



REVIEW OF ASPHALT PAVEMENT EVALUATION METHODS AND CURRENT APPLICATIONS IN NORWAY

Carl Christian Thodesen¹✉, Bjørn Ove Lerfald², Inge Hoff³

¹SINTEF: Infrastructure – Road and Railway Engineering, Høgskoleringen 7a, 7465 Trondheim, Norway

²Veidekke Industri Competence Center, Sluppenvegen 13, 7037 Trondheim, Norway

³Dept of Civil Engineering, Norwegian University of Science and Technology, Høgskoleringen 7a,
7491 Trondheim, Norway

Emails: ¹carl.thodesen@sintef.no; ²bjorn.ove.lerfald@veidekke.no; ³inge.hoff@ntnu.no

Abstract. Evaluation methods and tools used to assess pavement conditions provide an invaluable service to infrastructure engineers, technicians, budget planners, and decision makers. These tools provide information relevant to the maintenance and rehabilitation of a nation's infrastructure. As the pavement network continues to grow and age, new methods of condition evaluation will need to be implemented to maintain conditions databases so that managers and decision makers may develop accurate ideas with regards to the state of the network. This paper introduces various concepts and technologies used today within the road evaluation sector, these include: sensor technologies, pavement condition surveys, imaging techniques, deflection testing, and ground penetrating radar (GPR). These technologies are then discussed within the Norwegian context and their applicability reviewed.

Keywords: condition evaluation methods, sensor technologies, pavement condition survey, deflection testing, ground penetrating radar.

1. Introduction

The ability to adequately evaluate a nation's pavement infrastructure is a key to maintaining a fully functioning pavement network. Especially, as older pavements begin to decay and budget restrictions influence the amount of affordable rehabilitation. Therefore, it is necessary for governments to better track the conditions of their pavement network with time, so that necessary rehabilitation and maintenance are performed at a min cost to the tax payer and with the max return for the government agency (Gendreau, Soriano 1998).

Norwegian roads have to some extent felt the effects of deterioration with time as large portions of the road network are not at acceptable levels. According to *Statistics Norway*, in 2007 Norwegian roads experienced 260 deaths and 12 082 injuries, it is believed that a portion of these accidents are attributable to road conditions. Additionally, years of insufficient funding for pavement maintenance has decreased the level of Norwegian roads to the extent that resurfacing may not be sufficient (Hoff *et al.* 2008). Nevertheless, there has been a gradual improvement in the number of deaths and traffic accidents in Norway since 1998. However, if such progress is to be maintained it is necessary to continue developing various facets of the

road construction and maintenance industry. An important part of this lies in the ability to know when maintenance and reconstruction is necessary. Specifically, in a country such as Norway where the road network spans over 93 000 km and the weather conditions are particularly demanding.

Condition monitoring provides vital information for managers and decision makers regarding the pavement condition, and what (if any) maintenance needs to be performed. Such information is an invaluable tool for budget planning as it allows informed decisions to be made based upon accurate and relevant information (Galehouse *et al.* 2007). Generally, pavements perform well during the first 75% of their life, and to the untrained eye, look as if they are in good condition. The number of years the pavement remains in good condition after this is largely dependent on the level of maintenance it receives. Optimum conditions are maintained through proper timing of major rehabilitations and good interim maintenance (Johnson 1988).

The pitfalls of not conducting adequate maintenance are numerous, and include: safety risks to the general public, decreased travel quality conditions, and increases in capital spent on rehabilitation projects. According to the Federal Highway Administration in the United States,

properly maintained pavements in a “good” to “excellent” condition require four to five times less investment in total annual maintenance compared to “poor” and “failed” condition pavements. This paper will introduce various technologies and methodologies commonly accepted as state of the art with regard to providing evaluations of pavement condition. Additionally, standard methods currently used in Norway will be discussed and compared to the general state of the art.

2. Pavement distresses

Due to their viscoelastic nature, asphalt pavements are sensitive to both loading and temperature. Therefore, the distresses typically seen in asphalt pavements are often attributable to extreme temperatures and loading, or combinations of these two factors. On low volume roads aging is also be an important distress factor, this is particularly applicable as between 90% and 95% of roads in Norway are classified as low volume roads ($AADT < 3000$ vpd). Often, pavement deterioration is a gradual process whereby one distress contributes and leads to another. However, if the driving force causing the distress is noticed early enough it is possible to perform corrective maintenance and rehabilitation before the distress develops and worsens.

