INNOVATIVE MEANS OF COLLECTING INTERNATIONAL ROUGHNESS INDEX USING SMARTPHONE TECHNOLOGY

by

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Abstract

International Roughness Index (IRI) is a widely used pavement performance measure collected with specially equipped vehicles; however, the cost of data collection may limit the ability of some road authorities to procure the data. Recent advances in smartphone technology have created interest in their potential to be low-cost mobile data collection platforms.

This study compared IRI from an inertial profiler to IRI calculated from a smartphone’s accelerometer over a 1 km test section of road in New Brunswick, Canada. The study also included four scenario tests to evaluate the effects of varying the following experimental factors: vehicle type, device manufacturer, mounting arrangement and speed. The correlation between the smartphone’s results and those collected using the inertial profiler was found to be 88.9% for 100m increments along the section. The scenarios returned average IRI values ranging from 0.8% to 85% different than the average IRI of 2.60 m/km collected using the inertial profiler, though the smartphone configurations had higher coefficient of variations ranging from 2.05 to 9.11 compared to the inertial profiler’s 1.12.
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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI</td>
<td>International Roughness Index</td>
</tr>
<tr>
<td>NBDTI</td>
<td>New Brunswick Department of Transportation and Infrastructure</td>
</tr>
<tr>
<td>PCI</td>
<td>Pavement Condition Index</td>
</tr>
<tr>
<td>FWD</td>
<td>Falling Weight Deflectometer</td>
</tr>
<tr>
<td>RTRRMS</td>
<td>Response-Type Road Roughness Measuring System</td>
</tr>
<tr>
<td>IRRE</td>
<td>International Road Roughness Experiment</td>
</tr>
<tr>
<td>HSDC</td>
<td>High Speed Data Collection</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>UMTRI</td>
<td>University of Michigan Transportation Research Initiative</td>
</tr>
<tr>
<td>PASER</td>
<td>Pavement Surface and Evaluation Rating</td>
</tr>
<tr>
<td>UNB</td>
<td>University of New Brunswick</td>
</tr>
<tr>
<td>MRDC</td>
<td>Maritime Road Development Corporation</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
</tr>
<tr>
<td>CSV</td>
<td>Comma Separated Value</td>
</tr>
<tr>
<td>COV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

Standard pavement performance measures are an essential part of any road authority’s ability to effectively and efficiently determine the most economic paving schedule in any given year. The current options available for collecting objective pavement condition data are costly and require specialized equipment. Many small road authorities may not be able to afford the services that provide data required to make informed paving and maintenance decisions.

Technologies currently embedded in smartphones widely available on the mobile market today could potentially provide comparable data to these costly methods of data collection. The proposed smartphone method of data collection could present a low-cost alternative to traditional forms of measurement, which may give jurisdictions of all sizes the ability to better manage their road networks.

There are a wide variety of pavement performance measures that quantify a host of road characteristics. For example, the following indices are commonly used in industry:

- Pavement Condition Index (PCI) - an aggregate measurement of surface distress used for paved roads, airports and parking lots (ASTM, 2011)

- Falling Weight Deflectometer (FWD) - provides engineers with an idea of the structural capacity of pavement (ASTM, 2009)
International Roughness Index (IRI) - a single numerical value that defines the roughness of any road section (ASTM, 2003).

The power of using objective information like this is displayed in Figure 1-1.

![Figure 1-1: Average Pavement Degradation (Adapted from Felio, 2012)](image)

Pavement condition is plotted on the y-axis, while time is plotted on the x-axis. An average road generally remains in good health for a large portion of its life cycle; however, it reaches a critical point where it begins to degrade at an accelerated rate. Performing minor maintenance at or just before this critical point may cost up to ten times less than major rehabilitation just a short period of time later. Using the aforementioned indices, engineers are able to track the condition of their roads and
applying these principles, they are able to make well-informed decisions regarding pavement operations and maintenance.

Although there are many pavement performance measures used in industry, this study specifically focused on collecting IRI. This is a numerical value defining road roughness as accumulated vertical metres of deflection (caused by road anomalies), per kilometre of roadway. The value theoretically starts at zero (perfectly smooth) and increases progressively with increased deflection.

1.1 Project Need

Currently, the IRI of a roadway is generally determined using an instrumented vehicle called an inertial profiler as displayed in Figure 1-2. These vehicles are costly to own; therefore, many jurisdictions currently have their roads surveyed by a specialized consultant. Furthermore, these services may be inaccessible to many smaller municipalities who are unable to afford the upfront cost of the data collection vehicle or associated consulting services. As an example, medium sized municipalities can be charged a one time fee of $80 000 to have their roads surveyed (Legace, 2012). This study was done to evaluate the feasibility of collecting comparable roughness data using low cost sensors embedded in smartphones widely available on the mobile market today. Although an analysis of the commercial potential of smartphone technology’s potential is outside the scope of this project, it is presumed deployment costs of such a system would be lower given their availability and ubiquitous use in society. This is significant as it could result in a more affordable option for obtaining this important data.
1.2 Goals and Objectives

The overall goal of this study was to explore the feasibility of using smartphone technology as a means of capturing road roughness. The following objectives were completed in order to meet the stated goal:

- Evaluate the effects of varying suspension, device, mounting arrangement, and speed to determine if any factors produce significantly different results using ANOVA tests and Tukey’s Method.

- Simultaneously log raw acceleration data with a smartphone and a standard inertial profiler in order to provide a one-to-one comparison between the two methods. Evaluate if the two resulting IRI averages from these tests were statistically different using a paired t-test.
1.3 Scope

The main focus of the study was to test the smartphone-based framework for converting raw acceleration into IRI. Data were collected on one stretch of roadway that was subjectively deemed to be in average condition. The chosen test section exhibited visible signs of moderate distress, including Alligator cracking, minor potholes, and transverse/longitudinal cracking, but was still passable at 80km/hr.

Five initial baseline runs were performed from within a standard inertial profiler to provide an estimate of the actual IRI. Four variables, including vehicle suspension, device manufacturer, mounting arrangement, and high/low speed, were then evaluated to determine if they had a significant impact on resultant IRI values. Each of these four factor groups were tested in separately; however, the same initial set of factors was used for the first test in each scenario. For subsequent tests the subject variable was swapped out while keeping all other variable constant. Using the vehicle scenario as an example, the first the initial set of factors was used, then the vehicle was swapped out for another and the tests were repeated. Each of these scenario tests were run eight times in order to determine an average IRI with the given set of factors. Customized algorithm and software development were considered outside the scope of this project due to limited time and resources.
Chapter 2: Literature Review

Research in the area of smartphone technology for the purposes of determining objective road condition is still an emerging field; however, it is crucial to understand the principals of road roughness and how it is currently collected. This section also profiles the limited uses of smartphone technology for the purposes of monitoring pavement performance measures.

2.1 International Roughness Index

The International Roughness Index (IRI) was originally adopted in order to standardize road roughness measurements in 1986 (Gillespie, et al., 1986). At the time, several instruments and methods were used to define roughness separated into two groups: static profilometers and response-type road roughness measuring systems (RTRRMS). In order to produce a meaningful index that would be repeatable, several countries organized the International Road Roughness Experiment (IRRE) which was held in Brazil in 1982. As a result of tests conducted at that conference, engineers were able to define a standard index called the International Roughness Index, which has subsequently been recognized and adopted worldwide.

The main goal of its development was to produce an objective value that was time-stable, transportable, and relatable to values collected by practitioners regardless of their location. The index is generally measured in m/km, that is metres of vertical displacement versus kilometres travelled. A single IRI value therefore represents the
roughness of a linear longitudinal slice for a given sample section; if a test vehicle is equipped with various sensors at different locations or several linear profiles are taken, the average of those IRI values is taken as the roughness of the test section. Figure 2-1 displays road characteristics associated with varying levels of roughness and use.

