Black Boxes data for Road Pavement Condition monitoring: a case study in Florence

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ABSTRACT:
The Road Pavement Condition (RPC) represents one of the most important aspects of a country's development. Maintaining an appropriate road service level and evaluating an effective road pavement maintenance program is one of the main current challenges for Road Authorities (RAs).
The road pavement damage represents the first risk element for most road users while travelling. In this context, road pavement conditions monitoring plays an important role in the entire process. However, the most efficient monitoring methodologies are sometimes prohibitively expensive for RAs.
To detect the road pavement anomalies high-performance and low-cost methodologies are needed in order to allow the reinvestment of the RA's budget directly on the maintenance and conservation of the existing pavement.
The research presents an innovative and proactive concept of road pavement management process, based on an efficient monitoring method which offers technicians the knowledge of the RPC before it represents a safety problem, especially for PTW drivers.
The paper focuses on the description of operating procedures that aims to perform a screening network based on the most deteriorated sections, by using the "floating car data" deriving from black boxes placed inside vehicles that routinely pass through the road network. A case study conducted in the Municipality of Florence has been described.
The main focus of the case study is to demonstrate that the vertical acceleration data obtained by black boxes allow us to identify the road sections which are in urgent need of maintenance. At the same time, the simple processing of the recorded data allows classifying the RPC in the entire network.

KEYWORDS: Road pavement distress, Inertial device, Acceleration, Monitoring, Low-cost

1 INTRODUCTION

Well-maintained roads are mandatory for efficient and safe transportation. Ageing and distress due to the traffic load and environmental factors are physical phenomena that inevitably deteriorate the road surface and consequently the riding comfort, safety and operating cost (Qiao et. al., 2020). Therefore, to guarantee a high-quality standard for the road network, preventive monitoring and appropriate maintenance are indispensable. Pavement condition monitoring represents the most important preventive step to maintain the quality of road pavement because it supports Road Authorities (RAs) both in defining maintenance programs and in obtaining critical information regarding pavement performance (Lekshmipathy et al., 2020). It also helps both the definition of the distress evolution over time and the best maintenance strategy.

The Pavement Management System (PMS) represent one of the most popular sustainable approaches in the planning and decision-making process. However, to be effective, it requires the availability of road pavement distress data and the possibility of data updating and maintenance. The monitoring systems are considered a significant step of the entire maintenance programme for this purpose.

Over time, more efforts have been made to implement advanced and effective monitoring systems at ever more contained costs, going from impractical manual and destructive methods through automated in-vehicle equipment to the most recent technology (e.g. image elaboration) (Di Graziano et al., 2020).

Currently, the monitoring processes for the identification of road surface anomalies and their severity can be divided into two categories: low and high-performance methodologies. The former is characterized by high time consumption, tends to the subjectivity of inspectors and shows a lack of precision and no correlation between the different indices derived. The second one, which offers an automated or semi-automated detection solution, is instead low time consuming improves productivity, but currently involves high implementation costs.

The most commonly used automated technologies, such as Road Surface Profiler, Ground Penetrating Radar, Laser Road Imaging system or video or image processing methodology, provides excellent results and accuracy but are very expensive. Moreover, these systems are designed to monitor nonurban roads, where speeds are generally higher than 50 km/h.

Frequently, however, the RAs' budgets are limited and, the road pavement monitoring and maintenance could be more and more expensive (both in terms of amounts of money and time) with the pavement ageing. In this context, each RA needs to have a sustainable approach to the problem. In fact, despite the costs for adequate maintenance that cannot be reduced, those for effective monitoring can. It, therefore, becomes fundamental to provide RAs with a tool that allows them to obtain a reliable screening of the road pavement condition of the entire road network, characterized by high performance, low-cost, user friendly and readable for the operators involved.

