
CP9	5.01

Note that CS1 was a parking lot path with control joints at approximate 4.9 m intervals, whereas CS2 and CS3 were sidewalks with control joints at approximate 1.5 m intervals. Average IRI for Concrete-Standard was 4.76 m/km. Average IRI for Concrete-Pervious was 4.44 m/km. Plots of the IRI values by site are shown in Figures 28 and 29.

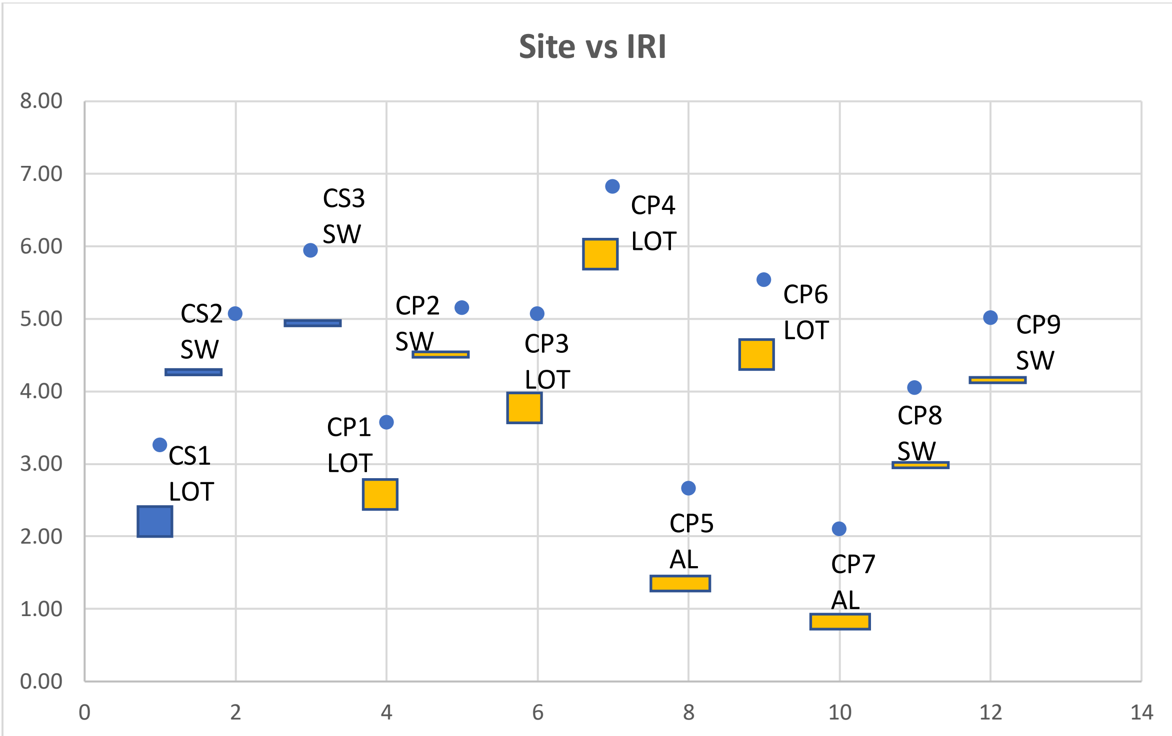


Figure 28. Graphical representation of IRI by Site (data points).

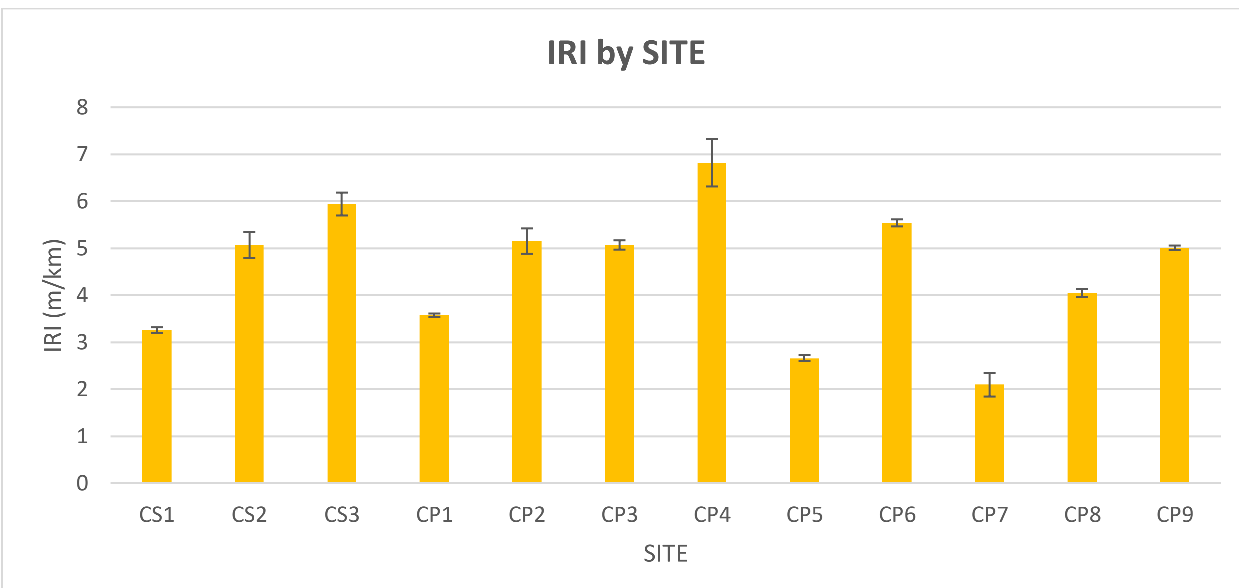


Figure 29. Graphical representation of IRI by Site (average values and standard deviations).

Items of note regarding the IRI results include the fact that the 2 smoothest pervious concrete surfaces were present in alley settings, and that sidewalks were positioned in the middle of the range.

IRI values are used by road roughness professionals to gauge the condition of new and existing road surfaces (Sayers and Karamihas, 1998). Approximate road conditions associated with IRI values are shown in Figure 30.

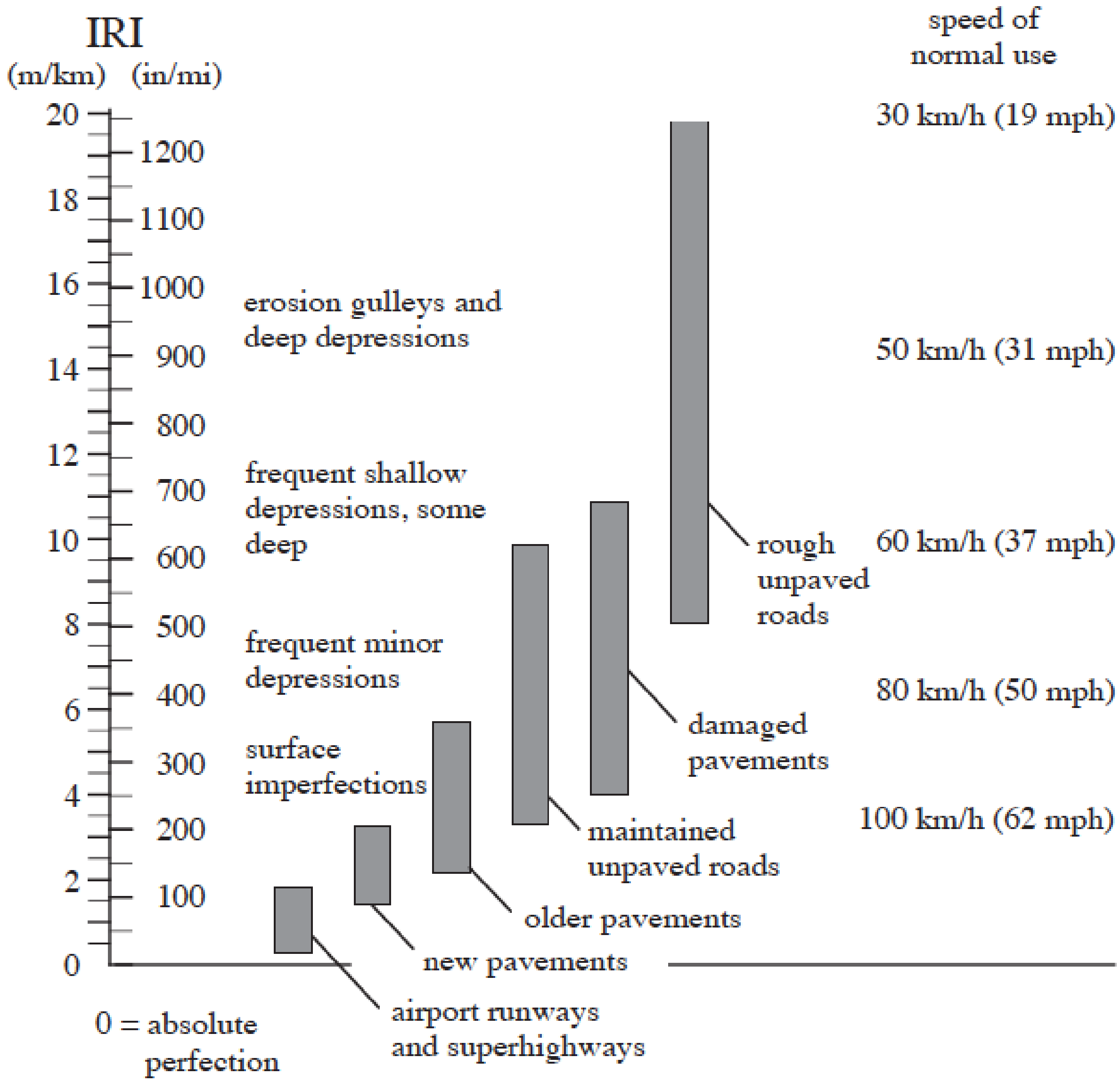


Figure 30. Road surface conditions associated with IRI values (Sayers and Karamihas, 1998).

Comparing the study's IRI values to the IRI range for roadways, we can see that the roughness compares favorably with roadways considered in good condition (Figure 31).

