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Review

Pavement distress detection methods: a review

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Abstract: The road pavement condition affects safety and comfort, traffic and travel times, vehicles operating cost and emission levels. In order to optimize the road pavement management and guarantee satisfactory mobility conditions for all the road users, the Pavement Management System (PMS) is an effective tool for the road manager. An effective PMS requires the availability of pavement distress data, the possibility of data maintenance and updating, in order to evaluate the best maintenance program. In the last decade, many researches have been focused on pavement distress detection, using a huge variety of technological solutions for both data collection and information extraction and qualification. This paper presents a literature review of data collection systems and processing approach aimed at the pavement condition evaluation. Both commercial solutions and research approaches have been included. The main goal is to draw a framework of the actual existing solutions, considering them from a different point of view in order to identify the most suitable for further research and technical improvement, also considering the automated and semi-automated emerging technologies. An important attempt is to evaluate the aptness of the data collection and extraction to the type of distress, considering the distress detection, classification and quantification phases of the procedure.

Keywords: pavement distress, pavement management, distress identification, data collection system

1. Introduction

Road condition is a critical aspect for the development of a country, in fact, it has been adopted as rating criteria by the World Bank [1] "the density of paved roads in good condition varies from 40 km/million inhabitants in low-income economies to 470 middle-income and 8,550 in high-income economies". Moreover, the road condition may crucially affect the national budget of a country, both with regard to direct costs, such as road infrastructure construction and maintenance and to the indirect cost such as the social cost coming from the incidental phenomena.

Road pavement is an important issue in infrastructure management for physical as well as financial reasons: Pavement Management System (PMS) is an efficient tool for assess maintenance interventions in order to preserve acceptable pavement condition during the lifespan, and whilst limiting costs in the long term [2]. Maintain an acceptable level of service for the whole road network, and in particular assess an effective pavement maintenance and rehabilitation program is challenging for the road public authorities. This issue is fundamental if related to the impact of pavement condition on comfort and safety for all the road user [3]: this consideration highlights the necessity of shifting from a reactive to a proactive maintenance approach, which strongly pervades the Pavement Management System.

A traditional reactive approach for pavement maintenance prescribes road repayments once significant structural damage has occurred: this approach leads to more severe and expensive rehabilitation that which can cause unsafe conditions for road users prior to the interventions, as described in [2,4,5].

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A proactive approach is pavement preservation oriented: it seeks to create a system of implementing relatively less invasive and small-scale repairs on roads prior to structural degradations occur, limiting the necessity of full depth road reconstruction. Compared to the reactive approach it will result in long-term savings, reduced traffic congestion, without leading to a massive safety condition reduction [2,6]. Data collection and analysis phases are crucial to perform a proactive approach, basilar for a successful PMS implementation, as reported by other authors [7,8].

Monitoring the pavement condition after construction, and comparing the actual with the desired performance level, allow evaluating the level of damage, identifying the cause of the problem and finally design the treatments and decide the prioritization of intervention, as resulted [9,10].

The pavement condition can be determined both manually and automatically: while the first is labor-intensive, time-consuming and prone to the subjectivity of inspectors, the second option offers an automated detection solution, which provides in minimizing the subjectivity, improving the productivity but it entails the higher cost of realization [2,8,11].

From this consideration arose that the benefits coming from a proactive approach had to face with some initial disadvantages, which have led to an overall delay in PMS adoption worldwide. Implementation costs of the system, operation costs for data acquisition and processing, time-consuming operations such as survey and data process, have represented a limitation, even more so considering the large extension of the road network.

In this regard, repeatability, accuracy, and objectivity of distress acquisition and detection of pavement, are a very important improvement in this kind of process [2,11].

At the same time, agencies were conscious that delay in PMS application would lead to a more rapid deteriorating of global road network and to economical lost [8]: this consideration has fed the interest of several road authorities and researchers in developing automated and semi-automated procedures for pavement assessment and evaluation. Several systems and procedures have been implemented during the last ten years, focused on improving survey technique, especially in order to overcome the limits of manual survey [6,9], in increasing operating safety, and improving the cost-benefit ratio [10].

It must be mentioned that almost of commercial solutions are high performance oriented, designed for high-speed roads and capable of acquiring a huge amount of georeferred data, often requiring a considerable economical resource for surveys and post-processing activities. For these reasons, a high-level PMS is often not achievable by many local agencies, which remain effective road management system lacking.

Moreover many studies in the literature are focused on the relation between PMS and particular pavement performances (such as roughness or adherence), but very few provide a global approach safety and comfort based [4,5,7].

This paper aims to provide an overview of current practices and emerging technologies in order to build a solid information base for pavement management based on safety and comfort criteria.

2. State of practice in pavement distress and Indices

The pavement distress labeling and quantification in term of type, severity, and extension are the first steps for a road maintenance assessment. This phase is often crucial because of a lack of standardization in the distress definition, that could lead to the inconsistency of the classification.

In literature, there are several distress identification catalogs by different researchers and organizations [12,13], which almost adopt the same identification and evaluation criteria. One of the most well-known and diffused references is the ASTM D6433-16 [14], which provides distress criteria identification and classification for both flexible and rigid pavement. Another American reference commonly used is the manual for the Long-Term Pavement Performance Program by the US Department of Transportation [12], which aims to collect pavement performance data in the United States and Canada. This classification is relevant because widely experienced and for its international orientation and integrity of classification, but it does not provide any numerical threshold for distress severity classification [8]. The European background in distress identification

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and management is limited to some isolated cases. In fact only, the French Institute of Science and Technology for Transport [15] and the Swiss Association of Road and Transport Professionals [16] have developed a systematical approach in pavement distress identification in their guidelines, while only recently Ireland has included the assessment of road pavement based only on the surface condition evaluation [17]. In Italy, the diffusion of standard procedures for distress identification is few and limited to CNR guidelines and isolated case of application of any road officers [18].