Alternative methods based on the use of an accelerometer installed in a moving vehicle can be a potentially useful tool for pavement condition assessment conducted in a cost-effective way (Loprencipe et al., 2021). In this context, smartphones have been recently proposed to evaluate the road pavement condition using different approaches and algorithms. Some smartphone applications are based on the IRI procedure (Word Bank). Other applications proposed new indices or given the pavement evaluation based on the acceleration peaks value (Forslof and Jones, 2015; Alessandroni et al., 2014; Lima et al., 2019). Already in 2008, the Pothole Patrol system proposed the use of the smartphones' accelerometer to detect potholes (Eriksson et al., 2008). Bus Net and Nericell are systems that instead utilized the smartphone combined with the monitoring system within the smartphones (such as GPS; accelerometer, etc.) to analyze pollution, traffic and road surface conditions (Zoysa et al., 2007; Mohan et al., 2008). A few years later Kyriakou et al. (2016; 2019) evaluated the results recorded by pitch and roll sensors within smartphones for the detection and the classification of road pavement anomalies. Li and Goldberg (2018) developed a low-budget system based on built-in sensors of low-cost smartphones using two descriptive indices, IRI-proxy and the number of the recorded transient events. Lekshmipathy et al. (2020) showed that the best method to collect routine pavement conditions is represented by the smartphone process compared to the image-process monitoring. However, several studies show that the smartphone accelerometer offers a limited precision in acceleration value measures if compared to the road profiling equipment or the black boxes devices (Souza et al., 2018; Staniek 2021).

Although the smartphone represents the most widely used device, they used different apps and different algorithms whose conduct to a different result (Tutor Drive). Therefore, the use of smartphones could provide different results, also about the precision, due to the different positions used for the smartphone (e.g. dashboard, floorboard, drivers pockets). In addition, several studies show that the smartphone accelerometer offers a limited precision in acceleration value measures if compared to the road profiling equipment or the black boxes devices (Souza et al., 2018; Staniek 2021).
One of the best approaches to road pavement condition assessment seems to be a solution able to detect the main road distress using real-time data crowdsourcing from inertial devices (black-boxes inside the car) taking into account also the type of distress (Martinelli et al., 2021) obtained with statistical analysis or a machine learning approaches.
This document shows the first results obtained with the proactive approaches provided in the analyzed case study located in an urban area of Florence (Italy). As mentioned above, several research and efforts have been directed in pavement sustainability for contribution to improving economic and social aspects of road pavement. However, these researches apply the concept of pavement management activities on highways and major roads; only a few studies have been applied on urban areas management and monitoring activities (Cottrel et al., 2009; Loprencipe et al., 2017) which, too often, are the most deteriorated.
The main objective of this paper is therefore to highlighted the experience conduct, the time consumption and the reliability of the results obtained. Some cost-benefit considerations can be made to explain the advantages of the monitoring procedure offered that, at the same time, allows the collection and post-processing of the pavement surface data along with the road network.

2 CASE STUDY IN FLORENCE URBAN ROAD

2.1 Study area

Firenze is a small city in the middle of Italy. The road network of the Florence Municipality is extended more than 1’000 km. The test road is located in the middle of the urban context (Figure 1: Location), and it represents the main arterial street in Firenze. The definition of the study area considered the choice of homogeneous sections and similar characteristics in terms of traffic, cross-section and pavement distress.

Figure 1: Location of the case study analysis

The road section analyzed serves all types of movement inside the city, both those of crossing and those of final displacement. A high level of traffic affects the area during the day.
The extension selected is about 2 km long (Figure 1). Two separate carriageways serve the movement from the suburb to the city centre and the opposite. Each carriageway is composed of three lanes. Parking, cycle path and sidewalk complete the road space. In Figure 2 a typical cross-section configuration is represented.

Figure 2: Cross section of the study area

The road axis is composed of two long straights connected by a bend (R = 250 m). Per each direction the road cross-section includes three approximatively 3.00 m wide traffic lanes, two lateral spaces with varible wide and two sidewalks. The selected section starts from the traffic-light intersection inside Piazza Beccaria and it ends at the traffic-light intersection inside Piazza Libertà (see the white path in Figure 1). Along with this section, numerous intersections (with different characteristics: signalized or not signalized) interrupt the vehicular flow along the 2 km selected. The posted speed limit is uniform and it is equal to 50 km/h.
All types of light vehicles (PTW, car, motorcycle, etc.) and heavy vehicles (trucks, bus, etc.) are admitted on this road. This is the first reason that affects the selection of the test road within the city road network. In fact, the pavement of the three lanes within the carriageway is characterized by very different distress levels.

2.2 Critical issue and main road pavement distress

The whole study area is characterized by flexible pavement. The different layers property are unknown (thickness, material performances, etc.).
A preliminary visual inspection is carried out along the three-lane which compose each carriageway. According to the ASTM appendix instructions, the main distresses are identified, localized and classified in terms of type and severity (ASTM, 2018).