For the purposes of this limited study, asphalt pavement failures were identified from the literature (Huang 2004) and suitable methods for detecting these types of failures were identified and discussed. As seen in Table 1, the types of distresses that occur on asphalt pavements are varied and their impact on the pavement may be structural as well as functional. In addition, such failures may also be due to loading on the pavement or they may be due to factors unrelated to loading. Regardless of the nature of these distresses, the pavement engineer must be able to accurately ascertain the failure affecting the pavement in question.

3. State of the art pavement evaluation methods

With the development of modern technology, a number of new condition evaluation systems have been developed to aid the pavement engineer in assessing the state of the road. State of the art condition evaluation methods are presented and discussed in this section; these methods encompass a significant portion of the methods used by developed nations today. Automated methods are increasing in popularity at the expense of performing manual evaluations; therefore, the manual evaluation methods are only described when they have not been substituted with automated techniques. The evaluation methods discussed are: sensor technologies, pavement condition surveys, imaging techniques, pavement deflection methods, and ground penetrating radar (GPR).

3.1. Sensor technologies

Given the increased time constraints and increases in pavement network sizes available today, there has been a tendency for transportation agencies to adopt more

Table 1. Typical asphalt pavement distresses (Huang 2004)

Distresses	Type of distress			
	Structural	Functional	Load associated	Non-load associated
Alligator or fatigue cracking	×		×	
Bleeding		×		×
Block cracking	×			
Corrugation		×		×
Depression		×		×
Joint reflection cracking	×			×
Lane/shoulder drop off or heave		×		×
Lane/shoulder joint separation		×		×
Longitudinal & transverse cracking	×			×
Loss of smoothness (IRI)		×	×	
Patch deterioration	×	×	×	
Polished aggregate		×	×	
Potholes	×	×	×	
Pumping and water bleeding	×	×	×	×
Raveling and weathering		×		×
Rutting		×	×	
Slippage cracking	×		×	
Studded tire wear		×	×	
Swell	×	×		×

automated pavement information registration systems. For this reason a number of sensor technologies have been investigated to perform pavement surface distress evaluations, methods have included: holographic systems, infrared systems, acoustic systems, and laser systems-

It is today standard practice for most profile measurements to be recorded with sensor equipped vehicles (Fig. 1) which drive along the roadway and record the transverse (rutting and studded tire wear) and longitudinal (roughness/smoothness) profile of the road (Haugødegård 2008; McGhee 2004). Profilers, as these vehicles are known, are equipped with accelerometers and a minimum of one of the following three types of sensors: laser, acoustic, or infrared. Using this type of equipment the accelerometers provide a horizontal plane, while the sensors function on the concept that the distance from the reference plane to the road surface is directly related to the time it takes for the signal to travel from the transducer and back (McGhee 2004).

Laser sensors are generally recognized as the most advanced (commercially available) method of providing sensor data. The high speeds at which laser sensors perform today allow for profile data intervals of 25 mm or less to be captured at normal traffic speeds. The number

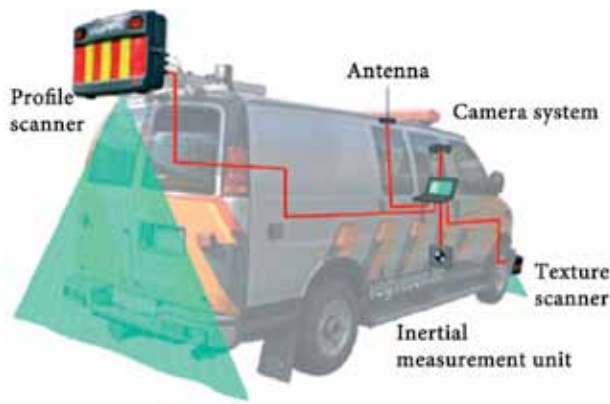


Fig. 1. Typical components of a ViaTech ViaPPS profiler

of sensors used generally varies from 1 to 37, where the varying configurations of lasers are used to capture several longitudinal locations as well as transverse profiles (McGhee 2004). Such equipment is commonly used by numerous European agencies today and has been purchased by many road authorities in an effort to automate their pavement evaluation procedures.