The common aim of all the above-mentioned Distress Catalogues, is to provide an as "objective as possible" common set of criteria to evaluate the pavement condition and define management strategies. In fact almost of the methods to perform a Pavement Management system are based on the development of pavement condition indices to express the structural and operational performance, by mean combining different distress type expressed in term of severity and extension, such as for Pavement Condition Index PCI [12-14]. To perform a preventive maintenance approach for a whole road network, is required the availability of detailed information about actual road conditions, that can be obtained only through an accurate distress identification and classification. On the other side to reach high level information, high investments in technologies and qualified staff are necessary.

In recent years, encouraged by the challenging goal of the EU in Road Safety [19], many researchers and public agencies have spent their energies and resources in investigating the role of road condition in the incidental phenomena [7,11,20,21]. Moreover, in a time of poor economic resources, many countries have to face with the impossibility of investing in sophisticated PMS and expensive extensive surveys: from these considerations emerges the effectiveness of a pavement classification tool, safety and comfort-oriented, requiring a defined set of information acquired by focused surveys [7,22,23].

2.1. Distress

This review paper treats only distress detected on the flexible pavement: this choice reflects the authors' aim to provide a state of the art useful to almost organizations involved in road management because of the huge diffusion worldwide of this kind of pavement.

As a reference guide for the distress classification the most well-known and appreciate Distress Catalogues have been considered [10,14] in order to identify the most frequent distress in flexible road pavement tightly coupled with the comfort and safety of the vehicles. As a result of this first step of the review, the contribution in term of comfort or safety reduction has been considered for each type of distress, according to its severity and extension.

According to the [10,13,14] the distresses types have been grouped into five families, as described below:

- A. Cracking.
- B. Visco Plastic deformation
- C. Surface defects.
- D. Miscellaneous distresses.

In the following paragraphs, the characteristics of each group of distress are summarized, in order to facilitate their identification and to evaluate their own contribution to comfort and safety level for road users.

2.1.1. Cracking group

Pavement Cracking comprises several kinds of distresses such as fatigue cracking, block cracking, edge cracking, longitudinal and transverse cracking and reflection cracking. Most of them are related to climatic causes, except for the Alligator cracking type, related to load, and slippage cracking caused by traffic. Their position, dimension, and orientation allow identifying the specific type of cracking and the relative causes, as reported in detail in Figure A1 in Appendix A. Moreover they have different effects on the global safety and comfort level of the road: for example, the presence of fatigue cracking advises the end of lifecycle for the pavement, far from the recommended standard.

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2.1.2. Visco Plastic deformation group

The Visco Plastic deformation group consists of all the deformations involving both superficial and bottom layers. Showing, corrugation and lane/shoulder drop off generally involve horizontal and vertical displacement of the top layer of the pavement structure, while bumps and sags, rutting, depression, potholes and swell may affect the whole structure. The first cause of visco plastic distresses is the load, followed by traffic and climatic effects. Their position, dimension, and orientation allow identifying the specific type of distress and the relative causes, as reported in detail in Appendix A, Figure A2

2.1.3. Surface defect group

The surface defect group encompasses bleeding, polish aggregate and raveling. When bleeding occurs, an excess of bituminous binder is present in the top layer surface, while in case of raveling an inadequate asphalt binder can cause the dislodging of aggregate. In case of Polish aggregate, the top layer surface becomes smooth because of the aggregates' exposition to the traffic, producing a reduction in adhesion. Causes of surface defects are related to bituminous materials characteristics and to the traffic effect. Their position, dimension, and orientation help in identifying the specific type of distress, as reported in detail in Appendix A, Figure A3

2.1.4. Miscellaneous Distress

The last three distress are patching and utility, cut patching, railroad crossing, catch basins, and manholes cover. They are frequent in the urban area and easily recognizable by their peculiar shape, as summarized in Appendix A, Figure A4.

2.2. Indices review

Distresses Catalogues provides a common language to identify, describe, and evaluate the severity of distresses, in order to minimize the subjective component of the visual process, to guarantee the repeatability of the method and to facilitate the communication within the authorities.

These aspects, in fact, are essential for a Road Agency motivated in realizing an efficient Road Network Management system: standardized data collection procedures, robust pavement condition indices, and experts in pavement data collection procedures are essential requirements for the system.

Primary aspects which guide the PMS definition are the comfort, the safety, and economic issues [7,8,23]: a proper maintenance strategy can be defined trough balancing them, using specific tools supported by the current pavement condition information and considering the Agency's priority.

In literature [9,23-25], there are several tools which enable to synthesize the current pavement condition, to define the priority intervention order, including prediction of performance and economic analysis. On the basis of the tool adopted, specific input data are necessary, characterised by different accuracy and precision levels, and acquired by different technique, which contributes to determine the global performance and cost of a PMS. Several authors [21,26,27] focused their researches on the analysis of the relation between accidents and pavement conditions, expressed in term of common indices: according to the literature review Pavement Condition Index -PCI, International Roughness Index - IRI, Ruth Depth - RD, and Pavement Serviceability Index - PSI are the most used ones in representing a global or peculiar aspect of the road pavement. Table 1 summarises the above mentioned indices.

2.2.1. Pavement Condition Index PCI

The Pavement Condition Index (PCI) was developed to provide a measure of pavement integrity and surface operational condition based on a numerical scale, where 100 represent the perfect conditions to 0 the failed pavement. It is based on visual survey: the degree of deterioration is a function of distress type, distress severity, and amount or density on the considered sample unit.

