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STATE OF THE ART IN MONITORING ROAD CONDITION AND ROAD/VEHICLE INTERACTION

Technical Committee 4.2 Road Pavements
World Road Association
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This report summarises the current state of the art regarding the collection of road condition and road/vehicle interaction data, providing an overview of current practice and emerging technologies. Technologies in the development and experimental stages are generally not discussed. The document is intended to concisely inform the reader of the range of technologies available, and not to replicate the considerable detail that is available elsewhere for specific technologies.

Each of the commonly measured road condition and road/vehicle interaction data parameters is discussed, providing a definition of each of these parameters, a description of the common measurement methods and a description of the condition/interaction indicators that are derived from the measured data.

The need for robust quality management in the collection of road condition data is highlighted, and guidance provided.
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INTRODUCTION

Road pavements comprise a major component of public infrastructure, and are designed to have long service lives delivering safe, smooth, all-weather access for people and goods.

Assessing the condition of pavements after construction allows a comparison of the characteristics of the constructed pavements to be made against the design goals. Over their long life span the condition of these pavement assets is usually monitored by road owners to ensure that the pavements are providing the expected efficient and safe travel conditions for which they were designed. If condition monitoring indicates that the desired performance of the pavement is being compromised, collected condition information can be used to identify the cause of the problem, assist in the design of treatments, and in prioritising the application of those treatments in the most efficient manner within operational and budget constraints.

Nearing the end of the operational life of the pavement, collected condition parameters can be used as an input into the selection and design of rehabilitation or re-construction options.

Beyond these broad uses condition data can also be utilised to:

• assess the quality of construction;
• benchmark current condition;
• measure the changes in performance over time, informing the prediction of future condition;
• fulfil requirements to report asset value and indicators of network performance;
• assess the performance of service providers;
• guide the selection of future maintenance and replacement needs.

This report summarises the current state of the art regarding the collection of road condition and road/vehicle interaction data. It aims to provide an overview of current practice and emerging technologies. The use of condition data is generally described but, as noted above, the uses of data are widespread with each worthy of separate discussion. The report’s scope is limited to the description of indicators that are derived from condition data, and where appropriate provides examples of the use of those indicators in decision making.

Technologies in the development and experimental stages are largely not discussed. The document is intended to concisely inform the reader of the range of technologies available, and not to replicate the considerable detail that is available elsewhere for specific technologies. The report does not include specific discussion of assessing winter conditions, leaving such discussion to more specialised documents.
1. REPORT STRUCTURE

Following this overview of the structure of the report, sections 2 to 5 describe each of the commonly measured road condition and road/vehicle interaction data parameters. For each parameter a definition is provided, followed by a description of the common measurement methods that are used (with reference to specialist equipment where appropriate) and a description of the condition/interaction indicators that are derived from the measured data.

A wide range of parameters can be used to characterise the functional and structural condition of road pavements and the interaction between vehicles and the road surface. It should be noted that some data are technical parameters, from which are derived functional indicators, and others are second order indicators used to directly quantify an effect from the surface condition. For example, Illustration 1 shows the range of functional indicators that can be derived from longitudinal evenness information.

Illustration 1 - Longitudinal condition and its effect on road functions
(source: VTI, Sweden)

Following the descriptions of specific parameters, sections 6 and 7 discuss the need for robust quality management in the collection of road condition data. The principles discussed are considered to be fundamental to the provision of data that can be confidently used to inform engineering and investment decisions.