![Figure 2-1: IRI Roughness Scale (Gillespie, Paterson & Sayers, 1986)](image)

Once a profile of the desired road section is produced, a standard algorithm is used to convert the profile to a single IRI value. The World Bank outlines the source code for performing these calculations in their publication “Guidelines for Conducting and Calibrating Road Roughness Measurements” (1986). However, with advances in computer technology, organizations have created user-friendly applications to facilitate this conversion. ProVal is one such application that is produced by the Transtec Group through a contract with the United States Federal Highway Administration. This
program supplies a host of profiling and data processing features along with the basic IRI analysis tool.

2.2 Static Profiling Methods

There are many pieces of equipment available for measuring an accurate longitudinal profile of a desired road section depending on the accuracy required by the user. Technically, rod and level survey tools can be used to achieve a road profile. To do so, the instrument is set up in much the same way for general profiling; however, the requirements for measuring a road profile for the purposes of determining roughness are much more stringent. The rod and level method requires measurements to be taken at intervals of under 30cm, which can be time consuming depending on the section of roadway (Karamihas and Sayers, 1998).

For precise measurements, a manual device called the Dipstick is used (Karamihas and Sayers, 1998). The user must “walk” the device along the required survey line, pivoting about the legs of the instrument, taking height measurements after each pivot. These devices provide accurate profiles; however, the data collection process is labour intensive and time consuming. For this reason, the use of the Dipstick and other precision profilers are generally reserved for calibration purposes and in some cases quality control.
2.3 Dynamic Profiling Methods

For the purposes of monitoring in-place pavement condition, response-type road roughness measuring systems (RTRRMS) are implemented into high-speed data collection (HSDC) vehicles. These units are equipped with accelerometers, which provide an inertial reference line between the ground and vehicle travelling at speed and a height sensor to determine the distance between the inertial reference point and the ground (Gillespie et al., 1986). The basic layout of an inertial profiler is shown in Figure 2-3.

![General Layout of an Inertial Profiler](image)

**Figure 2-3: General Layout of an Inertial Profiler (FHWA, 2005)**
The standard speed at which these vehicles are designed to run in order to produce optimal results is 80km/hr; however, in cases where this is not feasible due to road geometry or other conditions, speeds as low as 50km/hr can produce desired results with a high degree of accuracy. In extreme situations where 50km/hr cannot be maintained, the standard procedure is to apply a calibration factor to the raw data collected but it is recommended that this be avoided (Gillespie et al., 1986). This method of data collection is generally preferred for monitoring the condition of roadways.

2.4 Current Smartphone Technology

There are many smartphones currently available on the mobile market varying in size, design, and technical specifications; however, the accelerometer chips used by leading manufacturers, including Apple, Samsung, and Blackberry, are largely produced by STMicroelectronics. These accelerometers measure acceleration along the X, Y, and Z planes and are used to accomplish various functions. For example, when browsing a webpage, physically moving the device can alter whether the page is displayed in landscape or portrait view. This is possible because the accelerometer within the device is able to monitor orientation in real-time and shift the display accordingly. Software developers have applied this basic technology to a host of other applications which expand the functionality of the devices.

Table 2-1 displays a comparison between key operating statistics between the accelerometers used in each respective device. All are provided by STMicroelectronics;
however, it should be noted that the iPhone and Blackberry have dedicated accelerometer chips, while Samsung employs an accelerometer/gyroscope combo chip.

Table 2-1: Sensor Operating Characteristics (STMicroelectronics, 2009, 2010, 2012)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>iPhone 5 - LIS331DLH</th>
<th>Blackberry Z10 - LIS3DH</th>
<th>Samsung SIII - LSM330DLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Range</td>
<td>±2.0 g</td>
<td>±2.0 g</td>
<td>±2.0 g</td>
</tr>
<tr>
<td>Sensitivity Change vs Temperature</td>
<td>±0.01 %/°C</td>
<td>±0.01 %/°C</td>
<td>±0.05 %/°C</td>
</tr>
<tr>
<td>Zero-g Offset Accuracy</td>
<td>±20 mg</td>
<td>±40 mg</td>
<td>±60 mg</td>
</tr>
<tr>
<td>Zero-g Offset Change vs Temperature</td>
<td>±0.1 mg/°C</td>
<td>±0.5 mg/°C</td>
<td>±0.5 mg/°C</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40 to +85 °C</td>
<td>-40 to +85 °C</td>
<td>-40 to +85 °C</td>
</tr>
</tbody>
</table>

2.5 Application of Smartphone/Embedded Technology in Pavement Management

Smartphone technology is rapidly increasing in sophistication as manufacturers aim to maximize the functionality of the devices. The following section discusses the use of emerging smartphone technology for the purposes of monitoring pavement condition.
Research in this field to date has mainly focused on using acceleration data collected from either smartphones or external hardware to track the location of road anomalies. A group called “The Pothole Patrol” performed a study at the Massachusetts Institute of Technology that tracked the movement of taxis from a particular company in Boston (Eriksson et al., 2008). The taxis were equipped with accelerometers to measure vibrations of the test vehicles, and GPS units for tracking purposes. This information collected was then sent to a central server for analysis.

However, the project was faced with several issues. Heavy braking to negotiate turns or even slamming the vehicle’s door when stationary would cause sharp increases in vibrations logged by the on board sensors. Additionally, the acceleration response caused by driving over several normal roadway features, including railway crossings and bridge joints, were comparable to standard road distress. To mitigate these errors, two methods were employed. First, software installed on the units was able to constantly log the velocity of the test vehicles. Any vertical acceleration experienced at velocities lower than a certain threshold was deleted from the data set using a high-pass filter.

In order to deal with additional roadway features, the team measured accelerations produced as vehicles travelled over various known pothole locations. Using these as footprints, they were able to filter out unwanted anomalies. Upon visual inspection, it was found that 90% of areas that were identified by the data as having severe vertical acceleration were in fact potholes.

A group from the Opole University of Technology has also conducted research similar
to that of the Pothole Patrol team (Aksamit and Szmechta, 2011). The key difference is that for this study, they employed mobile smartphone technology instead of embedding hardware into specific test vehicles. The main issue with using smartphone technology was evaluating their ability to detect adverse road conditions when the device was placed in a number of different locations within a test vehicle. To test this, the team performed several experiments on different roads of varying condition with phones placed on the dashboard of the test vehicle, and in the users pocket.

It was found that although the acceleration signal’s amplitude was generally higher when placed in ones pocket, the data produced in both locations yielded similar results for all conditions. The testing system was then distributed to anonymous individuals for the purposes of tracking their location and acceleration data as they went about their daily business. Using these methods, the team was able to identify areas that exhibited road anomalies within their testing region, although no work was done to filter out common road structures like manhole covers or speedbumps. In general, the team was able use the acceleration data along with GPS data to locate anomalies within 10-20m accuracy.

Smartphone applications that track road distress are beginning to hit the mobile market. The City of Boston has recently developed an smartphone-based application that works similarly to the research conducted at the Opole University of Technology (Kuennen, 2011). It has been distributed throughout the City via the Google Play store and Apple App Store. Users download the application and it collects vertical acceleration along with anonymous GPS tracking data as they drive municipal streets. This allows officials
to receive real-time updates on the conditions of their roadways, specifically sections that require immediate repair. Engineers state that using this information collected from Boston’s citizens replaces the need for installing costly in-pavement sensors, and allows them to efficiently perform maintenance on potholes in their road network.

The use of smartphone technology to determine objective road condition is quickly becoming a reality. In recent years, the University of Michigan Transportation Research Institute (UMTRI) has explored the potential for correlating smartphone accelerometer data to the Pavement Surface and Evaluation Rating (PASER) system (MDOT, 2013). UMTRI has built an android based application called DataProbe which is being used to collect raw field acceleration; however, the data collected is currently being archived for further study.