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The method, developed by the U.S. Army Corps of Engineers [13] has been adopted as standard procedure by many agencies worldwide, and published as ASTMS standard, for both road and airport, [14] and [28] respectively, and adopted as a basis for PMS commercial software [28]. It guarantees consistent and accurate results but it needs high-level accuracy for the input data, moreover, it is prone to the human capacity for distress detection and it is time-consuming.

2.2.2. International Roughness Index (IRI)

The International Roughness Index (IRI) is a standardized roughness measurement, developed by the World Bank in 1980 [28], which provides a ride quality classification in term of longitudinal profile, traveled by a wheel path. The IRI is defined as the filtered ratio of the accumulated deviation of the vehicle's suspension divided by the traveled distance. The profile necessary for the calculation of the index can be obtained by any valid measurement instrument, starting from static rod level to high-speed inertial profilers, as reported in [29]. Pavement roughness is directly linked to ride quality - comfort and to safety, because is one of the causes of load loss accident [30].

2.2.3. Rut Depth (RD)

Rut Depth (RD) measures the longitudinal pavement deflection along the wheel path as a consequence of the accumulation of visco plastic deformations of layers and subgrade. The main causes of rutting distress are heavy traffic load repetition or lateral movement of the material of the layers. Rut Depth is an important indicator linked to road safety because during wet weather conditions high rutting level can facilitate the hydroplaning phenomena and loss of control of the vehicles [31]. RD measurement is simple but it needs high accuracy in data acquisition: it can be calculated from profiles obtained with any valid measurement method, ranging from static rod and level surveying equipment to high-speed inertial profiling systems.

2.2.4. Present Serviceability Index (PSI)

Present Serviceability Index (PSI) is a parameter used to describe the functional condition of pavement with respect to ride quality: it provides a valuation of the ability of the road to serve traffic: it takes into account several road characteristics such as slope variance, rut depth, cracking and patching surface, as reported in [27]. The PSI is used to provide a comprehensive evaluation of pavement conditions, for both safety and comfort aspect: the complexity makes several input data necessary to the calculation.

Table 1. Indices review for road pavement surface evaluation.

Index	Information	Measurement	Survey method
PCI	Pavement surface	Type, severity, amount of distress	Visual inspection
IRI	Ride quality	Roughness	Road profile
RD	Deformation	Longitudinal pavement deflection	Road profile
PSI	Ride quality	Functional performance	Visual inspection

3. Method of distress classification based on Comfort and Safety

The above mentioned indices are based on the analysis of various type of data, acquired by many technologies, characterized by different level of performance and costs.

IRI and RD are focused only on specific characteristics (roughness and visco plastic deformation), far from describing exhaustively the current pavement condition; moreover considering the requested accuracy standard [14,29], the survey and post-process activities result

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expensive and time-consuming. PCI is based only on a visual approach and, especially for the evaluation part, it is performed manually by the operator: this can lead to high costs and longtime execution. PSI has an intermediate function but it needs different information for its calculation. From this analysis emerges that those indices are high performance oriented, defined for primary roads or high-speed road, and often require massive economic resources for survey and post-processing activities. Consequently often they don't fit the emerging information need of many local agencies which cannot implement a high-level PMS, but they only need a way to better manage their road network. Furthermore from the literature review emerges that many studies focus on the relation between road accident occurrence and pavement conditions but little has been done to incorporate pavement safety management within a PMS [8,24,32].

Among the wide literature review about the effect and pavement condition on driving condition, an interesting attempt is made by S. Tighe et al. [21] which proposed to consider the safety in a PMS design. In particular in their study they integrated the road safety with PMS considering eight criteria: among them the first three deal with pavement condition, such as Skid resistance and surface texture, Roughness (e.g., IRI), Surface condition (ruts, faults, potholes, cracks, spalls, etc.), while the others deal with road geometric and functional road characteristics, as summarised in in Table 2:

Table 2. Integration of pavement condition in a PMS, [22]

Class of factor	Safety attributes or indicators	Sensitivity of drivers
Surface Texture or Friction	macro and micro texture characteristics; skid resistance or skid number measurement; vehicle tire type standard	Low
Pavement Roughness or Ride Quality	Riding comfort rating or roughness; roughness vs speed	High
Pavement Surface Distress	Severity and extend of surface distress; distress index	Medium
Pavement Geometric Design and Location	Width of lane and shoulders, median and pedestrian paths; gravel or paved shoulders; cross-slope	Medium
Visibility of Pavement Surface Features	Pavement surface color and reflectivity; lane markings and signings; visibility at night and in bad weather conditions	High
Paving Materials and Pavement Mix design	Type of pavement; texture and color of paving materials; mineralogy and anti-skid proprieties	Low
Road safety Measures and Facilities	Safety warning sings; safety protection facilities	High
Environmental and Weather condition	Place and time of accident occurrence; roadside obstacle and safety facilities; precipitations	Very High

3.1 Distress classification criteria

The general aim of this work is to provide a simple and effectiveness framework dedicated to road management activities: integrating the classical approach of the pavement condition analysis with the high performance of the new technologies allows to choose the best pavement distress detection method.

As first goal the present work tries to suggest a simple set of criteria to perform a pavement condition analysis, comfort and safety oriented: the distresses present in the catalogues, fully described in Appendix A, are classified considering their influence on safety and comfort for the road user. The criteria have been defined through the trend arose from the literature review and through a panel interview with flexible pavement experts. This step allows to define, for each distress, geometrical thresholds or pavement states that affect the driving condition for the users in term di safety and comfort. As reported in Figure 1.

