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# A review on automated pavement distress detection methods

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**Abstract:** In recent years, extensive research has been conducted on pavement distress detection. A large part of these studies applied automated methods to capture different distresses. In this paper, a literature review on the distresses and related detection methods are presented. This review also includes commercial solutions. Thereafter, a gap analysis is conducted which is concluded that in particular the distresses related to pavement micro-texture need serious additional research in order to be implemented in a cost-effective fashion. Depth-related distresses are detectible fairly well, but rely on expensive tools.

**Subjects: Intelligent & Automated Transport System Technology; Transportation Engineering; Pavement Engineering**

**Keywords: pavement distresses; automated detection methods; literature review; pavement management**

## 1. Introduction

In May 2016, the American Society of Civil Engineers (ASCE) has stated that the American infrastructure is deteriorating in a rapid phase and according to the prognosis, in the coming decade, the economy will lose almost four trillion dollars as a result (ASCE, 2016). This warning shows the importance of the concept called Infrastructure Management (IM) which answers to this question: how to

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## PUBLIC INTEREST STATEMENT

Just as every product, roads deteriorate over time. From loss of adhesion to actual holes and cracks, pavements decrease in quality as a result of usage and exposure to outdoor climate. Of course, these deteriorations can be found and registered manually, but not only is this very time-consuming, also the accuracy and method are dependent on the particular inspector. For several decades, automated detection methods were used to speed up the activity and standardise in quality. However, the diversity in methods is huge and vary highly in aspects such as accuracy, versality, labour-intensity and costs; in acquisition as well as operation. In order to automate this detection in an affordable way, different techniques have to be used in order to cover every aspect of road quality monitoring. A thorough review of automated detection methods with their ups and downs was lacking in literature, where this study covers that gap.

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maintain infrastructures to enhance their performance and prolong their life span with a limited budget? Hartmann and Dewulf (2009) describe IM as "activities and decisions that reduce the expenditures over the life-cycle of an infrastructure asset whilst extending the period for which the asset provides its required purpose, function and performance". An important share of the infrastructure consists of pavement, physically as well as financially. Pavement Management also falls within this scope i.e. maintaining the pavement in a desired condition whilst reducing costs in the long term is therefore the big challenge. A planning tool is the Pavement Management System (PMS), on which the management decisions are made based on long-term policies. The steps within this PMS are containing of road inventory, pavement inspection, assessment, prediction, analysis and finally the work planning (Shahin & Walther, 1990).

In order to make decisions about the pavement maintenance planning, the pavement condition has to be determined. This is possible in two ways: either manually or automatically. As manual pavement inspection is labour-intensive and dependent on the inspector, it is prone to subjectivity and high in labour costs. Latest developments in computer science offer more and more possibilities for automated detection and classification of pavement distresses. Therefore, automated distress and road condition measuring equipment is used to determine state of the road and detect distresses. After detection, automated data processing is used for classifying and reviewing.

Koch, Georgieva, Kasireddy, Akinci, and Fieguth (2015) conducted extensive studies on automated condition assessment, but aimed at the data processing part rather than data collection equipment. Mathavan, Kamal, and Rahman (2015), on the contrary, aimed their research at the collection techniques, but confined themselves to three-dimensional (3-D) techniques. This paper is therefore aimed at the entire pallet of detection instruments in relation to the distresses and road condition and goes mainly together with "pavement inspection". However, these instruments may also play a role in the "road inventory" and "condition assessment". The orientation of this research within IM is shown in Figure 1.

This review paper describes pavement distresses detected and measured automatically. Also, the pavement automated data collection devices are expressed herein along with pavement distresses these devices can capture. Finally, the recent achievements and limitations of pavement automated data collection are summarized. Based on a gap analysis the research challenges and fields of study which are open for future research are determined. A visualisation of the research methodology as applied in this study is presented in Figure 2.

**Figure 1. Automated pavement inspection.**

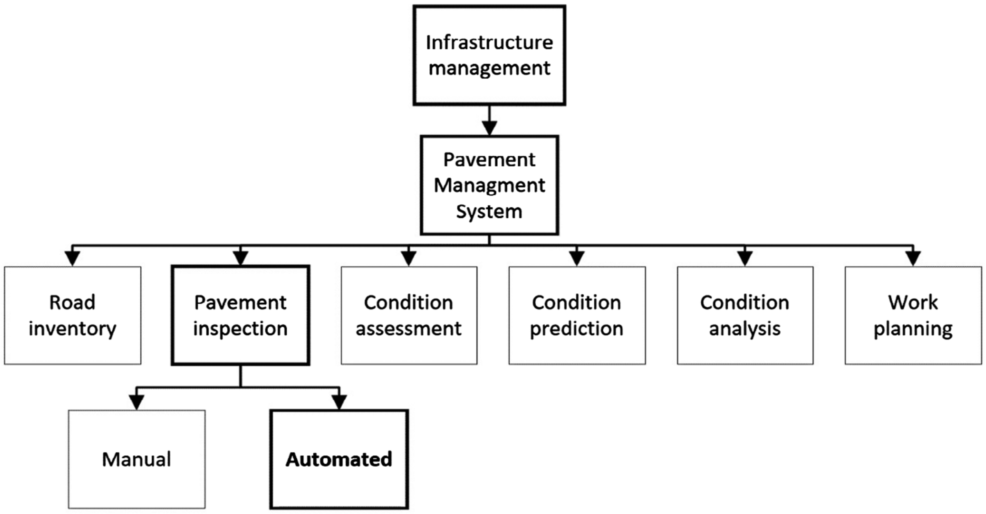
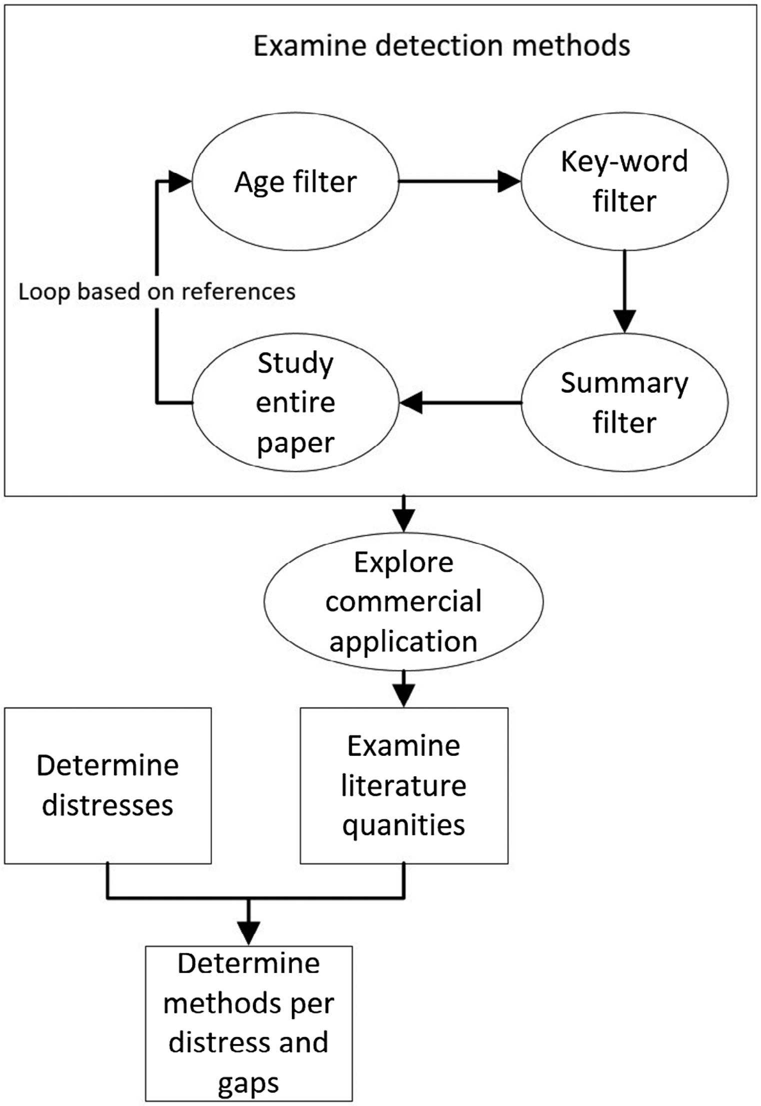


**Figure 2. Research methodology.**



## 2. State of practice is pavement distress detection

Pavement distresses are categorised in different ways by different researchers and organisations. One of the systematics that is used commonly, is the one developed by the US Department of Transportation and is discussed in the manual for the Long-Term Pavement Performance program (LTPP). In this paper, the LTPP report is used as a starting point (Miller & Bellinger, 2014). This systematics is chosen because of its international orientation and its integrity in distress classification. The classification in terms of distress severance is, however, not included, as this classification is relevant in the data processing part rather than the distress detection phase. For the sake of completeness, some more general pavement condition measures are distinguished in order to facilitate a broader pavement condition analysis instead of a mere distress analysis. The pavement distresses which have been automatically detected and measured by researchers are discussed below.

