SIDEWALK ROUGHNESS DATA CLASSIFICATION BY CLUSTER ANALYSIS

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SIDEWALK ROUGHNESS DATA CLASSIFICATION BY CLUSTER ANALYSIS

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SUMMARY

As sustainability becomes an important aspect of city and transportation planning, individuals are encouraged to choose walking as a mode of travel. In Atlanta, 8.6% of the population under the age 65 are individuals with disabilities, and the sidewalks are indispensable for their mobility; however, many of these sidewalks do not meet the standards of Americans with Disabilities Act (ADA) and need to be repaired.

Georgia Institute of Technology researchers developed the Semi-Automated Sidewalk Quality and Safety Assessment System to evaluate and prioritize sidewalk repair projects. This thesis extends the sidewalk roughness levels estimation developed in previous studies. The objectives accomplished in this study are: 1) comparison of the performance of two different tablets for collecting sidewalk vibration data, and 2) exploration of the effects of other related factors on the sidewalk roughness classification result.

To accomplish the first goal, k-means cluster analysis is conducted using RMS acceleration data (sidewalk vibration data) collected by Toshiba Thrive™ and Getac® Z710 tablets to classify sidewalk roughness levels. The chi-squared test and Wilcoxon signed-rank test are used to compare the clustering results from the tablets' RMS acceleration data. This thesis also explores the potential benefits of using other related factors (such as jerk and gyroscope data) on sidewalk roughness classification result. The analytical results show that both tablets generate essentially the same sidewalk roughness classification results and that the sidewalk roughness classification results are dependent of the types of input data used in clustering.

CHAPTER 1. INTRODUCTION

This study focuses on the comparison between the performance of two different devices for collecting sidewalk vibration data and the classification of sidewalk roughness using varying data inputs. As sustainability becomes an essential part of transportation planning, people are being encouraged to choose walking as the primary active mode of travel [1]. Creating a pedestrian-friendly community encourages healthy travel activity. Therefore, assessing the condition of sidewalks has become an essential element of sustainable transportation system planning. In this study, two different devices are used to collect sidewalk vibration data along a control route in the Virginia-Highland neighborhood of Atlanta, Georgia. The levels of roughness for the sidewalk in control route are assessed using k-means cluster analysis, based primarily on the sidewalk vibration data, and comparisons are conducted between the clustering results of the data collected from different measuring devices and using different variables. The effects of the different combination of input data on sidewalk roughness classification result are explored by chi-squared and Wilcoxon signed-rank tests.

1.1 Need for the Research Study

Assessing the condition of sidewalk can employ a variety of criteria, from roughness and vibration to the presence of specific sidewalk defects. Georgia Tech researchers developed a semi-automated sidewalk quality and safety assessment system that could be used to evaluate the sidewalk quality in the city of Atlanta, GA [2]. The ultimate goal of the Georgia Tech system was to prioritize pedestrian projects with the most priority. The most innovative part of this previous study involved the development of an Android™ app called Sidewalk Sentry to collect the sidewalk vibration data, GPS location data, and sidewalk video. Sidewalk vibration data, an indication of surface roughness, collected using triaxial accelerometers, was an important factor in evaluating the sidewalk quality [2]. The Toshiba Thrive™ tablet was the device used with the Sidewalk Sentry application in this previous study [31]. The team recently added a new Getac® Z710 tablet to their field studies because the Toshiba Thrive™ is no longer manufactured. Therefore, the research team needed to compare the performance between two different measuring devices for collecting sidewalk vibration data. In the previous study, the roughness level of sidewalk was classified using k-means clustering results based on the root mean square (RMS) acceleration data and the root mean square (RMS) jerk data. Therefore, there is also a need to explore the effects of different combination of input data on sidewalk roughness clustering results. This thesis study addresses all these needs.

1.2 Data and Methods Overview

The sidewalk vibration data were collected at Virginia Highland control route using a Toshiba Thrive™ tablet and Getac® Z710 tablet at the same time. The devices were affixed to a manual wheelchair and data were collected in parallel using the Sidewalk Sentry application. These two tablets were measuring the same vibrations at the same time. After the field collection, the high-frequency sidewalk vibration data were converted to second-by-second RMS acceleration data and RMS Jerk data, and gyroscope data were converted to RMS gyroscope data. The gyroscope measures the rotation around the axes, in this case, there are three gyroscope channels in each device and the rotation will be measured around three axes. K-means cluster analysis was applied to group the sidewalk in the control route into five groups based on roughness level. Chi-squared test and the

Wilcoxon signed-rank test were conducted to assess the similarity and difference between the clustering results.

1.2.1 Data Collection

The Toshiba Thrive™ tablet and Getac® Z710 tablet were affixed to a manual wheelchair and measured the same vibration at the same location. As described on detail in Chapter 3, the wheelchair was pushed along a control route in the Virginia-Highland neighborhood in Atlanta, GA at between two and three miles per hour. Three rounds of data were collected in the 1.9 miles route. Each tablet has their specific sampling rate, the average sampling rate for a Toshiba Thrive™ tablet is about 100 Hz, the average sampling rate for a Getac® Z710 tablet is about 60 Hz. The raw sidewalk vibration data included three-axis accelerometer reading and GPS information for each sample. The Toshiba Thrive™ tablet also recorded the gyroscope reading in field collection. A total 6930 seconds (nearly two hours) of vibration data were recorded during the three traverses on the control route.

1.2.2 Data Analysis

In the data analysis effect, all of the raw high-frequency three-axis accelerometer reading and gyroscope reading were converted to second-by-second RMS acceleration data, RMS Jerk data, and RMS gyroscope data to reduce the effects of tablets' orientation on the wheelchair. To compare the performance between two tablets for collecting sidewalk vibration data, the distribution of resulting RMS acceleration data processed from raw vibration data collected by both tablets, and the distribution of the difference in the values of two tablets' RMS acceleration data for each sample, were assessed. The distribution of RMS acceleration was used to compare the sensitivity of both tablets and the distribution of the difference in the values of two tablets' RMS acceleration was used to check the similarity between the data collected by both tablets. The satellite time was used for data matching.

The k-means cluster analysis was used to classify the roughness level of the sidewalk in control route. Five sample groups which represented "Lowest", "Low", "Medium", "High" and "Highest" levels of roughness were generated by applying the k-means cluster analysis on the sample's RMS acceleration data processed from the two tablets separately. After clustering, each sample from the same sidewalk location has two roughness scores, the first score from Toshiba cluster analysis, and a second score from the Getac® cluster analysis. The distribution of the difference between the roughness scores of each sample was also assessed. The chi-squared test would be applied to test whether the sidewalk roughness clustering result was dependent of the type of measuring device when the RMS acceleration data were used as input and the Wilcoxon signed-rank test would also be applied to test whether the median difference between the roughness scores assigned by two clustering results was zero. The cut points of each group for both tablets were also identified.

To explore the effects of different combination of input data on sidewalk roughness clustering result, the sidewalk vibration data collected by Thrive™ tablet were used. All three-axis accelerometer reading and gyroscope reading were converted to RMS acceleration data, RMS Jerk data, and RMS gyroscope data. Three clustering results would be generated based on RMS acceleration data, the combination of RMS acceleration data and RMS jerk data, and RMS gyroscope data. These three clustering results would be used to test the effect of adding RMS jerk data on the sidewalk roughness clustering result and the effect of using RMS gyroscope data on the sidewalk roughness clustering result. The chi-squared test would be applied to test whether the distributions were significant different and the Wilcoxon signed-rank test would be applied to test whether the median difference between the clustering scores of the test sample in each case was zero.

1.3 Overview of Results

After conducting the data collection and analysis, the results indicate that the Getac® Z710 tablet accelerometers are more sensitive to sidewalk vibration, yielding a wider spread of RMS acceleration for the sidewalk sections and different vibration cut points for the five classifications. However, the final classification results generated by both tablets and their respective cluster cut points are essentially the same.

The largest differences in roughness scores occur for sidewalk sections at higher roughness conditions, where sub-second vibration data are more variable. The chi-squared test and Wilcoxon signed-rank test indicate that the sidewalk roughness clustering result is independent of the types of measuring device and the median difference of the samples' two roughness scores assigned by two clustering results is zero. In essence, the devices yield the same roughness clustering results.

Interestingly, different combinations of input data (acceleration, jerk, gyro readings, etc.) do impact sidewalk roughness classifications when using multi-variable k-means cluster analysis. From the k-means clustering results based on the different combinations of input variables, chi-squared test result, and Wilcoxon signed-rank test result, the study indicates adding RMS jerk data into the k-means cluster analysis for sidewalk roughness classification can yield a larger spread in the index scores across the samples, which could prove useful in the future.

1.4 Thesis Contents

Chapter 2 of this thesis contains the literature review and important previous studies and concepts which related to this study. Chapter 3 contains the detailed methodology and the field data collection of this study. Chapter 4 presents the results and discussion of this study. Chapter 5 contains the conclusion of this study.

CHAPTER 2. LITERATURE REVIEW

2.1 Sidewalk Roughness and Pedestrian Mobility

Sidewalk design and quality assessment is attracting more and more attention as an important part of community and transportation planning. Sidewalks separate pedestrians from the roadway and provide a safe and comfortable space for walking. As stated by Jennifer Evans-Cowley in her study about sidewalk planning in small cities, there is an urgent need for transportation planner to improve the conditions for pedestrians due to the growing interest in walking [3]. Sidewalks can attract mobile urbanites and firms and support stationary activities [4]. The Transportation system that encourages walking can help reduce traffic congestion and improve the safety of motorists [3]. An essential step for achieving urban sustainability is reducing society's dependence on the automobile [5]. Also, as sustainability plays an important role in transportation planning, people are encouraged to choose walking as the mode of travel [1]. Several previous studies show that sidewalks are beneficial to safety, mobility, and human health [6]. A 1987 FHWA study shows that the pedestrian crash rate is more than twice as high for the roadways without sidewalks than the roadways with sidewalks on both sides [7]. Eyler, et al., had conducted a study shows that when sidewalks are accessible for people, people are more willing to walk and reduce the physical inactivity which could cause obesity, diabetes, and heart disease [8]. Most importantly, sidewalks provide a safe and accessible space for members of the disability community as well as the general public.

More than 2 million citizens in the United States regularly use wheelchairs [9]. According to the 2016 Disability Status Report conducted by Cornell University, there are

7.1 percent of all ages have an ambulatory disability and 2.4 percent of all ages have a visual disability [10]. Therefore, accessible and good quality sidewalks are essential for the disability community to fully participate in work, education, commerce, services, etc.

In 1990, Congress adopted the American with Disabilities Act (ADA) to protect the civil rights of disabled citizens, with a special focus on providing equal access for people with disabilities to schools, workplaces, and any other public spaces. The Title II of the ADA required that all new facilities and buildings be accessible to the people with disabilities. Also, transportation agencies were required to develop a transition plan to update the existing facilities to meet the requirement of accessibility of ADA [11]. In 1991, the Department of Justice published the ADA Standards for Accessible Design [12]. The U.S. Access Board (USAB) published the first definitive ADA Accessibility Guidelines (ADAAG) in 2002 which defined the standards for sidewalk and curb ramp design. The USAB ADAAG (USAB guidelines) have been revised in 2004, 2006, and 2010 (the latest requirements for pedestrian infrastructure design) [13].