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	DISTRESS	SEVERITY	IMPACT ON SAFETY	IMPACT ON COMFORT	TYPE OF INFORMATION
Cracking	FATIGUE CRACKING	L	0	0	2D 3D
		M	0	1	
		H	1	2	
	BLOCK CRACKING	L	0	0	2D 3D
		M	0	1	
		H	1	2	
	EDGE CRACKING	L	0	0	2D 3D
		M	0	0	
		H	1	1	
	LONGITUDINAL AND TRANSVERSE CRACKING	L	0	0	2D 3D
		M	0	1	
		H	1	2	
	JOINT REFLECTION CRACKING	L	0	0	2D 3D
		M	0	0	
		H	1	1	
	SLIPPAGE CRACKING	L	0	0	2D
		M	0	0	
		H	1	1	
Visco Plastic deformations	BUMPS AND SAGS	L	0	1	3D
		M	0	1	
		H	1	2	
	RUTTING	L	0	1	3D
		M	0	1	
		H	1	2	
	CORRUGATIONS	L	0	1	3D
		M	1	1	
		H	2	2	
	DEPRESSIONS	L	0	0	3D
		M	1	0	
		H	2	1	
	POTHOLES	L	1	1	2D 3D
		M	1	1	
		H	2	2	
	SWELL	L	0	0	2D 3D
		M	0	0	
		H	1	2	
	LANE / SHOULDER DROP OFF	L	0	0	3D
		M	1	0	
		H	2	1	
	SHOVING	L	0	0	2D 3D
		M	0	1	
		H	1	2	
Surface defects	BLEEDING	L	1	0	2D
		M	1	0	
		H	2	0	
	POLISHED AGGREGATE	L	1	0	2D
		M	1	0	
		H	2	0	
	RAVELING	L	1	0	2D
		M	1	0	
		H	2	0	
Others	PATCHING-UTILITY CUT PATCHING	L	0	0	2D
		M	0	0	
		H	1	1	
	RAILROAD CROSSING *	L	1	1	2D
		M	1	1	
		H	2	2	
	MANHOLE	L	1	1	2D
		M	1	1	
		H	2	2	

Note. * Poweredtwowheeler's safety is particulary affected by the presence of railroad crossing

Figure 1. Distress classification according to safety and comfort criteria

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To encourage the technological penetration in the Road Administrations procedures is necessary to associate each distress with the type of information able to fully describe the pavement status and then to suggest the appropriate technological solution. Figure 1 summarises the process: in the left part, each distress is classified in term of impact on comfort and on safety, using a scale from 0 to 2 (where 0 is low impact and 2 is the maximum impact). In the right part of Figure 1, the type of information required (2D or 3D information) related to each distress, and spatial criteria for identification are illustrated.

The first thing that stands out from the analysis is that the low level of all distress is negligible in term of safety, excluding the ones which affect the adherence characteristics (Surface defect group), potholes, and manholes, while the railroad crossing is particularly dangerous for Powered two-wheelers. Comfort is poorly not affected by surface defect group, while Visco plastic deformation, manholes, and railroad crossing have an evident effect on users driving condition.

Moreover, the right side of the figure clarify which technology is appropriate for the survey: 3D is the most complete information but it is limited to only a few kinds of distress for economic aspects These considerations are helpful in one hand because allow excluding the low distress level from the analysis purpose, and on the other hand are a guide to choose the best technology for the information acquisition.

4. State of art in distress detection

Quantification of pavement crack data is one of the most important criteria in determining optimum pavement maintenance strategies. The simplest survey method is to visually inspect the pavements and evaluate them by subjective human experts. This is a traditional approach, which involves high survey costs, is time-consuming and often produces unreliable and inconsistent results. Furthermore, it exposes the inspectors to dangerous working conditions on highways [2,3]. To overcome to the limitations of the subjective visual evaluation process, several attempts have been made to develop automated devices in pavement distress acquisition and detection. These innovative methods, in fact, provides non-subjective, high productivity, and accurate data set, which enable the production of quantitative analysis of the pavement condition.

The most recent systems are composed by one or more acquisition devices and post-processing applications for semiautomatic or automated data extraction procedures, based on computer vision and image processing algorithms [33-36].

However, due to the irregularities of pavement surfaces and to the miscellaneous presence of distresses on the pavement surface, there has been some limited success in accurately automated cracks detection and classification, which have limited the massive adoption of this kind of system [37-39].

While the use of automated pavement condition surveys is becoming more and more common, many agencies still rely on manual methods to provide their pavement condition data. There is no doubt that automated pavement condition surveys are more efficient and safer than manual pavement condition surveys; however, the quality of automated survey data has been under heavy scepticism since its conception. Several studies [2,37,39] have shown that in most cases, the results of the two procedures are statistically similar: the massive presence of irregularities might produce incorrect detection classification and quantification , especially when the irregularities are in the same portion of the surface [2].

Type, severity, and extent of pavement distresses are the keys to assessing the pavement conditions, and even to determine the most suitable survey technical solutions.

In this section, an attempt is made to present the current practices, and the emerging technologies for data acquisition, considering them in connection to the information requests for a PMS safety and comfort oriented. To correspond to the emerging information needs of the Road Agencies involved in PMS realization, the vehicles used for surveys are multisensors platform: generally, they provide a georeferred information using a positioning system based on GPS, integrated with the data from camera, laser, and other sensors, in order to fully describe the road

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environment. In order to provide a classification of the available detection technologies for a PMS data set acquisition, the following criteria have been considered, as reported in Table 3:

- Precision, indicates the statistical variability;
- Accuracy, indicates the systematic error as cause of difference from the true value;
- Spatial resolution, indicates the s the smallest change it can detect;
- Productivity, indicates the rate of production in time;
- Cost of implementation;
- Automation, implementability in automated process.