Most recently, the University of Illinois has developed a system for determining IRI using smartphone technology (Islam et al., 2014). The three-axis accelerometer embedded within a typical modern mobile device was first used to log raw acceleration data while driving. The raw acceleration data was then filtered and double-integrated using numerical techniques in order to convert to a displacement dataset. These displacement values were then inputted into ProVal software which converts the profile to an IRI value. Their system was able to produce IRI values that corresponded well with a standard inertial profiler, although specifics numbers have yet to be released. It was also found that calibration is needed for rougher pavement sections as the system does not account for suspension damping.
A short feasibility study was performed at the University of New Brunswick (UNB) to evaluate the potential of using smartphone technology to measure IRI values (Cameron, 2012). The goal of this study was to build a basic framework for converting raw vertical acceleration data into IRI. The following three steps were used to achieve this:

i. Raw vertical acceleration data collected from an off-the-shelf iPod Touch.

ii. Acceleration data converted to a displacement time series using DATS Toolbox software package.

iii. Displacement data converted to IRI using Proval.

This method was field tested on Route 2 between the Hanwell Road and New Maryland Highway in Fredericton, New Brunswick on March 2, 2012. The test section was 1km in length with few changes in grade and horizontal alignment. Samples were collected in a Ford F250 travelling at a constant 80km/hr. The results of these tests are presented in Figure 2-4 and Figure 2-5 for both the eastbound and westbound directions; IRI values are reported every 100m.
Correlation = 0.767

Figure 2-4: IRI Comparison Eastbound

Correlation = 0.681

Figure 2-5: IRI Comparison Westbound
The field data collected as part of the study was compared to IRI values that the Maritime Road Development Corporation (MRDC) had obtained in 2011 using industry standard methods. A correlation of 0.767 was found between the smartphone and inertial profiler for the eastbound direction, while a correlation of 0.681 was found between the smartphone and inertial profiler for the westbound direction. It was also found that MRDC had micro-resurfaced the road just prior to testing, which may account for the variability between the two datasets; however, the results of this test showed promise for further research.

Although the studies mentioned above focused on the use of smartphone technology to assess the condition of roadways, the UNB feasibility study was intended to take the data processing involved a step further by using raw acceleration to determine the IRI of test sections, which is a completely objective, standardized measure of roughness. Employing the techniques that were explored by others was useful for pinpointing areas of high distress, allowing engineers to commission repairs as needed, which can be particularly advantageous in larger jurisdictions. However, providing IRI values for entire road sections and networks is far more powerful as it allows engineers to track and evaluate the condition of their streets over time. This can then provide the means of creating a robust and cost effective pavement management system, which would not otherwise be possible.

It appears no work has been done to evaluate the factors that have an effect on collecting roughness data using a smartphone. Researchers at Illinois have proposed a different method of converting raw acceleration to standard road roughness; however, little was
done to test their system against varying factors. These factors include, but are not limited to, vehicle type, smartphone device, mounting arrangement, and speed. In addition to proposing a novel method of converting raw acceleration into IRI, this study was also done to explore how these various factors affect the resultant roughness values.

2.6 Conversion Techniques

In order to determine the IRI of a road section, one must obtain metres of vertical displacement compared to distance travelled. As the raw data acquired from the inertial sensors in smartphones are output in units of acceleration, it is necessary to apply signal-processing techniques in order to obtain the desired vertical displacement data. Numerically integrating the raw acceleration data twice would be the most direct method of obtaining the required output; however, error accumulates with each integration step making this method unreliable. In order to perform the conversion from acceleration to displacement, the data must first be converted into the frequency domain, where it is possible to apply factors to facilitate the conversion. This method is desirable as it does not add or subtract information; it simply converts the data such that it is displayed in a useful manner.

To convert the raw acceleration signal from the time domain to the frequency domain, a Fast Fourier Transform (FFT) is applied. This transfers the acceleration time series into the frequency domain. Here, each point in the dataset is divided by the negative angular frequency of the signal’s components squared which converts from acceleration to
displacement. An Inverse Fast Fourier Transform (IFFT) is then applied to convert back to the time domain. The resultant is displacement time series or profile.

This profile can then be converted to IRI using a software package called ProVal, which is openly distributed by the Federal Highway Administration (FHWA). The program allows profiles to be viewed and analyzed using a host of tools and is widely used in industry. Figures 2-6 and 2-7 display the package’s user interface.

![ProVal Main Viewer](image)

**Figure 2-6: ProVal Main Viewer**
Figure 2-7: ProVal Import Wizard
Chapter 3: Methodology

The feasibility study performed at UNB provided a novel framework for converting raw acceleration collected from a modern smartphone to IRI; however, it left two major questions. First, the roughness data produced by the conversion method was compared to old inertial profiler data, but tests were never done in unison at the same time to provide a true comparison between the two methods of data collection. The second gap was the lack of factors evaluated, as only one vehicle, mounting type, phone, and speed were used during field testing. If this method of data collection were to be deployed in a real-world setting, it was necessary to determine how varying these factors affected the resulting roughness data.

In order to answer the two major questions presented above, two separate testing arrangements were used as part of this study. The first arrangement used a standard inertial profiler in order to determine a baseline estimate of the IRI of the test section for comparison purposes, and the second being scenario tests to evaluate the effects of varying certain changes to the smartphone system. The following list presents factors that were tested as part of the scenario testing:

i. Vehicle Suspension
ii. Smartphone Device
iii. Mounting Arrangement and Location
iv. Speed
There were various test scenarios associated with each of the factors listed above. For each individual scenario, only the subject variable was changed, and all other factors were kept constant. This was done to isolate the variability caused by each individual change to the system. Each scenario is discussed below, and a breakdown of each test is shown in the appendix of this report.

3.1 Data Collection and Processing

Although each of the tests used varying equipment, the overall collection process for each run remained constant. The device was always held in an upright plum position during testing, securely fastened to the mount. Vertical acceleration caused by bumps was then logged using the accelerometer of the chosen smartphone device as the test vehicle drove along the 1km test section.

The accelerometer was capable of measuring acceleration along three axis; however, the vertical component was only used. This was done to eliminate unwanted changes in acceleration along the other two axis caused by slight changes in speed and steering adjustments. Only considering the vertical component also simplified further steps in the process as there was no need to combine readings from the three axis. Data logging was initiated and ceased at predetermined points along the test section. A logbook was used in order to record prevailing conditions for each test, it was also used to track tests that needed to be omitted due to traffic interruptions.
The acceleration signal for each test was recorded using a third party application loaded on the given device. The applications were carefully chosen because they provided a consistent sampling rate which was essential for converting the acceleration signal into a useable displacement dataset. If the program’s sampling rate was not consistent when data logging, the conversion algorithm produced severely inaccurate results. The applications used were tested to evaluate this prior to use in the field. Each of the programs stored individual tests as comma-separated values (CSV) files.

Ideally, the same recording application would have been loaded on each of the three devices; however, this was not possible due to the different operating systems employed by the three companies. The list below displays the applications used to record acceleration information for each of the devices used, as well as the recording frequency. One will note that data was logged at different frequencies, this was again due to differences between the programs used.

- iPhone 5 – “xSensor Pro” recorded at 32hz
- Samsung Galaxy – “Accelerometer Monitor” recorded at 48hz
- Blackberry z10 – “Accelerometer Recorder” recorded at 48hz

When daily testing was complete, the raw acceleration stored in CSV files for each test was transmitted from the smartphone device to a computer via email. Raw acceleration collected from each smartphone device was always centred about -9.81m/s² (-1g) in the vertical direction due to the effect of gravity on the accelerometer. If the raw data were used to convert directly into displacement, the results would be erroneous as the
acceleration signal must oscillate approximately about zero. The data were corrected by subtracting the average acceleration due to gravity observed in the Y-axis from each observed acceleration value in the Y-axis using Microsoft Excel as shown in the following equation.

\[ A_c = \bar{A} - A_t \]

Where:

- \( A_c \) = Corrected Acceleration
- \( \bar{A} \) = Average Acceleration
- \( A_t \) = Individual Acceleration Points

Excel Macros were used extensively in order to expedite this part of the data manipulation process. First, the raw CSV files contained information that was not required, including x and z-axis acceleration, GPS coordinates, and gyroscope information. A macro was used in order to delete this unwanted information, leaving only the vertical acceleration and time. A separate macro was used in order to determine the corrected acceleration obtained using the equation shown above.