Unfortunately, many of sidewalks in Atlanta do not meet the ADA standards [2]. Poor quality sidewalks are harmful to pedestrians and put people with disabilities at risk. Identifying and ranking poor quality sidewalks is a tough task, and the lack of spatial sidewalk inventories is another obstacle for transportation agency to improve the sidewalk quality. To help solve these problems, a Georgia Institute of Technology research team developed a semi-automated sidewalk quality and safety assessment system, which was designed to help transportation and planning agencies to prioritize sidewalk improvement and pedestrian infrastructure improvement projects in 2015 [2]. The sidewalk assessment system included an Android™ sidewalk quality assessment application and implementation of a weighted ranking system. The sidewalk quality assessment Android application is called Sidewalk Sentry and can be installed on Android™ system tablets to collect sidewalk video, accelerometer data, and gyroscope data for evaluating sidewalk quality. The weighted ranking system was used to rank the sidewalks based on their quality [31]. The weighted ranking system incorporated the field data collected by Sidewalk Sentry with pedestrian safety indicators, the land use data, and demographic data. The sidewalk surface roughness was one of the most important factors to indicate the overall sidewalk quality in the system. Grouping sidewalks based on their surface roughness levels was one technique that the research team applied in developing the weighted ranking system. Developing the entire automated sidewalk quality and safety assessment system was a complex and time-consuming, hence, this study will only focus on the techniques of collecting and analyzing sidewalk roughness data. The result of this study will be beneficial for the future study and the improvement of sidewalk quality and safety assessment system.

2.1.1 Americans with Disabilities Act (ADA) Requirements

Building good quality sidewalk is essential for people with disabilities or visual impairment to work and travel, especially for the people who use the wheelchair. Although most pedestrian facilities are currently accessible for people with disabilities, it is important to note that there was a long time in American history that schools, workplaces, and other public spaces were not accessible for the disability community which diminishes the disabled's right to participate in all parts of society [11]. In 1990, the Americans with Disabilities Act (ADA) was adopted by Congress to reduce the discrimination against the disability community in all aspects of society including the pedestrian facilities. The first definitive ADA Accessibility Guidelines (ADAAG) were published by U.S. Access Board (USAB) in 2002, which defined the standards for sidewalk and curb ramp design.

2.1.1.1 ADA Background

Members of the disability community have historically not been treated equally in employment and public spaces were not accommodated for people with disabilities [2]. In the 1960's Congress found that discrimination against people with disabilities was occurring in many essential aspects of society, such as housing, employment, education, transportation, health services, and voting [2] [11]. The lack in legal system also caused the people with disabilities had no legal recourse to indict these discrimination [11].

The Americans with Disabilities Act (ADA) was introduced by Congress in 1988 and signed into law in 1990 [2]. The goals of ADA were to diminish discrimination against individuals with disabilities and provide enforceable standards to prevent the discrimination against individuals. There are five titles in the ADA, Title I defined disability and required the same employment opportunities for people with disabilities. Under Title I of ADA, the employers are required to provide accommodations to the employees with disabilities. Title II prohibits discrimination against people with disabilities in public entities operated by state and local government agencies. Under Title II, the state and local governmental operated facilities should be accessible to people with disabilities. The necessary update should be done in the current governmental facilities to guarantee they were accessible to disabled. Title III prohibits discrimination against people with disabilities in public accommodations and services operated by private entities such as restaurants, private schools, and movie theaters. Title IV supports the right of people with hearing or speech disabilities to communicate over the telephone. Title V provides the miscellaneous provisions information.

The ADA Standards for Accessible Design were published in 1991 and the first definitive ADA Accessibility Guidelines (ADAAG) was published by U.S. Access Board (USAB) in 2002. The standards for sidewalk and curb ramp designs were included in ADAAG. The ADAAG has been revised by several times, the latest ADAAG for pedestrian infrastructure design is 2010's edition of ADAAG.

2.1.1.2 Sidewalks and the ADA

The ADA Accessibility Guidelines (ADAAG) provides the standards for sidewalk and curb ramp design. The first definitive ADA Accessibility Guidelines (ADAAG) was published by U.S. Access Board (USAB) in 2002 and the latest version of ADAAG is 2010's version. Table 1 summarizes the ADAAG design standards for sidewalk width, running slope, cross-slope, obstructions, pavement material, change in level, and vertical clearance [13].

Table 1. Standards for Sidewalk Design.

Sidewalk Design Features	ADAAG Standards (2010 version)
Clear Sidewalk Width	36 inches (915 mm) minimum at the walking surfaces. 60 inches (1525 mm) minimum at the turn.
Running Slope	Not steeper than 1:20 (5%) for walking surface.
Cross-Slope	Not steeper than 1:48 (2%) for walking surface.
Obstructions	Obstruction should be clear from the walking surface.
Pavement Material	Walking surface should be safe, non-corrosive, and firm.

Table 1 Continued

Change in Level	Vertical: ¼ inch (6.4 mm) high maximum. Beveled: Between ¼ inch (6.4 mm) high minimum and ½ inch (13 mm) high maximum with a slope not steeper than 1:2. Ramps: Higher than ½ inch (13 mm).
Vertical Clearance	80 inches (2030 mm) high minimum.

2.1.2 Sidewalk Quality in Atlanta

The total length of sidewalk network in Atlanta is about 2,200 miles, as estimated by the City of Atlanta [14] [15]. Although the motor vehicles still dominate the travel modes choice in Atlanta, 4.7% of commuters in Atlanta walk to work and 10.3% of them choose public transportation which includes a quarter mile walking distance on the trips [16]. Also, according to United States Census Bureau's data from 2012 to 2016, 8.6% of population under age 65 years in Atlanta have a disability [17]. Therefore, the sidewalks with good quality are essential for many people to work, travel, and live in Atlanta and poor quality sidewalks should be repaired quickly. However, many sidewalks in Atlanta are in bad condition, which can be harmful for pedestrians, especially for those people with disabilities. According to the 2010 Department of Public Works State of the Infrastructure

Report, 18% of the sidewalks and 10% of curb ramps require repair. The City of Atlanta estimates that $152 million in funding is needed to repair these poor quality sidewalks [15]. The City of Atlanta was litigated from the U.S. Department of Justice (USDOJ) for the bad quality sidewalks which not met the standards of the Americans with Disabilities [18]. In 2015, the "Renew Atlanta" 2015 infrastructure bond passed by the residents in Atlanta; the bond will allot $187.9 million to transportation projects [19]. The amount of the bond which would be used in pedestrian infrastructure projects was not determined, but even the total amount of the bond is not enough to cover all the budget needed for repairing all bad quality sidewalks in Atlanta. Therefore, prioritizing the sidewalk projects is crucial so that funding can be allotted to the project with the highest priority.

2.2 Previous Sidewalk Quality Research Efforts

Several studies related to sidewalk quality measuring have been done before. The two most relevant studies were the study of developing the automated sidewalk quality and safety assessment system conducted by the research team at Georgia Tech and the study of developing the surface roughness standards for pathways used by wheelchairs which conducted by the research team at the University of Pittsburgh.

2.2.1 Sidewalk Quality and Safety Assessment

The 2015 sidewalk quality and safety assessment study was conducted by Guensler, et al., in Atlanta, GA. The goal of the study was to develop an automated sidewalk quality and safety assessment system to evaluate the sidewalk condition to prioritize the sidewalk improvement projects better [2]. Although a 100% automated sidewalk quality and safety assessment system was not successfully developed in this study, a semi-automated sidewalk quality and safety assessment system was generated successfully and can be used to objectively prioritize the sidewalk infrastructure project based on the different needs of the local community [31]. The methodology and the results of this study had profound impacts on further pedestrian facilities studies at Atlanta.

For the first step, the research team developed a sidewalk quality assessment Android™ application called Sidewalk Sentry™ which could be installed on an Android™ system electronic device. The Sidewalk Sentry™ application collects vibration data of sidewalk via accelerometer and gyroscope data. The accelerometer data were used to assess and identify the surface roughness level which was one of the factors for prioritizing the sidewalk projects. The Sidewalk Sentry™ application also collects the sidewalk video and GPS location data, and the research team developed a semi-automated video system to conduct width estimation and sidewalk defects identification under ADA standards [31]. With the Sidewalk Sentry™ application and the video analysis system, the research team successfully collected and analyzed 1,352 miles of sidewalks in Atlanta, these data and video analysis results are stored in a web database and were available to the City of Atlanta, Atlanta Regional Commission, and the Georgia Department of Transportation [2].

A weighted ranking system was later developed for prioritizing the sidewalk project based on different needs of the local communities [31]. Several variables and index weighting parameters like ADA index were included in the weighted ranking system, the users were allowed to prioritize the sidewalk project with different variables or indices to meet any specific objectives [2]. These variables and index weighting parameters were generated from the sidewalk quality data collected by Sidewalk Sentry™ application, pedestrian activity data, pedestrian crash data, demographic data, and population density data. The weighted ranking system has been used in a subarea of Midtown Atlanta to prioritize the pedestrian project investments based on the block-level pedestrian potential and deficiency variables. The results showed the blocks near rail stations, the Georgia Tech, and Technology Square should be prioritized [2] [31].

2.2.2 Vibration and Sidewalk Surfaces

In 2013, Jonathan Pearlman and his research team at the University of Pittsburg conducted a study to develop sidewalk surface roughness standards for pathway design. The lack of standards for designing a sidewalk surface under the ADA inspired their research team to explore sidewalk roughness measurements and generate a set of standards that could be used to assess sidewalk surface quality, especially for the people who must use the wheelchair to travel [9]. The study examined the relation between the surface roughness, subjective user response of roughness perception, and the vibration data collected from the accelerometer at the wheelchair [9]. In this study, 61 people were invited to participate and each of them would travel over nine surfaces with known varying roughness by the wheelchair [9]. Accelerometers were installed in wheelchairs to record the acceleration data along the x, y, and z axes. These data were considered to be the sidewalk surface vibration data. After traveling over the surfaces, participants were required to rate the roughness of each surface, the rating scale was from 0 to 5, 0 represented very poor and 5 represented very good. The three-directions acceleration data were converted to one direction RMS acceleration data to conduct the analysis. The result showed that the RMS acceleration increased with the increasing of surface roughness, and the rating from the participants decrease [9]. The result of this study provides a direct exploration of the relationship between the perceived sidewalk roughness and the surface vibration data.

