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Proposal for a Low-Cost Monitoring System to Assess the Pavement Deterioration in Urban Roads

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Abstract

Effective scheduling of pavement monitoring and maintenance activities plays a pivotal role in ensuring safety and comfort for road users. The Pavement Management System (PMS) is a traditional tool to assist the road manager in the decision-making process on which priority maintenance activities to carry out. However, for urban road networks the implementation of a PMS can be complicated due to the many functional and operational problems. This paper presents a prototype low-cost inertial sensor-based system for monitoring the pavement conditions in urban road networks. Starting by the measurements of the vertical accelerations collected in a vehicle riding on a rough pavement, the frequency-weighted vertical acceleration a_{wz} was calculated according to ISO 2631 standard. This parameter can be adopted as a Key Performance Indicator (KPI) by relating the road roughness to the human whole-body vibration (WBV) exposure on the road user. Some field tests were carried out identifying urban roads in an Italian city with different levels of pavement deterioration. Measurements to evaluate the pavement deterioration were performed using traditional visual inspections and the proposed sensor embedded in a test vehicle (run at different speeds) in order to identify a relationship between these indices in terms of performance classes.

Keywords: Pavement monitoring; Urban roads; Pavement Condition Index; Inertial sensor-based system; Pavement Management System.

1. Introduction

Effective maintenance planning within the urban road infrastructure management ensure benefits in terms of safety of road users (Popoola et al., 2020), riding comfort (Múčka, 2020), local government budget (Ragnoli et al., 2018), noise (Cantisani et al., 2013), and pavement service life (Giustozzi et al., 2012). The Pavement Management System (PMS) is a set of standard procedures (Ismail et al., 2009) used to assist the road manager in the pavement maintenance decision-making process and it is mainly based on the analysis of distress data. Indeed, proper planning of monitoring activities plays a pivotal role due to the perspective to design corrective interventions in time.

Visual deterioration inspections of the road surface have been the most commonly used approach to analyze the pavement conditions. The Pavement Condition Index (PCI) procedure is based on a visual survey of the number and types of distresses in a pavement, and it is referenced in the American Society for Testing and Materials standard D6433-

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20 (ASTM, 2020). Technical personnel estimates the road surface condition by walking or driving at low speeds, thus resulting in a significant investment in terms of time and money; consequently, in recent years several automated direct survey methods have been developed (Cafiso et al., 2017). Automated distress data may be collected and analyzed by traveling over the roads by using special equipment installed on specialized vehicles (D'Amico et al., 2022; Tsai and Li, 2012). However, the use of these vehicles for urban roads may not be technically consistent with the specifications of the sensing technology and due to the frequent local discontinuities (Loprencipe et al., 2021). The problem of an effective system for urban road network assessment, continuous over time and space, involves the impossibility to make appropriate planning strategies. For this reason, the monitoring and assessment of urban road surfaces is still an open challenge. In this regard, an interesting alternative provides for the use of the comfort index a_{wz} defined by the ISO2631 standard (International Organization for Standardization, 1997), based on the vertical accelerations measured inside a moving vehicle and due to road surface roughness (Arbabpour Bidgoli et al., 2019).

In this study, field tests were carried out in an Italian city identifying four urban roads with different levels of pavement deterioration. The ISO 2631 approach is taken into account to evaluate road users' comfort, and an inertial-sensor based system -consists of a Raspberry Pi (RPi) single-board microcomputer, a micro-electrical mechanical Inertial Measurement Unit, and a mini Global Positioning System (GPS)- is proposed as a reliable and easy-to-install measurement system. In detail, two identical Raspberry-based prototypes, placed in different positions inside a moving vehicle at different constant speeds, are employed; analysis between a_{wz} values, starting from accelerations measured on the two inertial sensors, are made. Traditional visual distress inspections also are performed in the field tests. The correspondences between a_{wz} and PCI values have been investigated based on a subdivision into performance classes.

2. Road Pavement Evaluation Methods

In this section, the procedures considered in this paper to assess the road surface conditions are discussed.