The new acceleration signal was then processed through a software program called DATS Toolbox by the company Prosig to convert it to a displacement dataset. Prosig is a company that provides hardware and software solutions in a wide spectrum of applications for the purposes of acquiring and manipulating data. This program was used as it provided an efficient, off-the-shelf method for achieving the required results, as
custom algorithm development was considered outside the scope of the project. The program was able to import datasets, then run the information through predetermined block algorithms, which output the required vertical displacement data. The only input required was the location of the corrected vertical acceleration file, as well as the sampling rate at which the tests were performed. All other calculations were done automatically by the program.

The next step in the process was taking the displacement data and converting it to an IRI value for any given test. To achieve this, a program called ProVal, distributed by the Federal Highway Administration, was used. This program was chosen as it allowed the user to import profiles directly from common text files and it is also widely used in industry for converting raw profiles into IRI values. Unfortunately, ProVal was only able to handle five individual samples; therefore, tests of eight samples were separated into two groups. The program automatically recognized profile information from the CSV files; however, a sampling interval needed to be manually input. This was calculated by multiplying the test speed by the quotient of total time over number of samples as shown in the formula below.

\[ I = V \times \frac{T}{S} \]

Where:

I = Interval Length (m)
V = Test Speed (m/s)
T = Total Time (s)
S = Number of Samples

Figure 3-1 breaks down the process graphically.

Figure 3-1: Data Collection Process

3.2 Pilot Test

A pilot study was performed in order to obtain the descriptive statistics required in order to calculate sample size as discussed below. The following setup was used as a pilot test:
i. Vehicle – 2001 Pontiac Sunfire
ii. Device – Apple iPhone 5
iii. Mounting Arrangement – Commercial Windshield Mount
iv. Speed – 80km/hr

The initial pilot test was performed on the section of Route 8 in Fredericton, New Brunswick that runs parallel to Prospect Street, between the Smythe Street onramp and Hanwell Road underpass using the aforementioned setup. Exit warning signs were used as a fixed reference to initiate and cease data logging. This section of roadway was chosen as the start and end points were easily accessible via Prospect Street. Figure 3-2 provides an overview of the study area.

Figure 3-2: Overview of Test Section (City of Fredericton, 2014)
Data was logged for 22 runs in the right-hand lane travelling northwest. The Apple iPhone 5 was fastened to the vehicle in a commercially available windshield bracket. The bracket included a suction cup, which securely fastens to the windshield of the vehicle, as well as a universal device mount.

These initial tests were used in order to determine expected descriptive statistics for the purposes of estimating required sample size for subsequent tests. The mean IRI, and standard deviation for the 22 runs was found to be 0.9302 m/km, and 0.0895 m/km respectively. An estimate of the required sample size for further testing was obtained using the following equation (Dowdy and Wearden, 1983).

\[
    n = \left( \frac{Vt}{E} \right)^2
\]

Where:

- \( n \) = number of required samples
- \( V \) = coefficient of variation
- \( t \) = student "t" test statistic
- \( E \) = acceptable error

The coefficient of variation (COV) was calculated to be 9.62% and the t-value at 5% level of significance was 1.960. In this case, it was estimated that an error of ±10% would be considered sufficient to provide a general estimate. This was chosen because of the expected range of IRI values coupled with the collection method, ±10% was deemed to be an acceptable level of error.
Using this method, the number of required samples required was calculated to be four. It is worth noting that this calculation assumes that the COV would remain constant for all scenarios; however, this would most likely not be the case due to random experimental error. To account for situations where the standard deviation of subsequent tests were higher than what was observed during the pilot test, eight samples were taken. This avoided the risk of not having a large enough dataset in order to statistically analyze the results.

3.3 Study Area

The section of Route 8 used in the pilot study was chosen as it provided safe, convenient reset locations. It was useful for determining statistics to guide further testing; however, being a high-level four-lane highway, it did not represent an average road of average condition. For these reasons a new test section was required to perform further testing. The following criteria were used when determining the new section of roadway.

- Speed limit greater than or equal to 80km/hr
- Safe reset locations
- Maintained by the Province of New Brunswick
- Approximately one kilometre in length
- Few changes in grade and horizontal alignment

The speed at which testing was done was chosen to align with the standard method of IRI data collection. It was also required that the test section be maintained by the
Province in order to access the New Brunswick Department of Transportation and Infrastructure’s standard inertial profiler.

The one-kilometre length requirement was chosen to reduce potential error in the results. Ideally, a shorter test section would be chosen in order to reduce the time required for each run thus increasing testing efficiency; however, this would not be advisable given the method of initiating and ceasing data logging. The data was collected by manually touching the given device’s screen at predetermined start and stop locations. The human error associated with this may have adversely affected the results on a shorter section as no two tests would start and stop at precisely the same location. A section length of approximately one kilometre was determined to provide an adequate balance between error and efficiency.

The need for few changes in horizontal alignment and grade also had to do with controlling for error in the experiments, as accelerometers are able to measure external g-forces imparted on the device. Large changes in grade would cause the vehicle to accelerate, which would add unwanted features to the signal being collected. Similarly, horizontal alignment changes would also disturb the signal as the accelerometer would pick up centripetal forces imparted on the device. Both of these situations could skew the test results; therefore, a section with few changes in grade and horizontal alignment was chosen.

The section of Clements Drive (Route 105) west of the Carlisle Road in Fredericton, New Brunswick was found to best match the above criteria. Note that data logging was
only initiated in the eastbound lane. A large parking lot at the intersection of Carlisle Road and Route 105 was used as the eastern turnaround location, while a vehicle turnoff providing access to a recreational trail was used as the western turnaround location. Only one road (i.e., roughness level) was tested due to time constraints; however, as mentioned it was chosen as it best represented a road in average condition. Figure 3-3 displays the study area in further detail.

![Figure 3-3: Clements Drive Test Section (City of Fredericton, 2014)](image)

3.4 Standard Inertial Profiler Comparison

The first major objective of the study was to perform tests from within a standard inertial profiler in order to have a one-to-one comparison between the two methods of data collection. The New Brunswick Department of Transportation and Infrastructure agreed
to allow these tests to be performed. Their organization collects IRI data on arterials, collectors and local asphalt highways on a three-year cycle (Cunningham, MacNaughton and Landers, 2010) using a Surface Systems and Instruments CS9000 Profiler owned by the Province.

The profiling system used in this study was mounted to a Ford F250 truck, and required reflecting strips to be placed at the start and end points of the test section. When the profiler travelled past these strips, a sensor initiated and ceased data logging. A Panasonic Toughbook was attached to the system and provided a stream of real-time results as tests were complete.

The test was done using the windshield-mounting bracket that was used in the scenario tests. Care was taken to mount the device as closely in line to the truck’s passenger side data recorder as possible to ensure that the roughness from the same longitudinal slice of road was logged. The inertial profiler recorded data from a point in line with both wheels, and generally the roughness is taken as an average of the two measurements. It was possible to separate these two datasets; therefore, only the passenger side profile was used for comparative purposes. Due to time constraints of the Province’s technicians, only five runs were completed as opposed to the eight that were performed during scenario testing.
3.5 Scenario Testing

The following sections discuss each of the scenarios that were evaluated as part of this study. Each test was performed in the location mentioned above.