2.3 Basic Concepts of Vibration Measurement

The concept of vibration and its measurement is important for this study. The International Standard ISO 2631-1 provides complete information about the concepts of vibration and its measurement [20]. Exposure to whole body vibration can cause discomfort and at high levels can lead to health risk [20]. The ISO 2631-1 standard can be used to test the vibration for vehicles and define the acceleration as the primary quantity of vibration magnitude and the acceleration should be measured based on a coordinate system originating at the point where the vibration enters the human body [20]. The measurement process of vibration includes averaging vibration over time and frequency bands, and it is common to use weighted root-mean-square acceleration to evaluate the quantity of surface vibration [20]. The equation for calculating weighted root-mean-square acceleration is shown below [20]:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{0.5}$$

Where $a_w(t)$ is the weighted acceleration as a function of time and T is the duration of the measurement.

In vibration analysis, it is necessary to combine the accelerations for the three component directions (x, y, and z) into a single acceleration value for analyzing the vibration related to comfort issues [20]. Generating weighted root-mean-square accelerations for three conventional directions into a single weighted root-mean-square acceleration is presented in the equation below:

$$a_v = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{0.5}$$

Where a_{wx}, a_{wy}, and a_{wz} are the weighted root-mean-square accelerations with respect to the orthogonal axes x, y, z, respectively and k_x, k_y, k_z are weighting factors [20].

The vibration measurement is always included in medical studies. DiGiovine, et al conducted a study to compare the four different cushions' ability to minimize the vibration transmitted from the wheelchair [21]. The vibration data were measured by the triaxial accelerometer install on the wheelchair's seat tubes [21]. Wolf, et al., had conducted another study which evaluated the amount of vibration transmitted to the wheelchair users [22]. The triaxial accelerometer mounted on the wheelchair was also used for measuring vibration data [22].

2.4 Existing Methodology for Measuring Sidewalk Roughness

The main focus of this study is classifying sidewalk roughness levels. Several previous studies related to sidewalk roughness measurement and classification were identified and reviewed. In both the Georgia Tech and Pearlman studies, sidewalk roughness levels were measured using vibration data [2] [9]. The Georgia Tech study converted the sidewalk vibration data into root-mean-square (RMS) accelerations and applied k-means cluster analysis to the RMS acceleration data to classify the sidewalk roughness levels [2].

Triaxial accelerometers record three orthogonal-axes acceleration data which can be related back to the severity of surface defects. In previous research efforts, three-axis acceleration data were converted into RMS acceleration data for use in vibration assessment. Pearlman's study concluded that perceived sidewalk surface roughness level is highly correlated with the surface vibration data [9]. The Georgia Tech research effort also utilized sidewalk vibration data to categorize the sidewalk roughness levels [2]; however, these data were not tied to consumer perceptions. Instead, the Georgia Tech study employed cluster analysis to group sidewalk roughness conditions along a control corridor that contained a comprehensive cross-section of sidewalk conditions.

2.5 Sidewalk Roughness Assessment and the Getac® Z710 Tablet

Sidewalk roughness is an important factor in semi-automated sidewalk quality and safety assessment system developed by the Georgia Tech research team [2]. The sidewalk roughness was classified by the value of RMS acceleration data which derived from the sidewalk vibration data [2]. The paper by Akanser, et al., explained the methodology for classifying sidewalk roughness levels [23]. The research team considered the RMS acceleration data was positively correlated with the sidewalk roughness level and k-means cluster analysis with L1 (city-block) distance was applied to group the RMS acceleration data [23]. Five groups of sidewalk roughness data were generated by k-means cluster analysis, the initial centroids of these five groups were the RMS acceleration values of the data samples at 10th, 30th, 50th, 70th, and 90th percentiles. Each group represented a level of sidewalk roughness from "worst" to "best" [23].

In the previous Georgia Tech study, sidewalk vibration data were collected by the Toshiba Thrive™ tablet running the Sidewalk Sentry™ Android™ application which recorded sidewalk video as well as three-axis acceleration data [2]. The performance of the Toshiba Thrive™ tablet was stable and met the research requirements. Unfortunately, the Toshiba Thrive™ tablets are no longer being manufactured, and new sidewalk vibration equipment is needed to continue research efforts. The research team had tested several alternative tablets which included Nexus 7 tablet, Nexus 10 tablet, Samsung Galaxy Tab 2 tablet, and iPad Mini tablet, but none of these tablets met the team's research requirements [2]. The Getac® Z710 is the new tablet that introduced by the research team, and there was a need to evaluate whether the Getac® Z710 system could meet the field research needs of the team and whether the new system performed comparably to the old system.

CHAPTER 3. METHODOLOGY AND DATA COLLECTION

3.1 Goals, Objectives, and Hypotheses

This study compares the performance of two different tablets for collecting sidewalk vibration data and also compares the sidewalk roughness clustering results across these tablets using different data inputs. Because the sidewalk roughness parameter is an important factor used in the semi-automated sidewalk quality and safety assessment system, and because the previous tablets used to collect vibration data are no longer manufactured, there is an urgent need to find an alternative tablet to meet the measuring requirements for the future study. Besides, there is a need to explore other factors that may also relate to sidewalk roughness levels.

In this study, two types of tablets are tested for their performance of collecting sidewalk vibration data; the Toshiba Thrive™ tablet and Getac® Z710 tablet. The hypothesis is the performance of these two tablets for classifying sidewalks using cluster analysis of sidewalk vibration data is the same.

To explore other factors that may be useful in sidewalk roughness levels classification, the effect of adding jerk (rate of change of acceleration) data into sidewalk roughness classification, and the effect of using gyroscope data in sidewalk roughness classification are explored. The hypotheses are:

1. Adding jerk data into sidewalk roughness classification will yield different clustering results than using only acceleration input.

2. The clustering result of sidewalk roughness classification with only gyroscope data input will be different than the clustering result of sidewalk roughness classification using only acceleration data input.

The methodology of this study would be explained in the further sections below.

3.2 Methodology Overview

All of the analyses in this study begin with sidewalk vibration data collection. The Toshiba Thrive™ tablet and Getac® Z710 tablet are used for collecting the sidewalk vibration data. For each tablet, the Android™ Sidewalk Sentry app is installed on the system. Sidewalk Sentry would record the vibration data, GPS location data, and sidewalk video during the collecting process. The two tablets are mounted onto a high-density polyethylene platform, installed on a standard manual wheelchair with the brand of INVACARE. While the wheelchair traveling through the control route, the sidewalk vibration data are automatically collected by both tablets at the same time. The setup for the wheelchair and tablets is shown in Figure 1.

Figure 1. The Wheelchair and Tablets Setup.

After data collection, the raw sidewalk vibration data are processed into several formats including RMS of raw acceleration data, RMS jerk data, and RMS gyroscope data. These data are used to the analysis of sidewalk roughness level classification. For the sidewalk roughness classification process, k-means clustering is applied to group the sidewalks based on the roughness level, the chi-squared test and Wilcoxon signed-rank test are used to test the difference between the clustering results. The detailed methodology would be explained in following sub-sections.

3.2.1 Data Collection Overview

A sidewalk pathway in Virginia Highland was chosen as the control route due to its highly variable sidewalk quality conditions. This control route is referred from the previous automated sidewalk quality and safety assessment system study conducted by Georgia Tech and the map is shown in Figure 2 [2]. The length of route is about 1.9 miles and starts from Highland Terrace NE. The route is characterized by diverse topography. The pavement types for the entire route is vary, from smoothed concrete to rough hexagonal pavers. The widths and the grades of the entire control route are also diverse. The widths along the route are inconsistent, and a few stretches are missing parts of the sidewalk. The grades of the route are steep in some places, and some surfaces are very rough. The overall quality of the sidewalk on the control route is poor, the cracks and higher vertical displacements could be found throughout the route and the Figure 3 through Figure 8 below show the varying characteristics and sidewalk defects along the route.

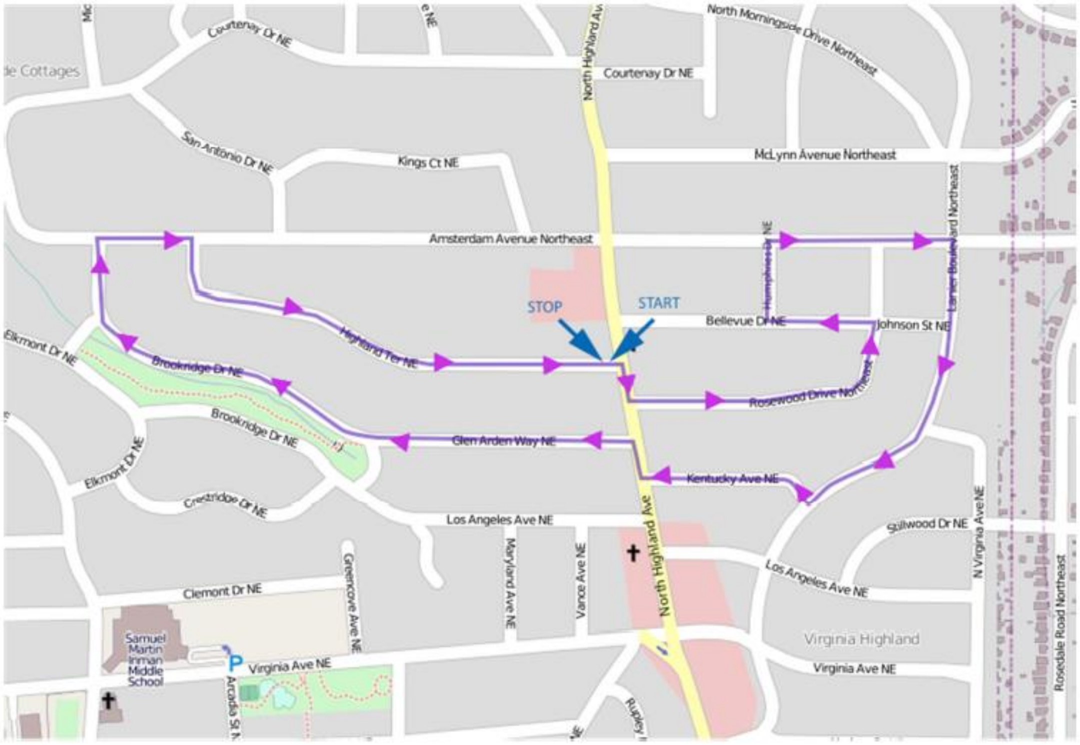

Figure 2. The Map of Control Route [2].

Figure 3. The Concrete Pavement of Control Route.

Figure 4. The Mix Type Pavement of Control Route.

Figure 5. The Hexagonal Pavement of Control Route.

Figure 6. The Surface Crack along the Control Route.

Figure 7. The Vertical Displacement along the Control Route.

Figure 8. The Missing Sidewalk along the Control Route.

Data collection was conducted during clear weather to ensure good quality video data. Three rounds of measurements were performed along the control route. In each round, the wheelchair is pushed in a steady speed which is around 1.5 miles/sec to 2.0 mile/hour along the control route without stopping for more than a few seconds to cross streets. While the wheelchair is moving along the sidewalk, the Sidewalk Sentry app automatically collects sidewalk data which include accelerometer (vibration) data, gyroscope (rotation) data, GPS location data, and sidewalk video. After the three rounds of data collection, the raw data are downloaded into a computer to start the data processing.