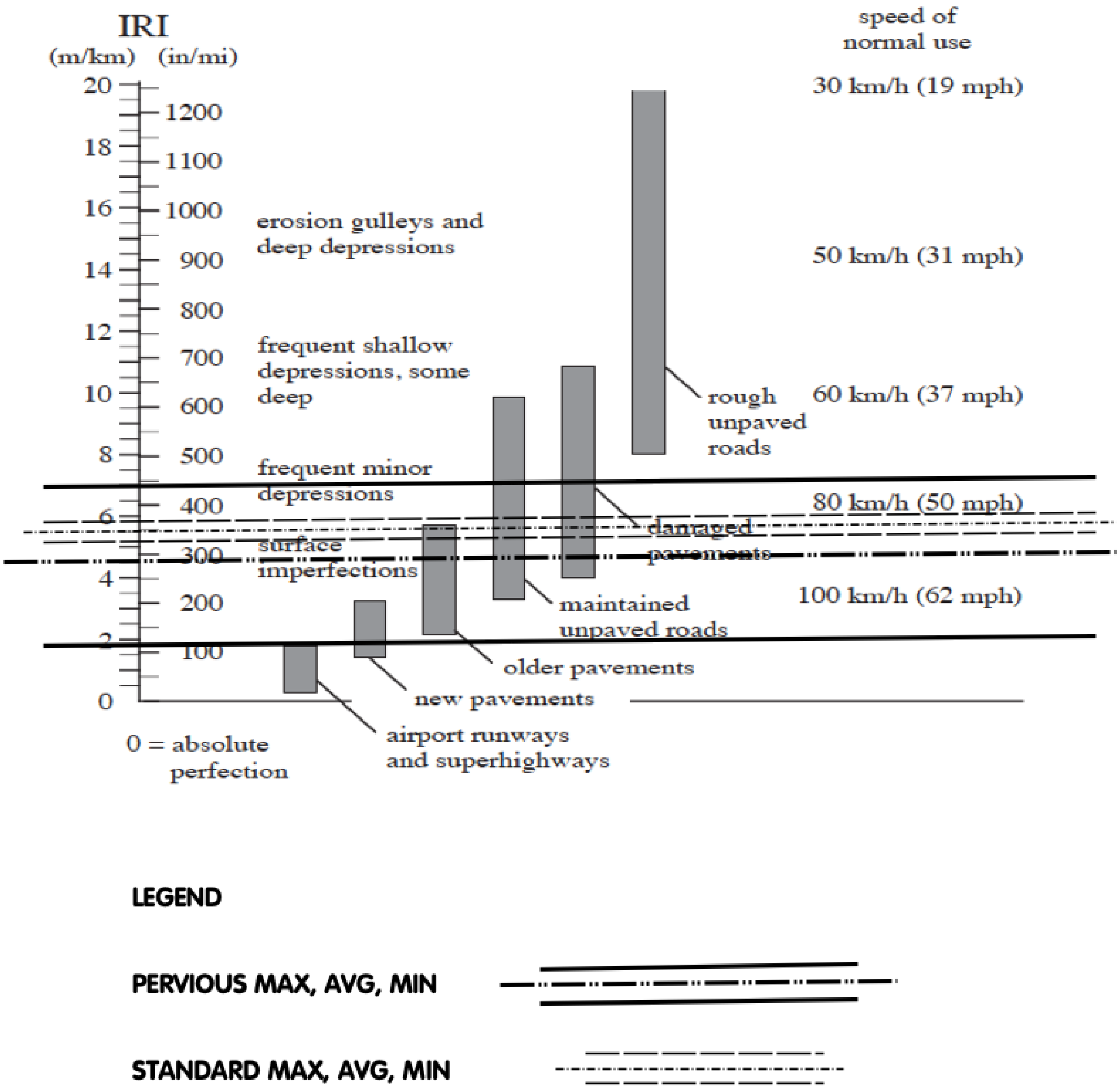


Figure 31. Road condition and IRI values, with study accessible pathway results added (adapted from Sayers and Karamihas, 1998).

5.2.2 Wheelchair Pathway Roughness Index

The SurPRO 4000 profilometer produced usable data for Concrete-Standard trials, and for Concrete-Pervious sites CP1 through CP5. XY data files did not exist on the device for sites CP-6 through CP-9. Average readings for WPRI by site are provided in Table VII, and Figures 32 and 33.

Table VII. Average WPRI values by Site.

Site	**WPRI** (avg)
	(mm/m)
CS1	2.6844
CS2	1.8907
CS3	5.5690
CP1	5.2508
CP2	4.8204
CP3	5.2651
CP4	3.5271
CP5	3.6545

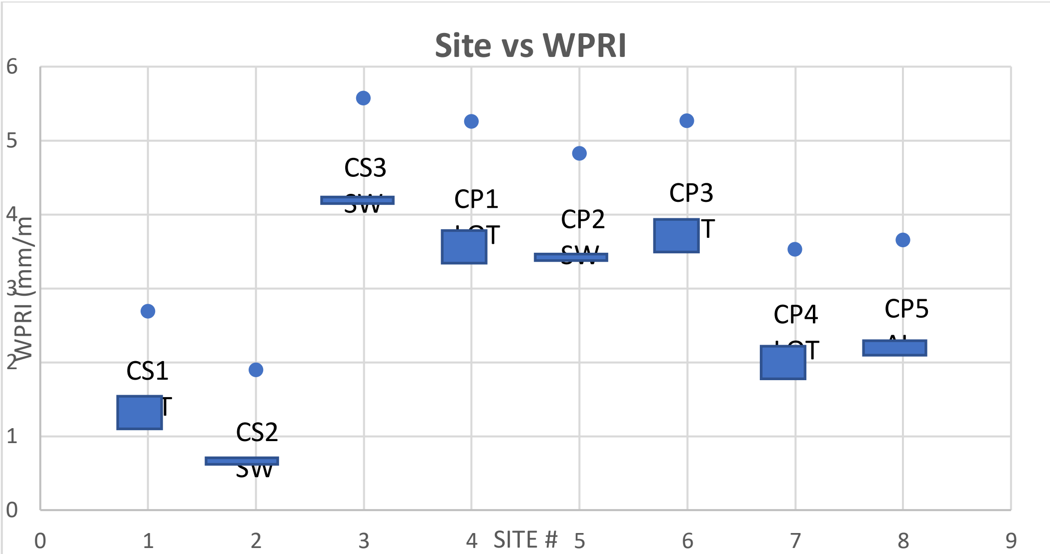


Figure 32. Graphical representation of average WPRI values by site. Note that WPRI values exist for CS1 – CS3, and CP1 – CP5 only.

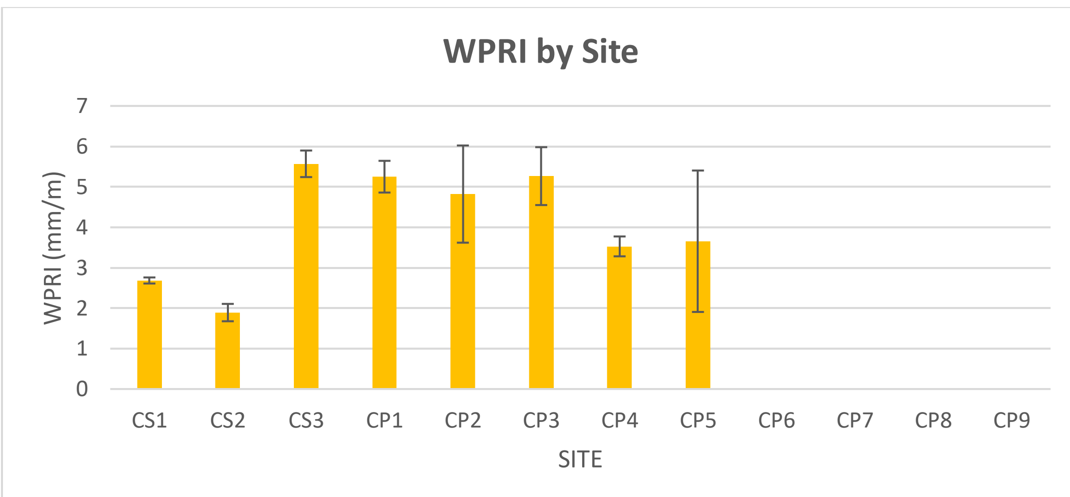


Figure 33. Graphical representation of average WPRI values by site, with standard deviations.

Note that most of the WPRI values for Concrete-Pervious are in the 3.00 – 6.00 mm/m range. Duvall (2016) found WPRI values in the range of 20 – 170 mm/m in his study.

5.3 Whole-Body Vibration

To calculate whole-body vibration, a Matlab program based on ISO 2631-1:1992 was utilized. The program *vibrationdata.m* is an open-source program utilized by ergonomists to take acceleration data and produce frequency-weighted whole-body vibration results. For acceleration data taken at the seat, in the z-direction, a frequency weighting value W_k is taken as 1.00 for the calculations (Mansfield, 2005).

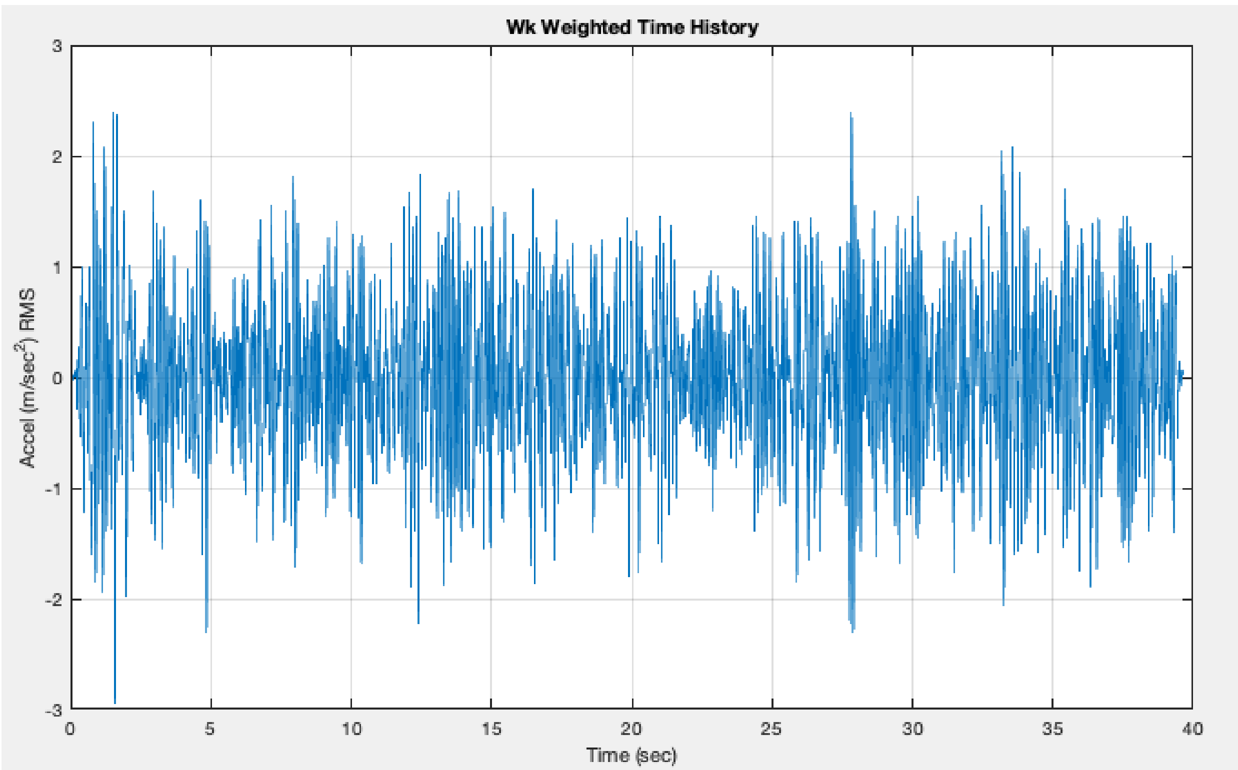


Figure 34. Typical accelerometer output plot (CP8, 0.75 m/s, A2).