3.2. Pavement condition survey

Pavement condition index (PCI) evaluations are generally carried out by teams of inspectors carrying: hand odometers (to measure distress lengths and areas), a straight edge, a ruler to measure the depth of ruts and depressions, and the PCI distress manual (Greene *et al.* 2004). This procedure involves carrying out visual inspections of the pavement and recording the following aspects of the asphalt pavement distresses: alligator cracking, bleeding, block cracking, corrugation, depression, joint reflection, cracking (longitudinal and transverse), oil spillage, patching, polished aggregate, raveling/weathering, rutting, slippage cracking, and swell. Clearly this method provides a quite comprehensive analysis of the pavement surface, however, it is known to be time consuming and somewhat subjective.

Distress factors are weighted in the PCI system, whereby “deduct values” are used to specify the effects of a distress (including type, severity, and density) on the pavement. These deduct values incorporate the experiences of the program designers into the program so that the distresses measured provide a realistic indication of the pavement distress level (Shahin *et al.* 2002). There have been advances within this field as well; recently pen tablet computers have been added to the PCI tool box to aid in the recording of measurements. Such equipment eliminates errors in manual recording and allows the inspector to enter the data into electronic form immediately (Shahin *et al.* 2002). In addition to this there have some investigations of using automated technology to perform PCI studies. Results from this study suggest that evaluations of distress type and quantity are similar between automated and manual techniques; the evaluation of intensity was inconsistent though. These findings are

quite similar to errors noticed when the survey is performed manually, whereby the intensity level tends to be subjective and varied from inspector to inspector (Cline *et al.* 2002). With use of the PCI system some users have commented on its inherent drawbacks, these include (Wang, Watkins 2010):

- the visual survey must be done during the day time to identify the surface distresses; this means that the high volume roads need to be closed during the evaluation;
- human errors are part of the system as the rating index is of a subjective nature;
- the evaluation is time consuming;
- there are also significant variations in the consistency and repeatability of the results;
- no high definition visual data is recorded for future use.

3.3. Imaging techniques

Crack detection systems allow for crack data to be acquired through the use of condition evaluation vans and provide detailed quantification regarding the type, severity, and extent of cracking present in a pavement. The concept behind imaging techniques is for a data collection vehicle to scan a particular area and then for cracking data to be interpreted using appropriate software. Automated crack detection is to date not as widespread as automated roughness and rutting measurements, in part due to industry skepticism of the reliability of these systems (McGhee 2004). In the past there were efforts to use methods utilizing acoustic or laser sensors to relate cracking to abrupt variations in the pavement texture. These methods have not gained widespread use, and today the tendency is to focus on imaging techniques (McGhee 2004).

Crack recognition systems incorporate the use of high speed digital photography to capture the pavement crack images and then to process these using algorithms which analyze the crack images (McGhee 2004). Generally the process of automated data capture and pavement crack index evaluation proceeds in the following manner (Jitprasisiri 1996):

- pavement surface images are collected using a digital camera mounted on a van, often artificial lighting is provided to improve the contrast and eliminate shadows;
- image processing algorithm, based on a variable thresholding technique, automatically processes images;
- images are divided into smaller tiles; the amount of cracking is computed based on the average grey value of each tile;
- the program automatically determines the number of darkened tiles and computes the crack index in each image.

To date this method has not been as widely adopted as laser profiling; in part this is due to the complexity involved in eliminating shadows from the pavement pictures as well as providing detailed algorithms that analyze the

extracted data. Research continues in this field as it provides data not always obtained using laser profilers, in addition such equipment can be mounted on to laser profiling vans and performed simultaneously, therefore this technology should be kept in mind for future applications.

3.4. Pavement deflection testing

Pavement deflection testing is a tool used for the evaluation of pavement strength, such testing is performed as numerous pavement distresses are caused due to insufficient pavement strength. Therefore, pavement deflection testing is not used to evaluate actual pavement distresses; rather, deflections are an indication of the pavement strength and therefore an indicator of how prone the pavement is to future failure and to investigate causes for rapid damage development. According to the Asphalt Institute, structural capacity is defined as the ability of a pavement to support traffic without developing appreciable structural distress. Structural integrity with regards to pavements refers to the condition of the pavement surface, specifically in regards to the presence of surface fracturing and decomposition.