3.2.2 Data Processing

The accelerometer data includes data streams for x, y, and z axes (triaxial accelerometer data). For Toshiba Thrive™ tablet, the sampling rate is about 100 Hz. Therefore, 100 samples will be measured in each second. The sampling rate for Getac® Z710 is about 60 Hz.

The timestamps associated with data collection are derived by the app from GPS signals. The time stamp increments once per second. Hence, for readings taken at 100 Hz, the time stamp remains unchanged for 100 values. The GPS location data includes the time ID, latitude, longitude, and speed information for each second. Gyroscope sensors on the Toshiba Thrive unit provide data from three rotational axes (roll, pitch, and yaw). Three axis gyroscope data values and ID are also included in each sample measurement.

The tri-axis acceleration data values for each individual reading at 100 Hz (Thrive) or 60 Hz (Getac) are combined into a total acceleration value by the equation below:

$$a_{Total} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

Where a_{Total} is the total acceleration value for each sample, a_x is the acceleration value for x-axis, the a_y is the acceleration for y-axis, the a_z is the acceleration for z-axis. The direction for each axis is shown in Figure 9. This process is conducted for both tablets' data.

Figure 9. Tablet Setup and Axis Directions for Acceleration.

For the purpose of comparing the performance of two different tablets for collecting sidewalk vibration data, both tablets' total acceleration data are converted into second-by-second RMS acceleration data, based on the equation provided by International Standard ISO 2631-1 for one-second interval.

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{0.5}$$

Where $a_w(t)$ is the weighted acceleration as a function of time and T is the duration of the measurement [20]. The results of two tablets' RMS acceleration data are matched by Time ID; therefore, second-by-second RMS acceleration data values are time-aligned and occur at the same location during data collection.

For the purpose of exploring the effect of adding RMS jerk data on sidewalk roughness classification, the total acceleration data for Toshiba Thrive™ tablet are converted into one-second RMS acceleration data. The RMS jerk data are determined by calculating the derivative of total acceleration data and then converted into one-second RMS value. To the effect of using RMS gyroscope data into sidewalk roughness classification, the total gyroscope data for each sample of Toshiba Thrive™ tablet are determined by the same approach of calculating total acceleration data, then the RMS gyroscope data are derived by the equation provided by International Standard ISO 2631-1 for one-second intervals.

3.2.3 Cluster Analysis and Tablet Performance Comparisons

To compare the performance of collecting sidewalk vibration data by two tablets, the resulting RMS acceleration data are used to represent and analyze each tablet's performance in collecting sidewalk vibration data. There are three objectives related to performance comparison in this study:

1. Sensitivity analysis of data collected across the two tablets.
2. Applying k-means cluster analysis to the two tablets' RMS acceleration data separately to classify the sidewalk roughness levels.

3. Comparing the clustering results derived from two tablets' RMS acceleration data.

To compare the sensitivity of two tablets, the distribution of RMS acceleration data for each tablet's data are generated and the range of the distribution plots are compared. The distribution with a wider range of values indicates a higher sensitivity. The distribution of the difference in the values of two tablets' RMS acceleration data for each sample is also assessed.

For classifying the sidewalk roughness levels, the k-means cluster analysis method will be applied. The k-means cluster analysis is an analysis method for finding and grouping cohesive groups in data [24]. The analysis starts from K tentative centroids, then repeat the following steps:

a) Collecting data around the centroids to form the cluster.
b) Updating centroids as the clusters' means.

These two steps will repeat until the centroids are not changing [24]. Also, the distance metric plays an important role in k-means cluster analysis, the distance metric calculates the distance between the element to centroid and determine how the similarity of two elements is calculated [25]. There are four common distance metrics that are typically used in k-means cluster analysis:

1. Euclidean distance: The root of square difference between coordinates of pairs of objects [25]. It can be defined as the straight-line distance between the two points. The equation for calculating the Euclidean distance is shown below:

$$DIST_{XY} = \sqrt{\sum_{k=1}^{m}(X_{ik} - X_{jk})^2}$$

Where $DIST_{XY}$ is the Euclidean distance object X and object Y, the X_{ik} and X_{jk} are the coordinates of the two objects and there are number of m coordinates for each object [25].

2. Manhattan distance: The absolute differences between coordinates of pair of objects (also known as city-block distance) [25]. The equation for calculating the Manhattan distance is shown below:

$$DIST_{XY} = |X_{ik} - X_{jk}|$$

Where $DIST_{XY}$ is the Manhattan distance between object X and object Y, the X_{ik} and X_{jk} are the coordinates of the two objects [25].

3. Chebyshev distance: It is also known as the maximum value distance. The distance is determined by the absolute magnitude of the differences between coordinates of a pair of objects [25]. The equation is shown below:

$$DIST_{XY} = max_k|X_{ik} - X_{jk}|$$

Where $DIST_{XY}$ is the Chebyshev distance between object X and object Y, the X_{ik} and X_{jk} are the coordinates of the two objects [25]. The Chebyshev distance could be used in warehouse logistics [26].

4. Minkowski distance: The generalized metric distance [25]. It can be used for both ordinal and quantitative variables [25]. The equation is shown below:

$$DIST_{XY} = (\sum_{K=1}^{d}|X_{ik} - X_{jk}|^{\frac{1}{p}})^p$$

As shown in the equation, when p equals two, the distance becomes Euclidean distance and when p equals one, the distance becomes Manhattan Distance [25].

The study shows that using different distance metrics in k-means cluster analysis could result in the different clustering result, the distortion in k-means clustering result with Manhattan distance metric is less than the result with Euclidean distance metric [25]. From the previous work conducted by Georgia Tech researchers, the sidewalk roughness levels were classified by using k-means cluster analysis with Manhattan distance metrics [23]. In this study, the Manhattan distance metrics is also used.

The k-means cluster analysis is applied to the both tablets' RMS acceleration data to classify the sidewalk roughness levels. The clustering results for each tablet' RMS acceleration data will be compared later. The initialization centroids are the RMS acceleration data samples at 10^{th}, 30^{th}, 50^{th}, 70^{th}, and 90^{th} percentiles which represent "Lowest", "Low", "Medium", "High", and "Highest" levels of sidewalk roughness. The final clustering result for each tablet's RMS acceleration data contains five groups which represent five levels of sidewalk roughness levels. A roughness score is assigned to each sample in each tablet's clustering result based on the group that is belonged to. The range of scores is from one to five, the one represents the "Lowest" condition of sidewalk roughness level and the five represents the "Highest" condition of sidewalk roughness level. As mentioned before, each sample represents the measurement of a specific location, for the same location, there will be two vibration data measurements by two tablets at the same time and has two RMS acceleration values accordingly; therefore, it will also have two roughness scores from two tablets' clustering results. The comparison between the roughness scores for each measured location will be conducted by generating the distribution plot of the difference between the roughness scores for the same location.

The clustering results of two tablets' RMS acceleration data are compared by chi-squared test and Wilcoxon signed-rank test. The chi-squared test is used to test the independence of two categorical variables and could be used to compare the distribution of clustering results [18] [27]. In this case, the chi-squared test is used to test whether the distribution of sidewalk roughness clustering results are dependent of the type of tablets for collecting data. The Wilcoxon signed-rank test is used to test whether the median difference of two data samples is equal to some value [28]. When the sample size is large, the distribution of the Wilcoxon signed-rank test statistic becomes a normal distribution approximately [29]. In this case, the Wilcoxon signed-rank test is used to test whether the median difference between the roughness scores assigned by two clustering results is zero.

In the end, the cut points of two tablets' clustering results will be assessed to establish numerical standards of sidewalk roughness classification. The cut point is defined as the boundary of two roughness level groups. Four cut points will be determined for each clustering result to distinguish five roughness level groups, all the samples between two cut points should belong to the same roughness level group. This process is conducted using the RStudio and could be tested by R programming to find whether the cut points meet the criteria. [30]

3.2.4 Cluster Results Comparison and Hypotheses Testing

To explore other factors which may relate to the sidewalk roughness levels, only the sidewalk vibration data collected by the Toshiba Thrive^{TM} tablet will be used. The effect of adding RMS jerk data into sidewalk roughness classification and the effect of using RMS gyroscope data into sidewalk roughness classification are explored.

To explore the effect of adding RMS jerk data into sidewalk roughness classification, k-means cluster analysis will be applied to the Toshiba Thrive^{TM} tablet's raw RMS acceleration data and the combination of Toshiba Thrive^{TM} tablet's raw RMS acceleration data and raw RMS jerk data. The chi-squared test is used to test whether the distribution of clustering results are independent of whether using the RMS acceleration data only or using the combination of RMS acceleration and RMS jerk data. The Wilcoxon signed-rank test is used to test whether the median difference between the roughness scores assigned by two clustering results is zero.

To explore the effect of using RMS gyroscope data in sidewalk roughness classification, k-means cluster analysis will be applied to the Toshiba Thrive^{TM} tablet's raw RMS acceleration data and the Toshiba Thrive^{TM} tablet's raw RMS gyroscope data. The chi-squared test is used to test whether the distribution of clustering results are independent of whether using the RMS acceleration data or using the RMS gyroscope data. The Wilcoxon signed-rank test is used to test whether the median difference between the roughness scores assigned by two clustering results is zero.

3.3 Limitations of the Methodology

With respect to data accuracy, the data collection process includes several limitations. First, the wheelchair cannot be manually pushed at a constant speed throughout the entire data collection session, and wheelchair speed does affect vibration readings [11]. Second, the position of two tablets are proximal, but not identical. They cannot be mounted at exactly the same location on the platform, which may impact each tablet's relative accelerometer's performance. Third, the comparison of the performance of collecting sidewalk roughness data by two tablets are based on the analysis of parallel collection of RMS acceleration data. Therefore, the results of this methodology should only be applied to RMS acceleration data as input for sidewalk classification.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Data Descriptive Statistics

The mean, standard deviation, and root mean square values of each tablet's acceleration, jerk, and gyroscope data are calculated per second as outlined in Chapter 3. Gyroscope data are not available as an instrument data stream from the Getac® Z710. The detailed descriptive statistics are shown in Table 2. The acceleration is in the unit of the meter per second square, the data collected by the Toshiba Thrive™ has higher mean and RMS acceleration values.

Table 2. The Descriptive Statistics of Sidewalk Vibration Data.

