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Pavement Roughness Evaluation with Smartphones

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Abstract-Researchers have linked pavements roughness to acceleration signals derived from smartphones, due to its low cost, simple handling and high productivity. It would facilitate a continuous data collection which is important for Pavement Management Systems (PMS). However, there are doubts about the quality and the form of application of collected data. This study performs vibration and field tests with smartphones in pavements with different roughness levels. In this study, acceleration signals were measured by a smartphone attached to a vehicle dashboard, at different speeds. RMSVA values (Root Mean Square of Vertical Acceleration) were calculated with such data. The results were then compared with the IRI (International Roughness Index) of the same pavements through Rod and Level method. Data acquisition rate of smartphones was found to be the main factor affecting its application for pavement roughness evaluation. RMSVA values showed a positive correlation with IRI, having Pearson correlation coefficients above 0.95 and acceptable repeatability for network-level surveys, with average coefficient of variation of 3 to 6%. It was concluded that smartphones are a viable alternative for pavement roughness evaluations.

Keywords*- Pavement Management System, Pavement Assessment, Pavement Roughness.*

I. INTRODUCTION

Drivers and passengers associate the condition of a pavement with their appearance (cracks, patches, colour, condition of berms, etc.) and feel discomfort during a trip due to the pavement roughness. These vertical accelerations, in turn, depends on: (i) the pavement roughness characteristics, (ii) on the vehicle speed, (iii) on the mass of the vehicle and (iv) its suspension parameters. The vehicle works as a mechanical filter, which affects the relationship between the user sensitivity and the pavement roughness condition [1]. This perception is justified, because the roughness affects the purpose of the road i.e. to provide softness, comfort and safety in the driving. As defined by [2], roughness is the most important factor related to the pavement serviceability-performance concept.

In addition to affecting the comfort and safety of drivers and passengers, roughness reduces the life of pavements, since the dynamic effect imposed by vehicles that travel on a road, especially the heavy ones such as buses and trucks, grows near the roughness, which accelerates deterioration of the structure [3].

This process results in higher costs for public and private agencies that manage the roads. The increase in costs is due to maintenance and rehabilitation services, applied to pavements in order to maintain acceptable levels of roughness in accordance with the functional class of the road.

Because of the inconveniences caused by pavement roughness, it is necessary to keep track of it, which can be done by different methods and quantified mainly by IRI (International Roughness Index) standardized by the World Bank in 1986. The methods for obtaining IRI are classified into four classes [4]:

- Class 1 - precision equipment that measure the true profile of pavements (Level and Mira, Dipstick, z-250, profilometer TRL, profilometer Walking Profilometer ARRB - Australian Road Research Board etc.);
- Class 2 - other perfilometric methods (profilographs, inertial profilometers equipped with lasers, infrared or ultrasound systems, the French APL - Longitudinal Profile Analyser etc.);
- Class 3 - response-type systems (longitudinal roughness integrator IPR/USP, Maysmeter, MERLIN, Riley, TRL Bump integrator etc.);
- Class 4 - subjective evaluations (panel ratings).

Despite the diversity of techniques available for pavement roughness evaluation, there are conflicts between the different classes of these devices, involving accuracy and convenience [5, 6]. In other words, there is no way to measure roughness with accuracy, high productivity and low cost.

Several systems use profilometers and sophisticated tools, with high acquisition and operation costs, which often require certain ability of the operators. Static precision equipment is also used, but this type of equipment is not practical for network-level surveys. The application of subjective assessments is also possible, which is common in developing countries. However, this is not a simple task.

Recently, researchers have linked pavement roughness to the acceleration measured by smartphones, due to its low cost, simple handling and high productivity. These advantages can facilitate the continuous data collection at the network level, which is important for pavement management systems [5, 6, 7, 8, 9, 10, 11, 12].

Smartphones collect the acceleration response of the vehicle chassis, a vehicle mount apparatus is required to attach smartphone on the windshield or on the dashboard of the vehicle. This type of approach is a response-type road roughness measuring system (RTRRMS) [4]. Although this method does not function as a conventional RTRRMS, in which displacements between the body and the rear axle of a vehicle are accumulated in one direction, smartphone's approach does not measure pavement's profiles as a profilometer.

There is a strong correlation between the in-car z-axis acceleration related to vehicle vibrations, caused by pavement roughness and the International Roughness Index (IRI) [13], due to this reason, some researchers have used the acceleration signals measured by smartphones to calculate the IRI or to correlate the frequency of these signals to pavement roughness. For the calculation of IRI, it is essential to process the acceleration signals for obtaining the deviations of a pavement profile along road longitudinal distance.

Therefore, it is necessary to calculate the displacement from the double integral of the acceleration signals. However, direct calculation of the double integral of acceleration signals measured by smartphones can cause undesirable errors in the obtained displacement. For example, there is a problem of the unknown initial conditions, namely the initial speed and position. There are also problems caused by the "noises".

Noises are random errors generated by: accelerometer itself, temperature or other physical effects [14], resonant motions produced by an inappropriate vehicle support, the engine roar at high speeds, during a gear shifting or at horizontal and vertical curves (mainly with small radius) of a road. Without proper data processing, both lead to serious integration errors [15].

II. Objectives

Investigation of the potential of smartphones for assessing pavement roughness, analyzing the quality and the form of application of the obtained data to the end.