3.5.1 Vehicle

The acceleration response caused by road roughness may be severely affected by variations in vehicle suspension. It was therefore necessary to quantify these effects by performing tests with different vehicle types. The following vehicle classes were evaluated:

- Compact Sedan – 2001 Pontiac Sunfire
- Sports Utility Vehicle – 2011 Nissan Rogue
- Three Quarter Ton Truck – 2008 Ford F250

The specific vehicle used for each suspension scenario was chosen partly based on availability; however, care was taken to ensure they were representative of different common passenger vehicle classes. The vehicle chosen for each test was to be average quality for the given class, and be in good repair. Luxury vehicles and older vehicles were not considered. Additionally, attributes like tire pressure was not monitored in order to better simulate a practical application of the system. Engine vibration was not accounted for due to equipment limitations. Table 3-1 displays equipment used for each test.
Table 3-1: Vehicle Scenario Equipment

<table>
<thead>
<tr>
<th>Vehicle 1</th>
<th>Vehicle 2</th>
<th>Vehicle 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Device</td>
<td>Mount</td>
</tr>
<tr>
<td>Pontiac Sunfire</td>
<td>iPhone 5</td>
<td>Windshield</td>
</tr>
<tr>
<td>Nissan Rogue</td>
<td>iPhone 5</td>
<td>Windshield</td>
</tr>
<tr>
<td>Ford F-250</td>
<td>iPhone 5</td>
<td>Windshield</td>
</tr>
</tbody>
</table>

3.5.2 Device

It was hypothesized that the variability in acceleration response collected from different smartphone devices should be minimal; however, tests were done with a device from each of the aforementioned companies to validate this assumption. The specific make and model of devices tested were as follows:

- Apple iPhone 5
- Blackberry Z10
- Samsung Galaxy SIII

Table 3-2 provides a summary of the experimental design used to delineate the differences of different cellphones devices on data results.

Table 3-2: Device Scenario Equipment

<table>
<thead>
<tr>
<th>Device 1</th>
<th>Device 2</th>
<th>Device 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Device</td>
<td>Mount</td>
</tr>
<tr>
<td>Pontiac Sunfire</td>
<td>Pontiac Sunfire</td>
<td>Windshield</td>
</tr>
<tr>
<td>Pontiac Sunfire</td>
<td>Galaxy SIII</td>
<td>Windshield</td>
</tr>
<tr>
<td>Pontiac Sunfire</td>
<td>Blackberry Z10</td>
<td>Windshield</td>
</tr>
<tr>
<td>Device</td>
<td>Speed</td>
<td>Road</td>
</tr>
<tr>
<td>iPhone 5</td>
<td>80km/hr</td>
<td>Route 105</td>
</tr>
<tr>
<td>Windshield</td>
<td>80km/hr</td>
<td>Route 105</td>
</tr>
<tr>
<td>Windshield</td>
<td>80km/hr</td>
<td>Route 105</td>
</tr>
</tbody>
</table>

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3.5.3 Mounting Arrangement

Ideally, displacement changes caused by bumps in a roadway would be extracted from the acceleration response of the chassis of the vehicle. This would require an accelerometer to be physically attached to the vehicle frame, which is not practical for a smartphone device from a real-world perspective. The mounting arrangement of the test device was therefore altered to fit varying conditions. A custom built T-Bracket, as well as commercially available windshield and car vent mounts were tested. Figure 3-4 displays the mounts used.

![Figure 3-4: Windshield Mount (Left), T-Bracket (Middle), Vent Mount (Right)](image)

The first image above displays the commercially available windshield mount used for testing. The bracket included two lower supports and two side supports. When the device was placed on the bracket, one of the side supports was horizontally adjustable in order to ensure an appropriate fit for any smartphone. A clamp in the back of the rig was
used to lock the adjustable arm in place. The bracket also included a suction cup, which securely fastened to the windshield of the vehicle.

The custom T-Bracket shown above was developed for use in the feasibility study previously mentioned. It was constructed out of two pieces of plywood fastened together to form a cross. A metal sliding piece was attached to the vertical arm of the rig. The device was then attached to the metal slider. During testing the researcher held the vertical arm in an upright position with it touching the floor of the test vehicle, which allowed for vertical acceleration caused by bumps to be translated to the device.

The third mount shown is a commercially available vent mount which was fastened to the vent grill cover of the test vehicle. This was achieved by pushing the locking teeth located in the back of the mount into the vent grill, then adjusting spacers to ensure a secure fit. The device for this mounting arrangement was then placed in an upright position within the universal mounting bracket and secured using an adjustable side support, much like the windshield mount previously discussed. Table 3-3 displays the equipment used for each of the mounting arrangement scenarios.

<table>
<thead>
<tr>
<th>Table 3-3: Mount Scenario Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mount 1</strong></td>
</tr>
<tr>
<td>Vehicle</td>
</tr>
<tr>
<td>Device</td>
</tr>
<tr>
<td>Mount</td>
</tr>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>Road</td>
</tr>
</tbody>
</table>
3.5.4 Speed

The original IRI conversion algorithm, developed for use by inertial profilers, was designed to handle data that was ideally collected at a constant 80km/hr (Gillespie, Paterson and Sayers, 1986). The absolute minimum speed required to collect useable roughness measurements is 50km/hr. Collecting data outside this range could cause the acceleration response to be exaggerated or dampened depending on the characteristics of the road, which could ultimately alter roughness measurements.

The specifications provided are for standard inertial profilers; however, it was necessary to evaluate the effects of speed in this study, as the data collection method was novel in this case. To evaluate this, tests were run travelling at both 80km/hr and 50km/hr to determine if there was a significant change in the resulting roughness data. Table 3-4 displays the setup used for these tests.

<table>
<thead>
<tr>
<th>Table 3-4: Speed Scenario Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle</strong></td>
</tr>
<tr>
<td>Pontiac Sunfire</td>
</tr>
<tr>
<td>Pontiac Sunfire</td>
</tr>
</tbody>
</table>

3.5.5 Vehicle/Speed Interaction

Due to time constraints, it was not possible to evaluate every combination of factors in order to determine if interactions existed. However, given that suspension systems vary
widely between vehicle classes, it was hypothesized that there may be an interaction between vehicle type and speed.

As a vehicle travels over a road, the roughness is felt through the suspension of a vehicle, and depending on the speed, roughness may be perceived higher or lower. This may directly translate to different acceleration responses for different combinations of vehicles travelling at high and low speeds; therefore, the scenario was tested in order to evaluate the potential interaction. Each vehicle was run at both 50km/h and 80km/h on Route 105. Table 3-5 lists equipment used for this scenario.

<table>
<thead>
<tr>
<th>Sunfire High</th>
<th>Sunfire Low</th>
<th>Rogue High</th>
<th>Rogue Low</th>
<th>F-250 High</th>
<th>F-250 Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunfire</td>
<td>Sunfire</td>
<td>Rogue</td>
<td>Rogue</td>
<td>F-250</td>
<td>F-250</td>
</tr>
<tr>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
</tr>
<tr>
<td>Windshield</td>
<td>Windshield</td>
<td>Windshield</td>
<td>Windshield</td>
<td>Windshield</td>
<td>Windshield</td>
</tr>
<tr>
<td>80km/hr</td>
<td>50km/hr</td>
<td>80km/hr</td>
<td>50km/hr</td>
<td>80km/hr</td>
<td>50km/hr</td>
</tr>
<tr>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
</tr>
</tbody>
</table>

3.6 Statistical Analyses

This method of roughness data collection could have large impacts in a practical sense given the ubiquitous nature of the technology. Throughout the study, all of the equipment used was commercially available with no custom alterations, except for the T-Bracket mount discussed earlier. However, if the technology were to be deployed in a real-world setting, it was crucial to evaluate each of the key identified factors to determine if any produced statistically different results than the base test. In order to
achieve this, each of the scenario tests were evaluated against the following initial set of factors:

i. Vehicle – Pontiac Sunfire
ii. Device – iPhone 5
iii. Mount – Windshield
iv. Speed – 80km/h

By altering single factors, while keeping all others constant, it was possible to evaluate if the changed factor had a significant effect on the results of the test. This was done by comparing the mean IRI collected for each of the given scenarios using a separate one-way analysis of variance (ANOVA) test. IBM SPSS software was used to perform these statistical tests, which executed the following standard ANOVA table shown in Table 3-6 (Devore, 2008).