The main findings of the visual inspection are summarized below:

- the road pavement distress is greater in each right lane because usually, the two right lanes are those where the HGVs passage is greater (i.e. buses, trucks, etc.). In fluid traffic conditions only light vehicles pass in the overtaking lanes (two per direction);
- the road pavement is affected by two types of cracking: transversal and alligator. The two types of distress are present within the lanes with different severity. In the right lane, transversal and alligator crackings are classified with high severity levels;

- the road pavement is also affected by potholes and patches. The severity of this type of distresses range from low to high (classified according to the ASTM appendix catalogue (ASTM, 2018));
- the rutting affected the two right lanes with medium or high severity levels. The presence along the path of rutting is not uniform.

All the distresses qualitatively summarized have been compared with the results obtained by the Pave Box Methodology to verify the result obtained with the proposed automatic process.

3 METHODOLOGY

3.1 Experimental Setup

The hardware components selected for the case study described in this paper are one very common Black-Box, with no specific performances.
The selected technology allowed to make the monitoring process independent of the characteristics of the devices inside the vehicle that routinely pass on the road network. Thus, according to the main goals of the monitoring procedure proposed and the crowdsourcing objectives (Meocci et al., 2021).

The black box used is equipped by:

- one inertial sensor which recording accelerations in the three-axis X, Y and Z;
- one 3-axis gyroscope, able to record the rolling, pitching and yawing movements of the car, and
- one GPS device.

The acceleration data generated by the inertial sensor are acquired at a frequency of 100 Hz according to the most valuable researches (Aleadelat et al., 2018; Mednis et al., 2011; Strazdins et al., 2011). Black boxes characterized by a sampling frequency less than 20 Hz are not recommended due to the limitation of the procedure in detecting small anomalies.
The maximum recorded acceleration value is 16 g (for each direction).
In order to carry out the experiment, the black box has been rigidly attached to the car floorboard, between pedals and the gearbox, as close as possible to the car's centre of gravity.

The position described allows to have a minimal impact on the data recorded by any curvilinear trajectories of the vehicle, also generating centripetal and/or centrifugal accelerations on the measurement. In these terms, the best position would be on the tunnel of the car, but, in most vehicles, this component is not horizontal, therefore its configuration could direct the value of the vertical acceleration recorded.

The black boxes used in the experiment do not require any installation procedure or other requirements to start the monitoring. It is only required that 5 seconds before starting the monitoring, the black box is switched on to stabilize the GPS connection. All tests are conducted with the black box in the same position. Data acquired by the black box are finally downloaded by micro-USB to the computer for the post-processing procedure.

3.2 Procedure

The procedure carried out has been conducted according to the process defined in (Meocci, 2021), which can be summarized by the steps shown in Figure 3.

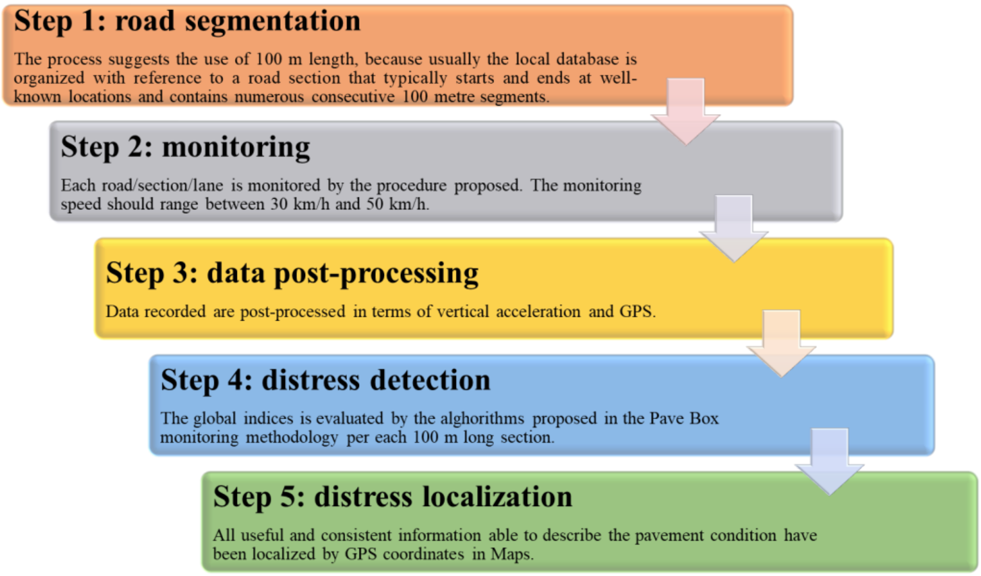

Figure 3: Procedure

The test is carried out by the same vehicle, a Fiat Panda 4x4. Before starting the test, each tire is checked and adjusted to the recommended tire pressure for the car used (2.4 bars).