III. Material and Methods

To accomplish the goals of this study, IRI values were obtained through data collected from Rod and Level method to serve as a comparative basis to the data obtained with a smartphone (Fig. 1). Three road segments with different roughness levels were selected: (i) a low roughness profile (IRI about 2 m/km), (ii) an intermediate and (iii) a profile with high roughness (IRI above 4 m/km). A length of 500 meters was selected for each segment to obtain a reasonable number of samples, whereas the IRI was calculated for 100 meters long segments. There are two reasons for selection of this distribution: 1) in general, a pavement management systems uses sections with 100-meter long or more; 2) the reduction of these segments could increase errors during the cross-matching between data collected by smartphone and through Rod and Level method. This procedure can be verified in Fig. 1.

(a) (b) (c)

Figure 1. Data collection with Rod and Level: a) Airport, b) Embrapa and c) MGS road

For the low roughness condition, a segment of Bartolomeu Airport Runway was used, which is located in Araraquara - SP/Brazil (Fig. 1a). For the intermediate condition, a segment of the road in Embrapa (Brazilian Agricultural Research Corporation) was selected, it is located in São Carlos - SP/Brazil (Fig. 1b). Lastly, a segment of the Municipal Road of Guilherme Scatena (Fig. 1c) located in São Carlos - SP/Brazil was chosen as the segment with the poor condition. To facilitate the text reading, segments of Bartolomeu Airport, Embrapa Pecuaria Sudeste and Estrada Municipal Guilherme Scatena will be named as Airport segment, Embrapa and MGS road respectively.

Data collected with the Rod and Level method were used to calculate the IRI, through the software named as ProVAL (Profile Viewing and Analysis). For this, the program needs the cumulative elevations values and the sampling interval of collection. In this study, an interval of 0.5 m is used. The index was obtained with the average IRI, calculated from the two wheel tracks of each segment.

After performing data collection with Rod and Level method from all three road segments, acceleration signals and its geographical coordinates were collected through the accelerometer and GPS of a smartphone. In this study, smartphone model, Samsung Galaxy S5 Mini, was used. It was fixed on a non-slip support known as Anti Slip Pad Car. Used on the vehicle dashboard, the adhesive silica gel allows a securely fixation of the smartphone to the car body (Fig. 2). Placed in a vertical position to the longitudinal axis of the vehicle, the device was arranged to measure the acceleration in the Z-axis of the smartphone.

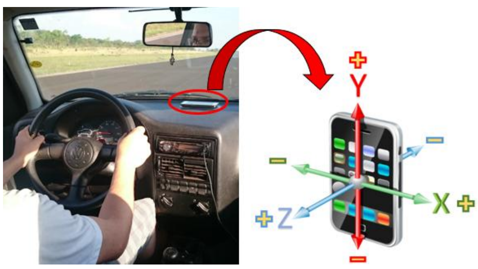


Figure 2. Data collection with smartphone

The data (acceleration and coordinates) were recorded with AndroSensor app. The software offers the options of data acquisition rate and speed to update the data. A higher speed to update data and a recording frequency of 100 Hz (one hundred samples per second) were selected. The Samsung Galaxy S5 Mini smartphone achieved an acceleration acquisition rate on average of 50 to 60 Hz. Whereas, the maximum acceleration acquisition rate achieved was 100 Hz. For example, an average rate of 50 Hz, features one hundred data samples in one second, i.e. fifty updated and fifty repeated data samples. The sampling interval depends on the speed of the vehicle during data collection, i.e. the lower the speed, the smaller the sampling interval. For example, a speed of 60 km/h and a frequency of 100 Hz generate an acceleration value of 16.67 cm each.

To work with positive values, rms values were calculated from the accelerations measured by the smartphone, which, in this research, were called RMSVA values (Root Mean Square of Vertical Acceleration), obtained from (1).

$$RMSVA = \sqrt{\frac{1}{n}\sum_{i=1}^{N} a_{zi}^{2}} \quad (1)$$

Where:

RMSVA: Root Mean Square of Vertical Acceleration (m/s²).

az: vertical acceleration (m/s²).

n: number of data.

The repetitiveness of RMSVA was analyzed from the calculation of the standard deviation (σ) and coefficient of variation (CV) of these values, according to the speed in the data collection and the evaluated segment. In this study, the speeds of 20, 40 and 60 km/h were used. Furthermore, as recommended by [16], the procedures for the calibration of RTRRMS and average RMSVA values for ten collecting trips were used.

Samples of RMSVA (smartphone) were then compared with the IRI (Rod and Level) by graphing dispersion between their values. This relationship was evaluated using Pearson correlation coefficients (r) in order to analyze how close is the connection between the data provided by the smartphone with the pavement roughness, based on a reference method.

After this analysis, the quality of acceleration signals provided by smartphones was investigated. For this, vibration tests were carried out with some models of this device, with two main objectives: 1) to evaluate the functioning of accelerometers installed on smartphones, based on a reference system and 2) investigate the possibility of calculating the IRI from smartphone's data.

Signals measured by three models of smartphones were analyzed through vibration tests. The signals derived from a piezoelectric accelerometer, with an acquisition data rate set at 500 Hz were used as a reference. The tests were performed with the aid of a shaker which imposes vibrations in frequencies selected by the user, in this case 5, 10, 15, 20, 30, 40 and 50 Hz. Smartphones and the piezoelectric accelerometer were attached to a steel plate, which was attached to the shaker by a screw. Since the two devices vibrated simultaneously, these should also show similar responses in terms of vertical acceleration (m/s²). Fig. 3 illustrates these assays.

