A low cost solution to assess road's roughness surface condition for Pavement Management

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Abstract
This paper proposes the use of tablet's built-in accelerometers to estimate a roughness index able to capture pavement roughness condition. Several experiments were conducted in mud, gravel, chip-sealed and paved roads at different speeds and with different vehicles. Approximately 300km of roads in the province El Oro (Ecuador) were visited as part of the testing. It was confirmed that standard deviation of vertical accelerations normalized by speed -in meters per second- was able to produce a roughness indicator useful to assess surface condition. A comparison between two common tablet platforms found differences that could be explained by frequency of data collection, travelled path and influence of x,y accelerations in z-accelerations. Speed-normalized standard deviations of vertical accelerations were found to respond largely to the number of observations collected per second. An experiment with different vehicle sizes showed the impact of the suspension system. A protocol for data collection is given. It is expected that governments unable to purchase laser profilometers can make use of this approach to obtain a proxy for the International Roughness Index and therefore be in capacity to develop performance models and implement a pavement management system.
Introduction

Pavement management systems have been employed to optimize maintenance and rehabilitation decisions in order to deliver good levels of service to road users while managing limited resources [1]. A typical goal for pavement management is to preserve roads surface condition good in order to reduce travel time, vehicle deterioration and gas emissions [1,2]. Poor road's surface condition may even result in damages of agricultural goods and discomfort for the driver [3]. To develop a pavement management system, one requires the knowledge of current condition and future deterioration [4, 5]. This in turn requires time series trends from evaluation of pavement's surface condition using a repetitive quantitative method [6,7]. Current technology for assessing road condition is expensive and often unavailable on poor countries. Local engineers often relay on visual inspections which are subjective.

There are several generally accepted methods for data collection and condition assessment, such as laser profilometers used to compute the international roughness index [7, 8]. Falling weight deflectometers to obtain deflection basin parameters [9, 10], laser beams capable of obtaining rut depth and fatigue cracks [11]. Other methods have explore the use of ground penetrating radar [12], among other artefacts. However, this methods require the use of equipment that in some cases results beyond financial capabilities of small municipalities or local governments in poor countries.

A low cost method to assess road surface condition is need it to quickly estimate maintenance and rehabilitation needs, even more when in the presence of gravel and earth roads. This paper suggest the use of vertical accelerations measured by built-in accelerometer from a tablet in combination with a GPS application capable of recording global position and speed. This method is expected to estimate a surface condition indicator useful for initial implementations of pavement management for earth, gravel and asphalt roads. This method is combined with visual inspections to estimate possible treatment for each segment.

Methodology

This study proposes a cheap solution to preliminary assess surface condition of the pavements of the Province El Oro in Ecuador. This paper deals with those roads categorized as strategic by the province [13], a summary of their characteristics is presented on Table 1.

An accelerometer is used to capture vertical accelerations which are expected to correlate to surface condition. An accelerometer can be found in most tablets and smart phones, they capture accelerations in three-dimensional fashion, for the purpose of this paper only vertical accelerations were of interest, although the long range trend of X-accelerations seem to map well horizontal curves and this could be used for road safety (Figure 1). It must be noticed that the method herein presented aims to typify average condition not to identify nor locate damage along the road.
Table 1. Summary of characteristics - Roads in El Oro, Ecuador.

<table>
<thead>
<tr>
<th>From</th>
<th>Precipitation (mm)</th>
<th>Elevation (meters)</th>
<th>Surface</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>317</td>
<td></td>
<td>5</td>
<td>Earth and Gravel</td>
<td>Poor</td>
</tr>
<tr>
<td>2527</td>
<td></td>
<td>3420</td>
<td>Asphalt cement</td>
<td>Good</td>
</tr>
</tbody>
</table>

Figure 1. X-accelerations and horizontal curves [14]
Observed standard deviations of vertical (Z-axis) accelerations were divided by observed speed in meter per second. These normalization step reflected the fact that the driver will drive at a speed that responds to the level of condition of the road's surface. Hence, if the road is in poor condition, the driver will slow down. Another factor is that of frequency of logging for vertical accelerations. Vertical accelerations were logged at about 50 observations per second and then collapsed at every second using the standard deviation of them.

The standard deviation captured variability or spread around the mean in the same units of the vertical accelerations. The larger the value, the larger the vertical accelerations. Once filtered by speed, it provided with an estimate of condition (Figure 2).

In other words, similar values of accelerations for two hypothetical segments, one driven at high speed and the other at low speed, resulted in different values; as the one with higher speed was divided by larger speed-range factors therefore resulting in overall lower levels of the condition indicator (i.e. filtered standard deviation of vertical accelerations).

The proposed indicator acts in similar fashion as the international roughness index (IRI) [7,8], lower values are associated with better condition and higher values with poorer condition.
Data Collection Protocol

There exist several mobile device applications able to log accelerations by taking advantage of the built-in accelerometers used to control screen orientation on mobile devices. However, very few are able to log coordinates (latitude, longitude) and speed together with accelerations. It is possible then to use a separate application to log coordinates and speed.