Tablets	Toshiba Thrive™	Getac® Z710
Mean Acceleration (m/sec^2)	10.84	10.54
St. Dev. Acceleration (m/sec^2)	0.54	1.2
RMS Acceleration (m/sec^2)	11.88	11.66
St. Dev RMS Acceleration (m/sec^2)	0.68	1.6
Mean Jerk (m/sec^2)	0.004	0.04
St. Dev. Jerk (m/sec^3)	6.86	7.44
RMS Jerk (m/sec^3)	676.34	411.172
St. Dev RMS Jerk (m/sec^3)	93.59	97.99
Mean Gyroscope data	0.44	NA
St. Dev. Gyroscope	0.17	NA

Table 2 Continued

RMS Gyroscope	0.52	NA
St. Dev. RMS Gyroscope	0.23	NA

The distributions of two tablets' RMS acceleration data are shown in Figure 10, and the distribution of the difference in the values of two tablets' RMS acceleration data for each one-second sample is shown in Figure 11. The range of the distribution of Getac® Z710's RMS acceleration data is wider than that of the Toshiba Thrive (Figure 10). However, as seen in Figure 11, the distribution of the difference in the acceleration data across the two tablets' RMS acceleration data is approximately normal. However, the result of chi-square goodness of fit test for the normality of the difference in the acceleration data across the two tablets' RMS acceleration data shows that the distribution is not normal, the statistic value for this distribution is 951.62 which is far greater than the 7.815 which represents the critical value of the level of significance of 0.05. But, given the very large number of data points collected, this is not surprise.

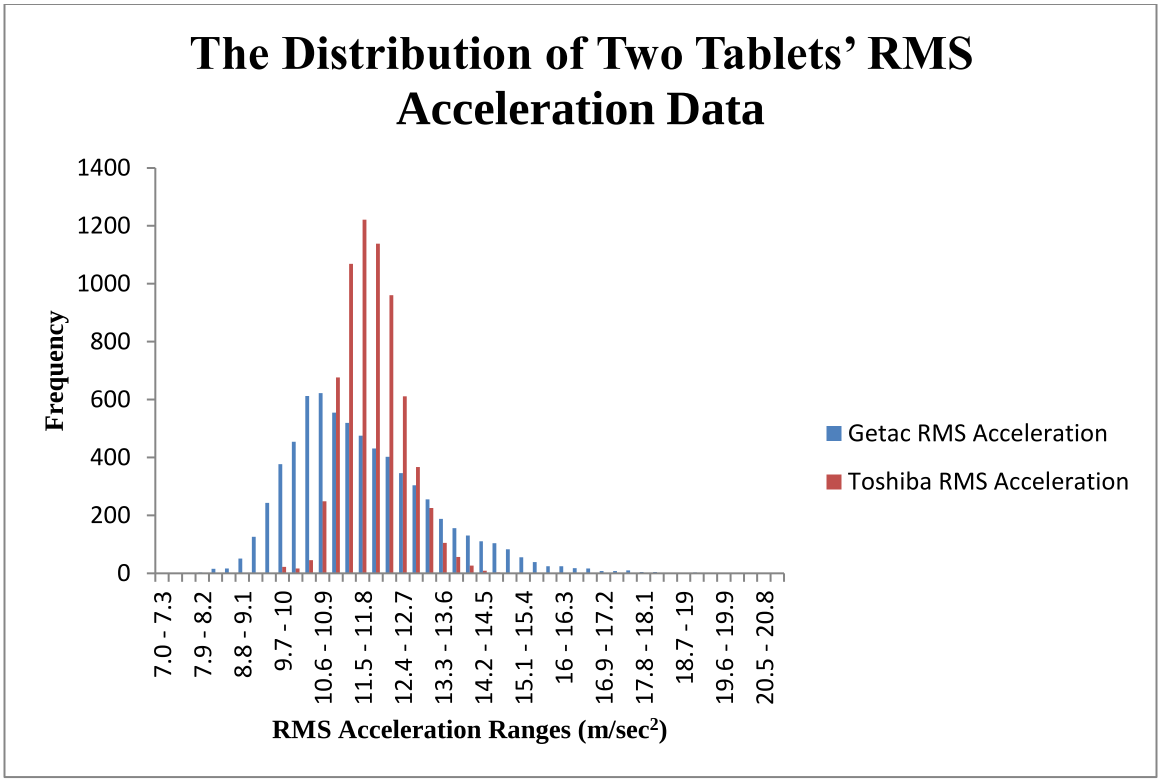

Figure 10. The Distribution of Two Tablets' RMS Acceleration Data.

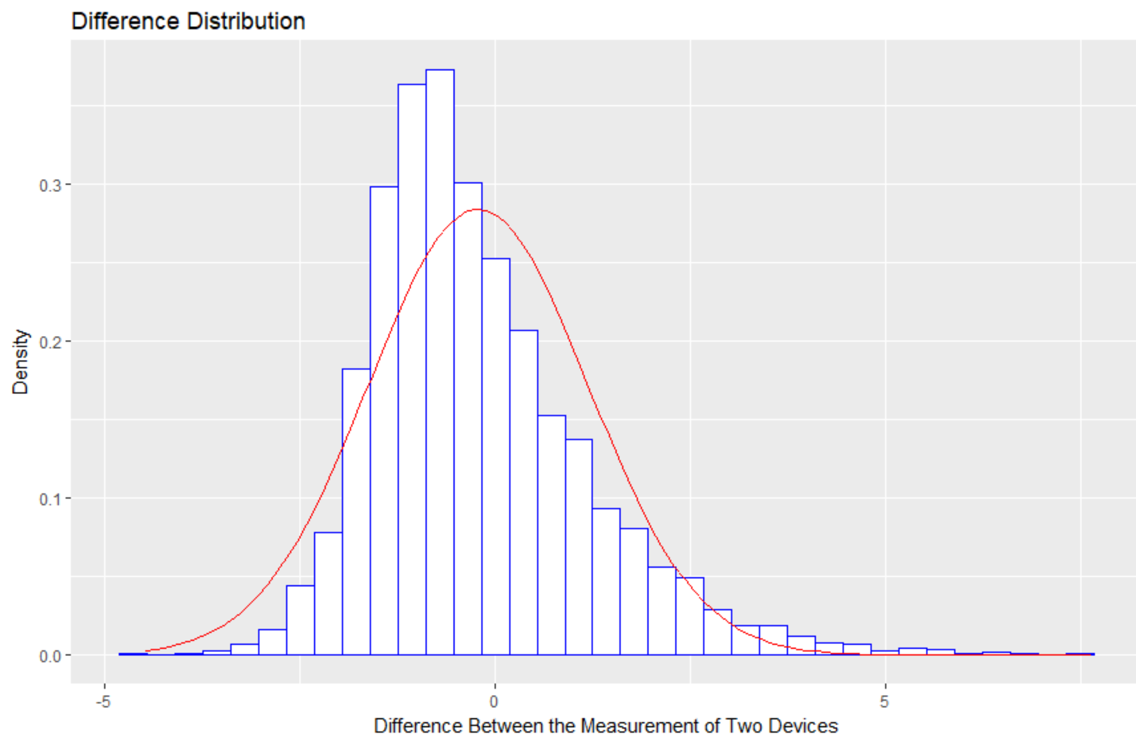

Figure 11. The Distribution of the Difference in the RMS Acceleration Data from the Getac® Z710 and Toshiba Tablets on the Control Route.

Five groups of sidewalk roughness levels are classified by applying K-mean cluster analysis on the RMS acceleration data. All data are classified to their cluster based upon cluster cut points for each tablet. Table 3 shows the clustering results of two tablets' RMS acceleration data. Because data were collected in parallel, the total numbers of the samples for each tablet are the same.

Table 3. The Clustering Results of Two Tablets' RMS Acceleration Data.

Score by Tablet	Lowest (Score:1)	Low (Score:2)	Medium (Score:3)	High (Score:4)	Highest (Score:5)	Total
Getac® Z710	1335	1777	1585	1360	754	6811
Toshiba Thrive™	1301	1697	1614	1400	799	6811
Total	2636	3474	3199	2760	1553	13622

4.2 Clustering Results across Tablets using RMS Acceleration Data

The roughness scores from two tablets' clustering results are compared for each measured location, the score of one represents the smoothest surface and the score of five represents the roughest surface. The difference between the roughness scores for each measured location is calculated. For example, if a specific measured location has a Getac® Z710 roughness score of 2 and a Toshiba Thrive™ score of 4, the difference in score for this location is -2. The range of the score difference is from -4 to +4. The frequency table of the difference value is shown in the Table 4 and the figure of the difference value for each point through the route is shown in the Figure 12

Table 4. The Frequency Table of the Difference Value.

Difference Value	-4	-3	-2	-1	0	+1	+2	+3	+4
Count	37	164	594	1517	2434	1347	486	180	52
Percentage (%)	0.5	2.4	8.7	22.3	35.7	19.8	7.1	2.6	0.8

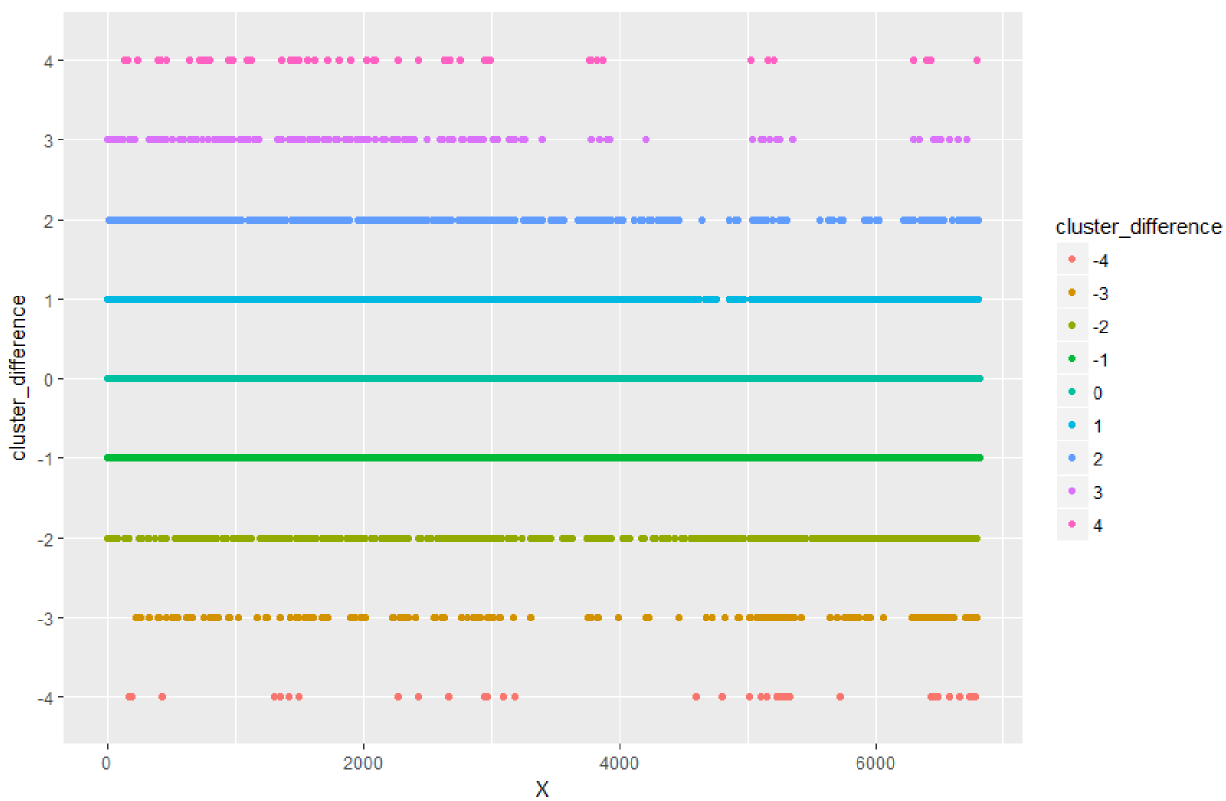

Figure 12. The Difference Value for Points through the Route.