### *2.1. Cracking*

Pavement cracking is subdivided into fatigue cracking, block cracking, edge cracking, longitudinal cracking, reflection cracking at joints and transverse cracking. This categorisation of cracks becomes merely relevant when cracks are being classified. Since one crack in itself is not different in characteristics from another type, the detection methods do not differ, in contrast to the data processing part. Therefore, not a lot of attention is paid to this subdivision of crack classification in this paper, nor is it in the major bulk of available literature.

Cracking is subject to several research studies, and the predominant part of recent literature is aimed at the processing part of images in order to classify cracking. Particularly Cord and Chambon (2012) and Oliveira and Correia (2009, 2013) contributed largely to this matter. Furthermore, several studies were dedicated to crack detection and classification from imaging techniques (Gavilán et al., 2011; Li, Zou, Zhang, & Mao, 2011; Mancini, Malinverni, Frontoni, & Zingaretti, 2013; Mathavan, Rahman, & Kamal, 2015; Premachandra, Premachandra, Parape, & Kawanaka, 2015; Yoo & Kim, 2016; Zou, Cao, Li, Mao, & Wang, 2012). The amount of cracking literature that is relevant to this research, however, is significantly smaller, but notwithstanding detailed and colourful; for instance the use of ground penetrating radar (GPR) and infrared (Kamal et al., 2016; Solla, Lagüela, González-Jorge, & Arias, 2014). Nonetheless, these techniques are mostly aimed at not only finding cracks, but amongst others potholes, rutting and patches (Huidrom, Das, & Sud, 2013; Mathavan, Kamal, et al., 2015; Moghadas Nejad & Zakeri, 2011; Uddin, 2014).

### *2.2. Patching and potholes*

Patch deterioration occurs when a portion of the pavement surface greater than or equal to 0.1 m² is removed and replaced or additional material is applied to the pavement after original construction. When larger pieces of asphalt deteriorate, patches are often used as a repair method. Proper patches are (almost) of a similar quality as the original pavement, but when patches deteriorate, it heavily influences driving comfort and could eventually become dangerous. This deterioration brings along cracks and loss of material in the edges which could lead to potholes. Potholes are bowl-shaped holes of various sizes in the pavement surface and the minimum plan of a pothole dimension is 150 mm.

These two distresses are not uncommonly researched together because of their mutual types of characteristics. Just as in crack detection, imaging-related techniques exist in abundance (Jo & Ryu, 2015; Kim & Ryu, 2014a, 2014b; Koch & Brilakis, 2011; Koch, Jog, & Brilakis, 2012; Ryu, Kim, & Kim, 2015). Those image techniques are comparable with the patch and crack detection techniques as for example discussed by Radopoulou and Brilakis (2015) and Hadjidemetriou, Christodoulou, and Vela (2016). However, potholes are also often discussed individually, using different techniques. In contrast to patches, potholes have a significant vertical drop of the surface, which enables it to be recognized on height differences, as is thoroughly researched (Casas-avellaneda & López-parra, 2016; He, Wang, Qiu, Zhang, & Xie, 2011; Joubert, Tyatyantsi, Mphahlehle, & Manchidi, 2011; Kamal et al., 2016; Kim & Ryu, 2014a; Yu & Salari, 2011). It is generally divided into vibration-based and laser-based techniques, also complementing each other. Though, commercial methods show some exceptions by using for instance sonar techniques.

### *2.3. Surface deformation*

The category of surface deformation consists of rutting and shoving as these involve horizontal and vertical displacements of the top layer. A longitudinal surface depression in the wheel path is called rutting. It may have associated transverse displacement. Shoving is a longitudinal displacement of a localised area of the pavement surface. Traffic can cause the asphalt to slide, which causes a heap on one side and often a prolapse on the other, resulting in an uneven pavement.

There is significantly less research on these distresses than there is on the previous three mentioned distresses. However, several studies are available in which these destresses are only mentioned and come often with techniques that are based on three-dimensional surface analysis, including laser, radar and other 3-D imaging methods (Huang, Hempel, & Copenhaver, 2011; Li, Yao, Yao, & Xu, 2009; Mathavan, Kamal, et al., 2015). However, rutting is in contrast to shoving also studied as an individual subject, but the methods used are similar to the ones explained in the multiple-distress studies (Rajab, 2013).

### *2.4. Surface defects*

The surface defects, where the structure of the top layer itself is damaged, encompass fall bleeding, polished aggregate and ravelling. Bleeding occurs when excess bituminous binder is on the pavement surface; usually found in the wheel paths. In case of polished aggregate, the surface binder is worn away to expose coarse aggregate. The asphalt top layer is worn away and a smooth surface occurs. Wearing away of the pavement surface caused by the dislodging of aggregate particles and loss of asphalt binder is called ravelling.

Finding useful literature on these distresses has turned out to be a difficult task, which indicates that not many investigations have been conducted on the subject. Furthermore, the detection techniques described in the scarce document are often in a more exploratory state, rather than used in practice. Examples are given by Mathavan, Rahman, Stonecliffe-Jones, and Kamal (2014) and Karaşahin, Saltan, and Çetin (2014). In multiple-distress studies, especially ravelling is regularly mentioned, but most techniques are comprehensive and 3-D methods that are laser-based and therefore expensive in acquisition. Furthermore, techniques are often non-dynamical and therefore difficult to implement in motorway speeds.

### *2.5. Miscellaneous distresses*

There are three distresses left which are not categorizable in one of the aforementioned distresses. These are lane-to-shoulder drop-off and water bleeding and pumping. The lane-to-shoulder drop-off is the difference in elevation between the travelled surface and the outside shoulder and is therefore often referred to as edge drop-off. Seeping or ejection of water from beneath the pavement through cracks is called water bleeding or pumping. An important remark is that bleeding and pumping never stands on its own, but that it is a consequence of severe occurrences of other distresses such as cracks and potholes. These distresses are not extensively researched individually. They are, however, sometimes mentioned in multiple-distress papers, but even those studies are hardly found. In the discussion, these distresses will be thoroughly discussed.

### *2.6. Pavement quality characteristics*

Although the following characteristics are not distresses, their examination can represent the state of the pavement as a whole and deserve – as they are not extracted from the LTTP report – some additional attention. It is therefore aimed at the macro state of the road rather than individual distresses, but indicates presence of single distresses. The first one is the pavement roughness, often quantified by the International Roughness Index (IRI). Sayers and Karamihas (1998) describe the IRI as "the roughness qualities that impact vehicle response, and is most appropriate when a roughness measure is desired that relates to: overall vehicle operating cost, overall ride quality, dynamic wheel loads (that is, damage to the road from heavy trucks and braking and cornering safety limits available to passenger cars), and overall surface condition".