The data collection procedure herein proposed uses two freeware android-device applications, namely: MyTracks and Accelogger [15]. The other application tested was Sensorlogger [16] for Ipad. Both recorded date/time, x-y-z accelerations, latitude, longitude, speed and accuracy (in meters).

Data collection started at rest (zero speed) and finished at rest as well, in order to have a known location given by a GPS unit. MyTracks required somewhere from 2 to 10 seconds to find GPS signals and triangulate the location of the device. A Lenovo thinkpad tablet was placed horizontally on the floor of a vehicle near the middle of it. Same vehicle was used for the entire data collection campaign. It consisted in a 1998 Mazda pick-up truck. Various vehicles were used for testing how observations vary for different dumping system (vehicles). It is important to mention that the aim was not to identify and classify damage (i.e., cracks, rut depth, etc) but rather to estimate a mean condition indicator per segment with a low cost solution. The idea is similar to that of IRI, but depends on the trajectory of the vehicle and as such will vary with the path followed by the driver, however variations should vanish with aggregation and averaging of observations per segment. Another important factor is that of the surface type and speed. Heavily damage surfaces will result in lower operational speeds as a measured taken by drivers to avoid violent movements and minimize vehicle damage. Overall, it was expected that drivers behaviour could be reflected by speed and condition could be characterized by vertical accelerations.

The method used for data collection is as follows:

Field work:
(1) Start at rest and set both devices to collect at the same time
(2) Wait for GPS signal
(3) Drive the vehicle non-stopping for 10 minutes, advisable to maintain constant speed and do not exceed 40kph on horizontal curves
(4) Either at the change of surface type or when 10 minutes are reached, stop the vehicle and the data collection of both devices at the same type (once at rest). Short changes of surface type should not be a reason to stop data collection.
(5) On a field-book, register date and time (beginning and ending), spatial location coordinates, surface type, qualitative appreciation of overall condition, possible treatment type.

Desk work:
(6) Estimate the standard deviation of vertical (Z) accelerations per second
(7) Estimate speed in meter per second
(8) Normalize the standard deviation of Z-accelerations dividing by the corresponding speed
(9) Obtain a spatial database with normalized Standard deviations of Z-accelerations

For the case of the Ipad application -SensorLog- both spatial location and accelerations were collected together. Each segment contained observations for a maximum of 10 minutes. With both tablets the logger took somewhere from 50 to 100 observations per second. It was observed that the logger took more points on rougher surfaces. The data was processed to obtain the standard deviation of Z-accelerations per second. For this, one should estimate how many observations were taken in total and how many seconds passed from start to end. Figure 3 shows the main steps of the procedure used to obtain the normalized standard deviation of vertical accelerations, latter used to obtain a surface condition indicator. Data collection of any segment was stopped with changes in surface type such that each segment contained only one type of surface.

**Analysis of Results**

Preliminary results show that the use of a normalized response (i.e., standard deviation normalized by ranges of speed) are capable of identifying roads at different levels of condition (good, fair, poor) disregarding of their surface material, as shown by segments five (s5) and eight (s8) in Figure 4.
Comparison of different material segments at same levels of qualitative condition showed similar values for the normalized response. This empirical result provides an argument in favour of the normalization by speed. It appears that it is capable of returning a response able to represent levels of condition (Figure 5).

Figure 4 Comparison Earth in fair- poor and asphalt in good condition

Figure 5 Asphalt Good-Fair condition
A proxy for International Roughness Index

The Root Mean Square is often used to capture variation on cyclical responses of sinusoidal form. Equation 1 suggests that if the mean is zero, the RMS equation is equivalent to the Standard Deviation and Equation 2 shows speed normalized RMS and speed normalized standard deviations of z-accelerations. As shown, either normalized-measure captures variability on the vertical scale (z), and its units are of frequency (1/s).

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^{N} a_{zi}^2} = St.Dev. = \sqrt{\frac{1}{n} \sum_{i=1}^{N} (a_{zi} - a)^2}$$ \[1\]

$$\frac{RMS}{v_{yi}} = \sqrt{\frac{1}{n} \sum_{i=1}^{N} \left( \frac{a_{zi}}{v_{yi}} \right)^2} = \frac{\sigma_z}{v_{yi}} = \sqrt{\frac{1}{n} \sum_{i=1}^{N} \left( \frac{a_{zi}}{v_{yi}} - \bar{a}_z \right)^2}$$ \[2\]

Where $\sigma_z$ is the standard deviation of the z-accelerations ($a_z$) if the speed $v_{yi}$ is constant for all observations used to compute the RMS. For this research, speed was treated as a constant because there is corresponding value per observation (every second).

A close correlation between the speed-normalized z-acceleration and the international roughness index (IRI) has been suggested elsewhere [17], values of RMS normalized by speed and multiplied by 100 could be used as proxy for IRI [17]. For this research values of speed-normalized standard deviation of z-accelerations were equivalent to those of RMS normalized by speed, and then multiplied by 100 to obtain a roughness index in m/km.