Each device has been classified from "Low" to "Very High" in terms of above mentioned criteria.

Table 3. Technological solutions classificaation.

Technology	Information	Precision	Accuracy	Spatial resolution	Productivity	Cost	Automation
Camera	2D	Medium	Medium	3-6 mm	High	Low	High
Linear scan Camera	2D	High	High	2 mm	Medium	Medium	Medium
3D laser imaging	3D	High	High	1 mm	High	High	Medium
TLS	3D	Very High	High	3-6 mm	Medium	High	Low

4.1. Digital camera

Digital cameras in distress detecting is a mature technique: commercially available devices acquire 2D images in the visible spectrum of light. The image is captured through a digital photosensitive sensor CCDs (Charge-Coupled Devices) or CMOS (Complementary Metal-Oxide Semiconductor). Currently, the two sensors are comparable in performance and usable without any difference [40] but the CCDs are the most used sensors for the identification of distresses because they are cheaper and have a greater chromatic accuracy.

After the acquisition, a digital image processing is used to extract the distresses features using image analysis algorithms: the different distresses are separated and classified according to some parameters, such as the width, the direction of propagation [35,38,39,41], and the pixel colour variation [2,34,36,42].

Among the first application on features detection using 2D images, several authors tested the method on potholes, getting good results. Images were first segmented into the defect and non-defect regions, using histogram shape-based thresholding; subsequently, the regions having characteristics such as to be classified as potential potholes were analyzed by morphological operators. The particular shape and dimension of potholes make their identification easier by image detection algorithms, even using low camera resolution. Improving the resolution of the camera even crack identification and measurement become a reliable procedure.

In fact, most studies on 2D images show that the identification and classification of cracks have led to high success ratio: studies show that the accuracy of cracks measurement may be higher than 95%, with a lower limit of 70% [2,38,43,44].

A non-treasurable aspect of the camera in data acquisition process is the possibility of being easily implemented on a traveling vehicle, equipped with several sensors and a positioning system in order to improve the survey productivity and integrate the georeferred information component [34,45]. As the vehicle moves along the road, some factor, as the vehicle speed, camera position, and settings, environmental factors, might affect the final resolution of images and compromise the distress detection. .In order to properly detect the distresses, the images must undergo ortho-correction processes in order to correct the deformations, and exclude unwanted shadows and other light noise that occurred during the acquisition [46,47].

For example of final image resolution, a camera with an angle of view of 45 degrees approximately and placed at 1.2 m height provides a ground sample area of 1 m^2 and considering 20 mpx sensor resolution we can expect a ground sample distance (GSD) equal to 0.2 mm.

Most commercial vehicles used for inspections are equipped with cameras which are not used directly to measure and identify the distresses but are used to assist other measurement devices, such as linear cameras, triangulation device or LiDAR devices.

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Most recent applications in pavement inspection employ remote sensing procedure using UAVs (Unmanned Aerial Vehicles) and the image processing and pattern recognition techniques as for the terrestrial application [48]. However, at a certain height of flight, the spatial resolutions of these images limit the ability to detect the pavement distress, such as individual cracks, because most of their width is less than 0.01 m. A CMOS with sensor resolution 12 mpx integrated on a UAV platform flying at a height of about 5 meters, produces a spatial resolution of about 3 mm, with a maximum accuracy of about 7 mm [49]. Under these conditions rutting, alligator cracking, and transverse cracking distresses have been identified.

4.2. Line scan camera

The line-scan camera is ideal for applications requiring both high acquisition rates and high resolution. A line scan camera produces a sequence of single lines pixels, (generally 2000x1 pixel until 8192 pixels per line in higher resolution devices): to build up a two-dimensional image of the pavement, either the camera is moved perpendicular to the line of pixels, generally by a terrestrial vehicle [50]. Line scan camera can assure a high daily productivity in survey phase, in fact, a high frame rate of the camera (such as 28 kHz) allows the vehicle to drive up to 90kmm/h, but it can result in a time consuming and expensive post-processing and distress detection phase [8,51].

Line-Scan cameras were mainly used for crack detection from 2D images: the distress visibility is inversely proportional to spatial resolution. In fact for a camera characterized by a resolution equal to 2048 pixel per line mounted at the height of 1.80 m, the visible crack width is equal to 2 mm; Increasing the resolution to 4096, the visible crack width comes down to 1 mm [41,52].
An important improvement in high resolution distress detection has been the adoption of Laser-Illumination based technology in 2005, which overcame the to the sunlight and shadows disturbs [3,8,51,52]. The commercial solutions based on this technology are the called Laser Road Imaging Systems [53] :they can work nighttime or daytime, as long as the pavement is dry. LRIS system uses two cameras which produce synchronized and partially overlapped pair images to form a single image.

4.3. 3D laser imaging

Several pavement surfaces distress is tridimensional: 2D dimension (surface) and the height differences (depth). 3D sensors include a variety of technological solutions, and most of them are based on laser profilers in combining with imaging. This technology has been widely applied for quality controls in manufactory, and only in recent years, it has been applied in pavement surface analysis [3,8,52].

One of the most used 3D reconstruction technique is based on the triangulation, in which a laser line, or a LED linear light as an auxiliary light, projects a ray on the road surface. One or more CCD cameras realize the triangulation system, by means detecting the shape of the laser line projection on the near flat pavement.