5.3.1 Whole-Body Vibration by Accelerometer Location

Figure 35 shows the data from the CP9 site only, for the 5 trials at each wheelchair velocity, by accelerometer location (A1 at footplate, A2 at seat-to-mannequin interface, A3 at backrest, A4 at wheelchair frame cross-member).

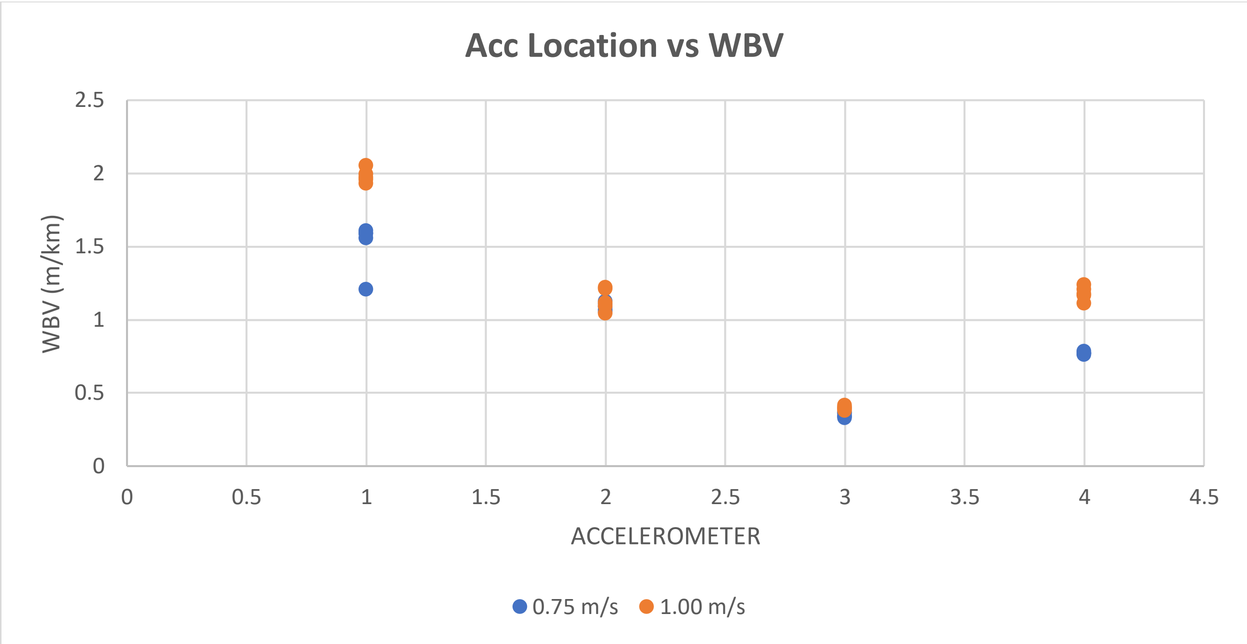


Figure 35. Whole-body vibration at each accelerometer location, single trial site (CP9).

Measurements at A1 are highest, attributable to the position on the aluminum footplate, directly above solid caster wheels. A2 values are lower, and aided by some vibration dampening by the rear pneumatic wheels and the seat cushion. A3 values are still lower, as the accelerometer is closer to the rear pneumatic wheels and is also positioned on a padded backrest sling. A4 values, although on the rigid wheelchair cross-member, are close to the rear pneumatic wheels.

5.3.2 Whole-Body Vibration by Study Location

A total of 120 trials were conducted. This was achieved via 5 trial runs at 0.75 m/s and 5 trial runs at 1.00 m/s, at each of the 12 sites. Regarding pervious concrete specifically, a total of 90 trial runs were made at the 9 pervious locations. Individual data points are shown in Figure 36, average values by location in Figure 37.

A listing of the individual whole-body vibration calculation results appear in Appendix C.

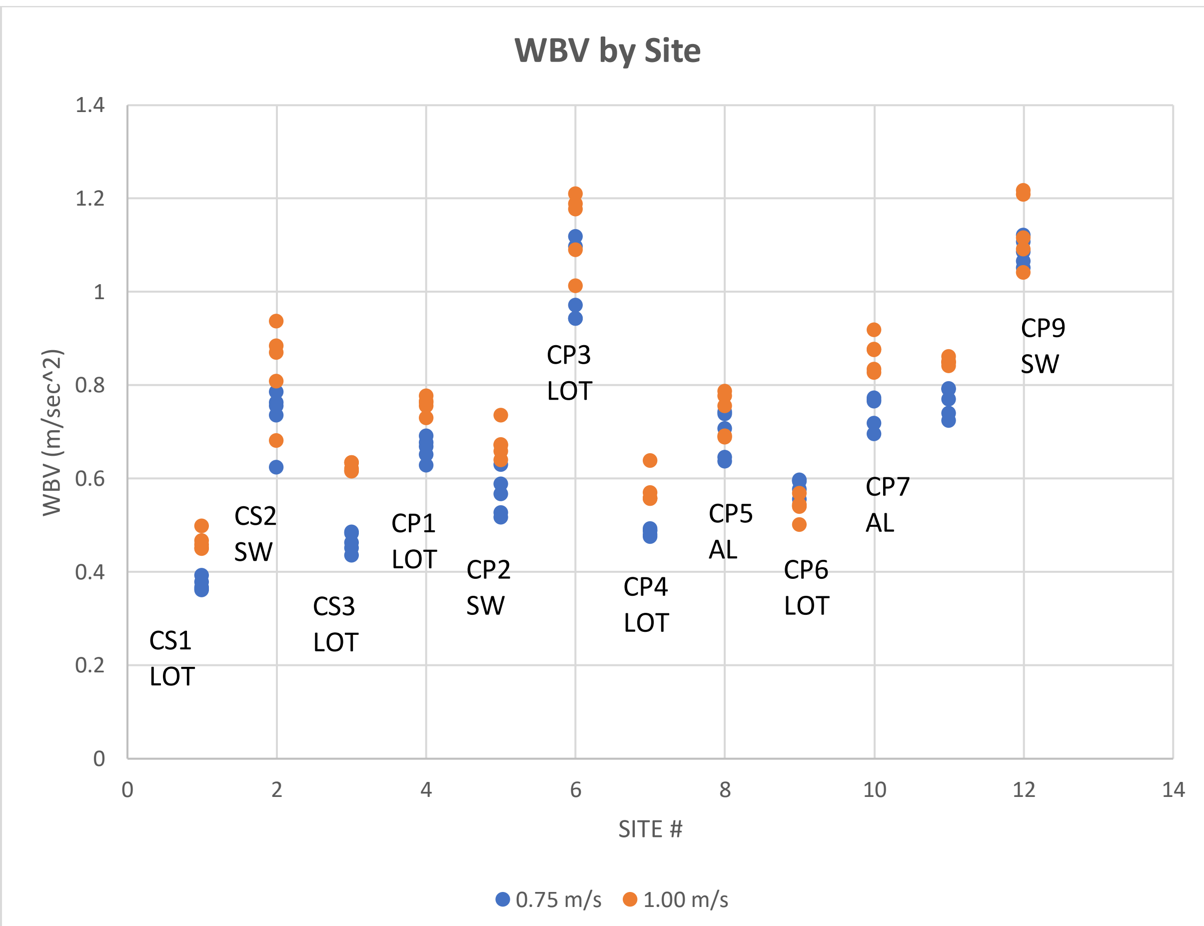


Figure 36. Whole-body vibration by Site (individual data points).

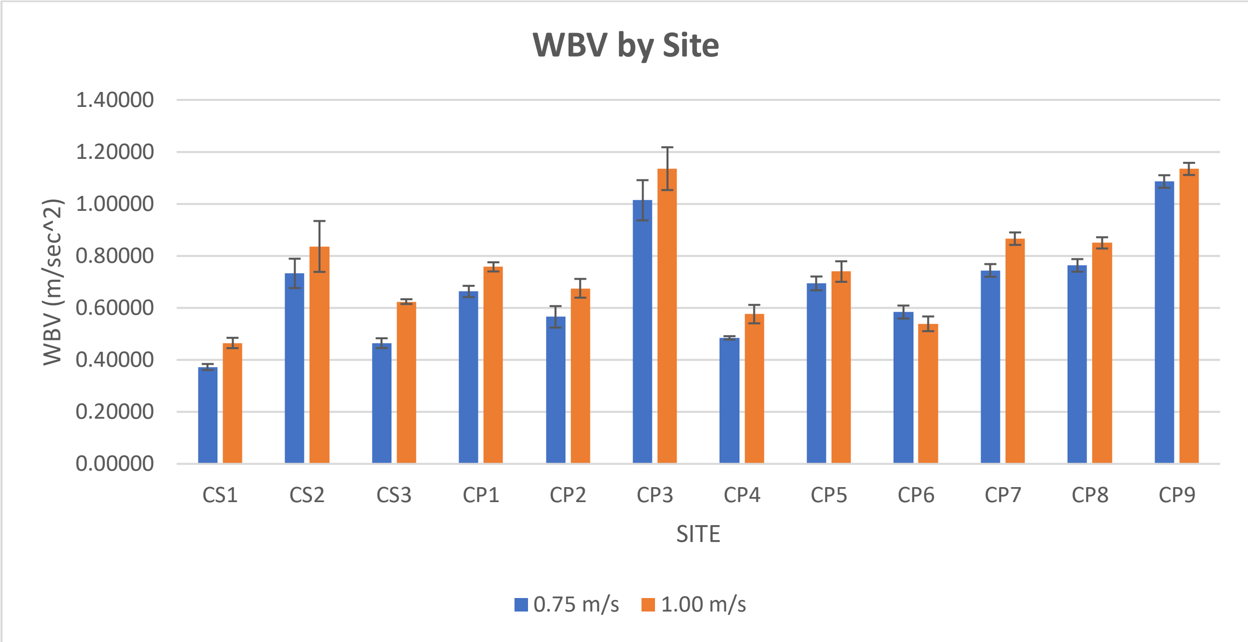


Figure 37. Whole-body vibration by Site (average values and standard deviations).

These results can be averaged and compared to values found in other studies where whole-body vibration results were reported. Table 38 summarizes these results, and notes any differences in experimental design.

Table VIII. Comparison of WBV across studies.