Today, not all these methods are equally used due to coverage and efficiency issues, older methods such as the Benkelman beam require larger crew sizes and yield less test data. The *COST 325 New Road Monitoring Equipment and Methods Report* states that the Lacroix Deflectograph has also been used for a number in years in various European countries, this method functions on the same principles as the Benkelman Beam. Generally speaking though, the most used methods are the falling weight deflectometer (FWD) and Dynaflect, while the development of the rolling dynamic deflectometer (RDD) also holds promise (Bay, Stokoe 1998).

FWDs are the most common method of providing bearing capacity data for transportation agencies today (Bay, Stokoe 1998; Gendreau, Soriano 1998). However, emphasis has been placed on the gathering of network level data for highways; therefore the *COST 325* report recommends FWD testing to be used more on project level evaluations. The RDD presents a particularly attractive solution as it provides a more practical method for obtaining network level data. The RDD provides continuous coverage and operates with a relatively small crew size (two people), it is estimated that the RDD evaluates distances of up to 14.4 km/day (Bay, Stokoe 1998). Such technologies provide greater output than discrete methods and as such should be considered for future use.

3.5. Ground Penetrating Radar

GPR is a non-destructive method used to investigate the pavement subsurface, this is done by transmitting electromagnetic waves into the subsurface and recording the electric echoes induced by dissimilar dielectric properties (Benedetto, Pensa 2007; Hoff *et al.* 2008). Advantages associated with the use of GPR include the speed of operation and almost full coverage of the pavement section (Hoff *et al.* 2008; Celaya *et al.* 2010). Results obtained from

the use of a GPR survey include cross-sectional representations of what lies beneath the road surface. Today GPR is typically used in conjunction with other instruments to determine properties such as bearing capacity, deflection, unevenness, and rutting (Scullion, Saarenketo 2000).

GPR surveys are typically performed using antennas (vehicle mounted or manual) which transmit short pulses of electromagnetic energy. The short bursts of electromagnetic energy are then reflected when they hit an object or layer interface. The reflected energy is gathered and “displayed as a waveform showing amplitudes and time elapsed between wave transmissions and reflection” (Saarenketo 2006a, 2006b). GPR has been used somewhat intermittently in the field of roadway condition evaluation, in part due to the difficulties of interpreting the recorded signals. The main benefits of using GPR in road evaluation lie in its abilities to evaluate layer thicknesses. Additionally, it has been reported that when used appropriately GPR provides accurate network level information using measurement vehicles operating at highway speeds. There has been some reported use of GPR for pavement evaluation, where its use for pavement layer thickness appears to be the most popular. Agencies have reported questionable results with regards to the use of GPR for void detection and location of asphalt stripping (Cao *et al.* 2007; Scullion, Saarenketo 2000).

4. Norwegian practice

In Norway a number of standards have been developed to evaluate the conditions of the road surface, as seen in Table 2 a number of these refer to the use of ALFRED ultrasound equipment, today this technology has been replaced by the ViaPPS van (Haugødegård 2008). Nevertheless, this indicates that road profile measurements are an integral part of the Norwegian system of road condition evaluation and PMS.

Since 2008, the ViaPPS pavement profile scanner has been used to gather profile and roughness measurements in Norway (Haugødegård 2008). This method of data acquisition utilizes a laser scanner mounted on a van which provides more accurate information to allow the

Table 2. Profiling methods used in Norway according to the *Norwegian Public Roads Administration*

Test Method	Håndbok 015	Similar ASTM
Profile with JULY/ALFRED	15.421	E 950
Manual profile measurement	15.422	E 1703
Rutting measurement with JULY/ALFRED	15.423	E 950
Calculation of specific studded tire wear (SPSV)	15.425	–
Transverse profile with JULY/ALFRED	15.426	E 950
Evaluation of surface damage	15.427	D 5340



Fig. 2. Studded tire wear in Norway (Haugødegård 2008)