The second largely comparable indexation with a slightly different aim is the skid resistance which is the force developed when a tire that is prevented from rotating slides along the pavement surface (Mahone & Runkle, 1972). This measure incorporates slip and differs from roughness in the way that it is aimed at the grip of the top layer of the road rather than the texture of the top layer as a whole. It is therefore a useful indicator of occurrence of bleeding, ravelling and polished aggregate, but is aimed on the macro-texture of the road.

Thirdly, the substructure of the pavement represents the layers beneath the top layer and incorporates the base layers and foundation of the road. Assessment is about thickness of the layers, air holes, lamination, materials used and quality of the materials. Although this information is not directly relevant to road safety and driving comfort, it expresses the quality of the road as a whole and may therefore be of interest to base infrastructure maintenance decisions and PMS policies on.

Fourth, the "other" group has been analysed which incorporates the surroundings of the road, including ditches, abutting buildings, road signs, weather conditions and other contextual information.

Naturally, this study is not aimed at these factors, but as a significant part of the most commercial solutions incorporate one of these features, they are mentioned in the distress detection method analysis as far as the focus of the source was at detection of pavement distresses. It is moreover useful for a broader PMS approach.

### *2.7. State of practice*

For all types of distresses as classified above, ways of detection are presented in literature; be individual as well as amongst other distresses. A scheme is provided in Table 1 in which the type of detection method is linked to the type of distress. The first thing that stands out is that with 3-D sensors all distresses can be detected. This, however, is a logical consequence, as every distress has a deviation in depth. This may be on a macrotexture level on one hand such as potholes, and on microtexture level such as bleeding on the other. The scheme is based on an extensive literature study on the different detection methods. The mere linkages are shown, but the detection methods are described in depth later. The table will be discussed more thoroughly after elaborating the different detection methods. The scheme distinguishes scientific detection methods, which are often researched in a technical way, but not (yet) implemented in practice on one hand and methods in practice which are used in commercial initiatives. Those methods in commercial vehicles are not mentioned in the previous paragraphs which confines it to the scientific papers, because nearly all commercial techniques are aimed at multiple distresses and integrity. However, these are just as important and are therefore discussed as follows. In general, the latter contains of often more obvious ways, whilst the first group includes more progressive techniques.

## 3. Automated devices in distress detection

For determining the pavement condition, location and severances of distresses, an integral solution by means of a single inspection vehicle is sought, consisting of different detection and measuring methods and supporting equipment. More than a decade ago, this has also been discussed by Bennett, De Solminihac, and Chamorro (2006), but since then the technology has not stood still. Apart from detection equipment, data should also be collected, synchronised and analysed, which calls for additional equipment such as global positioning system (GPS), frame grabber, data storage and DMI (Zhang, Qiu, Shamsabadi, Birken, & Schirner, 2014). Because these tools do not have any relation with the particular distresses, the paper elaborates merely on detection equipment rather than the entire configuration of the vehicle.

**Table 1. Relation between distresses and detection equipment**

| | Camera | Accelerometer | 3-D sensor | Microphone | Sonar | Pressure | Friction | Deflectometer |
|---|---|---|---|---|---|---|---|---|
| Cracking | C/P | | C/P | | | | | |
| Patching | C/P | | C | | | | | |
| Potholes | C/P | C/P | C/P | P | P | C/P | | |
| Rutting | P | | C/P | | C | | | |
| Shoving | C | P | C/P | | | P | | |
| Bleeding | P | | C/P | | | | | |
| Polished aggregate | | | P | C/P | | | | |
| Ravelling | | | C/P | C | | | | |
| Edge drop-off | | | C | | C | | | |
| Water bleeding and pumping | | | C | C | | | | |
| *Additional road information* | | | | | | | | |
| IRI | C | C/P | C/P | C/P | | C/P | C | |
| Skid resistance | | | C | | | | C | |
| Substructure | | | C/P | | | | | C |
| Other | C | C | C/P | P | C | | | C |

Notes: C = commercial development; P = from scientific research papers.

### *3.1. Cameras*

#### *3.1.1. Single camera*

Regular single cameras are used commonly for detecting different distresses on the basis of two-dimensional (2-D) images. These cameras come in different types. One of the most applicable equipment is the single-mounted, high-speed charge-coupled device (CCD) camera for a 2-D result, which is used for more than 20 years for distress detection and in particular crack and pothole detection (Li et al., 2011; Mancini et al., 2013; Moghadas Nejad & Zakeri, 2011; Premachandra et al., 2015; Puan, Mustaffar, & Ling, 2007; Wang, Birken, & Shamsabadi, 2015; Yoo & Kim, 2016). A newer type, but with the same application, although mostly applied when lower resolution is sufficient and sensor speed is an important criterion, is the metal-oxide-semiconductor (CMOS) sensor for constructing integrated circuits such as image sensors (Joubert et al., 2011; Ryu et al., 2015). These in digital imaging commonly used cameras have several advantages, such as the reasonable price, easy-to-use output, accessibility and high maturity of the technique. In most recent years, the CMOS sensors seem to become prevalent, as their disadvantages such as low resolution have largely been overcome (Waltham, 2010). Extremely high-resolution cameras are also used for the evaluation of microstructure for the detection of for example bleeding under a strictly controlled environment in terms of illumination (Karaşahin et al., 2014). However, appliance in high-speed vehicles does nowadays not seem within reach due to technical and cost-related implications.

To clearly visualise the cracks and exclude unwanted shadows and other light noise, very strong illumination is used in most cases on the pavement. Mathavan, Rahman, et al. (2015) applied, in the contrary, a cheap Sony Cybershot DSC-W180 without additional illumination, but a complex self-learning algorithm compensates for this simple data collection technique. This off-the-shelf camera is available for less than 80 lb.

In a similar way, this was studied by Cord and Chambon (2012) and Oliveira and Correia (2013), whose research was aimed at the image processing part rather than the data collection part. Consequently, in their publications no clear information about the type of camera was given. Mertz et al. (2015) utilized built-in smartphone cameras for the image collection, which had some clear limitations regarding the lens quality. Also the built-in RGB CMOS camera in the Kinect was used for gathering images, but this device is discussed more in-depth later on in this paper.

Almost all commercial inspection vehicles are equipped with a camera, but mostly not for detecting the cracks, as cracks are detected by for example line-scan cameras. Scanning the environment and support of the other equipment is herein the main purpose for the more integral PMS approach. These vehicles are not only designed for distress detection, but to collect data required in asset management as a whole and detect for example traffic signs, noise barriers and weather condition for which the other equipment can be corrected and validated to and are often installed to capture a 360° view such as with the off-the-shelf LadyBug system, which captures a 360° dome-view by making use of six cameras in one system.

#### *3.1.2. Video camera*

Huidrom et al. (2013) proposed to collect data with video cameras from which images were extracted. In this respect, the application was comparable to the area-scan and line-scan cameras. These are to be used for identification of patches, among cracks and potholes, as these three types of distresses have clear 2-D characteristics. Prasanna, Dana, Gucunski, and Basily (2012) conducted video imaging for identifying cracks. A comparable method was developed by Radopoulou and Brilakis (2015) who used the video images from already installed parking cameras on passenger cars. Also, potholes detection on the basis of video cameras has been researched (Koch & Brilakis, 2011). Just as the patch detection as described before, rear view parking cameras integrated in modern passenger cars are used for data collection. A fish-eye lens is installed in order to widen the angle of view of the camera. Dash cameras (also called black-box cameras) were studied by Hadjidemetriou et al. (2016) for detecting patches, as high resolution is not a prerequisite. The same types of cameras were used by Jo and Ryu (2015) for the detection of potholes and by Varadharajan, Jose, Sharma, Wander, and Mertz (2014) for a broader range of road inspection. Rajab (2013) has proposed usage of video cameras in order to detect rutting, but the accuracy and reliability remain vague and therefore additional research is required.