Study	**WBV** (m/sec^2)	**Pathway material**	**Accelerometer location**	**Loading**	**Velocity** (m/sec)
Hedman (2019)	0.7333	Pervious concrete	Seat cushion-mannequin interface	Mannequin	0.75
	0.8082	Pervious concrete	Seat cushion-mannequin interface	Mannequin	1.00
Duvall (2013)	1.5	Wood boards	Seat frame	Consumers	1.00
Garcia-Mendez (2013)	0.83	Community	Seat cushion-seat pan or seat sling interface	Consumers	0.73 (avg)
Wolf (2005)	0.4998	Brick paver, square (no chamfer)	Seat cushion-seat pan interface	Indiv w/out disability	1.00

5.4 International Roughness Index vs. Whole-Body Vibration

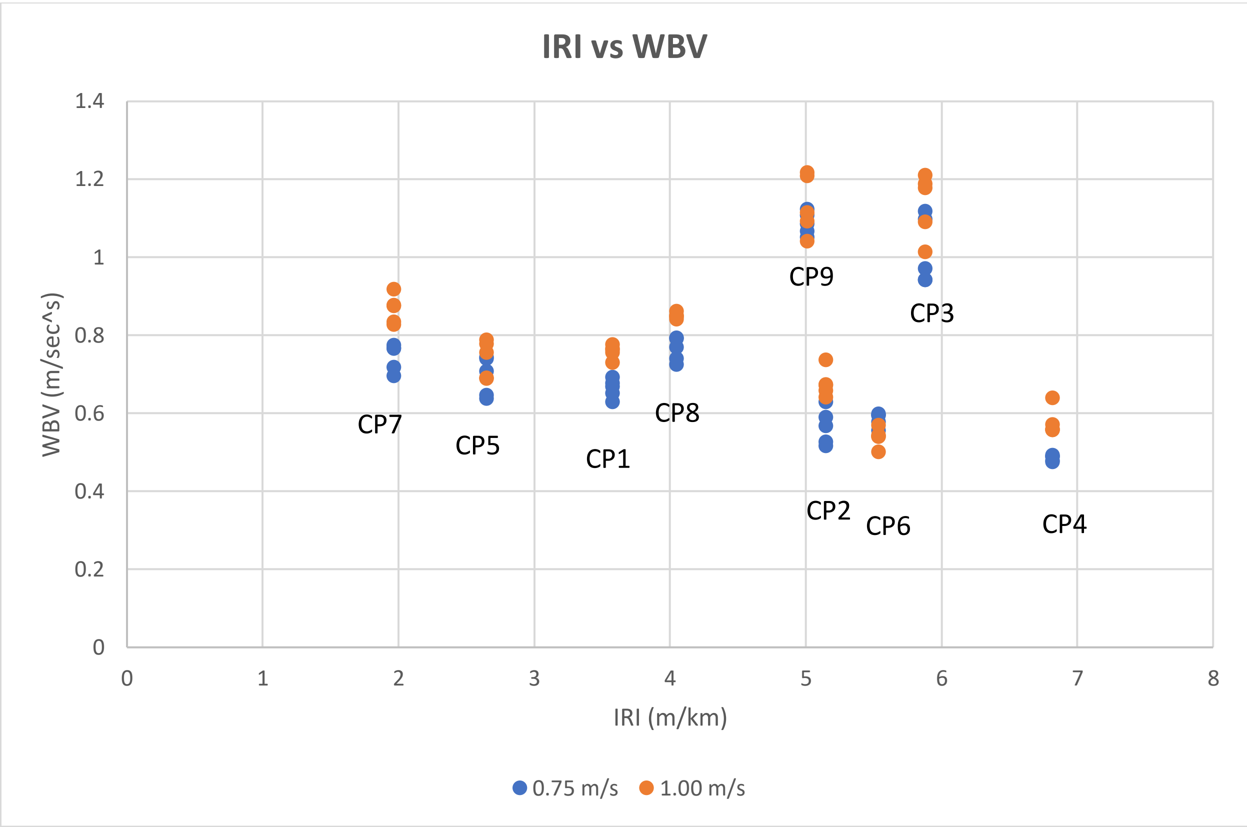


Figure 38. IRI vs Whole-Body Vibration.

Given the distribution of data, especially for sites CP2, CP6, and CP4, a clear relationship between IRI and whole-body vibration is not present. Conceivably one could emerge with more data, especially for pathways with IRI values in the 5.00 – 7.00 m/km range, if CP2, CP6, and CP4 are found to be outliers.

5.5 Wheelchair Pathway Roughness Index vs. Whole-Body Vibration

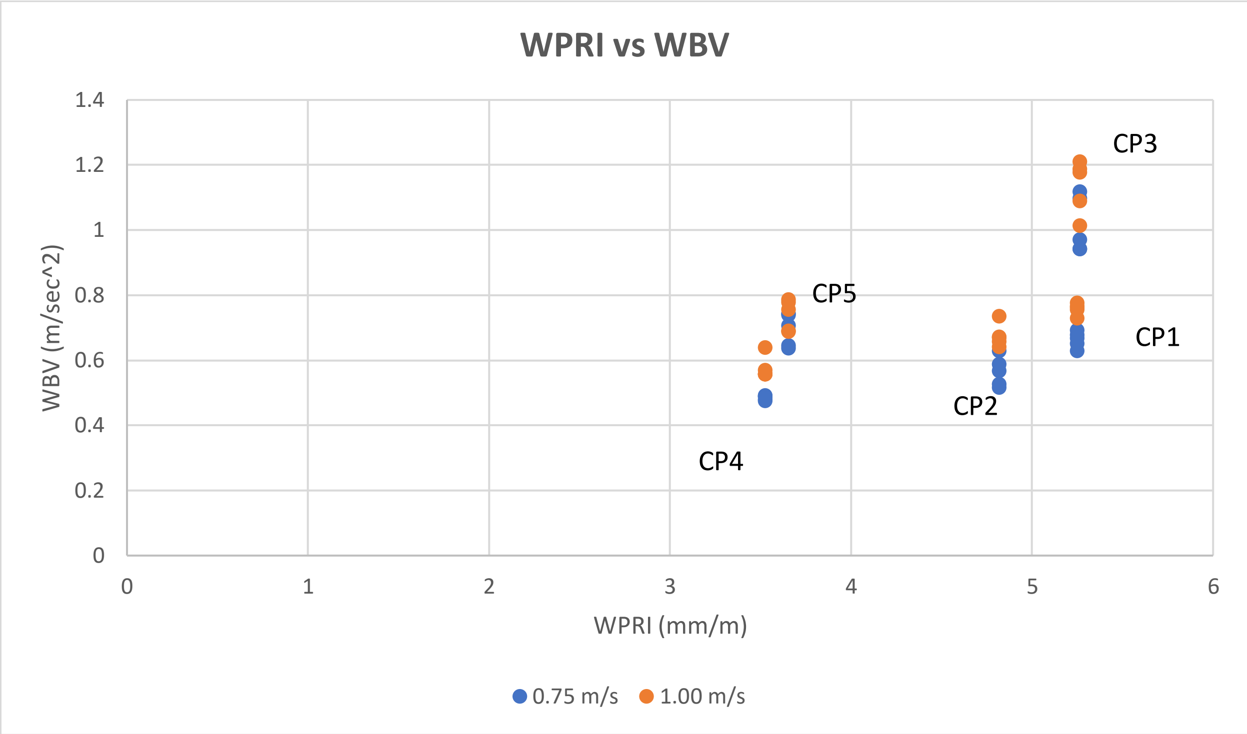


Figure 39. WPRI vs Whole-Body Vibration.

The WPRI values were found to exist in a narrow range, as compared with the range for IRI and WPRI from other studies (using a different measurement device). Additionally, no linear relationship exists between the IRI and WPRI using the SurPRO 4000 as the data collection device (Figure 40).

IRI vs WPRI

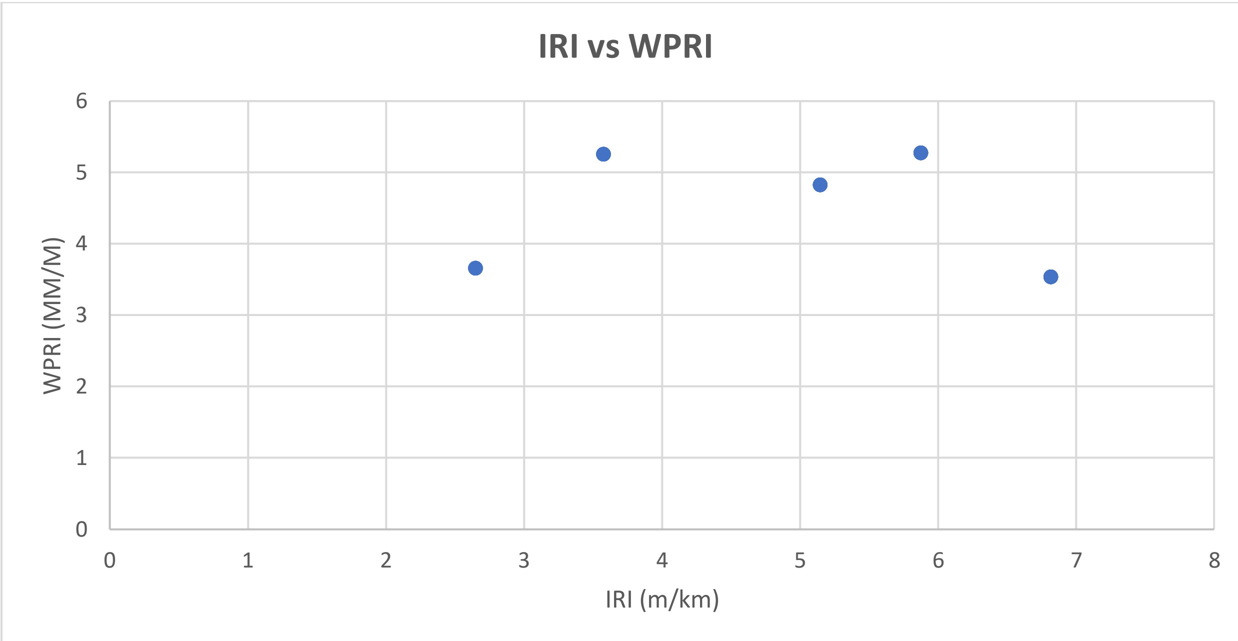


Figure 40. IRI vs WPRI.

5.6 Influence of Wheelchair Velocity

The experimental design (powered wheelchair towing the data collection manual wheelchair) enabled data collection at two wheelchair velocities, 0.75 m/s and 1.00 m/s). Results are shown in Table IX and Figure 41.

Table IX. Whole-body vibration by site and wheelchair velocity.