3.3 Data collection and analysis

According to the pavement condition procedure proposed by the Pave Box methodology (Meocci et al., 2021), the data resulting from the monitoring are focused on the evaluation of the **Global Pave Box Index**. The index offers a global evaluation of the entire road segment damage. The index can be useful both to screen the entire road network and to compare the different road sections within the network, which is characterized by different road damages.

In equation (1) the global index is shown.

$$GPB = \left(\int_0^L \sigma(\overline{a_v})^2 dl\right) \times \frac{100}{L} \qquad (1)$$

where a_v represents the vertical acceleration values, $\overline{a_v}$ represents the centred moving average across a range of 20 values (0.2 s) evaluated as in equation (2).

$$\overline{a_v} = \frac{\sum_{i-9}^{i+10} a_v}{n=20} \qquad (2)$$

As a function of the value obtained, the road section could be classified into four different classes corresponding to the different distress severity: low, fair, high and need to repair. The first three classes must be considered in the priority algorithm, the last one instead needs immediate repair (Table 1).

Table 1: GPB index rating scale

GPB rating scale	Severity levels
GPB<0.40	good
0.40<GPB<0.65	fair
0.65<GPB<1.45	high
GPB>1.45	need to repair

Each lane is monitored only once. The survey is carried out at a speed ranging from 30 km/h to 50 km/h. The car's transversal position is assumed in the middle of the lane (as far as possible).

4 RESULT AND DISCUSSION

4.1 Segmentation

The study area is segmented following the previously defined criteria. Specifically, 7 sections and 8 sections are defined for direction 1 (suburb to the city centre) and direction 2 (city centre to the suburb) respectively. The sections are simply defined with reference to the division of the entire road based on the signalized intersections (light position/STOP marking). This represents the main reason because, often, each section differs from the others in terms of length and start-end points. In Table 2 the sections' information is summarized.

Table 2: segmentation of the study area

Direction 1			Direction 2		
Section ID	**Length [m]**	**Number of subsection**	**Section ID**	**Length [m]**	**Number of subsection**
1	190	2	1	210	2
2	275	3	2	180	2
3	250	3	3	135	1
4	230	2	4	300	3
5	290	3	5	200	2
6	310	3	6	225	2
7	165	2	7	275	3
-	-	-	8	205	2
Average	244	-	-	216	-

4.2 GPB evaluation

The recorded measurements (a_v) constitute the dataset to be processed for both the identification and classification of the pavement surface distresses severity through the GPB index. In Table 3 and Table 4, GPB indices evaluated in the data post-processing are summarized. First, the table showed the GPB indices obtained at 100 m by 100 m. Then, in bold, the GPB assessments for the overall section are indicated in colours of the distress severity.

Table 3: GPB index values – direction to the city centre

Section ID	Length [m]	GPB [m/s^2]		
		Lane 1 (right)	**Lane 2 (central)**	**Lane 3 (left)**
1	180	0.94; 1.90 **1.58**	0.22; 0.08 **0.16**	0.27; 0.15 **0.23**
2	270	1.34; 0.69; 2.31 **1.61**	0.38; 1.55; 0.29 **0.79**	0.34; 0.39; 0.07 **0.30**
3	240	0.64; 0.37 **0.42**	0.12; 0.07 **0.09**	0.05; 0.09 **0.08**
4	250	0.24; 0.91 **0.46**	0.68;0.57 **0.61**	0.95; 0.24 **0.48**

5	290	0.34; 0.32; 0.27 **0.32**	0.24; 0.14; 0.18 **0.19**	0.33; 0.45; 0.27 **0.36**
6	150	**0.46**	**0.12**	**0.17**
7	150	**0.33**	**0.03**	**0.41**