The distribution of the difference between the roughness scores for each location is shown in Figure 13. The distribution is shown in each Toshiba Thrive™ roughness score level. In Figure 13, the distribution of all samples with a Toshiba Thrive™ roughness score of 1 is narrowest and the distribution of all the samples with a Toshiba Thrive™ roughness score of 5 is the widest. The trend shows that the rougher the surface, the wider the distribution of the difference between the roughness scores for each sample.

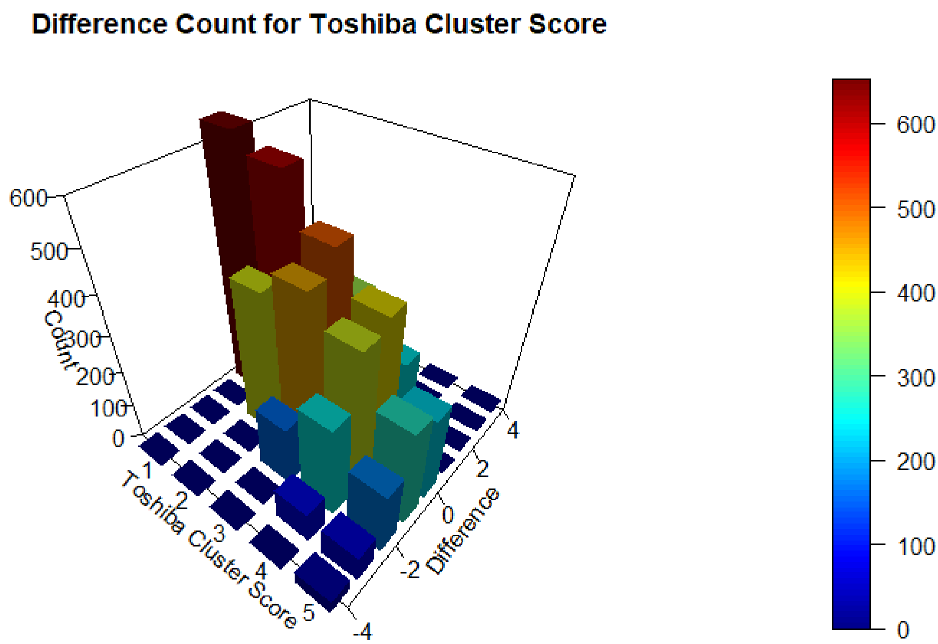

Figure 13. The Distribution of the Difference between the Roughness Scores for each Location.

4.3 Hypotheses Testing About the Clustering Results of Two Tablets' RMS Acceleration Data

The chi-squared test and Wilcoxon signed-rank test are used to compare the clustering results from the two tablets' RMS acceleration data and test the hypotheses. The chi-squared test is used to test whether the sidewalk roughness clustering result is dependent on the type of tablet used for collecting data. The Wilcoxon signed-rank test is used to test whether the median difference between the roughness scores assigned by two clustering results is zero. The null and alternative hypothesis, and the testing results are shown below:

1. Chi-squared test:

   Null Hypothesis: The clustering result is independent on the type of measuring device.

   Alternative Hypothesis: The clustering result is dependent on the type of measuring device.

   $X^2 = 4.43$

   Df=4, critical value for 0.05 is 9.49, the null hypothesis cannot be rejected. Therefore, the sidewalk roughness clustering results do not appear to be dependent of the type of tablet used for collecting data.

2. Wilcoxon signed-rank test:

Null Hypothesis: The median difference between the roughness scores assigned by two clustering results is 0.

Alternative Hypothesis: The median difference between the roughness scores assigned by two clustering results is greater than 0.

$Z=(W-\mu_W)/\sigma_W) = -2.87$, the null hypothesis cannot be rejected. Therefore, the median difference between the roughness scores assigned by two clustering results does not appear to be statistical different from 0.

4.4 Clustering Result Cut Point using RMS Acceleration Data

The cut points of the clustering result of two tablets' RMS acceleration data are used to establish the numerical standards of sidewalk roughness classification. The cut point is the boundary of two roughness level groups. The cut points of the clustering result of Getac® Z710 tablet's RMS acceleration data are shown in Table 5, and the visualization of these cut points is shown in Figure 14. For a given sample with an RMS acceleration value, the level of roughness of this sample can be identified by looking into the cut points results.

Table 5. Clustering Result Cut Points for the Getac® Z710 RMS Acceleration Data.

Cluster Groups	Clustering result Cut Points for the Getac® Z710 RMS acceleration data
10%, Lowest (1)	0<=RMS Acceleration<10.32239
30%, Low (2)	10.32239<= RMS Acceleration<11.22064
50%, Medium (3)	11.22064<=RMS Acceleration <12.25448

Table 5 Continued

70%, High (4)	12.225448<=RMS Acceleration <13.70554
90%, Highest (5)	13.70554<=RMS Acceleration

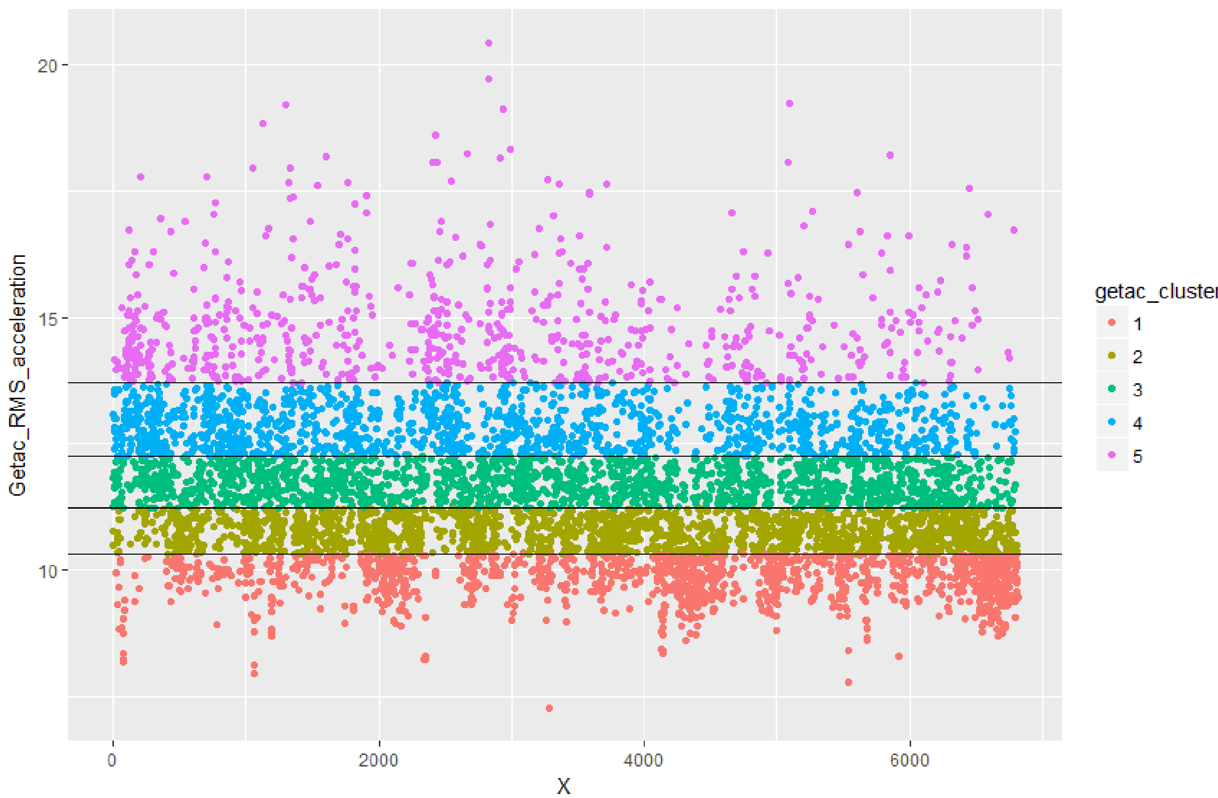

Figure 14. Visualization Clustering Result Cut Points from Getac® Z710 RMS Acceleration Data.

The cut points of the clustering result of Toshiba Thrive™ tablet's RMS acceleration data are shown in Table 6, and the visualization of these cut points is shown in Figure 15. The cut points result of Toshiba Thrive™ tablet's data is similar to the result of Getac® Z710 Tablet's data.

Table 6. Clustering Result Cut Points from the Toshiba Thrive™ RMS Acceleration Data.

Cluster Group	Cut points of the clustering result of Toshiba Thrive™ tablet's RMS acceleration data
10%, Lowest (1)	0<=RMS Acceleration<11.29099
30%, Low (2)	11.29099<= RMS Acceleration<11.72517
50%, Medium (3)	11.72517<=RMS Acceleration <12.15097
70%, High (4)	12.15097<=RMS Acceleration <12.69867
90%, Highest (5)	12.69867<=RMS Acceleration

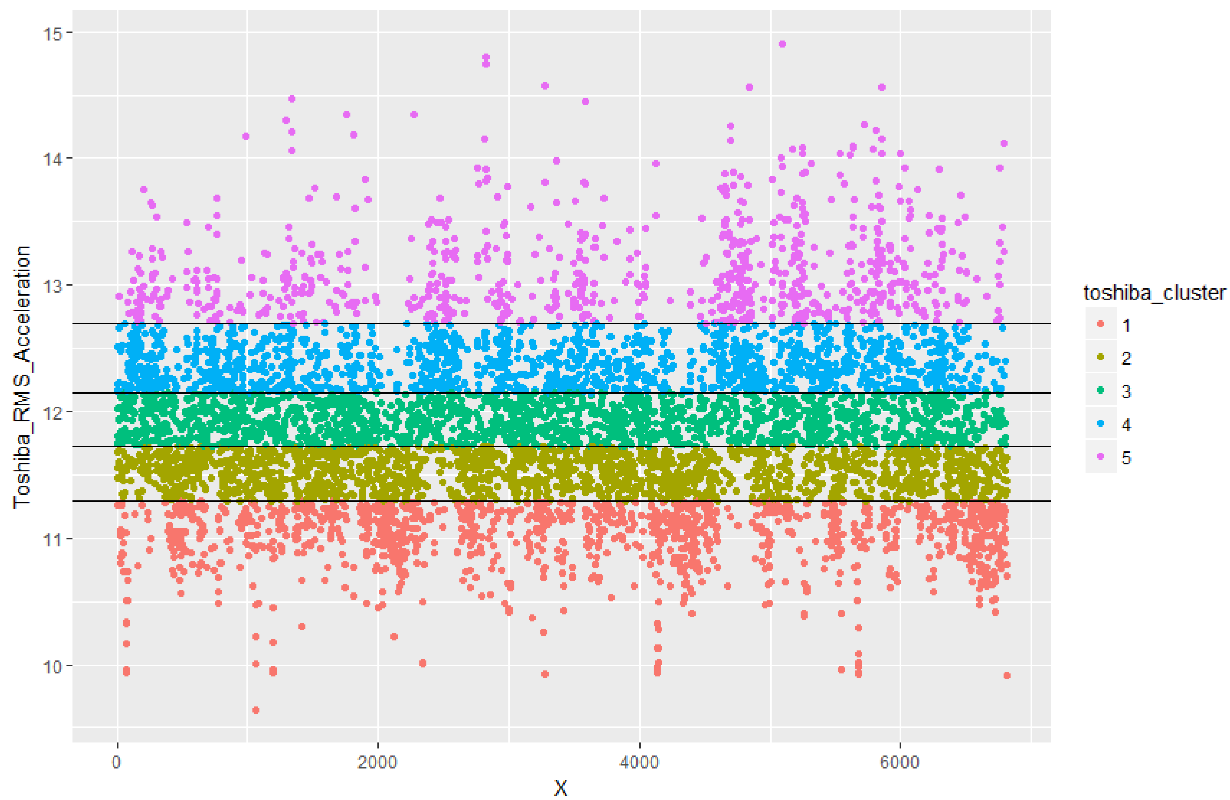

Figure 15. Visualization of Clustering Result Cut Points from the Toshiba Thrive™ RMS Acceleration Data.