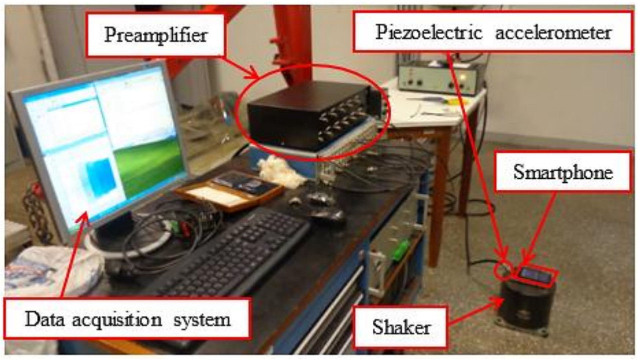


Figure 3. Set of equipment used in the vibration tests

Vibration tests were performed with three models of smartphones: (*i*) Samsung Galaxy S5 Mini, (*ii*) Motorola Moto X Play and (*iii*) Sony Xperia SP. These devices were tested with an acquisition data rate of 50 Hz to avoid getting repeated data in this analysis because the acquisition data rate was not constant for higher frequencies.

After performing data collection surveys with smartphone and checking the effect of vibration frequency at the acceleration signals measured by three models of smartphones, some tests were carried out to analyze the influence of the frequency spectrum of the information collected on the roads. This analysis was important to verify the effect of the frequency spectrum of pavement profiles on the application form of the data collected by the smartphone as discussed in the results section.

To obtain the spectrum of acceleration signals collected on the roads, a piezoresistive accelerometer was used, which was connected to a data acquisition board and then digitized. The measured signals were analyzed in the frequency domain by Fourier Transform. The signals with frequencies up to 100 Hz were plotted on charts, by using a Butterworth second order low pass filter in 100 Hz. Because above 100 Hz, lower magnitude events occur with approximately constant amplitude, these are related to noise produced by the piezoresistive accelerometer, present in the entire frequency band of this device. Such a signal can be ignored, as it is not related to the roughness of pavements. The accelerometer remained mounted on the smartphone's screen, so that the two devices should measure their signals in the same direction, perpendicular to the vehicle longitudinal axis. In Fig. 4 the components used in this step are presented.

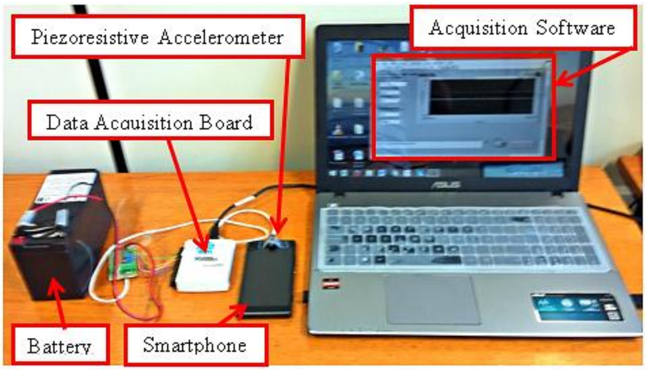


Figure 4. Devices used in the signal spectral analysis collected on the roads

This analysis showed the presence of high-frequency events in the spectrum of the information collected on the roads. It is clear by these results with the failures observed in the signals provided by smartphones at the vibration tests, that it is impossibile to use the data provided by smartphones in the frequency domain which is necessary for the calculation of IRI due to aliasing effect. It was analyzed that the AndroSensor app could be a cause of the failures in the signals provided by the smartphones, particularly with respect to the limitation of the smartphone's data acquisition rate.

Therefore, a new vibration testing was carried out, with a new app, developed for the collection of acceleration signals, called Accelerometer Analyzer. The app allows the use of some fixed rates. For new testing, the data acquisition rate called "Game" which corresponds to 50 Hz was used. Another data acquisition rate called "fatest" corresponds to a rate that varies in accordance with the smartphone capacity. Once again, the signals measured by smartphones were compared to the piezoelectric accelerometer with a data acquisition rate of 500 Hz.

Thus, it became possible to analyze the performance of the new app in relation to the attenuation of acceleration peaks in high frequency oscillations, as well as the possibility of a proper calculation of vertical displacements, from an acceleration signal provided by a smartphone used for the IRI calculus. The same oscillation frequencies (5-50 Hz) were used which were appplied in the previous vibration tests with the inclusion of frequencies of 75 and 100 Hz. These frequencies were added because relevant magnitudes were not observed at frequencies above 100 Hz in the spectral analysis. In addition, this second stage of vibration testing also did estimate the performance of all three smartphones used in this research, when these were used in field surveys with Accelerometer Analyser app.

IV. Results

From the elevation values measured by rod and level, with a sampling interval of 0.5 m, the IRI was calculated through the software ProVAL. These values were calculated for every 100 meters of three segments with total length of 500 meters each. Acceleration signals were also collected for the same segments with a smartphone attached to a vehicle panel, caused by vibrations related to the pavement roughness, along with their coordinates provided by the smartphone's GPS. The acceleration signals were used to calculate RMSVA values for the same 100 meters long segments in which IRI values were obtained.

The analysis of repeatability for the data collected by the smartphone was performed using values of "Average RMSVA". These values are related to the average of ten collecting trips made on each segment. Considering the average values of RMSVA obtained in each section (average of the five RMSVA values obtained for each 100 meters of the total length of 500 meters in each segment) and speed used during the surveys (20, 40 and 60 km/h). Table 1 shows the standard deviation and coefficient of variation obtained from "Average RMSVA" values.