Table 4: GPB index values – direction to the suburb

Section ID	**Length [m]**	**GPB [m/s²]**		
		Lane 1 (right)	**Lane 2 (central)**	**Lane 3 (left)**
1	180	0.36; 0.11 **0.25**	0.17; 0.06 **0.13**	0.32; 0.11 **0.24**
2	135	**0.22**	**0.08**	**0.11**
3	300	0.26; 0.14; 0.11 **0.17**	0.09; 0.09; 0.11 **0.10**	0.13; 0.18; 0.09 **0.13**
4	200	0.25; 0.14 **0.20**	0.59; 0.28 **0.44**	0.38; 0.18 **0.28**
5	225	0.54; 0.71 **0.63**	0.69; 0.53 **0.54**	0.40; 0.13 **0.24**
6	275	0.22; 0.79; 0.25 **0.70**	0.07; 0.15; 0.07 **0.11**	0.002; 0.12; 0.10 **0.008**
7	205	1.23; 1.00 **1.09**	0.32; 0.39 **0.35**	0.14; 0.20 **0.17**

Tables show that the carriageway direct to the suburb has better road pavement conditions than the opposite. In fact, within the carriageway directed to the city centre, there are two sections in the right lane, that need immediate restoration. In Figure 4 the moving variance of the acceleration (right lane-section 1) is represented. The Figure shows also the big pothole represented by the first peak that in the preliminary survey was classified as “high severity pothole”(ASTM, 2018).

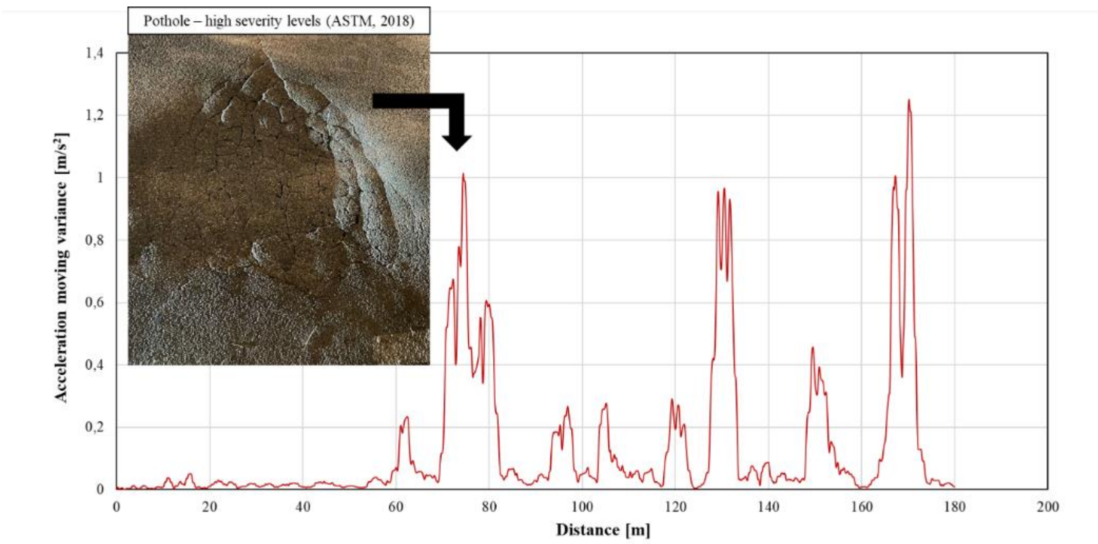

Figure 4: section 1, right lane – direction: City-Centre

For the city-centre direction, in the right lane, only two sections can be classified as “good condition”. The other lanes instead show good or fair road pavement condition. The result obtained is consistent with the high number of HGVs in this lane. The others lane instead are mostly driven by light vehicles (cars and PTWs).

Generally, the two sections near Piazza Beccaria (in both directions) are the ones with the worst paving conditions.

5 CONCLUSION

Despite the many technologies available for monitoring road pavements, the RAs too often cannot use them because of their high costs, especially in urban areas. Therefore, the proposed distress-detection process is designed to satisfy the needs of RAs, using a data collection based on crowdsourcing.

This paper would like to show a case study implemented in the Municipality of Firenze, along the main arterial street using the Pave Box Methodology.

The methodology consists of the post-processing of the vertical acceleration and GPS data recorded by an inertial device within a car (black box) to evaluate the presence and severity of road pavement distress. The approach aims to quickly screen (in Real-Time) the road pavement condition within the road network and define the priority list in order to prevent and/or quickly repair the road anomalies as a function of their severity.

The survey illustrated is conducted at a time less than 3 hours. The overall road length monitored is approximately 12 km (6 lanes per 2 km each one).

In the end, the presented case study demonstrates the RAs the power of the low-cost and user-friendly process proposed.

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