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>d.f.</th>
<th>SS</th>
<th>MS</th>
<th>$F_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor A (Between Groups)</td>
<td>$a - 1$</td>
<td>$SSA = \sum_{i=1}^{a} n_i (\bar{y}_i - \bar{y})^2$</td>
<td>$MSA = \frac{SSA}{(a - 1)}$</td>
<td>$\frac{MSA}{MSE}$</td>
</tr>
<tr>
<td>Error (Within Groups)</td>
<td>$N - a$</td>
<td>$SSE = SST - SSA$</td>
<td>$MSE = \frac{SSE}{(N - a)}$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$N - 1$</td>
<td>$SST = \sum_{i=1}^{a} \sum_{j=1}^{n} (y_{ij} - \bar{y})^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The one-way ANOVA method shown in Table 3-6 would only determine if at least one of the factors used in testing yielded significantly different results, it would not identify which specific factor. In the event that the null hypothesis was rejected in the initial test,
Tukey’s method was used to determine which factors were statistically different or similar. This method simultaneously evaluates whether or not the calculated averages are statistically similar via pairwise comparisons. The first step in executing this method is to arrange each of the required averages in ascending order. A critical range “\( w \)” is then calculated using the following equation (Devore, 2008).

\[
w = Q_{\alpha,j,(j-1)} \sqrt{\frac{MSE}{J}}
\]

Where:

- \( Q \) = Critical value for studentized range distribution
- \( MSE \) = Mean squared error
- \( J \) = Number of samples

This value is then compared to the sampled means. If \( u_i - u_j < w \), the values are taken to be statistically similar. Continuing with the set of sample means listed in ascending order, any values that differ by less than \( w \) are considered to be statistically similar. The means that are found to be statistically similar are generally highlighted or underlined for the purposes of displaying results of Tukey’s method. Therefore, for example there are five means \( X_1 < X_2 < X_3 < X_4 < X_5 \). For the purposes of the example \( X_1, X_2, \) and \( X_3 \) were found to be statistically similar using the method stated above, while \( X_3, X_4, \) and \( X_5 \) were also found to be statistically similar, the results would be presented as shown in Table 3-7.
The data collected from the inertial profiler comparison tests were analyzed separately. Averages from both the five runs collected via the standard profiler and the proposed method were compared to determine if they were statistically similar. To achieve this, a student t-test was performed. The average IRI collected from within the inertial profiler using the iPhone 5 was used for comparison purposes.
Chapter 4: Analysis and Results

The following chapter provides a breakdown of key results extracted from both scenario tests and the standard inertial profiler tests. This includes a general overview of all tests as well as results from the statistical tests performed as part of the study.

4.1 General Overview

The data in Table 4-1 synthesize the average IRI collected for all tests performed as part of this study. It should be noted that the item listed as “Initial Setup” refers to the tests performed using the Pontiac Sunfire, iPhone 5, and commercial windshield mount at 80km/hr on the eastbound lane of Route 105. These initial setup factors were randomly chosen, then for subsequent tests a single factor was changed. Additionally, the two items listed as “Inertial Profiler” and “Profiler (iPhone)”, refer to the data that were collected from within the inertial profiler. Overall, the average IRI collected for each method appears to revolve around the true IRI collected using the inertial profiler, except for the data collected while using the commercial vent mount.
Table 4-1: Average IRI for All Tests

<table>
<thead>
<tr>
<th>Factor</th>
<th>Samples</th>
<th>IRI (m/km)</th>
<th>Std. Dev</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial Profiler</td>
<td>5</td>
<td>2.6</td>
<td>0.029</td>
<td>1.12</td>
</tr>
<tr>
<td>Profiler (iPhone)</td>
<td>5</td>
<td>2.73</td>
<td>0.2</td>
<td>7.33</td>
</tr>
<tr>
<td>Initial Setup</td>
<td>8</td>
<td>2.74</td>
<td>0.16</td>
<td>5.84</td>
</tr>
<tr>
<td>Galaxy SIII</td>
<td>8</td>
<td>2.58</td>
<td>0.075</td>
<td>2.91</td>
</tr>
<tr>
<td>Blackberry z10</td>
<td>8</td>
<td>2.65</td>
<td>0.058</td>
<td>2.19</td>
</tr>
<tr>
<td>T-Bracket</td>
<td>8</td>
<td>2.35</td>
<td>0.11</td>
<td>4.68</td>
</tr>
<tr>
<td>Vent Mount</td>
<td>8</td>
<td>4.83</td>
<td>0.44</td>
<td>9.11</td>
</tr>
<tr>
<td>F-250 (80km/hr)</td>
<td>8</td>
<td>2.48</td>
<td>0.2</td>
<td>8.06</td>
</tr>
<tr>
<td>Rogue (80km/hr)</td>
<td>8</td>
<td>2.29</td>
<td>0.079</td>
<td>3.45</td>
</tr>
<tr>
<td>Sunfire (50km/hr)</td>
<td>8</td>
<td>2.41</td>
<td>0.072</td>
<td>2.99</td>
</tr>
<tr>
<td>Rogue (50km/hr)</td>
<td>8</td>
<td>2.63</td>
<td>0.054</td>
<td>2.05</td>
</tr>
<tr>
<td>F-250 (50km/hr)</td>
<td>8</td>
<td>2.34</td>
<td>0.14</td>
<td>5.98</td>
</tr>
</tbody>
</table>

In the early stages of this study, a pilot test on Route 8 was performed in order to determine required sample size for further testing as previously stated. The COV found in the pilot test was 9.62% giving an estimated sample size of four. Eight samples were taken for each of the main scenario tests on Route 105 to account for situations where the COV for any given scenario was found to be greater than 9.62%. The actual COV for each of the respective scenarios is displayed in Table 4-1, and the results show that none were greater than the COV found in the pilot test.

Figure 4-1 is a boxplot that graphically displays the IRI findings from all tests. The box bounds the inner-quartile range for each scenario, while the whiskers bound the 95% confidence interval about each mean. It can be seen that the range of IRI values collected by the inertial profile is noticeably smaller than the other methods tested which was to be expected. One will also note from the plot that the vent mount not only
produced IRI values that were higher than the rest of the methods tested, but the range of values was also much wider. These two items provided some general insight into the outcome of the tests; however, additional testing was warranted in order to determine which specific factors produced statistically similar results.

Figure 4-1: Box Plot of Results
4.2 Inertial Profiler Comparison

Testing was performed from within a standard inertial profiler in order to provide a true one-to-one comparison of both methods. Data were logged using an iPhone which was fastened inside the vehicle using the windshield mount, as well as the standard profiling equipment. Figure 4-2 is a box plot that graphically displays the comparison between the two methods of data collection.

Table 4-2 displays the results from the paired t-test and F-test that was performed in order to evaluate whether both data sets had significantly different means and variances.
Table 4-2: Statistical Tests for Profiler vs. iPhone Comparison

<table>
<thead>
<tr>
<th>Variance Test</th>
<th>Means Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>p-value</td>
</tr>
<tr>
<td>4.867</td>
<td>0.058</td>
</tr>
</tbody>
</table>

The p-value from this t-test was found to be 0.208, indicating that 20.8% of theoretical t-values would be greater than 1.369. At a level of significance of 0.05, we can state that both averages were drawn from the same population. Although the results were found to be statistically similar, the box plot reveals the interquartile range of the roughness data collected by the iPhone was substantially larger than that of the inertial profiler. Additionally, the iPhone method’s COV was approximately five times greater than the inertial profiler’s. However, at a level of significance of 0.05, we can state that the variances did not differ significantly given the p-value of 0.058, which indicates that 5.8% of theoretical F-values would be greater than 4.867.