TABLE I. Repeatability analysis of Average RMSVA (smartphone)

Segment	Speed (km/h)	RMSVA (m/s²)	σ	CV (%)
Airport	20	0.37	0.02	4.56
	40	0.59	0.03	4.6
	60	0.78	0.04	5.3
Embrapa	20	0.77	0.03	3.41
	40	1.12	0.04	3.56
	60	1.2	0.05	4.19
MGS Road	20	1.35	0.06	4.38
	40	2.78	0.14	5.23
	60	4.75	0.27	5.68

In general, speed and roughness level are the factors that can influence the repeatability of the data collected. Its because both may experience an obstacle to maintain the same conditions for a data collection such as the vehicle side position, the coincidence of the start point and the end point of the segments, the consistency of the speed and the influence of noise generated by a smartphone. The noise will affect the order of magnitude of the results, which is highest when the speed and roughness level are at their lowest.

Even with the influence of these factors, standard deviation values and coefficient of variation showed no significant difference with the change in segments and speed, with a minimum average coefficient of variation of 3.41% and a maximum average coefficient of variation of 5.68%. Reference [5] also found low coefficients of variation to analyze the repeatability of IRI values obtained from data provided by a smartphone. These were less than 20% for 3 of 40 segments (about 160 meters long) used in their study, obtained from five trips on each segment.

In their research, [9] mention the classification of IRI values, expected for each type of road presented by [13]. For example, in case of runways and highways, in which the expected IRI range is from 0 to 2 m/km, 10% variation in this range probably would not cause misclassification for pavement management purposes at network-level. Furthermore, when taken on comparative basis, for the limit of 5% for the coefficient of variation of an inertial profilometer [17], it may be said that the values achieved between 5 and 10%, are reasonable for a system based on smartphones.

After performing the repeatability analysis of RMSVA, such values were compared to IRI calculated from data collected with the rod and level method. In order to observe the strength of the relationship between these variables for the three evaluated segments, with subdivisions of 100 meters, this analysis was performed through the calculus of Pearson correlation coefficients (r) between these values. As cited before, RMSVA values are related to the average of 10 trips made for each evaluated speed. The results are shown in Table 2.

TABLE II. CORRELATION BETWEEN RMSVA (SMARTPHONE) AND IRI (ROD AND LEVEL)

Segment	Speed (km/h)	Correlation between RMSVA and IRI (r)
Airport	20	-0.05
	40	-0.08
	60	0.30
Embrapa	20	0.60
	40	0.81
	60	0.76
MGS Road	20	0.95
	40	0.96
	60	0.96

From the results shown in Table 2, it can be observed that the correlation between RMSVA and IRI varies according to the pavement roughness level and vehicle speed. A greater correlation is observed when roughness level is higher and vehicle speed is lower.

Regarding the roughness level, lower correlation coefficients (and even negatives) can be noticed in the Airport and Embrapa segments. Its because the change in the roughness level over the 500 meters measured was lower in these segments. In the Airport segment, e.g. the average roughness level was 1.9 m/km, with the lowest value of 1.6 m/km and the highest value of 2,1 m/km. Thus, the RMSVA remained almost constant over the 500 meters, a slight drop in values for the last segment of 100 meters was observed, followed by the lowest value of IRI measured with rod and level method in the last 100 meters of the segment with an IRI of 1.6 m/km.

At Embrapa, roughness variation was slightly higher in relation to the Airport segment, with an average of 3.4 m/km, with the lowest value of 2.8 m/km and the highest value of 3.7 m/km, an increase in correlation coefficients was also observed, in relation to the Airport segment. Furthermore, because of higher roughness level, less influence of the smartphone noise was observed on the RMSVA values.

With respect to the influence of speed, if it is too low, the pavement rougness cause lower excitation of the vehicle suspension system, resulting in lower magnitude vibrations and consequently, in lower amplitudes of acceleration signals. Therefore, the RMSVA has less variation according to different wavelengths present in the pavement profile, which influences the calculus of IRI.

As mentioned in [4], the minimum operating speed for a RTRRMS is limited to approximately 25 km/h, since at low speeds there is the effect of "tires envelopment" on the high roughness frequency due to the absorption of small protuberances in the contact with the vehicle tires. In addition, at lower speeds, longer profile wavelengths can not be taken into account by the vehicle and therefore the pavement roughness may remain underestimated.

Furthermore, the acceleration signals measured by smartphones are affected by disturbances known as "noises". As mentioned in the introduction section, noises can be generated by random errors of accelerometer, temperature or other physical effects. The output of the accelerometers, as used in inertial profilometers, should be valid regardless of the noise and the vehicle speed. However, in the real world of electronics and imperfect sensors, the noise generated by these devices may be considered acceptable only if the acceleration measured by the accelerometer is significantly higher than the noise. Moreover, if the signal is in the same level as the noise, false pavement profiles will be obtained, and hence resulting in an incorrect roughness index [13].

For this reason, the noise generated by accelerometers installed on smartphones have the greater effect at lower speeds, since the noise amplitude approaches to the measured signal and thus reduces their relationship to the actual roughness of the pavement. This influence varies depending on the smartphone model and the app used to record the acceleration signals. In this study, it was noticed that the noise produced by the smartphone was around 0.10 to 0.15 m/s^2 in terms of RMSVA, even when stationary, noise values were the same.

It is assumed that for above mentioned reasons, in studies which have used smartphones for the evaluation of pavement roughness, better results for higher speeds were obtained, as realized by [11], who used speeds between 60 to 80 km/h to obtain roughness indexes. Unfortunately, for technical and safety issues, it was not possible to collect data with speeds higher than 60 km/h in the segments evaluated in this research.

Nevertheless, the RMSVA values followed a pattern, varying according to the level of pavement roughness. In the graphs of Fig. 5, the relationship between IRI (rod and level) and RMSVA (smartphone) is presented for all three speeds used (20, 40 and 60 km/h), with subdivision of 100 meters from all evaluated segments.