4.5 Clustering Result of Using Other Inputs to Classify the Sidewalk Roughness Level

To explore the potential effect of adding RMS jerk data into sidewalk roughness classification, K-mean cluster analysis will be applied to the Toshiba Thrive™ tablet's raw RMS acceleration data and the combination of Toshiba Thrive™ tablet's raw RMS acceleration data and raw RMS jerk data. The clustering result of Toshiba Thrive™ tablet's raw RMS acceleration data and the clustering result of the combination of Toshiba

Thrive™ tablet's raw RMS acceleration data and raw RMS jerk data are shown in Table 7. The clustering result of the combination of Toshiba Thrive™ tablet's raw RMS acceleration data and raw RMS jerk data has fewer samples in the "Lowest" and "Low" categories and more samples in "Medium", "High", and "Highest" levels. Using the combination of Toshiba Thrive™ tablet's raw RMS acceleration data and raw RMS jerk data tends to classify more samples in rougher levels. The summary of the frequency of each classification result is shown in Figure 16.

Table 7. The Clustering Result of Toshiba Thrive™ Tablet's Raw RMS Acceleration Data and the Clustering Result of the Combination of Toshiba Thrive™ Tablet's Raw RMS Acceleration Data and Raw RMS Jerk Data.

Clustering by Variable	**Lowest (1)**	**Low (2)**	**Medium (3)**	**High (4)**	**Highest (5)**	**Total**
Raw RMS Acceleration	1301	1697	1614	1400	799	6811
Raw RMS Acceleration and Raw RMS Jerk	931	1625	1707	1676	872	6811
Total	2232	3322	3321	3076	1671	13622

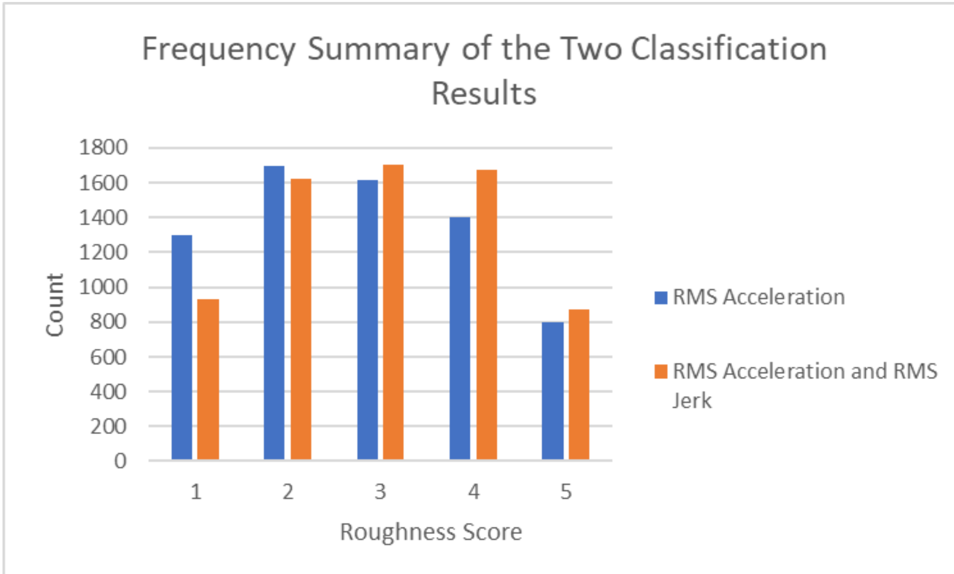

Figure 16. The Summary of the Frequency of the Classification Result of Toshiba Thrive^{TM} Tablet's Raw RMS Acceleration Data and the Classification Result of the Combination of Toshiba Thrive^{TM} Tablet's Raw RMS Acceleration Data and Raw RMS Jerk Data.

To explore the potential effect of using RMS gyroscope data in sidewalk roughness classification, K-mean cluster analysis will be applied to the Toshiba Thrive^{TM} tablet's raw RMS acceleration data and the Toshiba Thrive^{TM} tablet's raw RMS gyroscope data. The clustering results of Toshiba Thrive^{TM} tablet's raw RMS acceleration data and the Toshiba Thrive^{TM} tablet's raw RMS gyroscope data is shown in Table 8. The clustering result of raw RMS gyroscope data has more samples in "Lowest" and "Low" levels. Using the raw RMS gyroscope data tends to classify more samples in smoother levels. The summary of the frequency of each classification result is shown in Figure 17.

Table 8. The Clustering Results of Toshiba Thrive™ Tablet's Raw RMS Acceleration Data and the Toshiba Thrive™ Tablet's Raw RMS Gyroscope Data.

Clustering by Variable	**Lowest (1)**	**Low (2)**	**Medium (3)**	**High (4)**	**Highest (5)**	**Total**
Raw RMS Acceleration	1301	1697	1614	1400	799	6811
Raw RMS Gyro data	1744	1851	1573	1063	580	6811
Total	3045	3548	3187	2463	1379	13622

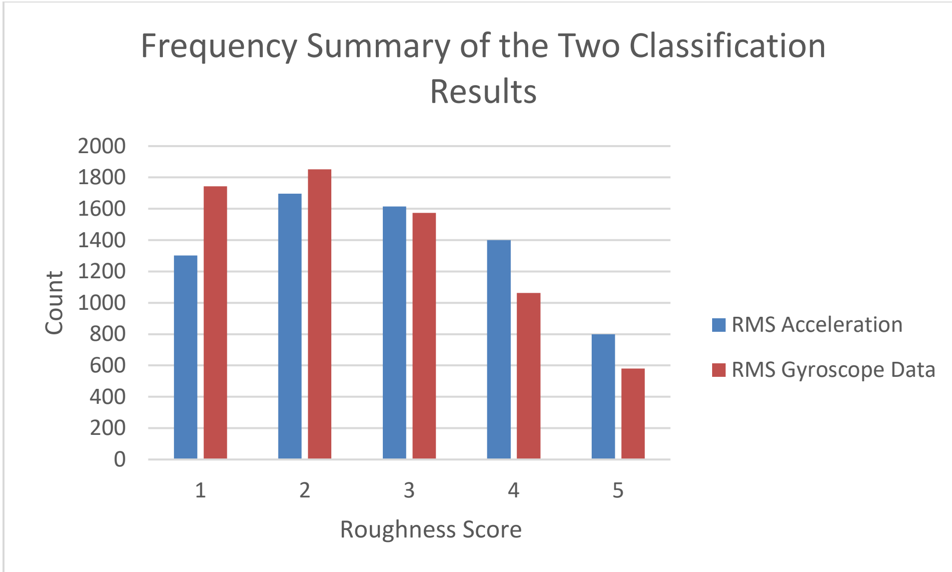

Figure 17. The Summary of the Frequency of the Classification Result of Toshiba Thrive™ Tablet's Raw RMS Acceleration Data and the Classification Result of Toshiba Thrive™ Tablet's Raw RMS Gyroscope Data.

4.6 Hypotheses Testing About the Clustering Results for Using Other Inputs

The chi-squared test and Wilcoxon signed-rank test are used to compare the clustering results and test the hypotheses related to the clustering results. The null and alternative hypothesis, and the testing results are shown below:

1. For exploring the effect of adding RMS jerk data into sidewalk roughness classification:
   a. Chi-squared test:

- **Null Hypothesis**: The clustering result is independent of whether using the RMS acceleration data only or using the combination of RMS acceleration and RMS jerk data.
- **Alternative Hypothesis**: The clustering result is dependent of whether using the RMS acceleration data only or using the combination of RMS acceleration and RMS jerk data.
- X^2= 93.4537
- Df=4, critical value for 0.05 is 9.49, the null hypothesis should be rejected.
- Therefore, the sidewalk roughness clustering result does not appear to be independent of the type of input data and using the combination of RMS acceleration and RMS jerk data will generated a different classification result than using the RMS acceleration data only.

b. Wilcoxon signed-rank test:

- **Null Hypothesis**: The median difference between the roughness scores assigned by two clustering results is 0.
- **Alternative Hypothesis**: The median difference between the roughness scores assigned by two clustering results is less than 0.
- $Z=(W-\mu_W)/\sigma_W) = -23.3554$
- The null hypothesis should be rejected.

- Therefore, the median difference between the roughness scores assigned by two clustering results does not appear to be statistical greater than 0.

2. For exploring the effect of using RMS gyroscope data into sidewalk roughness classification:

   a. Chi-squared test:

      - **Null Hypothesis**: The clustering result is independent of whether using the RMS acceleration data or using the RMS gyroscope data.
      - **Alternative Hypothesis**: The clustering result is dependent of whether using the RMS acceleration data or using the RMS gyroscope data.
      - X^2= 152.551
      - Df=4, critical value for 0.05 is 9.49, the null hypothesis should be rejected.
      - Therefore, the sidewalk roughness clustering result does not appear to be independent of the type of input data and using the RMS gyroscope data will generated a different classification result than using the RMS acceleration data only.

   b. Wilcoxon signed-rank test:

      - **Null Hypothesis**: The median difference between the roughness scores assigned by two clustering results is 0.

- **Alternative Hypothesis**: The median difference between the roughness scores assigned by two clustering results is greater than 0.
- $Z=(W-\mu_W)/\sigma_W) = 21.4798$
- The null hypothesis should be rejected.
- Therefore, the median difference between the roughness scores assigned by two clustering results does not appear to be statistical lower than 0

4.7 Overview of the Results

The analytical results presented above indicate that the Getac® Z710 tablet is more sensitive to the sidewalk vibration data, but the sidewalk roughness level classification results using the data collected by both tablets are the same based on the results of the chi-squared test and Wilcoxon signed-rank test. Also, the greatest disparity between sidewalk roughness classifications across the two tablets usually occurred at locations with very rough surfaces, which is not surprising.