WBV BY SITE, WC VELOCITY			
	WC VELOCITY		
	0.75 m/sec	1.00 m/sec	
	WBV	WBV	% DIFF
	(m/sec^2)	(m/sec^2)	
CS1	0.37266	0.46637	25.15%
CS2	0.73268	0.83632	14.15%
CS3	0.46342	0.62406	34.66%
CP1	0.6632	0.7577	14.25%
CP2	0.56548	0.67536	19.43%
CP3	1.01398	1.1356	11.99%
CP4	0.48462	0.576	18.86%
CP5	0.69418	0.73976	6.57%
CP6	0.58402	0.53876	-7.75%
CP7	0.74406	0.86622	16.42%
CP8	0.7636	0.85008	11.33%
CP9	1.0862	1.1346	4.46%
Average increase at higher velocity (all):			14.13%
Average increase at higher velocity (CP only):			10.62%
Average WBV (CS only):			
	0.5229	0.6423	
Average WBV (CP only):			
	0.7333	0.8082	

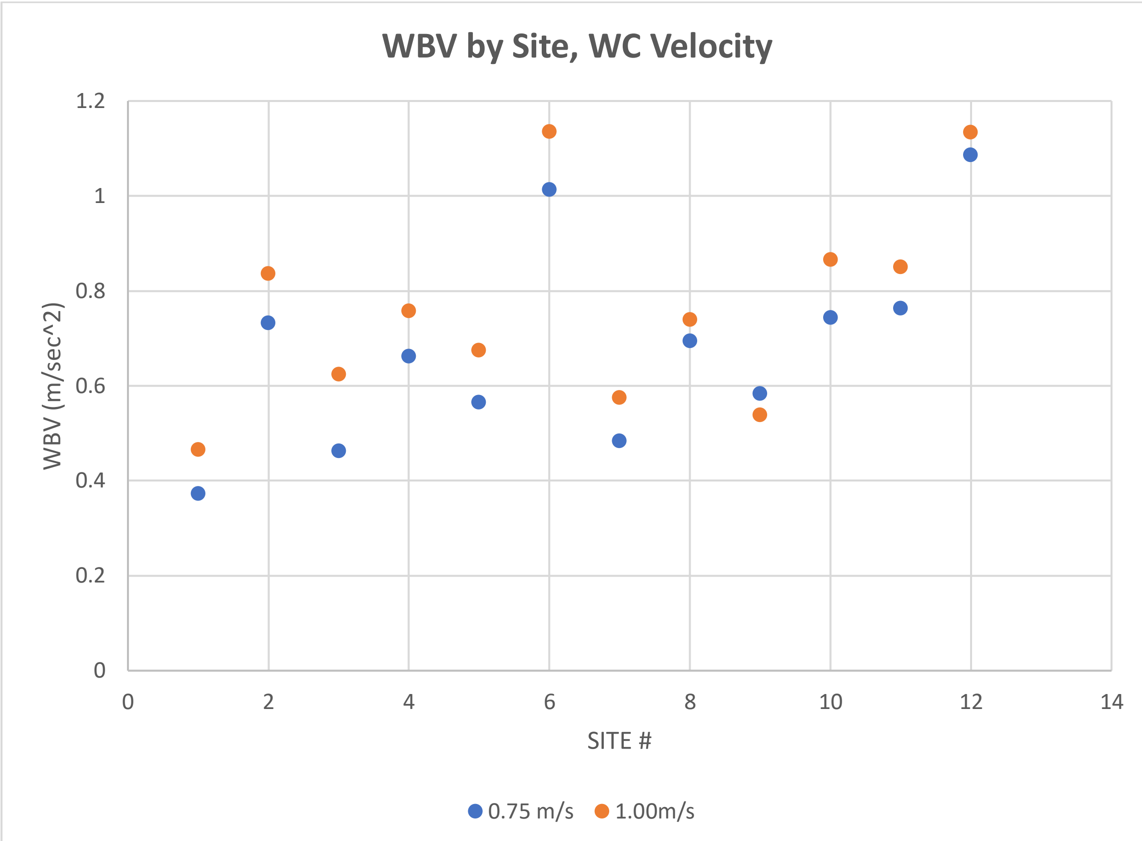


Figure 41. Graphical representation of whole-body vibration by site and wheelchair velocity.

The results indicate that the choosing of an assumed manual wheelchair velocity is significant when analyzing whole-body vibration experienced by manual wheelchair users. Across all Concrete-Standard and Concrete-Pervious sites, simulated travel at 1.00 m/s resulted in an increase in whole-body vibration of over 14%. For the Concrete-Pervious sites only, the increase was over 10%.

5.7 Whole-Body Vibration and Exposure

In order to assess the risk to wheelchair users, we need to combine the results of the whole-body vibration measurements with the estimated exposure during a typical day. We can bring the HAAT Model to this consideration of whole-body vibration and exposure by refining the Context-Physical aspect.

The importance of studying the amount of mobility achieved in a typical day by wheelchair users as been recognized. Warms et al (2007) noted that decreased mobility is associated with health issues including obesity. Increased mobility of wheelchair users has been associated with an increased quality of life of individuals with spinal cord injury (Anderson, 2004; Wood-Dauphinne, 2002).

Affordable, commercially-available accelerometers have made it possible to study the actual amount and type of travel that manual wheelchair users achieve. In a validation study of accelerometer use, Sonenblum et al (2012a) found that wheelchair users propel theirs chairs between 1 and 2 km per day, propel at speeds of 0.2 – 0.7 m/s, and are wheeling less than 1 hour per day. Further study indicated that wheelchair travel could be broken up into separate "bouts" of travel, where a sample of 21 participants indicated a median daily level of activity of 90 bouts, taking place over 54 minutes, and totaling 1.6 km (Sonenblum et al, 2012b). The use of bouts of travel was similar to the analysis of Orendurff et al (2008) regarding travel by ambulators. Sonenblum described manual wheelchair bouts of travel as occurring voluntarily between functional activities, quantified by distance traveled and a minimum velocity.

It is worth noting that other research has occurred regarding other focused user groups. Levy et al (2010) found that manual wheelchair users increased distance traveled per day after the introduction of power-assist rear wheels, although the increase occurred after a 2-week adjustment period. The study did not include an analysis of duration of daily travel.

Sonenblum et al (2008) studied the daily travel of powered wheelchair users, and found increased amounts of time in their device (10.6 hours) and time while traveling (58 minutes), and distances within the range found regarding manual wheelchair users (1.085 km). An interesting aspect of this study was the characterization of travel by environment – in the home, indoors but at a location which is not the home, and outdoors. Essentially, three different types of physical contexts of the HAAT Model. Results varied regarding outdoor travel, with 11 of 21 participants travelling outdoors only 2% of the time, and 6 travelling outdoors 30%-70% of the time. Among the most active travelers, 7 travelled 60-89 minutes, 4 travelled 90-120 minutes, and 1 travelled more than 120 minutes (170 minutes).

Cooper et al (2008) studied the mobility of 18 pediatric wheelchair users (9 manual, 9 powered), and found that the average manual wheelchair user travelled 1.60 km/day at a velocity of 0.67 m/s, and the average powered wheelchair user travelled 1.75 km/day at a velocity of 0.75 m/s.

Karmarkar et al (2008) found that for 50 manual wheelchair users, age 60 years and older, residing in nursing homes, distance travelled ranged from 121 m to 1.50 km. Average velocity was 0.60 m/s. Although not noted in the study, it is assumed that most or all travel took place within the nursing home facilities, on tile flooring.

Sonenblum's most recent study (2017) further defined bouts of mobility: transition from one activity to another, duration of at last 5 seconds, velocity of at least 0.12 m/s, and ended when 0.75 m or less were wheeled within 15 seconds. Daily wheelchair use for the median of the 69 participants included 83 bouts of travel, 1.41 km distance, time in the wheelchair of 11.1 hours, and time spent wheeling 45.1 minutes. The study indicated a median velocity of 0.72 m/s (Sonenblum, personal communication, 2017).

For the consumer perspective, DiGiovine (2015) assembled a focus group of powered wheelchair users to comment on their experiences with mobility and whole-body vibration. Relevant to this study, the group of 15 consumers cited cracked sidewalks as both a barrier to travel and a cause of vibration, and the consumers and 9 rehabilitation professionals stated that future wheelchair design should focus on minimizing shock and vibration.

With a sense of the level of whole-body vibration experienced by manual wheelchair users when travelling across pervious concrete surfaces, and the duration of travel in the community, we can examine the relative risk that travel across these surfaces brings.

To examine the risk, ISO 2631-1:1997, *Annex B, Guide to the Effects of Vibration on Health* (International Organization for Standardization, 1997) is used. As an annex, it is *informative* in nature, but provides guidance as to the assessment of risk based on current research.

Annex B provides two equations regarding the accelerations which may cause health issues.

$$(a_{w1}) (T_1^{1/2}) = (a_{w2}) (T_2^{1/2}) \qquad \text{(Annex B, Eq. B.1)}$$

where

a_{w1} and a_{w2} acceleration values in weighted r.m.s. form, for first exposure and second exposure, respectively

T_1 and T_2 corresponding durations for the first and second exposures

and, based on a different body of research more conservative guidance is suggested:

$$(a_{w1}) (T_1^{1/4}) = (a_{w2}) (T_2^{1/4}) \qquad \text{(Annex B, Eq. B.2)}$$

The B.1 and B.2 equations are plotted in *Annex B, Figure B.1 – Health guidance caution zones* (International Organization for Standardization, 1992).

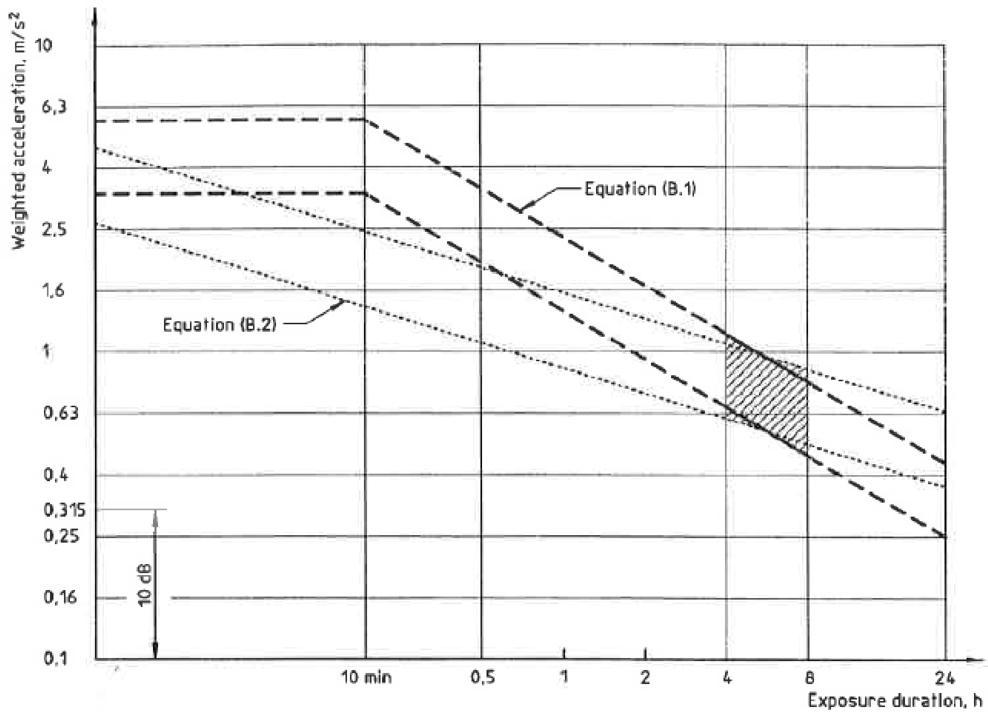


Figure 42. ISO 2631-1:1992, Annex B, Health guidance caution zones.