2.1 Frequency-Weighted Vertical Acceleration (a_{wz})

Huma exposure to whole-body vibration during transportation can be evaluated in terms of the perceived comfort of road users. In this regard, the comfort index as described in the ISO 2631-1 standard, namely the frequency-weighted vertical acceleration (a_{wz}), is calculated based on the analysis of data from measurements of vertical accelerations in the passenger compartment of vehicles due to the presence of road surface roughness. The procedure is applied considering the seated position as body posture. The reliability of this index to monitor road conditions has been demonstrated in some studies (Duarte and de Melo, 2018; Loprencipe et al., 2021; Bruno et al., 2022), which have also found correlations between a_{wz} and some pavement Key Performance Indicators (KPIs).

Starting from the measurement of accelerations in the time domain, it is necessary to calculate the spectrum relative to this signal in the frequency range between 0.5 and 80 Hz. This range is subdivided into one-third octave bands and the reference standard indicates the values of the 23 central frequencies (0.5, 0.63, 0.8, 1, 1.25, 1.6, 2, 2.5, 3.2, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 32, 40, 50, 64, 80). The root-mean-square (r.m.s.) values of the acceleration for all bands in one-third octaves $a_{z,i}$ are then multiplied by the corresponding weighting factors $W_{k,i}$ given in the technical standard currently in use. Finally, it is possible to calculate the weighted r.m.s. acceleration according to Equation 1.

$$a_{wz} = \sqrt{\sum_{i=1}^{23} \left(W_{k,i} \cdot a_{z,i}\right)^2} \quad (1)$$

ISO 2631-1 also provides for public transport threshold values for the frequency-weighted vertical acceleration because of the expected comfort level, as shown in Table 1.

Table 1: a_{wz} threshold values (International Organization for Standardization, 1997).

a_{wz} (m/s^2)	*Comfort Level*
Less than 0.315	Not uncomfortable
0.315-0.63	Little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
Greater than 2	Extremely uncomfortable

In order to automate the a_{wz} calculation procedure, a code developed in the MATLAB® environment has been used, and the measurements of the inertial platforms as input are requested.

2.2 Pavement Condition Index (PCI)

In this research, the results in terms of frequency-weighted vertical acceleration have been analyzed also comparing them with the Pavement Condition Index calculated in the same study area.

The PCI methodology is based on visual surveys performed in sample units to assess pavement surface conditions by the identification of the type, severity, and density of each distress according to the ASTM D6433-20 standard. In this study, the simplified procedure for distress identification and assessment for urban road surfaces (Loprencipe and Pantuso, 2017) is adopted, which involves a catalog of 12 pavement distresses and three PCI rating ranges (Figure 1) based on the numerical value of PCI varying between 0 and 100.

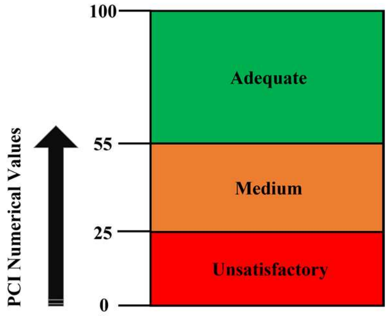

Figure 1: PCI rating scale for urban roads.

3. Road Pavement Measurement System

In this section, the measurement system adopted in this paper to monitor the asphalt pavement conditions is described in detail.

3.1 The Inertial Sensor Raspberry-Based System

Inside a vehicle, the road surface roughness induces vertical accelerations that are measurable and spatially positionable along the road through the combination of accelerometer sensors and GPS. A low-cost and easy-to-operate prototype (Figure 2), validated in a previous research (Loprencipe et al., 2021), has been used in this study being able to record continuously during the normal use of the vehicles by the users.