To explore other measurements that might be related to the sidewalk roughness classification, using a combination of RMS acceleration data and RMS jerk data to classify the sidewalk roughness levels will generate a different result than the result of only using RMS acceleration data, the classification result of using the combination of RMS acceleration data and RMS jerk data tends to have more samples with higher roughness score. Finally, using RMS gyroscope data to classify the sidewalk roughness levels will generate different classification results than the result of only using RMS acceleration data, the classification result of using the RMS gyroscope data tends to have more samples with lower roughness score. All these results are only based on the analysis of the Toshiba Thrive™ tablet's data. More research into use of those variables appear to be warranted.

4.8 Comparing Classification by Vibration Data across Tablets

As mentioned in Chapter 3, the resulting RMS acceleration data are used to analyze the performance of the two tablets in collecting sidewalk vibration data. The two tablets' sensitivities to the sidewalk vibration data are compared by comparing the ranges of the distributions of the two tablets' RMS acceleration data. The classification cut points for classifying the sidewalk roughness level from the units are different. However, both the chi-squared test and the Wilcoxon signed-rank test results show that the sidewalk roughness classification results by using the RMS acceleration data from two tablets are not significantly different.

4.8.1 Sensitivity Analysis

The sensitivity of the tablets is compared by comparing the range of the distributions of RMS acceleration data. The sensitivity represents how tablets are sensitive to the sidewalk vibration data, the tablets with higher sensitivity would be able to collect the data with a wider range of values. From the distribution of the two tablets' RMS acceleration data in Figure 10, the range of the distribution of Getac® Z710 RMS acceleration data has an obvious wider range than the distribution of the Toshiba Thrive™ RMS acceleration data. The result shows that the Getac® Z710 has a higher sensitivity than Toshiba Thrive™, yielding a wider spread of acceleration data. The distribution of the difference in the values of two tablets' RMS acceleration data for each sample is approximately normal, but the chi-squared test result shows that it does not fit for an actual normal distribution.

4.8.2 Sidewalk Roughness Levels Classification Results Comparison

The k-means cluster analysis successfully classifies the two tablets' RMS acceleration data into five groups. Each group represents a level of sidewalk roughness, and a roughness is assigned to each sample in each tablet's clustering cut point result. The chi-squared test result indicates that the clustering result is independent of the type of measuring device. The result of Wilcoxon signed-rank test indicates that the median roughness scores of the samples in two clustering results are the same. Both test results indicate sidewalk roughness classification by using two tablets' RMS acceleration data are the same.

The distribution of the difference between the roughness scores presented in Figure 13 reveals that the largest discrepancy in roughness scores occurs at locations where the level of roughness is high. Figure 13 shows that the measurements of rougher surfaces may need more attention because the measurement results across tablets at these locations disagree more often. That is, there appears to be more classification uncertainty in the assigned score for higher scores.

4.8.3 Cut Point Comparison

The cut points are generated from the clustering results of the two tablets' RMS acceleration data. The cut points generated from the clustering result of Getac® Z710 RMS acceleration are shown in Table 5 and the cut points generated from the clustering result of Toshiba Thrive™ RMS acceleration are shown in Table 6. The combined table of these cut points are shown in the Table 9. Although the cut points for each device are different, when the cut points for that tablet are applied to the measurements collected by that table, the classification results across the tablets are not significantly different. Hence, there appears to be no significant issue with moving from the old Toshiba Thrive™ system to the new Getac® Z710 system.

Table 9. Combined Clustering Result Cut Points for both Tablets

Cluster Groups	Clustering result Cut Points for the Getac® Z710 RMS acceleration data	Clustering result Cut Points for the Toshiba Thrive™ RMS acceleration data
10%, Lowest (1)	0<=RMS Acceleration<10.32239	0<=RMS Acceleration<11.29099
30%, Low (2)	10.32239<= RMS Acceleration<11.22064	11.29099<= RMS Acceleration<11.72517
50%, Medium (3)	11.22064<=RMS Acceleration <12.25448	11.72517<=RMS Acceleration <12.15097
70%, High (4)	12.225448<=RMS Acceleration <13.70554	12.15097<=RMS Acceleration <12.69867
90%, Highest (5)	13.70554<=RMS Acceleration	12.69867<=RMS Acceleration

4.9 The Exploration of Other Factors Related to Sidewalk Roughness Levels Classification

Two other factors which may relate to sidewalk roughness classification are explored. Combinations of RMS jerk data and RMS acceleration data, or the RMS gyroscope data can be used to cluster field measurement results. However, the results show that using these different inputs does not generate the same sidewalk roughness classification results as RMS acceleration does. Additional research in this area is warranted.

4.10 Validity and Limitations

The results of comparing the performance of collecting sidewalk roughness data by two tablets are based on the analysis of parallel collection of RMS acceleration data. Therefore, these results should only be applied to RMS acceleration data as input for sidewalk classification. Using acceleration jerk or gyroscope readings in cluster analyses may yield different results. The study of using other inputs to compare the performance of collecting sidewalk roughness data by two tablets may be conducted in the future.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As an important indicator of sidewalk quality and safety assessment, sidewalk roughness should be measured quantitatively and accurately. This study used the methodology developed by Georgia Tech researchers for the automated sidewalk quality and safety assessment system, using k-means cluster analysis to classify sidewalk roughness levels [2]. This thesis work included two main goals: 1) comparing the performance of two different tablets for collecting sidewalk vibration data, and 2) exploring the effects of other related factors on the sidewalk roughness classification results.

The two goals were accomplished in this study. Sidewalk roughness levels were successfully classified by both tablets using RMS acceleration data. The new Getac® Z710 tablet was more sensitive to the sidewalk vibration data, yielding a wider distribution of RMS acceleration data for the same sidewalk locations. Sidewalk roughness classification results for the two tablets using RMS acceleration data were not significantly different from each other, based on the results of the chi-squared test and Wilcoxon signed-rank test. In exploring discrepancies in roughness scores for the same samples across the devices, the result shows the most discrepancy in roughness scores occurs at the location where the level of roughness is high. This is not necessarily worrisome, given that the rough sidewalks in these stretches are still identified as rough, rather than smooth. The cut points used to assign sidewalks to different roughness values (from lowest to highest) are different across the units; however, when applied to the data collected by each unit, these cut points classify the sidewalks with the same roughness levels.

In exploring other factors which may be related to the sidewalk roughness classification, this study tested the effect of RMS acceleration and RMS jerk data, and tested the effect of using RMS gyroscope data on the sidewalk roughness classification results. The results show that using the combination of RMS acceleration and RMS jerk data will generate a different sidewalk roughness classification result than the method of using RMS acceleration data only, and the samples tend to have higher roughness scores. Sidewalk roughness classification result generated from using RMS acceleration data and RMS gyroscope data were also different, and the samples tend to have lower roughness scores. These results show that the sidewalk roughness classification is sensitive to the type of input data, the choice of input data should be careful. Additional research in this area is warranted.

5.2 Contributions of the Work

The most important contribution of this study is to test the performance of the Getac® Z710 tablet for collecting sidewalk roughness data. Because the Toshiba Thrive™ tablets are no longer being manufactured, the research team needed to find an alternative measuring device which can help them to collect sidewalk vibration data for their future studies. The result in this study shows that for using RMS acceleration data to classify the sidewalk roughness level, using the Getac® Z710 data generates the same roughness classification result as using the Toshiba Thrive™. The Getac® Z710 is not able to collect gyroscope data (data stream not available), but this is not an issue given that analysis of gyroscope data did not provide compelling reasons to include these values in roughness estimation.

The cut points for sidewalk roughness classification is another contribution of this study. These cut points are reliable and can be used to classify the sidewalk roughness level if the RMS acceleration data is collected using the units.

5.3 Implications and Transferability of the Research

From the result of comparing the performance of collecting sidewalk vibration data by two tablets, the most discrepancy in roughness scores occurs at the location where the level of roughness is high. This result indicates the sidewalk vibration data measured on the roughest surface locations is not always consistent across the units. This may be the result of the averaging process, or even wheelchair bounce where the device momentarily leaves the paved roadway. However, there is no evidence shows that which tablet has a higher accuracy in collecting sidewalk vibration data at the rougher locations. Further studies are needed for data collection on rougher surface.

From the result of exploring other factors which may be related to the sidewalk roughness classification, the choice of data streams for use in sidewalk roughness classification will affect the classification result. The RMS acceleration data may not be the best data to indicate the sidewalk roughness level, but there is no evidence shows that other data like RMS jerk and RMS gyroscope data are better than RMS acceleration for classifying the sidewalk roughness level.

With respect to the transferability of this study, the cut points result for both sidewalk roughness classification results by two tablets can serve as a reference for future data collection efforts. The methodology used in this study can be used in future studies to classify the sidewalk roughness level.

5.4 The Limitations of the Study

There are several limitations of this study. These limitations come from the technical issue, the selection of data, and the methodology itself. The results of comparing the performance of collecting sidewalk roughness data by two tablets are only based on the analysis of the RMS acceleration data. The Getac® Z710 is not able to collect gyroscope data, so the analysis of the impact of gyroscope data on Getac® Z710 roughness estimates cannot be assessed. Using RMS jerk data collected by two tablets may not generate the same results. Limitations of the data collection methodology itself includes the fact that the wheelchair cannot be pushed at a steady speed during data collection and the speed of wheelchair travel will affect the accuracy of vibration data [11]. Also, in this study, two sets of cut points are generated based on the clustering results of Toshiba Thrive™'s RMS acceleration data and the clustering results of Getac® Z710's RMS acceleration data. There are no standards for deciding which set of the cut points is better than the other. Finally, while the control route includes variable surface roughness conditions, none of these conditions are linked back to a specific rating framework related to ADA policy. That is, there is no preconception that a returned roughness value of 4 indicates that the sidewalk is so rough that it must be replaced within a conventional policy decision making framework. A future study should score sidewalks in advance, perhaps by expert panel review, and then assess the capabilities of the instrumentation to classify the sidewalks into their policy-related categories.

5.5 Suggestions for the Future Research

For the suggestions for the future study, two suggestions have been made based on the results of this study.

The first suggestion is expanding data collection and analysis of sidewalk vibration data on the rougher surfaces. Because the sidewalk vibration data measurement on rougher surfaces is less consistent across devices. Therefore, developing a method for collecting and analyzing sidewalk vibration data for rougher location may be important for sidewalk quality and safety assessment.

The second suggestion is continuing the study of finding the factors which related to sidewalk roughness parameter. The results of this study only indicate that the sidewalk roughness classification results of using RMS acceleration data are different with the classification results of using other types of data like RMS gyroscope data. However, there are no standards for determining which classification result is better than others, further studies are needed.

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