The plots indicate that there is agreement between the two equations for exposure duration of 4-8 hours. Annex B advises that health risks have not been clearly documented for exposures below the dashed line of the Eq. B.1 zone, but that exposures above have likely health risks.

Plotting the study's average whole-body vibration for all Concrete-Pervious site, risk is indicated for the duration levels of 2 hours and longer. With the average actual daily travel time plotted (54 minutes), the whole-body vibration experienced is below the hazard lines. Additionally, since travel outdoors is only portion of the daily travel time, the risk level is even lower (Figure 43).

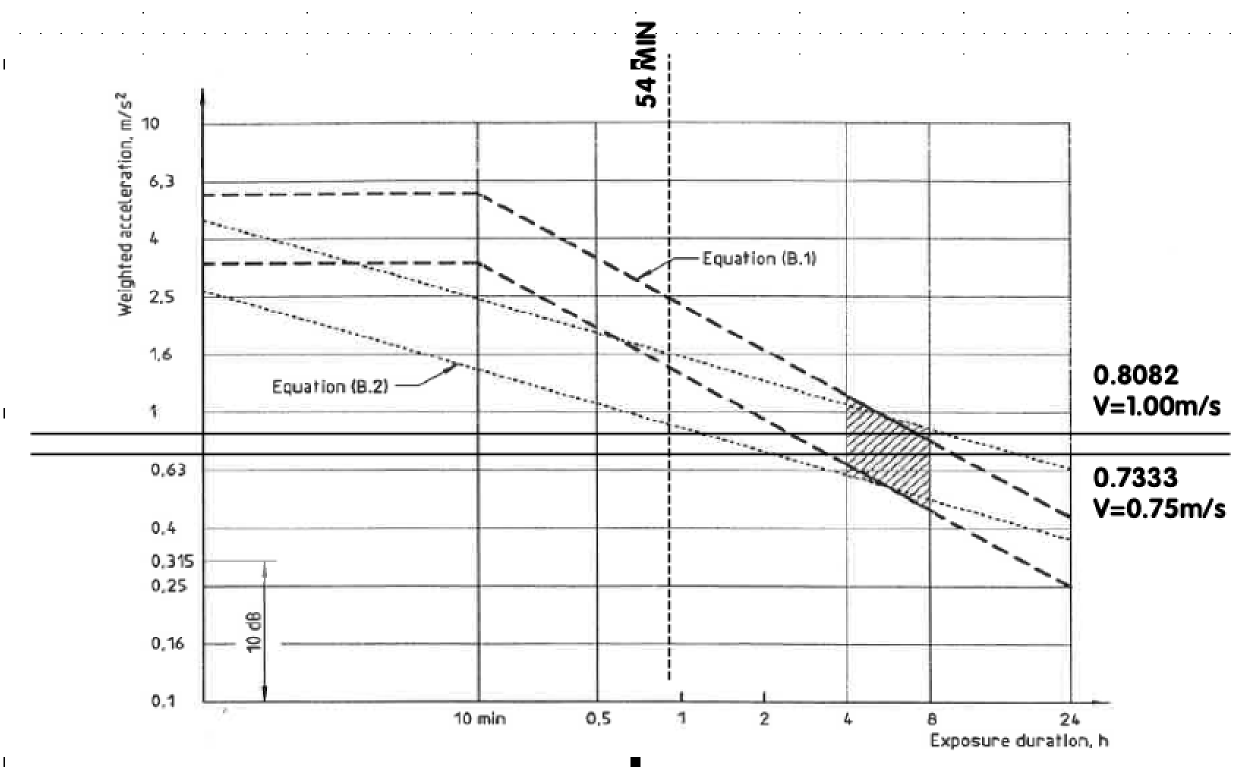


Figure 43. ISO 2631-1:1992, Annex B, Health guidance caution zones, with study data added, as well as daily time spent traveling by manual wheelchair users.

Finally, adding data from the Garcia-Mendez and Wolf studies, the study's whole-body vibration levels seem in line with previous work (Figure 44).

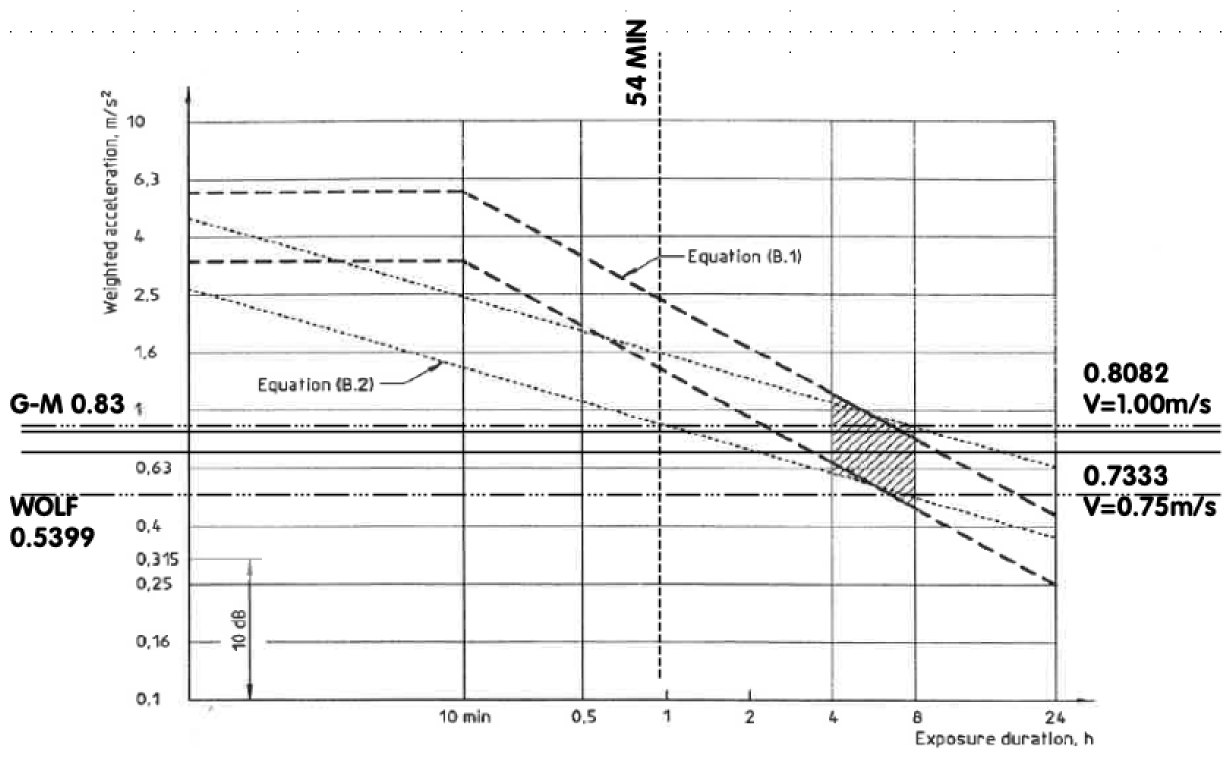


Figure 44. ISO 2631-1:1992, Annex B, Health guidance caution zones, with whole-body vibration data from Garcia-Mendez and Wolf added.

6. DISCUSSION

6.1 For Designers of the Built Environment

Use of pervious concrete for pathways holds both environmental and financial benefit. Maintenance of the surface, through power washing, vacuuming, and application of solutions to break down pollutants will help keep the surface a smooth as possible for all users. Keeping to a maintenance schedule is critical, as some of the newer pathways actually had the most loose aggregate on top.

6.2 For the Construction Industry

Pathways constructed of pervious concrete can produce smoother surfaces than traditional poured concrete. There is still a range of IRI roughness values, however, so attention to the size of coarse aggregate and compaction method is still warranted. Use of smaller, uniform-size aggregate will help produce smoother surfaces. Sufficient adhesion of the cement paste to the aggregate is crucial to avoid excessive loose material due to abrasion. Use of pervious concrete for pathways is only going to increase, and to the extent that the surfaces can serve all users optimally, the better.

6.3 For Road Roughness Inspection Research and Development Professionals

With all trial paths constructed of concrete, and in a dry condition, anticipated high coefficient of friction readings were confirmed. One site, however, had a coefficient of friction which was below the recommended value for horizontal surfaces. This may be attributed to sealcoating procedures, however the schedule of application was not known. Further study to learn the potential impact of sealcoating and other maintenance procedures is indicated.

The data regarding the IRI and whole-body vibration shows promise regarding the IRI being a predictor of vibration, but more data is needed. Data for 3 of the sites lie outside what would otherwise be a linear relationship between these two factors. In particular, more data is needed for pathways which have an IRI of between 4.00 and 7.00 m/km.

The use of the SurPRO 4000 to collect pathway XY data for the calculation of the WPRI proved to be a mismatch due to wheel diameter and interval of data collection. Additionally, a plot of IRI vs WPRI did not indicate a relationship between the two. Further study is needed to see if any commercially available road roughness device has a wheel diameter of 70 mm (2.75 in), so that the data can be used by ASTM E3028 properly. While the University of Pittsburgh states that it PathMeT device is the only one suitable for pathway roughness measurement (Duvall, 2016) to yield ASTM E3028 figures, it is questionable how many construction firms and inspection officials with have this device at their disposal (Figure 45).

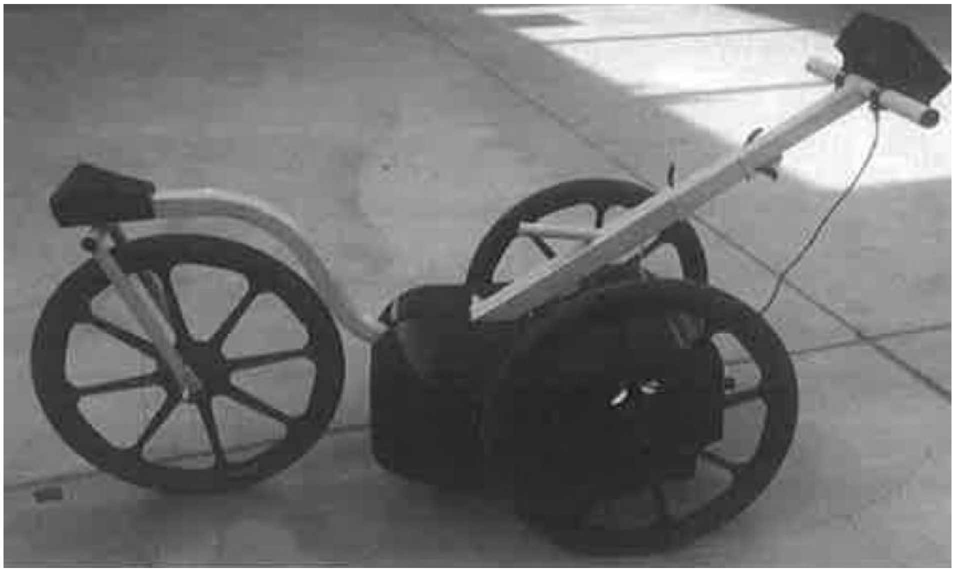


Figure 45. University of Pittsburgh PathMeT data collection device.