The final four sections of the report provide brief case studies. Highlighting the importance of quality management of the data collection process, the first case study describes the processes used in Quebec, Canada to ensure that collected data is of sufficient quality to be reliably used in informing decisions and policy. A case study from Japan demonstrates how new condition indicators have the potential to further aid maintenance decisions. The case study from Saudi Arabia shows how measurement of the ride quality of recent road construction projects was used to redefine specification acceptance criteria for use with future projects. The final case study describes a range of current research and development work looking to utilise the sensors that are contained in modern vehicles to collect more frequent, though lower quality, data than that obtained by specialist road condition survey vehicles.
2. SURFACE EVENNESS

2.1. INTRODUCTION

A road surface is a three-dimensional area constituting the wearing course that in most cases consists of asphalt or concrete material. A new laid wearing course is considered flat. When it has been in use the surface gets deformed due to the traffic load, weather/climate, geological conditions as well as the strength of the road construction. To simplify quantifying the degree of deformation, indicators have been developed that are based on the transverse (perpendicular to the direction of traffic flow) and longitudinal (parallel to the direction of traffic flow) profile (illustration 2). The evenness is accordingly defined by the vertical deviations of the pavement surface from a horizontal reference perpendicular or along the lane direction. Transverse evenness is discussed in section 2.2, and longitudinal evenness in section 2.3.

Illustration 2 - The three dimensional road surface with transverse profiles
(source: VTI, Sweden)

2.2. TRANSVERSE EVENNESS

2.2.1. Definition

Transverse profile is defined by the vertical deviations of the pavement surface from a horizontal reference perpendicular to the direction of travel. Transverse evenness is a measure of the variation within a transverse profile.

Different evenness indicators can be calculated to provide simple quantifications of the lack of evenness of the measured profile.
2.2.2. Measurement methods

Straight edge

Rut depth or transversal evenness can be measured with a straight edge – a ruler that is placed perpendicular to the direction of traffic. The ruler will rest on two points. The vertical distance from the bottom of the ruler to the surface is the rut depth (illustration 3). Often the maximum of all the possible depths is used as an indicator – the rut maximum depth. The length of the straight edge must be considered since this has a very large influence on the calculated indicator. Most straight edges have the length 0.5 to 3-5 meters. As a manual measuring method, straight edge measurements are of course not practical for measuring road networks but are useful for specific sections.

Illustration 3 - Example of a straight edge method
(source: Ministry of Transport of Quebec)

Profilometer

The PIARC dictionary defines a profilometer as a device used for measuring the profile of a road pavement within a given range of wavelengths of surface irregularities. Most profilometers used for rut depth measurements are designed to cover between 0.5 m of a lane and up to 4 m.

Modern profilometers use contactless distance measurement sensors, such as lasers, allowing the collection of transverse profiles whilst travelling at normal traffic speeds. These devices are often called dynamic profilometers. Using contactless sensors, transverse profiles can be measured by either a number of single point sensors to build up an estimation of the transvers profile, or by a continuously measuring sensor giving the full transverse profile (illustration 4).
2.2.3. Indicators

**Rut depth**

The most used expression for a transverse evenness indicator is rut depth. The PIARC dictionary defines rut depth as the maximum perpendicular distance between the bottom surface of a straightedge and the contact area of the gauge with the road surface at a specified location, usually measured in the wheel tracks.

It should be remembered that rut depth is a general term for transverse evenness. In the European standardisation work of CEN one specific rut depth indicator is defined as: the greatest deviation of the transverse profile of a pavement surface and a virtual straight reference line of set length, $L$, sliding on the surface of the profile within the limits of the analysed width, by leaving one edge of the rut towards the other edge. The length of the virtual reference should be mentioned with the results. Rut depth is normally expressed in millimetres. Other indicators were investigated by the FILTER project [1] as part of the PIARC project EVEN [2].

Ruts in the pavement surface manifest as a continuous depression in a longitudinal direction in the area of the wheel paths. Usually the length of the virtual straight reference line is about 1.5 to 2 m (about half the width of the lane). The length of the virtual straight reference line should be mentioned with the results.

In *illustration 5* typical indicators are show: maximum left, right rut depth and edge deformation sometimes called edge slope.
Transverse profile shape

Single, double and sometimes triple longitudinal depressions, of the order of 250 mm in width, located in the wheels tracks can be defined as small radius ruts. The transverse profile of these depressions is sometimes similar to single or twin tyre marks.