### *3.1.3. Line-scan camera*

The regular area-scan cameras as described before have some disadvantages in output, such as relative difference caused by the angle and difficulties in illumination, which are covered by using a line-scan camera, as schematised in Figure 3 (Zalama, Gómez-Garcìa-Bermejo, Medina, & Llamas, 2014). In the study of Gavilán et al. (2011) two line-scan cameras were used with a resolution of 2000 × 1 pixel, covering a pavement width of 4000 × 1 mm. A high frame rate such as 28 kHz allows the vehicle to drive up to 90 km/h. Quintana, Torres, and Menendez (2015) employed the same resolution, but a lower frame rate, possibly for financial reasons. The cracks are in the latter case illuminated with 20.000 lumens to overcome shadows and noise from sunlight, but due to the shape of the output, equally spread illumination is far easier than with the use of area-scan cameras and centred laser illumination can be used. Another example is the AMAC vehicle that uses the line-scan technique in combination with laser illumination, as discussed by Nguyen, Avila, and Bardet (2012).

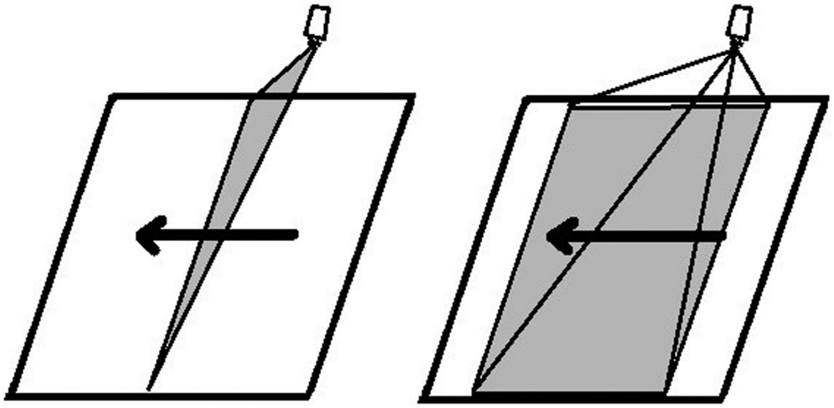
Furthermore, the commercial Laser Road Imaging System (LRIS) is utilized in this context which combines the linear camera with laser illumination for a clear crack visibility. This commercially available system is also regularly applied in practice, for example by ERI and International Cybernetics. Line-scanning also may be executed without the illumination, but this significantly increases the challenges in the image processing phase, equally to area-scan imaging. This line-scan method is only employed for pavement distresses that are visual without depth as used by for example NEXCO and International Cybernetics and are therefore perfectly suited for detection of cracks, patches and potholes.

### *3.1.4. Infrared camera*

Although the following approach is almost untouched, some companies can be found that make use of other bandwidths than the ones visible to the human eye. BridgeGuard for example uses the infrared spectrum for recognising cracks, patches and delamination, as these distresses cause the temperature to differ locally in the pavement which will be visible in the IR spectrum. Also, in the field of tunnel inspection, this technique can be found; mostly in relation to concrete structures. The main advantage of using the infrared spectrum is the easy recognition of delamination, which occurs mainly at bridge decks, which is therefore the priority of this BridGeguard.

Furthermore, Solla, Lagüela et al. discussed the combination of both GPR (later discussed in this paper) and thermal imaging (infrared) to obtain surface and subsurface information and detection of cracking in asphalt pavements (Solla et al., 2014). Infrared thermography has been proved to be

**Figure 3. Area scan vs. line-scan camera.**



an adequate technique for crack detection due to the temperature change occurring between the cracks and the rest of the asphalt surface. Combining both techniques in the inspection and characterisation of cracks in asphalt shows to be useful, given that the two of them together allow the estimation of the depth of the crack, the detection of presence of filling material and the preliminary identification of the origins and severity of the crack. Even further, Miah et al. (2015) combined the infrared technique with GPR, cameras and ultrasound for a complete distress detection system. The infrared camera images were then fused with the normal HD camera images in order to easily detect cracks, potholes and even rutting.

#### *3.1.5. Stereo imaging*

A way of creating a 3-D pavement visualisation by using only commercially available cameras is by stereo imaging. By using two (and preferably more) cameras, a three-axis image can be constructed from the different images from different angles (Mathavan, Kamal, et al., 2015). This method lacks in accuracy and requires a lot of calculation power, but the used equipment is cheap in acquisition. Although some applications – mainly scientific – are mentioned, industrial systems have been barely deployed because of its inaccuracy and need of significant calculation power. In recent years, Lei, Wang, Zeng, Wang, and Wu (2014) have researched the possibility of analysing the pavement surface micro-texture with this method, but the dynamical possibilities seem limited.

#### *3.1.6. Focus and defocus*

Another way of using mere cameras has been employed By applying a single camera vary in focus depth, a circle of confusion is created from which the actual depth can be calculated (Mathavan, Kamal, et al., 2015). It is, however, difficult to implement this method in a dynamic system. A solution is depth from defocus which needs much less images for the construction of a 3-D image and for example three cameras with different depths of focus may be enough for an accurate 3-D reconstruction. In the field of civil engineering, these methods have not been commercially used yet. However, these techniques may be a future solution in inexpensive 3-D reconstructions of road surfaces.

#### *3.1.7. Photometric stereo*

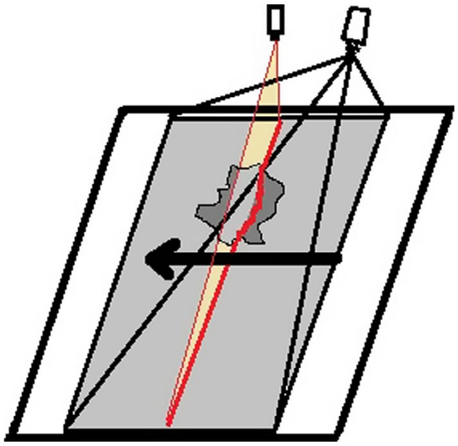
The final technique using merely cameras and artificial illumination is photometric stereo in which at least three light sources from different angles with preferably different colours illuminate the scene in turns. However, the set-up has to be static with respect to the scene which makes it difficult to be used under high speeds (Kamal et al., 2016). In the field of infrastructural management, this technique has not been commercially implemented, and due to its static implications, the applications for 3-D reconstruction of road surfaces in a dynamic system are limited. However, Lei et al. (2014) proposed this method to determine the surface texture from which ravelling, bleeding and polished aggregate can be derived, but this is nowhere implemented in commercial use yet and needs serious research before it can be implemented, due to its lack in dynamical possibilities.

### ***3.2. Laser***

Several distresses only manifest in terms of height differences. 3-D sensors are the solution to detect these distresses they sense in $x$, $y$ and $z$ dimensions. These 3-D sensors include several completely different techniques among which laser profilers are the most common. Furthermore, several 3-D sensors offer an integral detection approach by using depth measurements in combination with imaging.

One of the most used techniques for creating 3-D reconstructions is laser scanning in which a laser line is projected on the near-flat pavement and the camera detects under an angle the shape of the line which reflects the depth of the surface (Figure 4). This detecting system consists of a laser or a LED linear light as an auxiliary light which projects a ray on the road surface. Two CCD cameras are used to create a triangular system to which three dimensions can be extracted through an LED or laser projection (He et al., 2011; Huang et al., 2011; Li et al., 2009, 2011; Mathavan, Kamal, et al., 2015; Nguyen et al., 2012; Nguyen, Begot, Duculty, & Avila, 2011; Vilaa, Fonseca, Pinho, & Freitas, 2010; Yu & Salari, 2011).

**Figure 4. Schematisation of the laser scan principle.**



A big disadvantage is the high cost of this equipment, but the results in practice are pristine. In commercial use, this system is amongst others used by ARAN, ARRB Hawkeye, Dynatest, Pathway Services Inc., ROMDAS, AID, PaveTesting, ERI, Pavision, PaveVision3D Ultra, HSP, Qualitas and SSI. An additional advantage of this system is that because of the transverse profiling of the entire road, when using a sufficiently high projection frequency, apart from rutting and shoving also potholes, lane-to-shoulder drop-off and wide cracks can be detected and categorised, which is applied by for example Roadscanners' Road Doctor and was discussed by Tsai and Li (2012). This principle is optimised in the laser crack measurement system (LCMS). Mathavan et al. (2014) proposed to use this LCMS in combination with high-resolution 2D imaging for the detection of ravelling.