6.4 For Rehabilitation Research and Development Professionals

Given that the study showed a 10% increase in whole-body vibration for travel at 1.00 m/s as compared to 0.75 m/s, reaching some consensus in the field as to the most appropriate velocity is important. If actual travel velocity is estimated to be even lower, at 0.50 m/s, the risk involved in outdoor travel will be even lower than cited in previous studies.

The study of the time spent in actual bouts of mobility, and where these bouts take place, deserves continued research. Use of the ISO 2631-1:1992 Annex B Health Guidance is readily applied for a single source of vibration for a known duration. But daily wheeled mobility is complex, occurring over different surfaces for different durations. Weaving these variables into analysis of exposure to WBV is essential for a more accurate assessments of risk.

6.5 For Consumers

For most consumers, acquisition of a new wheelchair occurs infrequently. Most 3rd party payers will not consider support for a new wheelchair if the existing wheelchair is less than 5 years old. When there is the opportunity for wheelchair replacement, consumers should be aware of the components which can assist in reducing the vibration they experience. While the seat cushion and backrest are usually specified for pressure relief and lateral support, suspension systems and shock-absorbing front caster assemblies are available for many models. Careful selection of wheelchair components with a trained Assistive Technology specialist will be beneficial.

6.6 Limitations of the Study

Limitations of the study include a limited sample size. More data is needed to determine if there is a relationship between the IRI and WBV. Also, placement of an accelerometer beneath the seat cushion may have offered better comparison of results with other studies, rather than the footplate and wheelchair frame locations used in this study. Since data on the age of the different surfaces was rarely available, tracking the pathway characteristics by age was not possible. No information was available regarding pervious concrete aggregate size.

Even taking the recognized limitations into account, the study protocol has the potential to offer an objective examination of baseline data and documentation of reduced risk based on different surfaces in the community, as well as different wheelchair frame designs, suspension systems, front caster hardware designs, and seat cushions.

Study of pathway roughness through similar techniques may also be beneficial to research with other individuals with mobility impairments - those that ambulate with no aid, or those that use canes, walkers, or crutches – regarding performance criteria like speed of gait or avoidance of trips and falls.

While the study's analysis of pervious concrete use is good news for the current situation from the HAAT Model's Context-Physical perspective, efforts are underway to encourage individuals with disabilities to become more active, from tailored health and wellness smartphone apps, to urban design which promotes travel without the use of cars, to geo-mapping of planned trips to advise the individual of the most accessible route. However, even with increased mobility, travel across pervious concrete pathways will likely remain safe for users of manual wheelchairs.

Figure 46 shows site CP4.

Figure 46. End of data collection, site CP4.

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APPENDICES

APPENDIX A

Data Collection Scratch Sheets

WC PROJECT			
DATA COLLECTION SCRATCH SHEET			
DATE			
LOCATION			
TYPE			
	STD POURED CONCRETE		
	PERVIOUS CONCRETE		
	OTHER		
TEMPERATURE			DEG F
		VALUE	COMMENT
PREPARATION			
MARK OFF TRACK			
		98 FT, 5 INCHES	
BROOM CLEAN			
SLOPE - LONGITUDINAL			
SLOPE - CROSS			
SURFACE CONDITION			
ICE		OK?	
MOISTURE		OK?	
COEFFICIENT OF FRICTION			
TRIAL 1			
TRIAL 2			
TRIAL 3			
TRIAL 4			
TRIAL 5			

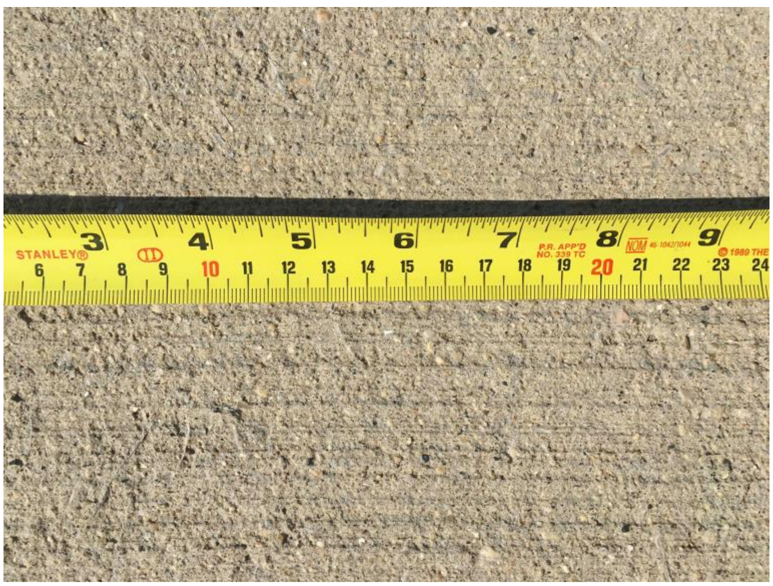
ROUGHNESS			
TRIAL 1	**FORWARD**		
	FILE NAME		
	IRI		
	REVERSE		
	FILE NAME		
	IRI		
TRIAL 2	**FORWARD**		
	FILE NAME		
	IRI		
	REVERSE		
	FILE NAME		
	IRI		
TRIAL 3	**FORWARD**		
	FILE NAME		
	IRI		
	REVERSE		
	FILE NAME		
	IRI		
TRIAL 4	**FORWARD**		
	FILE NAME		
	IRI		
	REVERSE		
	FILE NAME		
	IRI		
TRIAL 5	**FORWARD**		
	FILE NAME		
	IRI		
	REVERSE		
	FILE NAME		
	IRI		
TRIAL 6	**FORWARD**		
	FILE NAME		
	IRI		
	REVERSE		
	FILE NAME		
	IRI		

WHOLE-BODY VIBRATION			
VELOCITY	**0.75 M/S**		
TRIAL 1	**START TIME**		
	DURATION		36-44 sec
TRIAL 2	**START TIME**		
	DURATION		36-44 sec
TRIAL 3	**START TIME**		
	DURATION		36-44 sec
TRIAL 4	**START TIME**		
	DURATION		36-44 sec
TRIAL 5	**START TIME**		
	DURATION		36-44 sec
VELOCITY	**1.00 M/S**		
TRIAL 6	**START TIME**		
	DURATION		27-33 sec
TRIAL 7	**START TIME**		
	DURATION		27-33 sec
TRIAL 8	**START TIME**		
	DURATION		27-33 sec
TRIAL 9	**START TIME**		
	DURATION		27-33 sec
TRIAL 10	**START TIME**		
	DURATION		27-33 sec

APPENDIX B

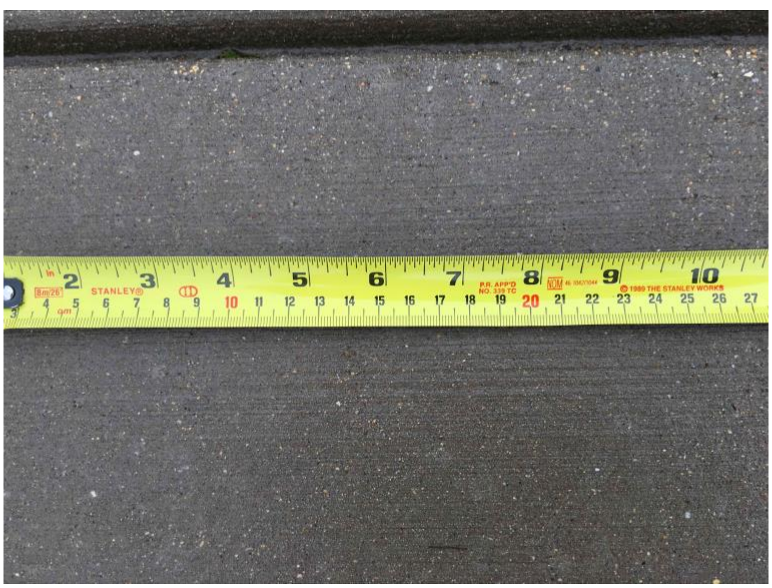
Site Photo Documentation

SITE CS1
UIC LOT 1A
1101 West Harrison
Chicago, IL
09/23/2018



SITE CS2
UIC DHSP Sidewalk
1640 West Roosevelt
Chicago, IL
10/21/2018

SITE CS3
Dayvita Dialysis sidewalk
1200 Sibley Blvd
Calumet City, IL
12/15/2018



SITE CP1
UIC Lot 1A
1101 West Harrison
Chicago, IL
09/23/2018

SITE CP2
Advocate Medical Group
2535 South King Drive
Chicago, IL
11/11/2018

SITE CP3
Civic Center Parking Lot
2100 Ridge
Evanston, IL
11/18/2018

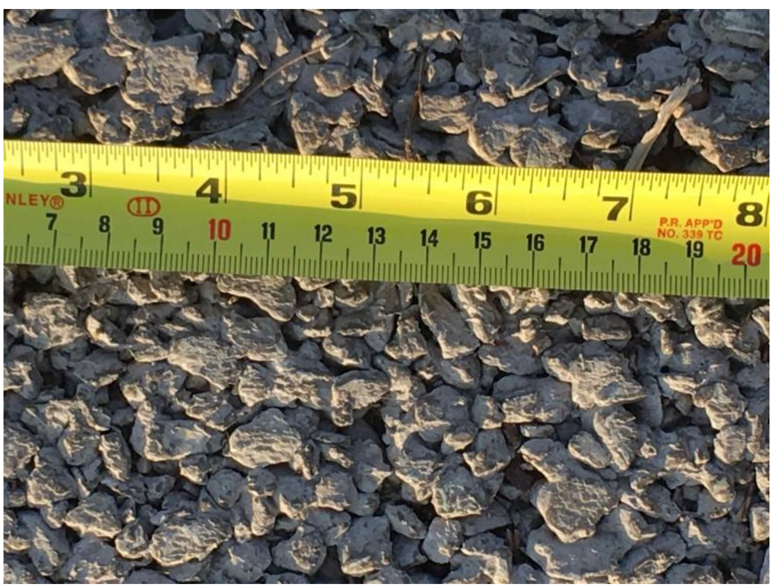
SITE CP4
Dayvita Dialysis Lot
1200 Sibley Blvd
Calumet City, IL
12/15/2018

SITE CP5
Alley
484 Lee Street
Des Plaines, IL
12/16/2018

SITE CP6
Comcast Service Center
721 East 112th Street
Chicago, IL
01/04/2019

SITE CP7
Alley
862 East Algonquin
Des Plaines, IL
01/05/2019

SITE CP8
Arrington Lagoon
1631 Sheridan Road
Evanston, IL
01/06/2019



SITE CP9
Chicago Park District Boathouse
2754 South Eleanor
Chicago, IL
09/19/2019