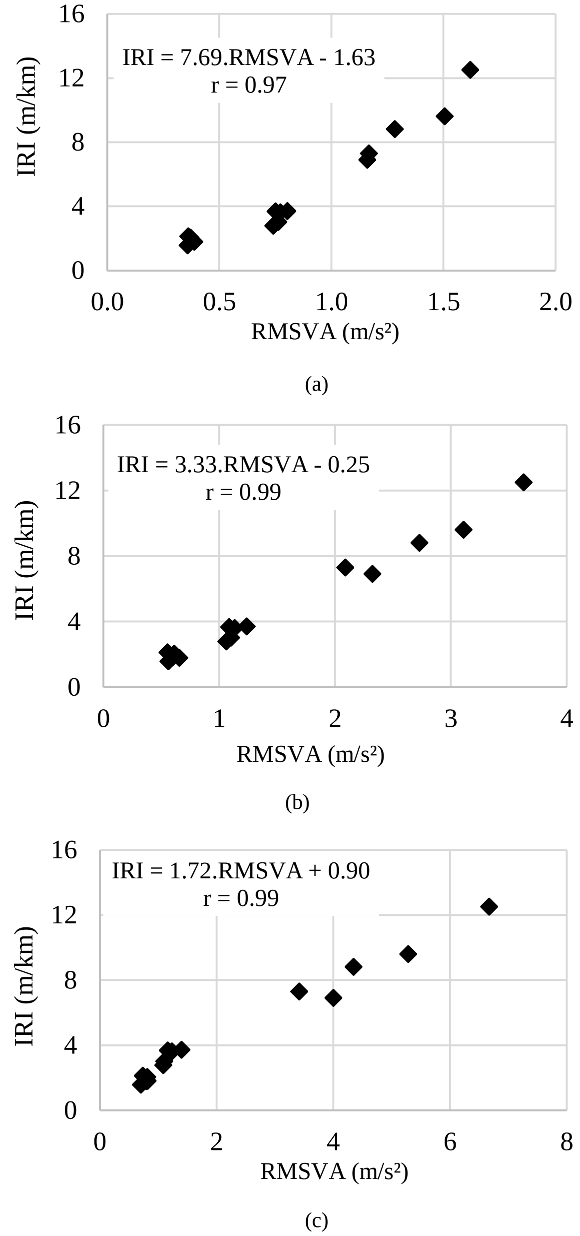


Figure 5. Correlation between IRI and RMSVA (smartphone), for all analyzed segments and speeds of (a) 20 km/h, (b) 40 km/h and (c) 60 km/h

After this analysis, the quality of acceleration signals measured by smartphones through vibration tests was investigated. The results obtained with all three smartphone models used in this study, using the AndroSensor app and a piezoelectric accelerometer (Reference), are shown in Fig. 6.

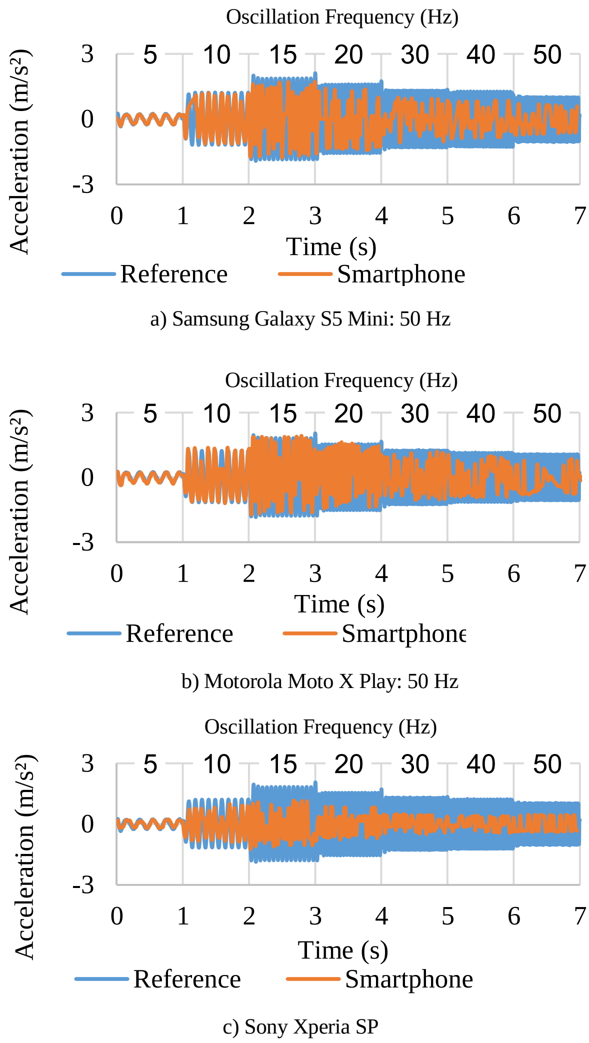


Figure 6. Acceleration measured by smartphones and a piezoelectric accelerometer

In Fig. 5, high values of Pearson's correlation coefficient are shown, indicating a strong correlation between the values of RMSVA and IRI. This highlights the importance of calibrating a RTRRMS as the smartphone system, with the help of a reference measurement method, such as the rod and level method. Considering the use of segments with different levels of roughness and different speeds, increases the reliability of the pavement roughness assessment.

In general, smartphones were able to observe different roughness levels of pavements in terms of RMSVA, relating to both repeatability and correlation with IRI, with correlation coefficients close to 1 for different roughness levels.