The abovementioned technique provides a transversal profile, but for several distresses, such as the micro-structure related ones and IRI, the longitudinal profile is much more useful. Commercially, by far the most used technique for determining micro-structure, roughness and surface distresses is the longitudinal laser profiler, for example used by ARRB Hawkeye, Dynatest, Pathway Services Inc., AID, PaveTesting, ERI, Pavision, PaveVision3D Ultra, HSP, Qualitas, LIMAB RoadRun, SSI and International Cybernetics. The profilers are usually installed above each wheel path as the surface defects mostly occur on those places due to the traffic load and are therefore a more detailed and complete version of accelerometer in application. Often, those results are validated by for example accelerometers as will be discussed later.

Comparable with laser scanning systems are structured light systems in which the camera detects a projection and makes use of triangulation. By using the structure light system, however, the projection is a pattern which is detected by a stereo pair of cameras. For example, Kertész, Lovas, and Barsi (2008) applied 20 individual laser projections and can apart from the in previously discussed distresses determine the IRI and ravelling and is therefore a more detailed version of the laser scanning method (Mathavan, Kamal, et al., 2015). However, due to its complexity and costs, this method is hitherto not used in practice.

### *3.3. Accelerometer and other vibration-based methods*

Distresses that cause a vertical difference in pavement texture cause a decrease in driving comfort by increasing vibration. This vibration can be measured in changes in tire sound, tire pressure and vibration of the tire, the axle and the car as a whole. Accelerometers, tire pressure sensors and microphones are used for identifying those occurrences, but herein the first and most common one is discussed.

Accelerometers measure the relative movement of the car in three dimensions. As potholes often are a result of heavy traffic loads, they do not uncommonly occur in the wheel paths of the pavement, which is also the case for shoving. These distresses will then be felt as a shock which could be measured by accelerometers. Casas-avellaneda and López-parra (2016) and Buttlar and Islam (2014) proposed the usage of modern smartphones integrated accelerometers in combination with the built-in GPS, compass, and data storage and export ability in order to detect potholes. Also a smartphone application was developed by Roadroid (2013) making use of these smartphone capabilities and processes in real-time. The accuracy, however, was not very high and only potholes on the wheel paths were detected, whilst motor cycles often drive in the middle of the road for which potholes are even more dangerous. Therefore, this built-in smartphone method is in practice merely used as a complementary and validating tool and is only appropriate for the inspection on network level. It is, also, not uncommonly employed supplementary on laser technologies.

More accurate, but still limited systems are accelerometers installed in the wheels, axle, in the car or within equipment such as laser profilers. These built-in systems are used in almost all commercial systems, such as ARRB Hawkeye, ROMDAS, Pathway Services Inc., ARAN, Dynatest, PaveTesting, Pavision, Roadscanners, the SSI and International Cybernetics. Those companies deploy it as a support tool for calculating for example the IRI. However, these commercial systems use these accelerometers merely as a complementary tool for validation and verification of for example laser profilers. Chiculita and Frangu (2015) have researched an inexpensive though reliable way for an accelerometer setup. A different approach to this same problem was discussed by Du, Liu, Wu, and Li (2016). Apart from this IRI, which is based on a quarter-car model, Katicha, El Khoury, and Flintsch (2016) have proposed a probe vehicle model in which the probe vehicle roughness index (PVRI; four wheel-based IRI) was calculated. Due to its four-wheel measurement, the accuracy of the estimation of road roughness was increased in this method.

### 3.4. Acoustic

Moreover, vibrations on a micro scale have an effect on tire noise, tire pressure variance, tire deformation and vibration of the tires. Apart from major differences in height such as bumps and potholes as discussed by Mednis, Strazdins, Liepins, Gordjusins, and Selavo (2010), defects such as ravelling, bleeding and polished aggregate can be detected on the basis of microphones near the wheel, under the car, as proposed by Zhang, Mcdaniel, and Wang (2013) and Wang et al. (2015) and even alongside the road as demonstrated by Kongrattanaprasert, Nomura, Kamakura, and Ueda (2010), who employed it to measure road condition in terms of wetness. This phonetic wetness detection was also studied by Abdi et al. (2015) by installing a microphone near the wheel. These techniques lack in accuracy in relation to distresses, but can be a valuable addition to validate and support other equipment, determine contextual conditions and to determine regions of interest (ROIs) of for example potholes. These techniques are largely aimed at network level surveys as the IRI can be determined by proper use of this equipment. In commercial use, this technique is applied by for example VOTERS, but most of the commercial alternatives give preference to the more detailed, but also more expensive laser technology or limit themselves to the use of cheap accelerometers for detecting for instance potholes.

### 3.5. Pressure sensor

Comparable with accelerometers, the tire-pressure reacts on the wheel encountering a bump or hole. With accurate pressure sensors, potholes can be detected (Wang et al., 2015). Due to the lack in accuracy, classification of potholes is nearly impossible and this method should, just as accelerometers, only be used as a complementary tool, as used for example by VOTERS. Erdogan, Alexander, and Rajamani (2011) applied piezoelectric sensors to determine changes is the shape of the tire as a result of pavement distresses from which the same conclusions can be drawn similar to pressure tools.

### 3.6. Radar

Another way to measure depth and create in this way a 3-D image is radar which comes in different manner. In the first variant, radar technology uses radio waves to determine range and angle of objects and makes use of short electromagnetic impulses. By using different frequencies, the structure of the road surface, the micro-structure of the road, the material of the road and even the sub-structure of the road can be determined through ground penetrating radar (GPR) (Busuioc et al., 2011). This technique is becoming more and more common in distress detection and is for example used by Pathway Services Inc., VOTERS, AID, ERI, Roadscanners, SITECO and International Cybernetics for determining the IRI. ERI applies the technique also for determining polished aggregate, and the transversal road structure.

Furthermore, GPR was employed for determining cracking and seemed to be the most effective and efficient by using a high frequency such as 5 GHz or more. Ahmad, Wistuba, and Lorenzl (2012) for example studied a method to detect cracking on the basis of 2 GHz GPR. Results of the GPR can be combined with for example camera images, to create a 3-D profile of the pavement. In combination with infrared imagery, this is implemented in GS Infrastructure's BrigdeGuard as discussed before. Plati, Georgouli, and Loizos (2012) claimed based on their review of GPR applications that even rutting can be detected. Reference data, however, is required to compare difference in layer thickness over time. Benedetto, Tosti, Bianchini Ciampoli, and D'Amico (2016) excellently discussed the differences in application and available GPR processing techniques and confirmed the techniques as described in this paragraph and added the use of inference of strength and deformation.

The second radar variant is the LiDAR. The Flash LADAR, in short LiDAR, makes use of the time-of-flight (TOF) method, for example used by ARRB Hawkeye. LADAR makes use of the distance of a given point by the time it takes for a short pulse to reflect. Due to the immense speed of light, this equipment is very sensitive (Mathavan, Kamal, et al., 2015). LiDAR creates a point cloud image for a whole scene and is therefore a relatively expensive tool which limits the amount of users practice. This method, however, is perfectly suited when not only the road has to be analysed, but a more complete infrastructure management program is envisioned, including for example analysis of the state of noise barriers, traffic signs and crash barriers as used by International Cybernetics (Landa & Prochazka, 2014). However, some, such as SITECO, use this system to analyse also the state of the road, but due to the relatively low resolution, most applications are merely focused macro-failures such as rutting, potholes and edge drop-off. Yu, Li, Guan, and Wang (2014) moreover showed a way to use the LiDAR system for crack detection.