3D Laser Imaging has the potential to measure different pavement surface distresses at high speed and in full automation: cracking, rutting, pothole, patching, faulting can be easily detected by the system [42]. According to several authors [2,3,8,53] the system can effectively detect cracks equal to and greater than 2 mm wide under controlled laboratory environment and consistent results under different lighting conditions were obtained [47]. This technology is mature and commercially available as Laser Crack Measurements System (LCMS) and adopted in several systems as ARAN, Dynatest, ROMDAS, PaveTesting, Pavision [3,8]. The system consist of two units, composed by a spread line laser and a 3D camera each, mounted off axis. The lasers scans a 4m line width, with 1 mm transversal resolution on the road surface, while the cameras capture an image of the projected laser line. The data captured are two type: height of the pavement surface and intensity on the pavement surface.

The longitudinal resolution is a function of the speed of the vehicle and of the laser scan rate: for example, 60 km/h driving speed and with a scan rate equal to 5 kHz, the scan line interval is equal to

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3 mm [54]. Moreover according with [8,35,36] the crack detection process may be improved using 2D high resolution camera.

A disadvantage of the system is the high cost of equipment, while an advantage of this system is that because the entire transversal road profile can be detected and categorized using a sufficiently high projection frequency laser and adequate cameras

4.4. Terrestrial laser scanner

Among the technological solutions commercially available for pavement distress detection, the laser scanner is one of the most recent, high performance and accuracy.

Laser scanner technique is based on LiDAR (Light Detection and Ranging) technology; it allows to obtain very accurate and high resolution 3D information of the object scanned by dense point cloud. It is based on two principles: time of fly and phase shift. The time-of-flight sensors estimate the distance between the target and the center of the instrument by the measure of the time elapsed between the emitted and the reflected laser signal, while the phase shift sensors are based on the measurement of the angular offset between the emitted and the reflected signal. Phase shift sensors have a more limited range than those at time of flight (<150m), on the other hand they have a higher acquisition frequency (more than a million points per second). The accuracy obtainable with time-of-flight instruments is between 3 and 6 mm @ 100m, values that increase with increasing distance [55].

Of particular interest are the Terrestrial Mobile Laser Scanners, also commonly called Mobile Laser Scanner (MLS) that allow the acquisition of 3D data by means of one or more scanners mounted on a mobile platform (Vehicles, boats, trains); this technique considerably reduces acquisition times and costs compared to traditional techniques [56]. Typical ranges of local accuracies and point density values for MLS of pavement surface and Machines control, the 3D accuracy request is of 1 centimeter and a density greater than one thousand points on a square meter. The density of the point cloud is a function of the traveling speed of the mobile platform [57]and of the angular resolution of the sensor and of the rotation velocity of the laser mirror: balancing these parameters the accuracy of the resulting 3D point cloud can be improved.

Applications of distress detection by laser scanner point cloud deal with the automated approach for detecting road roughness and potholes, using multi-level thresholding [58]. Moreover, excellent results [59] have been reached in comparing IRI values determined on profiles obtained by TLS with those obtained through standardized techniques (about 90% of correlation). Measurements performed with precision levels and laser profilometer have a correlation of 99% with TLS data; comparisons were made with data from three test areas, each with different roughness condition [60].

Moreover, due to the huge amount of information acquired, 3D point Cloud can be used for general road asset management: authors propose several application on low areas susceptible to drainage problems [61], or a semi-automatic procedures to reconstruct longitudinal grade and the cross-slopes of a taxiway starting from a DEM [61] and a method in order to identify and quantify the fault size at each joint of apron slabs from Terrestrial Laser Scanner data [62].

3. Results

The first step of the present review has been the classification of the common distress in term of impaction comfort and safety, in order to realize an effectiveness PMS. In order to correspond the information need, the most popular technological solution have been considered in order to classify them according to their appropriateness in capturing road pavement data. Figure 2 summaries the result of the review: each distress has been evaluated as "influent" (white block) or "not influent" (black block) on comfort and safety. Then, according to the geometric features of each distress, and according to the severity level, the appropriate technology for information acquisition has been evaluated, according to a symbolic scale where "-" means not adequate, "+" means adequate to the survey, "++" means totally adequate.

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	Fatigue cracking			Block cracking			Edge cracking			Longitudinal and transverse cracking			Joint reflection cracking			Slippage cracking			Bumps and sags		
Technology	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Camera		+	++		+	++			++		+	++			++			++	-	-	+
Line scan		++	++		++	++			++		++	++			++			++	-	-	+
Laser triangolation		++	++		++	++			++		++	++			++			++	-	+	++
Laser scanner		+	++		+	++			++		+	++			++			++	+	++	++

	Rutting			Corrugations			Depressions			Potholes			Swell			Lane / shoulder drop off			Shoving		
Technology	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Camera	-	-	+	-	-	-		-	+	+	++	++			+		-	+		+	++
Line scan	-	-	+	-	-	-		-	+	+	++	++			+		-	+		+	++
Laser triangolation	-	+	++	-	+	++		+	+	++	++	++			+		+	+		+	++
Laser scanner	+	++	++	+	++	++		++	++	++	++	++			++		+	++		+	++

	Bleeding			Polished aggregate			Raveling			Patching-utility cut patching			Railroad crossing *			Manhole		
Technology	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Camera	+	++	++	+	+	++	+	+	++			++	++	++	++	++	++	++
Line scan	+	++	++	+	++	++	+	++	++			++	++	++	++	++	++	++
Laser triangolation	+	++	++	+	++	++	+	++	++			++	++	++	++	++	++	++
Laser scanner	-	+	+	-	+	+	-	+	+			++	+	++	++	++	++	++