Norwegian Public Roads Administration to better utilize their PMS system. As seen in Fig. 1, ViaPPS is a vehicle mounted road scanner with the ability to map road condition and quality. The equipment is capable of recording 140 readings per second over the whole lane width. During operation it collects: rutting information (depth, area, and width), cross fall, marking quality, some cracking information, height of the road shoulder, measurement speed, reference position, transverse profile, international roughness index (IRI), mean profile depth, GPS coordinates, curve radius, and longitudinal profile. Approx 54 000 km

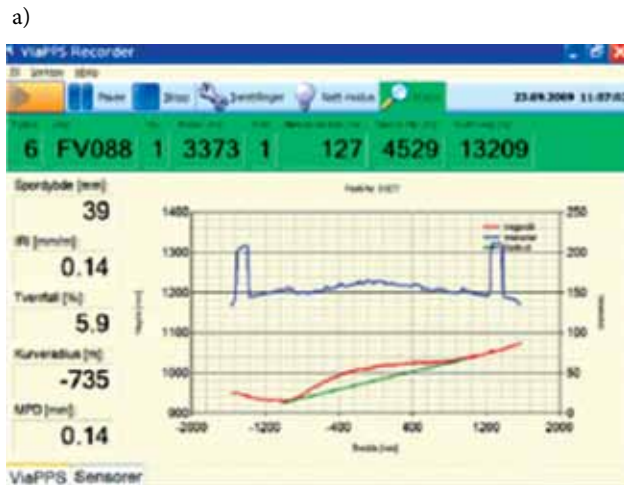


Fig. 3. ViaTech ViaPPS Analysis Screen shots illustrating: a – road profile, b – rut depth

(59%) of Norway’s road network is evaluated using this method (Haugødegård 2008).

The transverse road profile is a parameter of specific interest in Norway because, as seen in Fig. 2, for many Norwegian roads the primary cause of failure is studded tire wear. Crack recognition systems are not currently used in Norway, even though images of the Norwegian road network are regularly captured at 20 m intervals during condition evaluations. These images allow the user to take a virtual tour of the road network while sitting at their desk.

The software portion of the ViaPPS system provides data management for the various measured conditions. As seen in Fig. 3, the rut depth, IRI value, cross slope, curve radius, and MPD are all presented for the desired road profile. Additionally, information is provided to identify the road section. As seen in Fig. 3, the analysis does not provide a systematic evaluation of fatigue or low temperature cracking. A drawback of this method might lead to decreased focus on this issue, whereas it is in fact a cause of significant concern if the cracks are not addressed.

In Norway research has been conducted on the feasibility of using GPR data to collect pavement data information. This research indicated that there was a good correlation between pavement thicknesses determined from core samples and GPR data, however the accuracy of this method lies in determination of the dielectric permittivity coefficient. Research continues within this field for practical applications, therefore, this method requires additional development prior to being used on a network level (Lalague, Hoff 2010). Pavement strength testing is typically conducted using FWD type equipment; however, such testing is not usually performed at the network level.

5. Summary

As seen in Table 3, a number of technologies are today available for the evaluation of distresses in pavements. Some technologies are developed and ready for implementation while others are still under development. However, what is evident is that many of the available methods are mutual compatible and provide a comprehensive overview of the health of the pavement.

Table 3. Summary of evaluation methods and applicable distresses

Distress	Evaluation procedure				
	Sensor technologies	PCI/PSI	Imaging	FWD	GPR
Alligator or fatigue cracking		×	×	×	p
Bleeding		×			
Block cracking		×	×	×	p
Corrugation	×	×			
Depression	×	×			

Continued Table 3

Distress	Evaluation procedure				
	Sensor technologies	PCI/PSI	Imaging	FWD	GPR
Joint reflection cracking		×		×	p
Lane/shoulder drop off or heave	×				×
Lane/shoulder joint separation	×				
Longitudinal & transverse cracking		×	×	×	p
Loss of smoothness (IRI)	×				
Patch deterioration		×		×	
Polished aggregate		×			
Potholes	×			×	p
Pumping and water bleeding				×	p
Raveling and weathering		×			
Rutting	×	×			
Slippage cracking		×	×	×	p
Studded tire wear	×	×			
Swell	×	×		×	p

Note: × – confirmed use, p – potential use.