Through the results obtained by the vibration tests, a pattern of failures in the measurement of accelerations was observed, both in terms of amplitude and wavelength of the measured signals. The lower the data acquisition rate and the higher the frequency of the measured events, the greater the probability of attenuation of measured acceleration peaks, which also may result in the effect of aliasing.

This phenomenon occurs when the sampling signal happens at a lower frequency than the Nyquist rate, which is defined as the half of the original sampling rate. In this case, reconstructed signal has flaws that were not present when the original signal was sampled. The consequence of the aliasing is also present in the frequency domain, causing the overlap on the frequencies of the original signal and thereby doubles the frequency around the half of the sampling rate. For this reason, aliasing is also known as spectral folding [18].

The aliasing occurrence probability is higher when the data acquisition rate is smaller and the amount of high frequency events present in the pavement surface is greater. In this context, the use of smartphones for the measurement of the vehicle body vibration may affect the relationship between data collected by smartphones and the pavement roughness level if the data acquisition rate is inadequate. It depends on factors such as the speed at which data is collected, the pavement profile, the quantity and wavelength of the pavement surface defects (rutting, irregular patches, corrugations and potholes), as well as the own type of pavement surface.

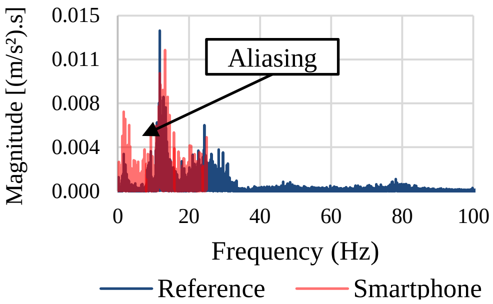
The results in vibration testing allowed the observation that the acceleration signals provided by smartphones presented failures especially in high-frequency vibrations, both in terms of amplitude and wavelength of the measured signals. To analyze this phenomenon in real conditions, field data collection was done with the use of a piezoresistive accelerometer (reference) and the smartphone Samsung Galaxy S5 Mini, on the same three pavements segments used previously.

The measured acceleration signals were analyzed in the frequency domain by Fourier Transform and frequencies up to 100 Hz were used to plot the graphs. Two graphs were plotted as an example, showing high-frequency events: (*i*) in the segment with high roughness level (MGS road) with speed of 20 km/h (Fig. 7a), and (*ii*) in the segment with the lower roughness level (Airport segment) with speed of 60 km/h (Fig. 7b).

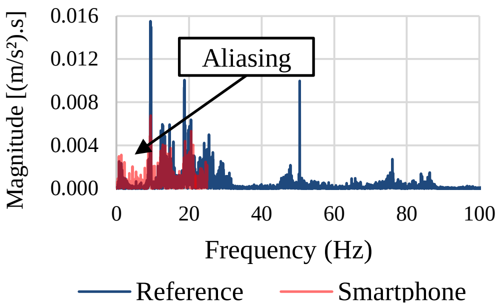
Sometimes the frequency spectrum of accelerations obtained by piezoresistive accelerometer had greater amplitudes than the smartphone i.e. for frequencies above 15 Hz. However, for most of the range of the frequencies below this value, the amplitudes of the spectra measured by the smartphone are greater than the reference sensor. These situations occur when using a low sampling rate, including the occurrence of aliasing effect while the sampling rate is lower than the Nyquist rate, which is consistent with the results obtained in the vibration tests.

After analyzing these results, more vibration tests were conducted to investigate the AndroSensor app as a possible cause of these failures in the acceleration signals measured by the smartphones. This time, the same method was used with the Accelerometer Analyser app which was applied for tests with AndroSensor app. The Accelerometer Analyser app allows the use of some fixed data acquisition rates. The option "fatest" was chosen in which the rate varies according to the capacity of the smartphone, and "game", which provides a rate of 50 Hz. This data acquisition rate was chosen to investigate whether the failures shown in Fig. 6 occurred for using low data acquisition rate or for possible defects caused by AndroSensor app.

The oscillation frequencies selected in the previous vibration tests were used with the Accelerometer Analyser app as well. Moreover, the oscillation frequencies of 75 and 100 Hz and the maintenance of the piezoelectric accelerometer data acquisition of 500 Hz were also included. These frequencies were added to estimate the performance of the smartphones during their use in field surveys with the new app. The smartphone Samsung produced the highest rate of 200 Hz, whereas, the smartphones Motorola and Sony achieved the rate of 100 Hz (Fig. 8).

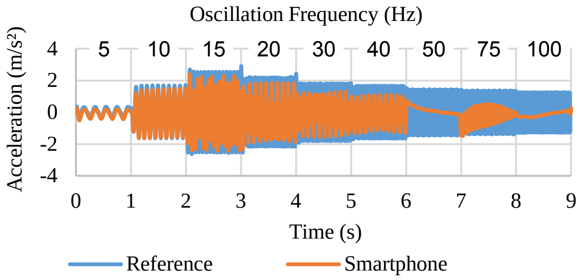


(a)

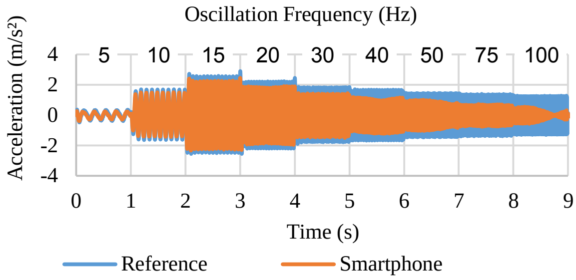


(b)