More in detail, the main consumer-grade components of the adopted device are:

- Raspberry Pi Zero W single-board microcomputer (https://www.raspberrypi.com/products/raspberry-pi-zero-w/);
- Inertial module InvenSense MPU-9250 (Invensense MPU-9250 Product Specification Revision 1.1, 2019). The maximum mean sample rate is about 83 Hz, due to hardware and software limitations;
- U-blox mini GPS module, NEO-6M model (https://www.u-blox.com/en/product/neo-6-series). The update rate of the GPS module has been set to 1 Hz.

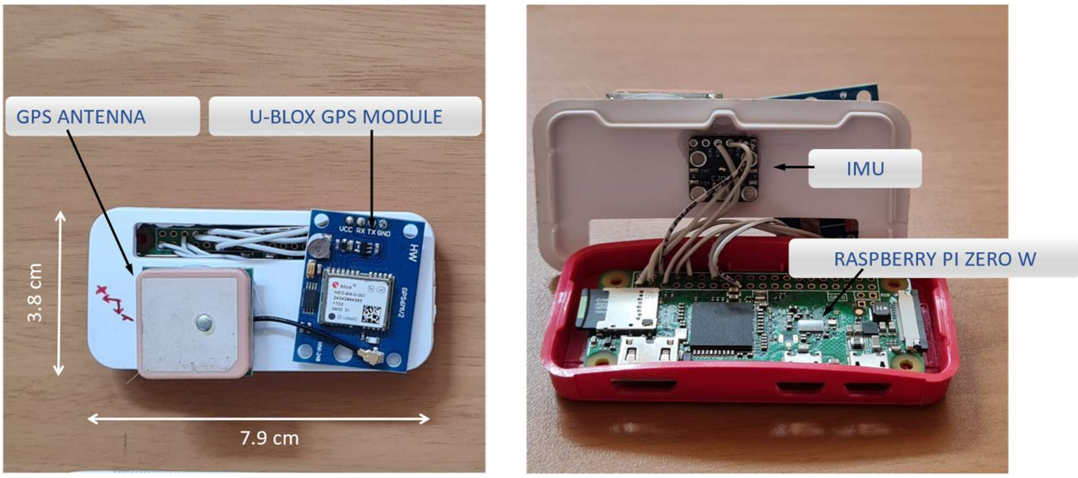

Figure 2: Main components of the prototype Raspberry-based IMU device.

The collected data, post-processed with specific algorithms developed in the MATLAB® environment according to ISO 2631-1 standard, have been then evaluated with reference to the weighted vertical acceleration.

4. Field Tests

This research was conducted using data collected in an Italian city, identifying four branches of urban roads (Branch #1, Branch #2, Branch #3, Branch #4) with flexible pavements having different levels of pavement deterioration, for a total length of about 4.7 km.

More in detail, two identical Raspberry-based inertial sensors, as described in Section 3.1, were employed simultaneously inside a test vehicle (Fiat Punto) at different positions. In particular, the "R1" and "R2" devices (names assigned to prototypes to distinguish them) were located on the dashboard and the passenger floor, respectively (Figure 3). As regards the fixing of the instruments, it was necessary to use only double-sided tape.

Figure 3: The proposed system for WBV measurement embedded in the test vehicle.

The tests were repeated each time maintaining a constant value of the speed, namely 30, 40, and 50 km/h. It should be noted that since these are urban roads in some sections the travel speed inevitably varied (for example due to the presence of speed limits, low planimetric radius, or intersections).

The acceleration data recorded by the prototypes were post-processed using a code developed in MATLAB® in order to obtain the frequency-weighted vertical acceleration a_{wz} for each sample unit, as defined in the PCI inspections. More in detail, the sample unit PCI size covered an area of 250 m^2, identifying sections approximately 8 meters wide and 27 meters long: the number of sample units investigated for the surveyed urban roads is then reported in Table 2.

Table 2: Characteristics of the branches investigated.

Branch	*Length (m)*	*Number of Sample Units*
#1	967.5	36
#2	2141.1	80
#3	909	34
#4	670	26
Total	4687.6	176

As the speed was constant at each survey, it was possible to associate the characteristic length of each PCI sample unit with a time interval for the collected acceleration data, useful to a_{wz} calculation. Moreover, a check with the concomitant GPS coordinates was made.