6. Conclusions

The need to collect pavement condition data is of critical importance to government agencies, especially as the road network continues to expand and the loading intensifies. For this reason, it is necessary for these agencies to harness available technology to gather more information with less manpower. The solution to this problem lies in the development and adoption of new technologies for the pavement management industry.

Pavement distress is a complex issue which may either be categorized as structural failure or a functional failure. Structural failures deal with the ability of the pavement to carry a load, while functional failures deal with the ability of the pavement to provide adequate levels of service (roughness, noise, etc.) and safety. Today numerous available technologies have been developed to harness the power of modern computing to extract pavement condition data. These methods include: sensor technologies, pavement condition surveys, imaging techniques, pavement deflection methods, and GPR. Due to the complexities involved in pavement failures, there is no one solution. Rather these various methods may be combined

to compliment one another and provide a comprehensive evaluation of the pavement in question.

In Norway highway pavements are generally built using flexible asphalt pavements, therefore the resulting distresses are of a predetermined nature. In the past the standard method of performing pavement evaluations typically consisted of sending a team of inspectors to various pavement sites and having them perform a visual inspection of the site. Typically, the inspectors would provide subjective evaluations of the various distresses witnessed on site and provide a rating for that particular pavement section. Additionally, when profile and strength data were required a myriad of manual tests were available for the inspectors to perform spot checks of the various pavement performance parameters. Examples of these manual procedures include the sand patch test for road texture, the Benkelman beam for strength, and rutting bar measurements bar for rut depths.

The problem with such evaluations are that they are time consuming and do not provide network level information. Additionally such methods may require the need to stop traffic, and as such cause traffic interruptions which may be unsafe for the inspectors as well as the motoring public. Therefore, the trend has whenever possible been to develop and use automated data gathering measures which avoid many of these pitfalls while also providing network level data. In Norway, the value of such automated techniques has been recognized. Following experiences with the ALFRED ultrasound equipment, further investments have been made in the ViaPPS laser equipped pavement profile scanner. This laser profiler is capable of evaluating: rutting information, cross fall, marking quality, road shoulder height, transverse profile, IRI, and mean profile depth. Within the Norwegian context transverse profile is particularly important as this is a primary indicator of pavement failure due to studded tire wear.

The FWD is still used in a limited capacity by the Norwegian road authorities for structural evaluations. Its use is limited due to the difficulty of obtaining network level readings using such technology. Inspection teams utilizing the PCI method are also used occasionally due to the ability of the human eye to identify different types of pavement distress not yet identifiable by imaging techniques. GPR is under evaluation for use as a pavement performance tool in Norway; however, to date it remains a tool that is still under development.

References

- Bay, J. A.; Stokoe, K. H. 1998. *Development of a Rolling Dynamic Deflectometer for Continuous Deflection Testing of Pavements. Project Summary Report 1422-3F Report*. The University of Texas at Austin: Center for Transportation Research Bureaus of Engineering Research.
- Benedetto, A.; Pensa, S. 2007. Indirect Diagnosis of Pavement Structural Damages Using Surface GPR Reflection Techniques, *Journal of Applied Geophysics* 62(2): 107–123. <http://dx.doi.org/10.1016/j.jappgeo.2006.09.001>.