4.2.1 Incremental Analysis of Profiler Versus Galaxy SIII

One of the sources of error associated with the smartphone method of data collection was the limited ability to start and stop data logging at a predetermined point. This would have little effect on passive monitoring of road condition; however, it may make the method inappropriate for determining the roughness of controlled sections, for applications in contract verification and quality control/assurance. In these situations roughness values are reported for very short sections of road in order to ensure to meet predetermined contract specifications.
To evaluate the smartphone’s ability to perform under these circumstances, the section was broken down into 100m intervals to evaluate how closely the proposed method of data collection followed the standard inertial profiler on shorter intervals. Due to time constraints, only the test that used the Galaxy SIII was evaluated in this manner, as it provided the closest IRI (2.58m/km) to the profiler’s results (2.60m/km). Figure 4-3 below displays the results of this analysis with the IRI of each method reported at every 100m along the test section.

The box plot’s results would suggest that decreasing collection interval would reduce the accuracy of the smartphone’s roughness data due to the higher variability. Contrary to
these results, the graph above shows that at intervals as low as 100m, the smartphone method is still able to produce meaningful results. Each of the data points averaged from both methods at each interval follow approximately the same trend throughout, with a correlation of 88.9% calculated using Microsoft Excel. One must note that the roughness values from the smartphone method shown above were extracted from only the Galaxy SIII scenario due to time constraints; therefore, further investigation would be required.

Further analysis was done on the correlation between the profiler and Galaxy SIII by plotting the datasets against each other, with the Galaxy SIII plotted on the x-axis and the profiler's roughness on the y-axis. Figure 4-4 displays the results of this analysis.

![Figure 4-4: Profiler Roughness plotted against Galaxy SIII Roughness](image)

\[ y = 0.8637x + 0.4094 \]
\[ R^2 = 0.7901 \]
If both datasets were exactly the same, the intercept of the trend line would be zero with a slope of one. The results show a slope of 0.8637 with an intercept of 0.4094, this indicates that the Galaxy SIII slightly overestimated roughness for the 100m increments over the 1km test section.

4.3 Impact of Smartphone Device

This scenario aimed to determine how varying smartphone devices affects the roughness values obtained through testing. Three major manufacturer’s products were used including iPhone, Blackberry, and Samsung. Table 4-3 displays the ANOVA table results for the smartphone device scenario. All tests were completed with a level of significance of 0.05. In this case where the p-value was determined to be 0.022, there is only a 2.2% probability of observing an F-value greater than 4.616. The null hypothesis that all devices in the group’s IRI results were drawn from the same population was therefore rejected.

Table 4-3: ANOVA Table for Smartphone Scenario

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>0.105</td>
<td>2</td>
<td>0.052</td>
<td>4.616</td>
<td>0.022</td>
</tr>
<tr>
<td>Within Groups</td>
<td>0.238</td>
<td>21</td>
<td>0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.342</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Given that the null hypothesis was rejected, further analysis was required to determine which averages were statistically drawn from the same population. Table 4-4 displays the results from the Tukey’s test that was performed, and as shown, the Galaxy and Z10,
and the Z10 and iPhone were found to be statistically similar. The table highlights these pairings in grey.

Table 4-4: Tukey's Pairings for Smartphone Scenario

<table>
<thead>
<tr>
<th>Device</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy</td>
<td>2.5838</td>
<td>2.6438</td>
</tr>
<tr>
<td>Z10</td>
<td>2.6438</td>
<td>2.6438</td>
</tr>
<tr>
<td>iPhone</td>
<td></td>
<td>2.7438</td>
</tr>
</tbody>
</table>

The results from this scenario were not as expected, as each of the three devices used have similar accelerometer chips all from the same company and all other factors remained constant. One possible reason for the discrepancy may have been caused by the application that was used to extract raw acceleration data from the devices. A single application was available for the Samsung Galaxy SIII and Blackberry Z10. The application was not available on Apple iTunes store, therefore a separate program was used to log acceleration from the iPhone. This may also explain why the variance in the data collected from the iPhone was significantly higher than that of the Galaxy SIII and Z10 devices.

4.4 Impact of Mounting Arrangement

This scenario was undertaken in order to evaluate the effects that varying the smartphone's mounting arrangement had on resultant IRI values. A custom t-bracket, as well as commercially available windshield and vent mounts were tested. The p-value found for these tests was found to be zero, implying that there is essentially a zero
percent probability of observing an F-value greater than 183.068. For these reasons, the null hypothesis that varying mounts will yield statistically similar results was rejected at a level of significance of 0.05.

Table 4-5: ANOVA Table for Mounting Arrangement Scenario

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>28.261</td>
<td>2</td>
<td>14.131</td>
<td>183.068</td>
<td>0</td>
</tr>
<tr>
<td>Within Groups</td>
<td>1.621</td>
<td>21</td>
<td>0.077</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29.882</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Investigating the results further using Tukey's method, it was found that none of the average IRI data collected using the separate mounting arrangements were found to be statistically similar. The t-bracket and windshield mount were found to be fairly close; however, as previously stated, the vent mount yielded a much higher average IRI.

Table 4-6: Tukey's Pairings for Mounting Arrangement Scenario

<table>
<thead>
<tr>
<th>Mount</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBracket</td>
<td>2.3525</td>
<td></td>
<td>4.825</td>
</tr>
<tr>
<td>Windshield</td>
<td></td>
<td>2.7438</td>
<td></td>
</tr>
<tr>
<td>Vent</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These results align with what was observed in the field, as the vent mount visibly allowed more vibration than the other two arrangements. The pieces that fastened the mount to the vehicle's vent were fairly flexible by design to allow it to be used in various vehicle makes and models. Consequently, these flexible tabs also allowed the
device to vertically travel noticeably more than the other mounting arrangements. These unwanted vibrations thus amplified the raw acceleration signal, yielding roughness readings that were approximately two times greater than all other scenarios.

Both the windshield mount and the t-bracket mount had more secure connections when compared to the vent mount and yielded average IRI results that were similar to those found in other scenarios. One possible explanation for the small discrepancy between the windshield mount and t-bracket arrangements was the location they were placed inside the vehicle during data logging. The t-bracket was held by an assistant seated in the passenger side of the test vehicle with the vertical arm touching the floor, while the windshield mount was fastened in the approximate center of the windshield. This essentially yielded two slightly different longitudinal profiles of the road. Although this may be one explanation for the discrepancy between both mounting arrangements, the error was considered to be minute as no two individual tests produces the same longitudinal profile regardless of the testing method given driver variability.

4.5 Impact of Vehicle and Speed

The vehicle and speed scenarios were done in order to determine if varying speed or vehicle type significantly affected the roughness results. High and low speeds of 50km/hr and 80km/hr were tested, while three vehicle types including a compact sedan, family SUV, and three-quarter-ton truck were used. In addition to the main effects, these tests were performed to evaluate whether or not there was a significant interaction between vehicle type and speed.
The ANOVA results in Table 4-7 show that there was no significant difference between the roughness values collected at 50km/hr and 80km/hr given a p-value of 0.187, indication an 18.7% probability of observing an F-value greater than 1.801, which warrants no further investigation. There was, however, at least some significant difference between the vehicles used, and an interaction between speed and vehicle type, as there is only a 0.2% probability of observing an F-value greater than 7.053 related to vehicle type, and essentially zero percent probability of observing an F-value greater than 29.405 for the interaction effects. These are discussed separately below using Tukey’s method and an interaction plot.