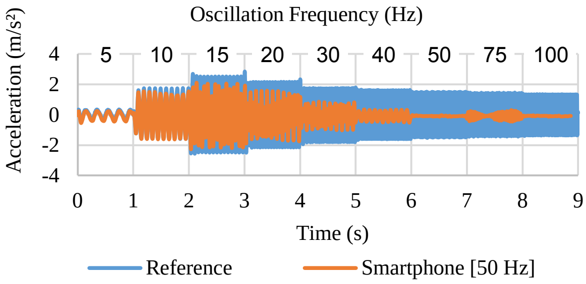
Figure 7. Signals in the frequency domain:MGS (a) Road at 20 km/h and (b) Airport at 60 km/h



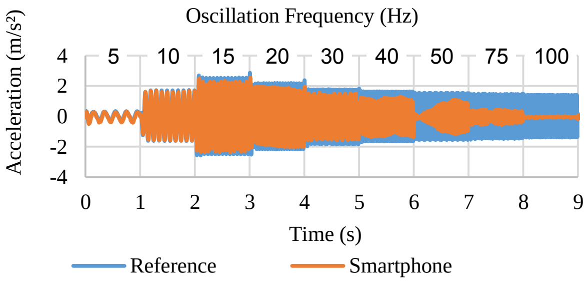
a) Samsung Galaxy S5 Mini: 50 Hz



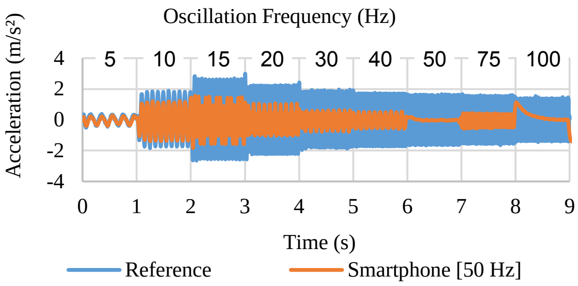
b) Samsung Galaxy S5 Mini: 200 Hz



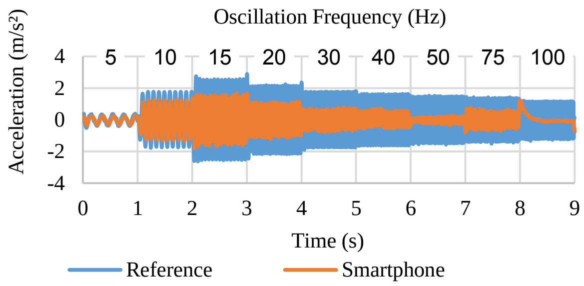
c) Motorola Moto X Play: 50 Hz



d) Motorola Moto X Play: 100 Hz



e) Sony Xperia SP: 50 Hz



f) Sony Xperia SP: 100 Hz

Figure 8. Smartphone signals with Accelerometer Analyser app

In Fig. 8, an improvement in acceleration signals obtained from the Accelerometer Analyser app can be observed, in relation to those measured with AndroSensor app, even for an equal data acquisition rate of 50 Hz. Increased data acquisition rate provided by the Accelerometer Analyser app reduced the attenuation of acceleration peaks, highlighting failures caused by both AndroSensor app and the effect of aliasing. Results also revealed the difference between the signals measured by different models of smartphones, as shown in Fig. 8, for the rate of 50 Hz. However, for Motorola Moto X Play and Sony Xperia SP the rate remained at 100 Hz.

These results emphasize the importance of the smartphone’s data acquisition rate especially when the data is in the frequency domain. It is recommended to use data acquisition rate as high as possible, in the applications where smartphone's data are used to correlate the accelerations frequency with the pavement roughness [6]. Use of higher data acquisition rate in the calculation of vertical displacements is also suggested, in order to determine the IRI values [5, 9, 11].

Although Accelerometer Analyser app provides a higher and uniform data acquisition rate than the AndroSensor app, it also presents certain inflexibility, since it just allows the choice of fixed rates (Normal, UI, Game and Faster), and not have the option to collect data of GPS. The AndroSensor app provides data from both sensors, but fails to measure the acceleration. It is possible to use an app to collect GPS data along with Accelerometer Analyser app. However, the ideal scenario would be to use a software that obtain signals from both sensors (accelerometer and GPS) to facilitate the correspondence between these data. An alternative is to develop a specific app with that objective, as in the work of [5, 11].

As evidenced in the vibration tests, low data acquisition rates can cause errors in the calculation of displacement and, consequently, in the obtained IRI, according to the characteristics of the pavement surface and vehicle response. This may be one of the factors that caused the differences in the results calculated by some authors. In the research of [5], e.g. the authors observed that for a road with IRI values of approximately 2 to 3 m/km, a smartphone underestimated IRI values obtained by a laser inertial profilometer. In the research of [11], for another road with similar roughness level, they obtained upper IRI values like those measured by a laser inertial profilometer.

Some researchers used data acquisition rates up to 100 Hz. In this situation, it would be possible to see a spectrum up to 50 Hz, which would reduce failures in the frequency domain. However, as explained by Nyquist theorem, at least two points are required to display a waveform and can result in mistakes. It is necessary to consider that the pavements measured in other studies have different characteristics. Moreover, a realiable suspension system to attenuate vibrations at high frequencies can reduce these errors. On the other hand, the use of a rigid suspension system for Response-Type Road Roughness Measuring System (RTRRMS) can give the vehicle a closer relationship with the road profile [13]. Thus, the appropriate system will depend on the measurement conditions and how the data will be applied.