- Cao, Y.; Dai, S.; Labuz, J.; Pantelis, J. 2007. *Implementation of Ground Penetrating Radar*. Report No. MN/RC 2007-34. Minnesota Dept of Transportation. 29 p.
- Celaya, M.; Nazarian, S.; Rao, Ch.; Von Quintus, H. 2010. Delamination Detection of HMA Airport Pavements with NDT Devices, in *FAA Worldwide Airport Technology Transfer Conference*, Atlantic City, New Jersey, USA.
- Cline, G. D.; Shahin, M. Y.; Burkhalter, J. A. 2002. Automated Pavement Condition Index Survey, in *Proc. of the Pavement Evaluation Conference*. October 21–25, 2002, Roanoke, Virginia, USA.
- Galehouse, L.; Moulthrop, J.; Hicks, R. G. 2007. *Pavement Preservation Compendium II: Principles of Pavement Preservation*. Report from US Federal Highway Administration, available from internet: <<http://www.fhwa.dot.gov/pavement/preservation/ppc03.pdf>>
- Gendreau, M.; Soriano, P. 1998. Airport Pavement Management Systems: an Appraisal of Existing Methodologies, *Transportation Research Part A: Policy and Practice* 32(3): 197–214. [http://dx.doi.org/10.1016/S0965-8564\(97\)00008-6](http://dx.doi.org/10.1016/S0965-8564(97)00008-6)
- Greene, J.; Shahin, M. Y.; Alexander, D. R. 2004. Airfield Pavement Condition Assessment, *Transportation Research Record* 1889: 63–70. <http://dx.doi.org/10.3141/1889-08>
- Haugodegård, T. 2007. *Utstyr for registrering av tilstand på vegnettet, System for håndtering av innsamlede data, PMS – Vegdatabanken (N)VDB*. Presentation at NPRA, Trondheim, Norway.
- Haugodegård, T. 2008. New Measurement Equipment for Pavement Condition, in *Joint Nordic/Baltic Symposium on Pavement Design and Performance Indicators Oslo, Norway*. February 13–14, 2007, Oslo, Norway [cited 6 November, 2012] Available from Internet: <<http://www.nvfnorden.org/lisalib/getfile.aspx?itemid=609>>
- Hoff, I.; Hoven, B.; Eide, E. 2008. Introduction of Ground Penetrating Radar in Pavement Rehabilitation in Norway, in *Transport Research Arena*. April 21–24, 2008, Ljubljana, Slovenia.
- Huang, Y. H. 2004. *Pavement Analysis and Design*. 2nd edition. Upper Saddle River, New Jersey, USA: Pearson Prentice Hall. ISBN 0131424734.
- Jitprasithsiri, S.; Lee, H.; Sorcic, R.; Johnston, R. 1996. Development of Digital Image-Processing Algorithm to Compute Unified Crack Index for Salt Lake City, *Transportation Research Record: Journal of the Transportation Research Board* 1526: 142–148. <http://dx.doi.org/10.3141/1526-18>
- Johnson, C. 1988. Pavement Maintenance Management. American Public Works Association Reporter 50(11).
- Lalague, A.; Hoff, I. 2010. Accuracy of Ground Penetrating Radar in Bituminous Pavement Thickness Evaluation, in *Transportation Research Arena*. June 7–10, 2010, Brussels, Belgium.
- McGhee, K. H. 2004. NCHRP Synthesis 334: Automated Pavement Distress Collection Techniques – A Synthesis of Highway Practice. 334. 2004. Washington, D.C., USA: National Cooperative Highway Research Program.
- Saarenketo, T. 2006a. *Electrical Properties of Road Materials and Subgrade Soils and the Use of Ground Penetrating Radar in Traffic Infrastructure Surveys*. PhD thesis. University of Oulu, 2006.
- Saarenketo, T. 2006b. GPR Applications in Europe, in *Proc. of the TRB 85th Annual Meeting*. January 22–26, 2006, Washington DC, USA.
- Scullion, T.; Saarenketo, T. 2000. Integrating Ground Penetrating Radar and Falling Weight Deflectometer Technologies in Pavement Evaluation, in *Symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli*, vol. 3. Ed. by Tayabji, S. D.; Lukanen, E. O. June 30 – July 1, 1999, Seattle, Washington. American Society for Testing and Materials, 2000. <http://dx.doi.org/10.1520/STP14758S>
- Shahin, M. Y.; Keifer, K. A.; Burkhalter, J. A. 2002. *Airport Pavement Management: Enhancements to Micro Paver*. Report for US Federal Aviation Administration Technology Transfer Conference. Available from Internet: <<http://www.airport-tech.tc.faa.gov/naptf/att07/2002%20TRACK%20P.pdf/P-57.pdf>>
- Wang, K. C. P.; Watkins, Q. 2010. Rapid 1-Mm Survey of Airport Runways with Laser Imaging Technology, in *2010 FAA Worldwide Airport Technology Transfer Conference*. April 20–22, 2010, Atlantic City, New Jersey, USA.

Received 15 November 2010; accepted 14 February 2011