The traditional visual inspections were also performed in the field tests to establish the relation between measured PCI and a_{wz}.

4.2 Test Results

The employment of the "R1" and "R2" inertial sensors has therefore made it possible to obtain the frequency-weighted vertical acceleration values for each sample unit of the roads investigated, taking into account the different speed values adopted. In a first analysis, for each branch the overall average of the a_{wz} values referred to the sample units have been evaluated (Figure 4).

Figure 4: The a_{wz} values for each branch.

Figure 4 shows that as the travel speed increases, the presence of the road surface roughness is generally associated with greater discomfort perceived by the user. Another relevant issue concerns the different a_{wz} values obtained by the two identical prototypes, which differ only for the positioning inside the same vehicle: the WBVs are reasonably more attenuated on the dashboard than on the passenger floor, and consequently a decrease in the a_{wz} values are returned.

As a further analysis, a linear regression approach has been used for modeling the relationship between the PCI and a_{wz} values for each sample unit, in order to predict the frequency-weighted vertical acceleration threshold values corresponding to the performance class shift in the PCI rating scale (Figure 1). The results, having made the distinction for the adopted Raspberry-based prototype -"R1" (Table 3) or "R2" (Table 4)- and the vehicle speed -30 (Table 3-4.a), 40 (Table 3-4.b), or 50 km/h (Table 3-4.c)- are as follows:

Table 3.a. a_{wz} - PCI R1/30 km/h

PCI	a_{wz} *(m/s²)*
0-25	>0.86
25-55	0.86-0.62
55-100	<0.62

Table 3.b. a_{wz} - PCI R1/40 km/h

PCI	a_{wz} *(m/s²)*
0-25	>0.98
25-55	0.98-0.73
55-100	<0.73

Table 3.c. a_{wz} - PCI R1/50 km/h

PCI	a_{wz} *(m/s²)*
0-25	>1.10
25-55	1.10-0.81
55-100	<0.81

Table 4.a. a_{wz} - PCI
R2/30 km/h

PCI	a_{wz} (m/s^2)
0-25	>1.57
25-55	1.57-1.11
55-100	<1.11

Table 4.b. a_{wz} - PCI
R2/40 km/h

PCI	a_{wz} (m/s^2)
0-25	>1.93
25-55	1.93-1.38
55-100	<1.38

Table 4.c. a_{wz} - PCI
R2/50 km/h

PCI	a_{wz} (m/s^2)
0-25	>1.92
25-55	1.92-1.45
55-100	<1.45

In this way, it has been possible to analyze again the average values of the adopted indices at the branch scale (Table 5) and to match them in terms of performance classes: only in one case out of 24 the expectation is not respected.

Table 5: a_{wz} - PCI results at branch scale and analysis in terms of performance classes.

Branch	*Device*	*PCI*	*a_{wz} (m/s^2)*		
			30 km/h	*40 km/h*	*50 km/h*
#1	R1	40	0.8	0.9	1.1
#1	R2	40	1.5	1.9	2.3
#2	R1	60	0.5	0.6	0.7
#2	R2	60	0.9	1.3	1.4
#3	R1	25	0.9	1.0	1.2
#3	R2	25	1.7	1.9	1.9
#4	R1	39	0.8	1.0	1.0
#4	R2	39	1.5	1.8	1.7

Finally, the same methodology has been applied but considering the single sample units. A case of PCI- a_{wz} scatterplot related to the totality of surveyed urban roads has been considered; for example by selecting one of the investigated cases, i.e. when the comfort index values have been calculated based on the accelerometer data collected by the instrument named "R1" and for the speed of 30 km/h (Figure 5).