The second generation (V2) Microsoft Kinect is also based on the TOF principle and is due to the publication of several research studies in this field worth mentioning. Actually, Pagliari & Pinto declared that the Kinect V2 is a phase measurement, which makes it not completely correct to define it as a time-of-flight sensor (Pagliari & Pinto, 2015). Since its launch, the Microsoft Kinect, a tool for 3-D visualisation by combining an IR sensor with camera, has due to its low costs been investigated for different purposes than gaming where it was developed for. The Microsoft Kinect, designed for the Xbox gaming console, combines infrared depth measuring with RGB image collecting in order to create a 3-D image, which is appropriate for collecting pothole data (Becerik-Gerber, Masri, & Jahanshahi, 2015; Kamal et al., 2016; Mahmoudzadeh, Firoozi Yeganeh, & Golroo, 2015; Moazzam, Kamal, Mathavan, Usman, & Rahman, 2013). With a frequency of 30 Hz, data of the road surface is collected in order to detect potholes. As 30 Hz restricts the driving speed, Joubert et al. (2011) have used an additional high-speed CCD camera in order to compensate for achieving a higher driving speed. The Kinect V2, developed for Xbox One, however, has a higher resolution, as well as a higher frequency which increases its possibilities; moreover because of its ability to use of the TOF principle it tends to be suitable for road and asset inspection.

### *3.7. Ultrasonic*

In order to find potholes, an ultrasonic sensor was used by Madli, Hebbar, Pattar, and Golla (2015). Although this technique measured depth, the x and y coordinates were not measured in an accurate way. Therefore, sonar was discussed apart. The HC-SR04 is applied to measure the elevation and as potholes are deeper than the rest of the pavement surface, the sensor finds the potholes. The accuracy of this system is however limited and the distance to which it is useful is also small. The ROMDAS utilizes this system, furthermore, for profiling of the road and combines the cheap ultrasonic sensor with the much more expensive laser profilers which its quantity of use can be reduced in this way. AID, furthermore, uses it for surface deformation detection, but the accuracy is limited. The application of ultrasonic techniques is therefore most suitable when employed in high quantities in a row and is, although not used often, promising for future implementation.

### *3.8. Deflectometers*

Not completely compatible with an integral vehicle, but worth mentioning are deflectometers. Deflectometers analyse, different than road distresses, multiple layers of the pavement in order to find voids, materials used, and depth dimensions by measuring the impact of a load on the pavement. It is presented in two ways. The first is the static method i.e., Falling Weight Deflectometer (FWD) as presented by AID, International Cybernetics and ERI and the second is the dynamic Rolling Weight Deflectometer (RWD) as presented by Pavision, which requires heavy and very expensive equipment. However, the speed is, even with the dynamical type, limited, but the asphalt quality and layer composition can be monitored accurate enough. This kind of equipment is solely aimed at pavement layer assessment and is not the main scope of this paper. For a more detailed view on this issue, Rehman, Ibrahim, Memon, and Jameel (2016) have recently published a complete review on non-destructive assessment of bridge decks, which offers also a good insight in the possibilities for pavement assessment.

### *3.9. Friction tester*

Finally, the two main ways of determining the skid resistance are the tire traction tester and the angled wheel. The first one uses a two-wheeled trailer, which is equipped with a parallelogram suspension, coil springs with air shocks and disc brakes, on a wetted surface. A spindle mounted two-axis transducer measures the horizontal forces and is used by for example Dynatest. The latter, similarly applied on a wetted surface, uses an extra wheel which is placed under a horizontal angle from which the horizontal forces are calculated from which the slip and skid resistance can be deduced, for example used by Dynatest, Pathway Services Inc. and SCRIM. A major disadvantage of these methods, however, is the fact that significant water storage has to be integrated in the system, which makes it less suitable for implementing in a common inspection vehicle. Furthermore, Singh and Taheri (2014) have proposed a method for friction estimation by making use of standard in-car sensors. For a similar purpose, on-board determination of the friction is determined by the vehicle jerk by using standard car equipment. Although these research studies have aimed at increasing driving safety, their outcome can be used for validation of friction. Just as in the case of the deflectometers, the integrational possibilities with the other tools are low, but the equipment could help analysing the state of the pavement in an accurate fashion.

## 4. Achievements and challenges

### *4.1. Quantitative analysis*

The relations between detection methods and distresses were presented in Table 1. In some cases many studies have been conducted on detection methods, whilst others are hardly mentioned. This makes some detection methods more complete, reliable and matures than others. To obtain a clearer view of this issue, the amount of literature per distress is estimated by means of entering certain key words in different combinations in scientific search engine Scopus. Those results are presented in Table 2.

Cracks, potholes, substructure and general state of the road in terms of roughness are according to the table thoroughly researched, whilst distresses that are more difficult to quantify in terms of severity, such as bleeding, pumping and edge drop-off, are sometimes barely touched. To avoid misinterpretation, it has to be noted that in some literature sources used in this research, different distresses are named, but the focus is not on one single distress. These papers are not included in this count. Also, a significant part of the papers are merely aimed at improving the detection tools in general rather than aiming at a specific distress. These are neither included in this list, as the distress is the main search criterion. Therefore, there might be more information about certain distresses than mentioned in the table.

**Table 2. Amount of literature per type of distress**

| | **Estimated No. papers** | **Keywords (used in different combinations)** |
|---|---|---|
| Cracks | 40 | Pavement, road, crack, cracks, cracking, asphalt, detection, monitoring, tools, imaging, 3D, spalling |
| Patching | 6 | Patch, patching, deterioration, detection, monitoring, asphalt, pavement, imaging, camera |
| Potholes | 20 | Pavement, road, pothole, potholes, asphalt, detection, monitoring, tools, 3D, camera, accelerometer |
| Rutting | 10 | Pavement, rutting, rut, road, asphalt, detection, monitoring, tools, profiler, laser, 3D, images |
| Shoving | 5 | Pavement, shoving, road, asphalt, detection, monitoring, tools, profiler, 3D, depth |
| Bleeding | 3 | Pavement, rutting, bleeding, seal coat, road, asphalt, detection, monitoring, tools, imaging |
| Polished aggregate | 1 | Pavement, polished aggregate, road, asphalt, detection, monitoring, tools |
| Ravelling | 4 | Pavement, ravelling, road, asphalt, detection, monitoring, tools, micro-texture, profiling |
| Lane-to shoulder drop-off | 0 | Pavement, drop-off, lane-to-shoulder, edge, edge drop-off, road, asphalt, detection, monitoring, tools |
| Water bleeding and pumping | 0 | Pavement, pumping, water bleeding, crack, pothole, road, asphalt, detection, monitoring, tools, imaging |
| *Additional road information* | | |
| IRI | 50 | IRI, roughness, measuring, pavement, asphalt, road, roughness, profiler, accelerometer |
| Skid resistance | 12 | Skid, skid resistance, asphalt, road, pavement, testing, measuring, slip, roughness, wheel |
| Substructure | 40 | Asphalt, pavement, thickness, layer, substructure, sub-structure, road, GPR, non-destructive, testing, monitoring, air, holes, NDT |
| Total | 191 | |

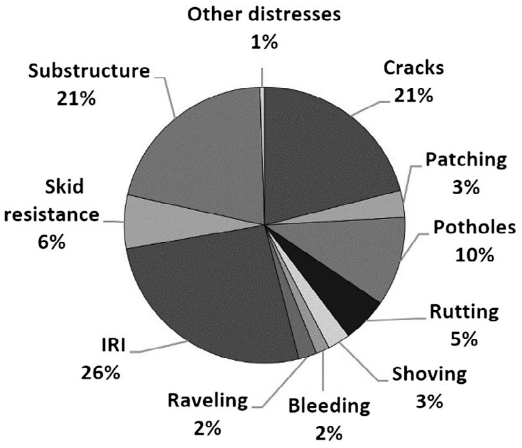
However, amount of literature has been estimated as accurate as possible and consists mainly of literature from the last 10–15 years. To provide a clearer view of the conducted research and the way this is divided between the different distresses, Figure 5 is illustrated. This figure shows the enormous focus on a few single distresses. The top 4 out of 13 comprise 78% of the available literature. This leaves only 22%, equal to 51 papers, for the remaining 9 types of distresses.