Normalization using speed (m/s) was validated using a comparison of observed values when driving a vehicle at several speeds and at different surfaces. An experiment was set to measure vertical accelerations in three test segments at 3 speed ranges as summarized on Table 1. Speed ranges were measured in meter per second and each value of vertical acceleration was divided by the observed speed in meter per second.

| Table 1. Target speeds (kph) for tested surfaces |
|---|---|---|
| Asphalt (poor condition) | Gravel (fair to good) | Earth (poor condition) |
| 40 | 20 | 20 |
| 60 | 40 | 30 |
| 20 | 60 | 10 |

A comparison of speed-normalized RMS for the materials and speeds given in table 1 is shown on Figures 6, 7 and 8.
Gravel Road

Figure 6. Comparison of speed-normalized standard deviation of Z-accelerations

Figure 7. Comparison of speed-normalized Standard Deviations of Z-accelerations
It should be noticed that no two trials ran over the exact same path, therefore the values of speed-normalized standard deviation of accelerations (or RMS normalized by speed) are close but not the same. This is also explained by the speed effect and vehicles ability to travel over the complete vertical irregularity (Figure 6, 7 and 8). At lower speeds the vehicle is able to go all the way down and back up on a given vertical deformation (for instance a pothole) but at higher speeds the accelerometer is not able to register the complete vertical variation because it will travel between fewer points of such vertical irregularity. This can be seen by comparing the vertical profiles of gravel roads at 20, 40 and 60kph in Figure 6.

**Comparison of Applications and Devices**

IPAD's platform application *Sensorlog* measures accelerations in terms of the acceleration of gravity (G) that is as a percentage of 9.81m/s² (16), therefore to convert to plain m/s² scale one must multiply the readings by 9.81. Android's platform application *Acceloger* collects accelerations in m/s² scale as described by the 15.

A test of equivalency among both applications was run; accelerations were measured on a 350m test track twice. A *Lenovo Thinkpad* tablet and an *Ipad 2* tablet were placed horizontally on the floor of the front passenger of a 2012 Toyota RAV. Figure 9 shows the profile of accelerations (before speed normalization).
Readings taken by Sensorlog had their horizontal axis located at -0.96, those of the Acceloger had their zero axis displaced to 9.5. The effect of both axis was removed before the calculation of standard deviation take place, this is therefore equivalent to the root mean square, because the mean either set of observations was zero. Normalization factor did not matter as it is the same for both sets of data.

It should be noticed that Sensorlog collected about 9 observations per second, meanwhile Acceloger did nearly 100 per second. In terms of processing capacity, data collection is limited to segments of about 10 minutes for Sensorlog and theoretically 100 minutes for Acceloger. Therefore making the latter more desirable for data collection.

![Comparison of accelerations: Acceloger versus Sensorlog. backward](image)

Observed differences between both applications could be explained by the sensitivity of the accelerometer built into the device (Ipad or Lenovo tablet), also by the fact that the Ipad application collected 10 times less observations per second, which could results in less sensitivity of the application itself, therefore exhibiting a tendency of observations to return to the zero-level, rather the observations collected with the Lenovo presented more sensitivity and remained at higher levels of variability.

**Comparison of Vehicle size**

The last experiment consisted in visiting the same test segment on the same day, with 3 vehicles of various sizes, namely a 45 passenger bus, a 12 passenger bus and a two axle truck.
Vehicle size does make a difference (specially for trucks) as seen on Figures 10 and 11. It was also confirmed that initial and final observations are highly affected by the influence of y-acceleration on z-accelerations resulting from brake/acceleration from/to rest effects. Therefore they must be removed. At station 0+900 there was a portion of heavily deteriorated unpaved road which induced large vertical movements on the vehicles.
Conclusions

A low cost solution is proposed to estimate a proxy for the international roughness index (IRI) in meters/kilometre. This method is used to capture surface condition on gravel, earth and asphalt roads in the province of El Oro, Ecuador. The proposed method is able to produce a repeatable indicator of segment condition, which is able to distinguish between major stages on the lifespan of any pavement and can theoretically be used to estimate performance models and develop a management system.

It was found that standard deviation of vertical accelerations normalized by speed in meters/second are capable of producing an indicator of surface roughness and therefore to capture road surface condition. Speed did play a strong role in measured roughness, at higher speeds the measurement seem more consistent are prone to localized damage or other undesirable elements that could have affected the readings. Dumping system of the vehicle do plays a role, which is larger with trucks meaning that such vehicles appear to be more sensitive to road condition and this in turn mean road condition can effectively impact fragile agricultural goods. All other tested smaller vehicles returned similar values. Vertical accelerations were found to be affected by horizontal alignment, that is, horizontal curves, accelerations in x partially counter rest some of the vertical accelerations. Accelerations in y at the start/end times from vehicles moving from/to rest increased z-accelerations. More testing is required, primarily to better correlate to IRI, and to better understand the need for a cleaning algorithm capable of filtering the effect from such outiers in the form of high and low pass shifters.

This method will be repeated in 2014 and subsequent years to collect data condition in order to built a database of time series of segment condition. This database will be used to develop deterioration curves and capture treatment effectiveness.

Location of instrument within the car should be tested in the future by placing the tablet at different horizontal and vertical locations in relationship with the car's damping system.

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