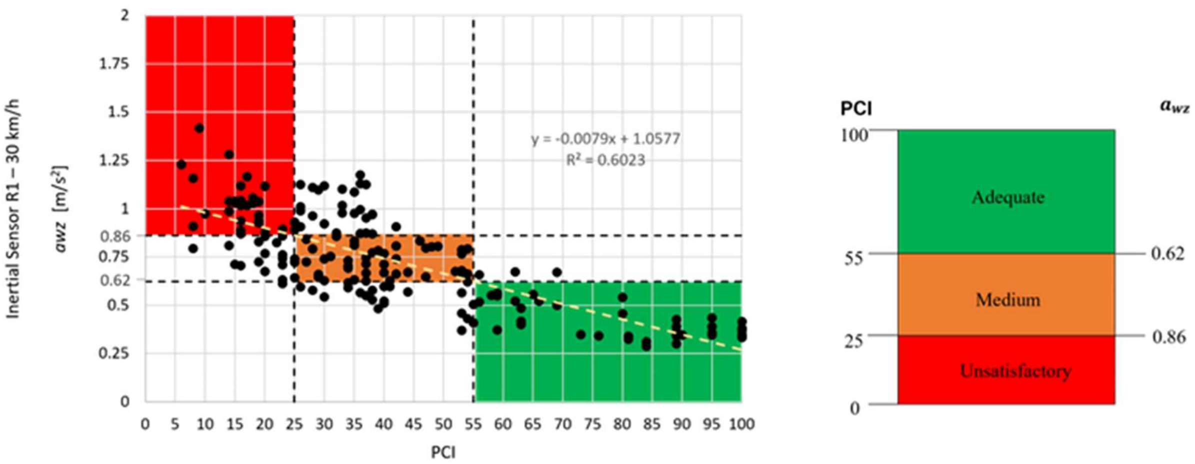

Figure 5: PCI -a_{wz} results referred to one of the investigated cases (“R1”, 30 km/h) by applying a criterion of performance classes.

Generally, it has been noted that the proposed methodology could be reliably applied for the Adequate conditions considering the sample units; in Figure 5 only 3 values out of 40 are outside the range. On the other hand, for the Medium and Unsatisfactory conditions, the introduced approach is ineffective to assess the pavement deterioration of each sample unit: when a variation in the travel speed occurs, it affects the results obtained with the PCI and a_{wz} approaches in a different way. In a sample unit the speed can both increase and decrease relative to the set reference value; this behavior, considering the number of sample units per individual branch, tends to eliminate this effect at the branch level and thus justify the applicability of the proposed method even for the Medium and Unsatisfactory conditions at the branch level (as confirmed in Table 5).

5. Conclusions

Urban roads are directly managed by small administrations, which generally do not have enough funds or sufficient qualified personnel to carry out costly automatic road pavement surveys and diagnostic monitoring.

In this paper, it has been proposed a low-cost and easy-to-install monitoring system to assess the pavement deterioration of urban roads using the frequency-weighted vertical acceleration a_{wz}. In addition, visual distress inspections through the traditional PCI procedure have been performed in order to find a relationship between the PCI and a_{wz} indices, considering a criterion of performance classes. Field tests were carried out in an Italian city, identifying 4.7 km of urban roads with different levels of pavement deterioration.

The results have highlighted that the repeatability of the a_{wz} values depends on the vehicle speed and the position of the instrument inside the vehicle. In particular, it has been noted that as the travel speed increases, the perceived comfort decreases; as regards the vibrations, they are more attenuated on the dashboard than on the passenger floor, and consequently a decrease in the a_{wz} values is returned.

In addition, the a_{wz} threshold values have been identified at the performance class shift in the PCI rating scale in order to identify a relationship between these indices in terms of performance classes; different speed values and the available Raspberry-based prototypes have been considered. Further analysis provided that in a preliminary monitoring phase of urban road networks, the proposed methodology can be reliable to evaluate the pavement deterioration level of a branch and partially (i.e. the Adequate conditions) of a single sample unit.

Future developments include the application on more urban roads, as well as the adoption of other monitoring speeds and vehicles with different physical and mechanical characteristics.

References

Arbabpour Bidgoli, M., Golroo, A., Sheikhzadeh Nadjar, H., Ghelmani Rashidabad, A., Ganji, M.R., 2019. Road roughness measurement using a cost-effective sensor-based monitoring system. Automation in Construction 104, 140–152. https://doi.org/10.1016/j.autcon.2019.04.007.