Those described amounts of literature are meaningless if the quality of the results is considered. Because the actual gaps cannot only be determined on the basis of the amount of available literature as presented in Figure 5, the amount of available detection methods, the maturity, the quality and the integrability of the methods determine in the end the suitability of the technique. After the gaps in literature and commercial exploitation are determined on the basis of the aforementioned criteria, decisions on further research can be made on the basis of distress detection accuracy, implementability of the technique and ultimately the estimated costs of implementation.

However, the actual gaps are not instantly evident from Tables 1 and 2 and for making clear for which distresses the most solutions are offered in literature and which solutions are used per distress in commercial vehicles, Figure 6 is plotted.

For every distress there are at least two options and that in particular the commercial methods offer a solution for every distress to detect. That, from a technical perspective, it is not necessary to conduct further research, but that the reason is prone to other criteria. The second phenomenon

**Figure 5. Division of literature in relation to distresses.**



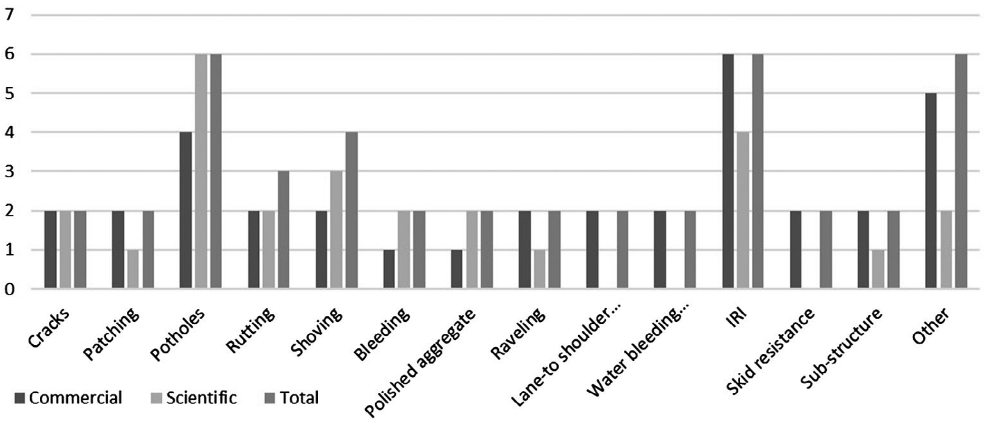
that can be clearly understood from this figure is the peak points in the graph. Especially for pothole detection and measurement of the pavement roughness, different methods can be found. This is the result of the fact that those distresses have different visual characteristics, such as colour, depth and microtexture. Striking is that the seemingly big gaps in for example crack detection methods as shown in Table 2 form in reality no gap at all, as they are the second most researched topic and the top researched distress if only the LTTP distresses as Figure 5 shows are considered.

### *4.2. Discussion of the detection methods*

Figure 6 shows that it has become obvious that the level of completeness in past research and implementation in practice have been strongly correlated with the category in which the type of distress belongs. It could be argued that distresses that display physical damages through the entire top layer of the asphalt in a vertical way, including cracking, potholes and patches, have been researched in a complete way and solutions are available in cost-effective and reliable pavement imaging methods. Mere camera techniques of less than 100 lb are available that detect for example potholes and patches.

This is in contrary to the category of surface deformations and consists of rutting and shoving. Although several suitable implementation methods can be found in practice, the larger part of these methods contain expensive laser-based techniques. Nevertheless, inexpensive, though less accurate techniques are sporadically to be found. The most promising technique seems the use of the cheap sonar sensors. The practical implementation, however, has not been encountered enough and therefore this technique might need some further research to optimise for reliable detection of surface deformations. With use of a series of these sensors is a linear way, all depth-related

**Figure 6. Amounts of method per distress.**



distresses are likely to be recognised, including: rutting, shoving, potholes and edge drop-off. However, a large majority of the commercial vehicles is equipped with expensive, laser-based detection tools.

The third group of distresses, containing of the surface defects, consisting of bleeding, ravelling and polished aggregate, is detectable on its failures in surface microtexture. This group has proven to be the most difficult to detect and classify and moreover not a variety of research has been found on this subject. Commercial firms employ usually expensive laser profilers to detect those distresses, but are often more aimed at the macro oriented roughness rather than a single case of distress occurrence. In cases of research regarding microtexture of roads, mostly static methods are proposed which are not suitable for this research. Consequently, this group of distresses, consisting of ravelling, polished aggregate and bleeding, forms a huge gap in literature and additional research needs to be conducted in order to detect these surface defects in a reliable, quantifiable and dynamical way.

The last two distresses which are mentioned in the LTTP report are easier to detect, but more difficult to quantify and express in terms of severity. Therefore, lane-to-shoulder drop-off and water bleeding and pumping are not considered as major gaps despite the meagre base of available literature, but due to its low representation in literature, research studies should be conducted, mainly for the processing part. Notwithstanding, especially for the edge drop-off, for example cheap camera techniques or ultrasonic devices are used in practice to image severe cases.

Finally, the more general aimed road condition inspections are thoroughly researched and in particular the pavement roughness is determinable in several ways. Measuring skid resistance, however, is proven to be possible in an accurate way, but requires a trailer or a specially equipped truck and is therefore not suitable for implementation in an inspection vehicle. Other methods, such as in-car sensors-based systems, are available but lack in accuracy. However, when solutions have been found on detecting polished aggregate, bleeding and ravelling, the skid resistance could be determined mathematically as it is solely dependent on the pavement surface microtexture. Also, the capturing of the environment is implemented frequently in practice and various inexpensive camera techniques are available for a complete view.

The use of GPR offers an excellent solution for determining the substructure of the pavement, but has also its downsides. Firstly, motorway speeds cannot be reached, especially when a deep substructure penetration is sought and a low frequency has to be applied. Secondly, radio frequencies broadcasted from for example passing cars may influence the results. Nevertheless, GPR offers a terrific insight in the composition of the asphalt layer when it is used with the right configurations, also top layer defects such as cracking and potholes can be detected. Current studies in this field show some flaws regarding applicability to a high-speed vehicle and accordingly, this technique deserves some further research to produce a system that offers a reliable, integral solution.

A fair deal of distress detection methods have been researched thoroughly and do need only further research on the data processing part. The group of surface defects as a whole, however, forms the biggest gap in literature. Especially at motorway speeds, these distresses turn out to be hard to detect and classify. Furthermore, cost considerations may cause more gaps, as laser and point cloud techniques are generally expensive in acquisition, let alone the acquisition of deflectometers. Also the exact list of requirements of the van can have major consequences for the techniques used, regarding space, weight, speed and dynamics. Finally, the completeness in terms of infrastructure management and the level to which road surveys should take place (project or network level) determine to a high degree the equipment which is suitable to use. For example, the Pavision RWD merely aims at assessing the substructure of the road, while VOTERS aims at assessing macrostructure, microstructure and the surroundings, whilst it does not give any attention to the deeper substructure.

## 5. Assessment of data collection devices

Data collection devices as described above have been applied to capture pavement condition either automatically or manually. It is of significant importance to evaluate appropriateness of each device in pavement condition data collection. In order to assess the devices, some criteria such as ability to capture data in a dynamic mode, implementability in automated data collection vehicles, integrability, and accuracy in detection of common distresses have been considered. As shown in Table 3, several devices under camera, accelerometer, 3-D-sensor, microphone, sound propagation, pressure, friction, and deflectometer are presented. Each device has been ranked applying five grades: very good, good, moderate, poor, and very poor in terms of above-mentioned criteria. As illustrated in this table, for instance, CCD camera can be applied in the dynamic integrated mode on a vehicle detecting crack, patch, pothole at a very good accuracy, whilst it can capture rutting with poor accuracy. The other devices also can be assessed in the same manner.