Figure2 Distresses – Technologies relation

The analysis summarized in Figure 3, shows that the cracking group (Fatigue cracking, Block cracking, Edge cracking, Longitudinal and transverse cracking, joint reflection cracking, and Slippage cracking) is easily recognizable by all technologies considered, excluding the low severity case. Visco-plastic deformation group (Bumps and sags, Rutting, Corrugation, Depressions, Potholes, Swell, Lane/shoulder drop off, and Showing) are perfectly detected by the Laser scanner, and good results are obtained using laser triangulation too because the required information is a difference in height. Surface Distresses (Bleeding, Polished Aggregate, and Raveling) detected by Camera, line scan, and Laser triangulation get good results, while the laser scanner is not performant. The Last group (Patching, Railroad crossing, and Manhole are easily detected by all the technological solution. This framework can address the survey design and planning starting from the information need for the PMS

5. Conclusions

A Pavement Management System should guide a Road agency in a proactive process, oriented in assuring safety and comfort to all the road users through the continues process of inspection, detection and mitigation of pavement conditions. This consideration highlights the importance of using specifics tool to identify the emerging pavement distresses, supported by the current pavement condition knowledge acquired by the technological solutions. A crucial point of the process is the identification of the alert level for each distress, and their effect of safety and comfort reduction for all the road user. Another important issue for a Road Agency is the choice of the proper equipment to employ for intensive road distress detection, depending on the project scope, the budget, the accuracy required.

The attempt of this paper review is drawing the boundary of this operative process focused on distress identification and technological overview aimed to obtain a proper information frame for the PMS implementation, based on information acquired by automated or semi-automated technologies. A note has to be made that the budget and the operational conditions are the most restrictive preconditions for the analysis in the process. In fact, the lack of the definition of a basic level of PMS, which implementation require a modest cost, has to be overcome, encouraging the implementing of low-cost technologies solution in the field of pavement distress detection.

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According to the evidence of the review, all the distresses play a role in the definition of a global condition index for the road pavement, but the ones affecting the adherence conditions and those which compromise the ride quality are essential to be detected for safety reasons. Moreover the knowledge of the current condition of the pavement is fundamental for the definition of an efficient PMS.

In this regard, the role of the technologies for the survey is essential in order to minimize the subjective factor o the traditional methods, and n order to improve the productivity and the repeatability. The considered technologies are different in performance and accuracy, moreover, they are specialized in acquiring some particular features of the alimentation, which can be good descriptive or not for a given distress. One of the issues preliminary to a PMS definition is to design the specifications of the survey.

Further researches should be addressed on the evaluation of accuracy and precision of the different type of devices, comparing them and analyzing the possibility of improvement due to image analysis technique on the final distress detection. In order to encourage the automation of the post processing , a definition of distress severity level in term of automated index could be very helpful.

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Appendix A

GROUP	DISTRESS	SEVERITY	LIMITS	TYPICAL DIMENSION	POSITION	INTERESSED LAYER
Cracking	**FATIGUE CRACKING** Interconnecting cracks	**LOW.** Fine, longitudinal hairline cracks with no, or only a few, interconnecting cracks. Not spalled	X <10 mm nonfilled	Poliedric shapes, max dimension 50 cm	Wheel path	Wearing course, Treated base
		MEDIUM. Network or pattern cracking are visible, slightly interconnected and spalled	10< X<75 mm nonfilled or X <75 mm with crack spalling < 10 mm			
		HIGH. Network or pattern cracks are well deined and spalled at the edges, whit some peaces theat may rock under the traffic.	X >75mm nonfilled or crack spalling >10 mm			
	BLOCK CRACKING Longitudinal and transverse cracking, intersecting orthogonally	**LOW.** Average Width w_a <=3 mm Few cracking, poorly deformed	X <10 mm nonfilled	Rectangular shape 0.3 x 0.3 m^2 a 3 x 3m^2	Extended areas	Wearing course
		MEDIUM. Cracks network	10< X<75 mm nonfilled or X <75 mm with crack spalling < 10 mm			
		HIGH. Regular Blocks	X >75mm nonfilled or crack spalling >10 mm			
	EDGE CRACKING Longitudinal cracking parallel to the outer edge	**LOW .** Low cracking with no breakup or raveling	\	Curve shape	Parallel to outer edge within 0.5 m	Wearing course
		MEDIUM. Medium cracking with breakup or raveling and limited loss of material	Loss of material X < 10% of the lenght of pavement			
		HIGH. Considerable cracking with breakup or raveling and limited loss of material	Loss of material X > 10% of the lenght of pavement			
	LONGITUDINAL AND TRANSVERSE CRACKING Parallel to centerline or laydown direction	**LOW .** Fine hairline cracks nonfilled	X < 10 mm		Long Cr: wheel path Trasv Cr: direction of laydown	Wearing course
		MEDIUM. Medium widht crack surrounded by light random cracking	10< X<75 mm nonfilled			
		HIGH. Any crack filled or not, surrounded by medium - high severity random cracking	X > 75mm			
	JOINT REFLECTION CRACKING Asphalt surfaced pavement	**LOW .** Nonfilled crac w< 10 mm, and sealed racks in good conditions.	X < 10 mm	Rectangular shape of the slab beneth	Slab joint	Wearing course
		MEDIUM Medium widht crack surrounded by light secondary cracking	10< **X**<75 mm nonfilled			
		HIGH. Considerable crack width and any crack filled or not, surrounded by medium - high severity secondary cracking, pavement severly-raveled broken	X > 75mm			
	SLIPPAGE CRACKING Half moon shaped cracks	**LOW** . Fine hairline cracks	X < 10 mm	Halfmoon shaped	Transverse to the direrction of travel	Wearing course
		MEDIUM. Medium crack or the area around the crack is moderately spalled or surrounded by secondary cracks.	10< X< 40 mm			
		HIGH. Considerable crack width anf the area around is borken into easily removed pieces	X > 40 mm			