ASTM, 2020. ASTM D6433-20, Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.

Bruno, S., Vita, L., Loprencipe, G., 2022. Development of a GIS-Based Methodology for the Management of Stone Pavements Using Low-Cost Sensors. Sensors 22, 6560. https://doi.org/10.3390/s22176560.

Cafiso, S., D'Agostino, C., Delfino, E., Montella, A., 2017. From manual to automatic pavement distress detection and classification, in: 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS). Presented at the 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), IEEE, Naples, Italy, pp. 433–438. https://doi.org/10.1109/MTITS.2017.8005711.

Cantisani, G., Fascinelli, G., Loprencipe, G., 2013. Urban road noise: The contribution of pavement discontinuities, in: Icsdec 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction. pp. 327–334.

D'Amico, F., Bianchini Ciampoli, L., Di Benedetto, A., Bertolini, L., Napolitano, A., 2022. Integrating Non-Destructive Surveys into a Preliminary BIM-Oriented Digital Model for Possible Future Application in Road Pavements Management. Infrastructures 7, 10. https://doi.org/10.3390/infrastructures7010010.

Duarte, M.L.M., de Melo, G.C., 2018. Influence of pavement type and speed on whole body vibration (WBV) levels measured on passenger vehicles. J Braz. Soc. Mech. Sci. Eng. 40, 150. https://doi.org/10.1007/s40430-018-1057-0.

Giustozzi, F., Crispino, M., Flintsch, G., 2012. Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability. Int J Life Cycle Assess 17, 409–419. https://doi.org/10.1007/s11367-011-0375-6.

https://www.raspberrypi.com/products/raspberry-pi-zero-w/, accessed on 05 May 2022.

https://www.u-blox.com/en/product/neo-6-series, accessed on 05 May 2022.

Invensense MPU-9250 Product Specification Revision 1.1, 2019.

Ismail, N., Ismail, A., Atiq, R., 2009. An overview of expert systems in pavement management. European journal of scientific research 30, 99–111.

International Organization for Standardization, 1997. Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration. Part 1: General Requirements. ISO, Geneva. ISO2631-1 .

Loprencipe, G., de Almeida Filho, F.G.V., de Oliveira, R.H., Bruno, S., 2021. Validation of a Low-Cost Pavement Monitoring Inertial-Based System for Urban Road Networks. Sensors 21, 3127. https://doi.org/10.3390/s21093127.

Loprencipe, G., Pantuso, A., 2017. A Specified Procedure for Distress Identification and Assessment for Urban Road Surfaces Based on PCI. Coatings 7, 65. https://doi.org/10.3390/coatings7050065.

Múčka, P., 2020. Vibration Dose Value in Passenger Car and Road Roughness. J. Transp. Eng., Part B: Pavements 146, 04020064. https://doi.org/10.1061/JPEODX.0000200.

Popoola, M.O., Apampa, O.A., Adekitan, O., 2020. Impact of Pavement Roughness on Traffic Safety under Heterogeneous Traffic Conditions. Nig. J. Technol. Dev. 17, 13–19. https://doi.org/10.4314/njtd.v17i1.2.

Ragnoli, A., De Blasiis, M., Di Benedetto, A., 2018. Pavement Distress Detection Methods: A Review. Infrastructures 3, 58. https://doi.org/10.3390/infrastructures3040058.

Tsai, Y.-C.J., Li, F., 2012. Critical Assessment of Detecting Asphalt Pavement Cracks under Different Lighting and Low Intensity Contrast Conditions Using Emerging 3D Laser Technology. J. Transp. Eng. 138, 649–656. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000353.

Zhou, Y., Chen, S., 2016. Vehicle ride comfort analysis with whole-body vibration on long-span bridges subjected to crosswind. Journal of Wind Engineering and Industrial Aerodynamics 155, 126–140. https://doi.org/10.1016/j.jweia.2016.05.001.