### *5.1. Future directions*

Based on these conclusions, several steps have to be taken in the future in order to determine the proper equipment to use. First of all, the project scope, boundary condition, budget and aim have to be determined in a tremendously accurate fashion. Only then, an integral concept that differs in a positive way from existing concepts can be designed. The scope includes the degree to which distresses and external factors need to be captured. For instance, when an entire infrastructure management program is aimed, it is sensible to endeavour as much system integration as possible.

Furthermore, boundary conditions have to be determined. These boundary conditions might immediately score out ostensibly suitable methods. Budget is one of these preconditions that should be at least estimated before the actual research to equipment begins. A note has to be made that the more difficult the processing is, the more man power is required, which also increases the costs. On one hand, this might limit the available solutions and on the other, a seemingly expensive solution might be used so integrally, that it is the most cost-effective solution at the end. Finally, there are numerous distress detection vehicles around the world with all comparable appliances. The aim of the research has to be completely clear before a choice in technique can be made. In other words, how does the aimed vehicle differ from its competitors and why would the client prefer this one above its more mature alternatives.

This last point leads to the next recommendation. Governmental organisations, such as municipalities or even the central government are likely to be the client. It is generally known that governmental organisations are often the most conservative ones (Seaden & Manseau, 2001). Although they are responsible for promoting innovation in order to stimulate economic growth, they are often the last who adopt innovations themselves, as they are concerned about risking public money. Therefore, it is recommendable to use proven techniques where possible and innovate only where proven techniques do not suffice. It is therefore concluded to innovate as much as possible in system integration, rather than product innovations. When these innovative techniques are necessary, it is suggested to further research the properties and characteristics of asphalt and its distresses. Different frequencies, spectra or properties may reveal new, easy ways for distress detection as shown by the little available literature about for example the thermal cameras.

A mere overview of past techniques is given and should only be used in order to determine areas for further research and for a research for implementation of existing systems. It should therefore not be misused for direct information extraction. Furthermore, the literature review has been conducted as complete as possible. Notwithstanding, some relevant literature might have been overlooked and there also have been some sources could not be accessed, which might cause incompleteness.

**Table 3. Level of appropriateness detection method in dynamic pavement assessment per distress**

| Type | Device | Dynamics | Implementability vehicle | Integrability | Distress | Accuracy | Distress | Accuracy | Distress | Accuracy | Distress | Accuracy | Distress | Accuracy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Camera | CCD | ++ | ++ | ++ | Cracking | ++ | Patch | ++ | Pothole | ++ | Rutting | − | Other | ++ |
| | Infrared | ++ | ++ | ++ | Cracking | ++ | Patch | ++ | Pothole | ++ | Rutting | +/− | Other | + |
| | CMOS | ++ | ++ | ++ | Cracking | ++ | Patch | ++ | Pothole | ++ | Rutting | − | Other | ++ |
| | Line-scan | ++ | ++ | +/− | Cracking | ++ | Patch | ++ | Pothole | ++ | | | | |
| | Video | ++ | ++ | + | Cracking | + | Patch | ++ | Pothole | ++ | Other | ++ | | |
| | Black-box | ++ | ++ | +/− | Patch | ++ | Pothole | + | Other | | | | | |
| | Smart-phone | ++ | ++ | − | Patch | ++ | Pothole | + | Other | | | | | |
| | Retrore-flectivi-tymeter | ++ | ++ | − | Other (marking) | ++ | | | | | | | | |
| Acceler-ometer | Smart-phone | + | ++ | +/− | Pothole | + | Shoving | + | IRI | + | | | | |
| | On wheel | ++ | ++ | ++ | Pothole | + | Shoving | + | IRI | ++ | | | | |
| | On wheel-axis | ++ | ++ | ++ | Pothole | + | Shoving | + | IRI | ++ | | | | |
| | In-Car | ++ | +/− | +/− | Pothole | + | Shoving | + | IRI | ++ | | | | |
| | In other tool | ++ | − | + | Pothole | + | Shoving | + | IRI | ++ | | | | |
| 3D-sensor | Laser profiler | ++ | ++ | + | Raveling | + | Pothole | +/− | Patches | +/− | Bleeding | +/− | IRI | ++ |
| | Line projec-tion | ++ | ++ | ++ | Pothole | ++ | Shoving | ++ | Cracking | + | Rutting | ++ | | |
| | Stereo vision | + | + | +/− | Ruttiing | + | Pothole | + | Shoving | + | | | | |
| | Kinect | + | ++ | + | Pothole | + | Shoving | + | Rutting | +/− | | | | |
| | GPR | + | + | ++ | Cracking | +/− | Pothole | + | IRI | +/− | Substruc-ture | ++ | | |
| | Time-of-flight | + | ++ | ++ | Cracking | ++ | Pothole | ++ | Rutting | ++ | Shoving | ++ | Other | ++ |
| | Struc-tured light | ++ | + | ++ | Pothole | ++ | Rutting | ++ | IRI | + | Raveling | + | | |
| | Photo-metric stereo | −− | +/− | + | Pothole | ++ | Cracking | ++ | Raveling | ++ | Polished aggre-gate | ++ | Bleeding | ++ |

(*Continued*)

**Table 3. (*Continued*)**

| Type | Device | Dynamics | Implementability vehicle | Integrability | Distress | Accuracy | Distress | Accuracy | Distress | Accuracy | Distress | Accuracy | Distress | Accuracy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Microphone | Tire | + | ++ | ++ | IRI | + | Pothole | +/– | Shoving | +/– | Polished aggregate | +/– | | |
| | Near road | –– | –– | + | Other | ++ | | | | | | | | |
| | Beneath car | + | + | ++ | IRI | + | Pothole | +/– | Shoving | +/– | Polished aggregate | +/– | | |
| Sound propagation | Sonar | + | ++ | ++ | Pothole | + | Rutting | + | Edge drop-off | ++ | Other | + | Shoving | +/– |
| Pressure | Pressure sensor | ++ | ++ | ++ | Pothole | + | Shoving | + | IRI | + | | | | |
| Friction | Tire traction | + | – | –– | Skid resistance | + | | | | | | | | |
| | Angled wheel | + | –– | –– | Skid resistance | ++ | | | | | | | | |
| Deflectometer | FWD | –– | –– | –– | Substructure | ++ | | | | | | | | |
| | RWD | – | –– | –– | Substructure | ++ | | | | | | | | |

Notes: ++ = Verygood, + = Good; +/– = Moderate; – = Poor; –– Very poor.

## 6. Summary

A wide range of research has been conducted on automated pavement distress detection and commercial firms have been using well-equipped vans for three decades in order to ease manual labour. These vehicles, and in particular the more recent ones, are sophisticated systems with too expensive equipment. During the last years, however, the calculation capacity of affordable computers as well as high precision sensors made an incredible progress. Furthermore, extensive research has been aimed at specific distresses such as cracks and potholes, whilst for example water bleeding has been barely touched. Therefore, new detection methods may arise for those distresses.

There are certainly distresses from which it is difficult to obtain useful detection methods from literature and commercially implemented equipment. The highest need for further research is demanded from the surface defects: ravelling, polished aggregate and bleeding. Those distresses are extremely difficult to detect during high speeds and especially bleeding and polished aggregated require a tremendously high resolution when making use of imaging techniques, even with making use of high-quality artificial illuminance.

More gaps have been found in the detection of rutting and shoving in a cost-effective manner. Literature offers suggestions for detection with ultrasonic techniques and even mere image processing is suggested. However, these methods need some serious additional research in order to be implemented on a distress detection vehicle. All remaining distresses have been researched fairly well or no additional investigation is considered necessary, but of course new techniques could always lead to improvements in terms of accuracy and cost-effectiveness.

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