Figure A1. Cracking Group

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GROUP	DISTRESS	SEVERITY	LIMITS	TYPICAL DIMENSION	POSITION	INTERESSED LAYER
Visco Plastic deformations	**BUMPS AND SAGS** localized upward/ downward displacements	**LOW, MEDIUM, HIGH** Lack of quality ride referred to comfort standard	**L**: bumps or sags cause low severity ride quality **M**: bumps or sags cause medium severity ride quality **H**: bumps or sags cause high severity ride quality	Localized, small displacements	All surface	Wearing course, Base and Subase
	RUTTING Surface depression in the wheel path	**LOW .** Light depth of the rut **MEDIUM.** Medium depth of the rut **HIGH.** High depth of the rut	6 <Y < 13 mm 13 < **Y**< 25 mm Y > 25 mm	Surface depression with lateral pavement uplift	Wheel path	Wearing course, Base and Subase
	CORRUGATIONS Closely spaced ridges and valleys occurring at regular intervals	**LOW, MEDIUM, HIGH** Lack of quality ride referred to comfort standard	Low severity ride quality Medium severity ride quality, ligh cracks and visible deformations High severity ride quality, considerable crack, high level deformation with	Closely spaced (3m)	Perpendicular to traffic direction	Wearing course, Base
	DEPRESSIONS Localized pavement area with elevation slighly lower than the surrounding pavement	**LOW** Low depth **MEDIUM** Medium depth **HIGH** High depth	13 < **Y**< 25 mm 25 < **Y**< 50 mm Y > 50 mm	/	Longitudinal direction	Wearing course, Base and Subase
	POTHOLES	**LOW, MEDIUM, HIGH** Referred to Max Depth and diameter of th potholes	**L, M, H** according to the table- levels of severity for potholes . See Tab A1	Shape and max diameter	All surface	Wearing course, Base and Subase
	SWELL upward bulge in the pavement's surface	**LOW, MEDIUM, HIGH** Lack of quality ride referred to comfort standard and presence of cracks	L: Swell causes low severity ride quality. M: Swell causes medium severity ride quality. H:Swell causes high severity ride quality.	Max longitudinal dimension 3m	Wheel path	Wearing course, Base and Subase
	LANE / SHOULDER DROP OFF difference in elevation between pavement edge and shoulder	**LOW, MEDIUM, HIGH** Referred to the difference in elevation between pavement and shoulder	**L:** 25 < **Y**< 50 mm **M:** 50 < **Y**< 100 mm **H:** Y > 100 mm	/	Close to the pavement edge	Wearing course
	SHOVING Permanent longitudinal displacement	**LOW, MEDIUM, HIGH** Lack of quality ride referred to comfort standard	L: Shove causes low severity ride quality. M: Shove causes medium severity ride quality. H: Shove causes high severity ride quality.	Short , abrupt wave in the pavement	Extended area	Wearing course, Base and Subase

Figure A2. Visco Plastic deformation Group

Table A1. Levels of severity for potholes

Maximum Depth of Pothole	Average Diameter (mm) (in.) 100 to 200 mm (4 to 8 in.)	200 to 450 mm (8 to 18 in.)	450 to 750 mm (18 to 30 in.)
13 to ≤25 mm (½ to 1 in.)	**L**	**L**	**M**
>25 and ≤50 mm (1 to 2 in.)	**L**	**M**	**H**
>50 mm (2 in.)	**M**	**M**	**H**

GROUP	DISTRESS	SEVERITY	LIMITS	TYPICAL DIMENSION	POSITION	INTERESSED LAYER
Surface defects	**BLEEDING** film of bituminous material on the surface that creates shiny, glasslike refelecting surface.	**LOW, MEDIUM, HIGH** related to the frequency in time	L: Very slight degree and is noticeable only during a few days of the year. M: Asphalt sticks to shoes and vehicles during only a few weeks of the year H. Extensively and considerable asphalt sticks to shoes and vehicles during at least several weeks of the year			Wearing course
	POLISHED AGGREGATE the surface of the aggregate become smooth	**LOW, MEDIUM, HIGH** quantity related	L: < 10% of the surface M: > 10 and < 25% of the surface H: > 25% of the surface	smooth surface	Wheel path	Wearing course
	RAVELING dislodging of the coarse aggregate particle	**LOW, MEDIUM, HIGH** quantity related	L. Only few initial area are interessed M. Considerable loss of coarse aggregate or clusters of missing coarse aggregate are present H: Surface is very rough and pitted, may be completely removed in places	Cluster or estenderd area	Wheel path	Wearing course

Figure A3. Surface defect Group

GROUP	DISTRESS	SEVERITY	LIMITS	TYPICAL DIMENSION	POSITION	INTERESSED LAYER
Others	**PATCHING-UTILITY CUT PATCHING**	**LOW, MEDIUM, HIGH** quantity related	L: < 10% of the surface M: > 10 and < 25% of the surface H: > 25% of the surface	more than 1 sqm	/	Wearing course
	RAILROAD CROSSING *	**LOW, MEDIUM, HIGH** Lack of quality ride referred to comfort standard	L. low severity ride quality. M. medium severity ride quality. H: high severity ride quality.		tracks area	Wearing course
	MANHOLE	**LOW, MEDIUM, HIGH** Lack of quality ride referred to comfort standard	L: R. causes low severity ride quality. M: R. causes medium severity ride quality. H: R. causes high severity ride quality.	more than 1 sqm		Wearing course

Note. * Poweredtwowheeler's safety is particulary affected by the presence of railroad crossing

Figure A4. Other Distresses

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