When data acquisition rate is less than the Nyquist rate, it causes attenuation of acceleration signals in real time and frequency domain with the aliasing effect. In this case, lower frequency signals may have higher magnitudes than they should and have lower magnitude at higher frequencies. Therefore, in approaches that treat these data in the frequency domain may get less accurate results, such as the correlation between the magnitudes of acceleration spectrum collected by smartphones and IRI calculated from data collected by another reference equipment or in the calculus of IRI.

This does not mean that the IRI values calculated by other researchers are incorrect. It depends on the selection of data acquisition rate, the spectrum of the pavement, the vehicle response, the operating speed and the algorithm used to calculate the displacements. If the interest is to apply the IRI values directly, the calculation should include the modeling of the vehicle or the assistance from other distance measuring sensors (laser, infrared or ultrasound), to remove the influence of the vehicle's response in the measured pavement perfil. Otherwise, regardless of whether the displacements were correctly calculated, the approach does not amount to a profilometer, even if the order of magnitude of the results is similar. Without the modeling of the vehicle, this approach requires a calibration procedure through a reference method as in RTRRMS.

The results emphasize the importance of data acquisition rate. It is recommended to use the highest data acquisition rate possible, mainly because it is not possible to know in advance the magnitudes of the signals collected on the roads, which depend on both the vehicle suspension response and the surface characteristics of the measured pavement.

V. CONCLUSIONS

This study investigated the use of smartphones for assessing the roughness of pavements, mainly due to its low cost, ease of operation and high productivity. For this, pavement segments with different levels of roughness were evaluated, and vertical acceleration signals were measured by a smartphone attached to a vehicle panel, at different speeds. The collected data were used to obtain RMSVA values (Root Mean Square of Vertical Acceleration). To confront these results, the Rod and Level method was used to collect reference profiles for the calculation of the IRI of those segments. The results indicate that smartphones are able to collect data related to the pavement roughness, especially for application on a Pavement Management System (PMS) at the network level.

It is noteworthy that one of the major constraints of this measurement system based on the use of smartphones (as occurs in a RTRRMS) is the need for system calibration from a method of reference roughness measurement, since the results vary according to the vehicle model, operating speed, smartphone model and app. In this study, IRI values were obtained by using the Rod and Level method. The method was carried out with the participation of at least two persons, one responsible for directing the level and recording the data and another to keep the Rod in position. With proper training, it was possible to measure each segment in approximately one to two days. As each segment had 500 meters in length, two wheel tracks were measured with a spacing of 50 cm, in total approximately 2000 points per segment.

The calibration standard of a RTRRMS by Level and Mira method [19] requires the use of 20 calibration segments (bases) of 320 meters in length. It is estimated that the calibration of the system would take about one to two months to be finalized depending on weather conditions, number of teams, resources, and other factors. For example, the spacing of 50 cm, the measurement of two-wheeled tracks for each segment and the time taken for measurement of the segments in this research,

It is important to keep good collection practices to avoid common mistakes in roughness evaluations from a RTRRMS such as maintenance of the system components: vehicle mass, tire pressure, suspension system and vehicle balance. The effect of these variables may be included in further studies, so that these factors may be exploited as part of calculating the IRI. It can be done with modeling the vehicle and process verification from road profiles with known roughness levels in order to calibrate and validate the models proposed.

Particularly in Brazil or in developing countries, this system can be used to evaluate the roughness of roads administered by government agencies in order to maintain a continuous data collection, with a reduced cost. This would allow the mapping of the roughness level of roads in an efficient way, especially when associated with a GIS, including local roads, where this system does not exist.

The system can complement the data collection performed by less frequently used equipment like inertial profilometers. Monitoring the variation of the pavement roughness level not only would allow a rational use of robust equipment, but also serve as a basis of comparison for such instruments, taken as a reference. It should be emphasized that despite assessments by some equipment and excellent repeatability, it does not mean that the results are necessarily correct. This is the distinction between precision and accuracy.

The repetitiveness of RMSVA values is at an acceptable level for application in a PMS at the network level. Considering 10 trips by segment size and speed, mean coefficients of variation in the range of 3 to 6% were obtained. Such RMSVA values showed a positive correlation with IRI calculated with data measured by the Rod and Level method, when considering all evaluated roughness levels, with Pearson correlation coefficients (r) of 0.97 to 0.99.

IRI computed from the acceleration measured by smartphones tends to be lower than IRI obtained by a profilometer, because this approach operates on the same principles of a RTRRMS, which obtains a pavement profile filtered by the vehicle response. The data acquisition rate can also contribute in obtaining low IRI values. The use of a low data acquisition rate may result in overestimated values, it may happen due to errors produced by the aliasing effect. In any case, the calculation of IRI with data collected by a smartphone can be exploited through vehicle modeling techniques.

It is worth noting the importance of the use of smartphone and app models that provide data acquisition rates as high as possible. This is because it is not possible to know in advance the frequencies and magnitudes of the signals collected on the roads, which depend on the vehicle response, which varies according to its speed and dynamics of mass-spring-damper. Furthermore, there is an influence of the characteristics of the measured pavement profile, e.g. the amount and wavelength of defects present in the pavement surface (rutting, irregular patches, corrugations and potholes), as well as the own type of pavement surface.

It is concluded that smartphones represent a viable alternative for assessing the roughness of pavements for network-level surveys where pavement management has to work with aggregated information related to the entire road network. And assisting in making administrative decisions, such as in planning, programming and budget, mainly due to its low cost, easy operation and high productivity. The system can present more potential according to the improvement of its sensors (accelerometers and GPS) and its use on a large scale.

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