<table>
<thead>
<tr>
<th>Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-Value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>0.03</td>
<td>1</td>
<td>0.03</td>
<td>1.801</td>
<td>0.187</td>
<td>0.041</td>
</tr>
<tr>
<td>Vehicle</td>
<td>0.231</td>
<td>2</td>
<td>0.116</td>
<td>7.053</td>
<td>0.002</td>
<td>0.251</td>
</tr>
<tr>
<td>Speed * Vehicle</td>
<td>0.964</td>
<td>2</td>
<td>0.482</td>
<td>29.405</td>
<td>0</td>
<td>0.583</td>
</tr>
<tr>
<td>Error</td>
<td>0.688</td>
<td>42</td>
<td>0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>297.677</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-8 displays the Tukey’s pairings for the vehicle scenario. As shown, the data collected from within the Ford F250 and Nissan Rogue yielded significantly similar results. The data collected using the Pontiac Sunfire were not statistically similar to either of the average roughness values collected using the other two vehicles. One will note that the Sunfire’s results were still very close to that of the F250 and Rogue.
### Table 4-8: Tukey’s Pairings for Vehicle Scenario

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>F250</td>
<td>2.4094</td>
<td></td>
</tr>
<tr>
<td>Rogue</td>
<td>2.4619</td>
<td></td>
</tr>
<tr>
<td>Sunfire</td>
<td></td>
<td>2.5756</td>
</tr>
</tbody>
</table>

Figure 4-5 shows that both the Sunfire and F250 reported higher average roughness values at 80km/hr when compared to 50km/hr; however, the Nissan Rogue reported the opposite. These results are not as expected, as one may assume that all three vehicles would at least report the same trend whether it be higher or lower roughness at the differing speeds. Under these circumstances, it is therefore not possible to say whether or not to expect higher or lower roughness depending on speed. This variability may be explained by the random factors associated with collecting data in this manner. Previously stated, a large source of error is inherently present as it is virtually impossible to log data over the same longitudinal slice of roadway for every test due to minor variability caused by the driver.
Figure 4-5: Vehicle/Speed Interaction Plot
Chapter 5: Conclusions and Recommendations

A smartphone-based method of collecting IRI was evaluated to first determine how well the values corresponded with a standard inertial profiler; and second, to evaluate the impacts of varying key factors that may affect the system. All testing was performed on a single one-kilometre long test section on Route 105 located northwest of Fredericton, New Brunswick. A total of 10 scenarios were tested along with the inertial profiler tests. These together produced 85 datasets which were evaluated.

5.1 Conclusions

To achieve the first major goal, tests were performed from within the NBDTI’s inertial profiler, with a commercially available iPhone fastened to the profiler’s windshield using an off-the-shelf windshield suction mount. Data from five separate runs were logged using both the profiler and smartphone, yielding roughness values of 2.60m/km and 2.73m/km respectively. After performing a student t-test, it was determined that both averages were statistically similar; however, the coefficient of variation using the smartphone method was substantially higher than that of the inertial profiler.

Additional analyses were performed to evaluate the smartphone method’s accuracy at shorter section intervals. The average roughness collected from the Galaxy SIII scenario was partitioned into 100m intervals and compared to corresponding inertial profiler values. This scenario setup was chosen as it provided the closest IRI results to the inertial profiler method. Both datasets were found to follow the same trend for the entire
section length, with a correlation of 88.9%. Due to time constraints, only one of the scenario tests was evaluated in this manner.

The second major goal was achieved by varying the following factors and evaluating their impact on the resultant roughness data:

i. Vehicle Suspension  
ii. Smartphone Device  
iii. Mounting Arrangement and Location  
iv. Speed

The initial factors were the Sunfire, iPhone, windshield mount, and 80km/hr. Factors were swapped out one by one to determine if they significantly affected the results. Three vehicles, three smartphones, three mounting arrangements, and two speeds were evaluated. The only factor that substantially skewed the results of testing was the vent mount, which produced IRI values that were approximately double the average of other tests. All other factor combinations produced average IRI values ranging from 2.34m/km to 2.74m/km.

Additional tests were done using each of the three vehicles at both high and low speeds of 80km/hr and 50km/hr. The average IRI results produced by the F250 and Sunfire were higher when travelling at 80km/hr compared to 50km/hr, while the opposite was true for the Rogue. This showed that no assumptions could be made regarding the effects of speed on varying vehicle suspensions. Further research may be required to evaluate this.
5.2 Recommendations

The following is a list of recommendations for the potential practical use of the proposed method of data collection, as well as the opportunities for further research.

5.2.1 Practical

- It is recommended that the smartphone device be securely fastened to the vehicle (ie. windshield suction mount) to avoid unwanted vibration during data logging. Vent mounts (or any mount that does not securely fasten the smartphone device to the vehicle) will not provide sufficient support, resulting in inflated roughness values.

- Although some factor combinations produced results that were found to be statistically different, the majority produced values in what may be a tolerable range. If this method of data collection were to be deployed, it is recommended that these results be reviewed on an agency-by-agency basis to determine if the given range of expected roughness values is acceptable.

- The Samsung Galaxy SIII coupled with the windshield mount and an average compact sedan produced results closest to the standard inertial profiler with a very low COV. This setup may be recommended for further field experimentation.
5.2.2 Further Research and Development

- This study used various software packages and methods to convert acceleration to roughness data. It is recommended that these be combined into a standalone smartphone application to reduce processing time and facilitate further testing.

- The correlation between the suggested methodology and the inertial profiler was found to be 88.9% at intervals as low as 100m; however, further analysis is required as only one combination of factors was evaluated.

- This study did not explore potential calibration factors to account for the variations in different combinations of suspension type, mount, speed, or smartphone. A possible research topic could be individually performing further analysis on each subcategory to investigate potentially creating correction factors.

- Additional testing could also be done to evaluate potential interactions between factors as only main effects were explored in this study (with the exception of the suspension/speed scenario). Other factors could also be considered like engine vibration, tire pressure, and road type, which were not evaluated due to time constraints.
References

Aksamit, P., Szmechta M. (2011). Distributed, mobile, social system for road surface defects detection. 5th International Symposium on Computational Intelligence and Intelligent Informatics. 37-40.


Appendix – Scenario Matrix
<table>
<thead>
<tr>
<th>Initial Case</th>
<th>Suspension 1</th>
<th>Suspension 2</th>
<th>Device 1</th>
<th>Device 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Pontiac Sunfire</td>
<td>Nissan Rogue</td>
<td>Ford F-350</td>
<td>Pontiac Sunfire</td>
</tr>
<tr>
<td>Device</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>Galaxy SIII</td>
</tr>
<tr>
<td>Mount</td>
<td>Windshield</td>
<td>Windshield</td>
<td>Windshield</td>
<td>Windshield</td>
</tr>
<tr>
<td>Speed</td>
<td>80km/hr</td>
<td>80km/hr</td>
<td>80km/hr</td>
<td>80km/hr</td>
</tr>
<tr>
<td>Road</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
</tr>
</tbody>
</table>

Nissan Rogue
Ford F-350
Galaxy SIII
Blackberry Z10

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<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mount 1</th>
<th>Mount 2</th>
<th>Speed 1</th>
<th>Correlation/ Covariance 1</th>
<th>Correlation/ Covariance 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pontiac</td>
<td>Pontiac</td>
<td>Pontiac</td>
<td>Nissan Rogue</td>
<td>Ford F-350</td>
<td></td>
</tr>
<tr>
<td>Sunfire</td>
<td>Sunfire</td>
<td>Sunfire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td>iPhone 5</td>
<td></td>
</tr>
<tr>
<td>T-Bracket</td>
<td>Vent</td>
<td>Windshield</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80km/hr</td>
<td>80km/hr</td>
<td>50km/hr</td>
<td>50km/hr</td>
<td>50km/hr</td>
<td></td>
</tr>
<tr>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td>Route 105</td>
<td></td>
</tr>
</tbody>
</table>

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Curriculum Vitae

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University attended: University of New Brunswick (08-12); BScE

Publications:

Cameron, C., and T. Hanson (2012). *Can a Smartphone Collect IRI?*. Presented in poster session at the Transportation Association of Canada Annual Conference, Fredericton, NB.