APPENDIX C

Whole-Body Vibration Results for Each Trial

DATA - IRI AND WBV				
IRI		a (m/s^2)	a (m/s^2)	
(m/km)		WBV075	WBV100	
		0.75 m/s	1.00 m/s	
3.26	1	0.3785	0.4503	CS1
3.26	1	0.3674	0.4506	
3.26	1	0.3636	0.4982	
3.26	1	0.3613	0.4587	
3.26	1	0.3925	0.4671	
5.07	2	0.7355	0.6812	CS2
5.07	2	0.7553	0.8088	
5.07	2	0.7862	0.8847	
5.07	2	0.762	0.9364	
5.07	2	0.6244	0.8705	
5.94	3	0.4506	0.6342	CS3
5.94	3	0.436	0.6162	
5.94	3	0.4627	0.6335	
5.94	3	0.4856	0.6157	
5.94	3	0.4822	0.6207	
3.57	4	0.668	0.755	CP1
3.57	4	0.6915	0.7656	
3.57	4	0.6507	0.7765	
3.57	4	0.6769	0.762	
3.57	4	0.6289	0.7294	
5.15	5	0.6292	0.6579	CP2
5.15	5	0.5664	0.6706	
5.15	5	0.5265	0.6725	
5.15	5	0.5888	0.6402	
5.15	5	0.5165	0.7356	
5.88	6	1.097	1.177	CP3
5.88	6	1.118	1.013	
5.88	6	0.9707	1.188	

5.88	6	0.9422	1.21	
5.88	6	0.942	1.09	
6.82	7	0.4886	0.6387	CP4
6.82	7	0.4749	0.558	
6.82	7	0.4791	0.5563	
6.82	7	0.4924	0.5699	
6.82	7	0.4881	0.5571	
2.65	8	0.6367	0.7774	CP5
2.65	8	0.6452	0.6905	
2.65	8	0.7425	0.7872	
2.65	8	0.739	0.6883	
2.65	8	0.7075	0.7554	
5.54	9	0.5946	0.5435	CP6
5.54	9	0.5775	0.5398	
5.54	9	0.5951	0.569	
5.54	9	0.5972	0.5405	
5.54	9	0.5557	0.501	
1.97	10	0.718	0.8273	CP7
1.97	10	0.7679	0.8772	
1.97	10	0.6953	0.9178	
1.97	10	0.7733	0.8753	
1.97	10	0.7658	0.8335	
4.05	11	0.7241	0.8619	CP8
4.05	11	0.7915	0.8415	
4.05	11	0.7402	0.8506	
4.05	11	0.7926	0.8481	
4.05	11	0.7691	0.8483	
5.01	12	1.066	1.208	CP9
5.01	12	1.107	1.092	
5.01	12	1.051	1.041	
5.01	12	1.122	1.115	
5.01	12	1.085	1.217	

VITA

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EDUCATION

Ph.D.	University of Illinois at Chicago, 2019, Civil Engineering
M.S.	University of Illinois at Chicago, 2004, Civil Engineering Area of Concentration: Structural Engineering
M.Eng.	University of Virginia, 1983, Mechanical Engineering Area of Concentration: Rehabilitation Engineering
B.S.	University of Illinois at Chicago, 1981, Bioengineering

PROFESSIONAL EXPERIENCE

1989-present	Director, Assistive Technology Unit University of Illinois at Chicago (UIC)
2005-present	Clinical Associate Professor Dept. of Disability & Human Development, UIC
1996-2005	Clinical Assistant Professor Dept. of Disability & Human Development, UIC
1984-1989	Director, Rehabilitation Engineering Rehabilitation Institute of Chicago
1983-1989	Clinical Rehabilitation Engineer Rehabilitation Institute of Chicago

PE LICENSURE

Illinois (062-054251), Wisconsin (34264), Michigan (6201058417)

CREDENTIALS

Assistive Technology Professional (ATP), RESNA, 1996 – present.
Certificate in Rehabilitation Engineering Technology (RET), RESNA, 2003 – present.
Certified Professional Ergonomist (CPE), BCPE, 2008 – present.

HONORS
Distinguished Service Award - 1996. RESNA
Fellow Award – 2003. RESNA

SELECTED PROFESSIONAL ACTIVITIES
RESNA, Rehab Engineering and Assistive Technology Society of North America, Member (1980-present)
ASME, American Society of Mechanical Engineers, Member (1988-present)
ASCE, American Society of Civil Engineers, Member (1998-present)
ASHRAE, American Society of Heating, Refrigeration, & Air Conditioning Engineers, Member (2005-2015)
HFES, Human Factors and Ergonomics Society, Member (2008-present)
NFPA, National Fire Protection Association, Member (2007-2015)

President, RESNA (2006-2008)
Chair, RESNA Special Interest Group on Job Accommodation (1994-1996)
Chair, RESNA Professional Specialty Group for Rehabilitation Engineers (1998-2000)
RESNA Board of Directors (1998-2000)
Chair, RESNA Board of Directors Task Force - Certification of Rehab Engineering Technologists (2000)

Chair, RESNA Standards Committee on Emergency Stair Travel Devices used by Individuals with Disabilities (2009-present)
Member, ASME A17 Task Group on Elevator Use During Emergencies (2005-present)
Member, ASME A18, Safety Codes & Standards - Platform Lifts & Stairway Chairlifts (2000-present)

Member, Program Committee, Human Behavior in Fire; 4th International Symposium, Cambridge, UK, 2009
Member, Program Committee, 5th International Pedestrian and Evacuation Dynamics Conference, Gaithersburg, MD, 2010
Member, Program Committee, Human Behavior in Fire; 5th International Symposium, Cambridge, UK, 2012
Member, Program Committee, Human Behavior in Fire; 6th International Symposium, Cambridge, UK, 2015

PUBLICATIONS

Selected Journal Articles

Lavender, SA, Hedman, GE, Mehta, JP, Reichelt, PA, Conrad, KM, Park, S. Evaluating the Physical Demands on Firefighters Using Hand-Carried Stair Descent Devices to Evacuate Mobility-Limited Occupants from High-Rise Buildings. Applied Ergonomics, Vol 45, p. 389-397.

Mehta, JP, Lavender, SA, Hedman, GE, Reichelt, PA, Conrad, KM, Park, S. Evaluating the Physical Demands on Firefighters Using Track-Type Stair Descent Devices to Evacuate Mobility-Limited Occupants from High-Rise Buildings. Applied Ergonomics, Vol 46, p. 96-106.

Lavender, SA, Hedman, GE, Mehta, JP, Reichelt, PA, Conrad, KM, Park, S. Evaluating the Physical Demands When Using Sled-Type Stair Descent Devices to Evacuate Mobility-Limited Occupants from High-Rise Buildings. Applied Ergonomics, Vol 50, p. 87-97.

Hedman, GE, Mehta, J, Lavender, SA, Reichelt, PA, Conrad, KM, Park, S. Consumer Opinion of Stair Descent Devices used during Emergency Evacuation from High-Rise Buildings. Assistive Technology, Vol 30, p. 1-10.

Selected Proceedings

Lavender, SA, **Hedman, GE**, Mehta, JP, Park, S, Reichelt, PA ,Conrad, KM, (2013). A comparison of the physical demands experienced when using different sled-type emergency stair descent devices that could be used for hospital healthcare facility evacuations. Poster presented at the HFES 2013 International Symposium on Human Factors and Ergonomics in Health Care: Advancing the cause. Baltimore, MD, March 11, 2013.

Lavender, SA, Mehta, JP, Park, S, **Hedman, GE**, Reichelt, PA, Conrad, KC (2012). Ergonomic evaluation of manually-carried stair descent devices used for the evacuation of high-rise buildings. AICHE 2012, Indianapolis, SR-110-03.

Lavender, SA, Mehta, JP, **Hedman, GE**, Park, S, Reichelt, PA, Conrad, KC (2012). Ergonomic evaluation of track-type stair descent devices used for evacuation of high-rise buildings. Proceedings of the Human Factors and Ergonomics Society 56th Annual Meeting, pgs 1211-1212.

Hedman, GE. Status report on the development of the RESNA performance standard for emergency stair travel devices. Human Behavior in Fire - 5th International Symposium, Cambridge, UK, September 2012.

Lavender, SA, **Hedman, GE**, Reichelt, PA, Mehta, JP, Conrad, KM, & Park, S. Ergonomic evaluation of manually-carried and track-type stair descent devices use for the evacuation of high-rise buildings. Human Behavior in Fire - 5th International Symposium, Cambridge, UK, Sept 2012, Interscience Communications, London 2012, pp 340-345, ISBN 978-0-9556548-8-6.

Hedman, GE. Travel Along Stairs by Individuals with Disabilities: A Summary of Devices Used During Routine Travel and Travel During Emergencies. *Proceedings from the 5th International Pedestrian and Evacuation Dynamics Conference*, National Institute of Standards and Technology, Gaithersburg, MD, 2010.

Hedman, GE. Stair Descent Devices: An Overview of Current Devices and Proposed Framework for Standards and Testing. *Proceedings of Human Behavior in Fire; 4th International Symposium*, Cambridge, UK, 2009.

Recent Presentations

Steve Lavender, Glenn Hedman, Paul Reichelt, Karen Conrad, Jay Mehta, Sanghyun Park. Stair Descent Devices: Results of a 3-Year Study: Ergonomic Evaluation of Evacuation Equipment Used by Firefighters. Co-Presented by Lavender and Hedman at the National Fire Protection Association annual meeting, Chicago, IL, June 11, 2013.

Steve Lavender, Glenn Hedman, Paul Reichelt, Karen Conrad, Jay Mehta, Sanghyun Park. Stair Descent Devices: An Ergonomic Evaluation of Evacuation Equipment Used by Firefighters. Co-Presented by Lavender and Hedman at the National Fire Protection Association annual meeting, Las Vegas, NV, June 12, 2012.

Steve Lavender, Glenn Hedman, Paul Reichelt, Karen Conrad, Jay Mehta. Stair Descent Device Performance: Current Research and Standards Efforts (Presented by Lavender & Hedman). FEMA Getting Real II: Promising practices in inclusive emergency management for the whole community. Sponsored by the Office of Disability Integration and Coordination. Crystal City Marriott, Arlington, VA, September 14, 2011.

Research Support

Principal Investigator, Project SDD: Stair Descent Device Performance for Firefighters. U.S. Department of Homeland Security – Federal Emergency Management Agency, Washington, DC, total funding $788,205 over 3.25 years, April 19, 2010 – April 18, 2013. No-cost extension to allow for additional study aim on consumer input, April 19, 2013 – July 31, 2013.

TEACHING RESPONSIBILITIES

DHD 440 - Introduction to Assistive Technology. Lead Instructor.
DHD 441 – Adaptive Equipment Design & Fabrication. Contributing Instructor.
DHD 559 – Ergonomics & Safety for Workers with Disabilities.
DHD 569 – Environmental Modification.