Simple longitudinal depression located in the tracks of wheels of more than 250 mm width can be defined as large radius rut. The cross-section form of the depression corresponds to a very flared parabolic curve. With the introduction of profilometers able to continuously measure transverse profiles, new possible ways of examining the profile have arisen. The transverse profile data can be used to develop indicators for theoretical water depth, structural condition and calculation of volumes of material needing to be filled / milled to restore the crossfall and evenness.

Possible causes of ruts are:

- asphalt stability reduced in hot weather (e.g.: too soft bitumen or overdose);
- asphalt too weak to resist heavy traffic (e.g.: creep);
- inadequate compaction of the asphalt at the time of installation (post compaction);
- wear of the coated surface (abrasion);
- accumulation of permanent deformations under the passage of heavy vehicles;
- inadequate compaction of granular layers during the construction;
- insufficient structural capacity of the roadway.
2.3. LONGITUDINAL EVENNESS

2.3.1. Definition

Longitudinal profile is defined by the vertical deviations of the pavement surface from a horizontal reference parallel to the direction of travel. Longitudinal evenness is a measure of the variations along a longitudinal profile.

2.3.2. Measurement methods

Longitudinal evenness can be determined either by direct response measurement or by using a model (or filter) applied on the measured longitudinal profile. Direct response measurement is dependent upon travel speed and physical characteristics of the response system, whereas the results of models or filters applied to measured profiles are independent of these factors. For this reason, measurement of the longitudinal pavement profile and application of a model/filter is the most common means of measuring longitudinal evenness [3].

In measurement, the true continuous profile is approximated by measuring the elevation of discrete points along the profile with a fixed distance between each sample. The generic term for a device that measures the longitudinal profile of a pavement is a profilometer or profiler.

Currently, most high-speed profilers use a vehicle-mounted laser to measure the distance between the road surface and a reference on the vehicle, coupled with an accelerometer to correct the profile for the inertial movement of the measuring vehicle. The sample interval is usually 50 mm or smaller. The advantage of using such inertial-profilometers is that the measurement results are independent of measuring speed as well as being independent of the dynamics of the measuring vehicle.

2.3.3. Indicators

Longitudinal evenness is related to ride quality. Different indicators have been developed to quantify the ride quality. Ride quality is affected by changes in road profile, and so ride quality indicators are calculated over a length of road section, e.g. 20 m, 100 m, 500 m. Other indicators are more suited to identify defects in a longitudinal road profile, e.g. faulting of plain concrete slab pavements or the evenness for different wavelengths.

International roughness index

The International Roughness Index (IRI) is a standardised calculated response of a car driving over the measured longitudinal profile. The car is a mathematical model of a quarter of a passenger car (illustration 6). The cumulated vertical suspension movement divided by the distance travelled, expressed in m / km (mm/m) or in / mi, is the value of the IRI [5]. Table 1 presents values of IRI expressed in units of inches/mile for a range of metric values of IRI.

Internationally, the IRI is the most used indicator for network management regarding evenness.
TABLE 1 - CONVERSION BETWEEN UNITS OF IRI

<table>
<thead>
<tr>
<th>m/km</th>
<th>in/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>127</td>
</tr>
<tr>
<td>3</td>
<td>190</td>
</tr>
<tr>
<td>4</td>
<td>253</td>
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<tr>
<td>5</td>
<td>317</td>
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<td>6</td>
<td>380</td>
</tr>
<tr>
<td>7</td>
<td>444</td>
</tr>
<tr>
<td>8</td>
<td>507</td>
</tr>
<tr>
<td>9</td>
<td>570</td>
</tr>
<tr>
<td>10</td>
<td>634</td>
</tr>
</tbody>
</table>

Besides its use to measure the evenness condition of a road network, the IRI can also be used for the quality control of new roads. In section 10 a case study from Saudi Arabia illustrates how acceptance limits can be defined.

Power spectral density

Power spectral density (PSD) is the limiting mean-square value of a road profile spectrum per unit bandwidth, i.e. the limit of the mean-square value in a rectangular bandwidth divided by the bandwidth, as the bandwidth approaches zero. The PSD spectrum is characterised by fitted straight regression line(s) and expressed by indices related to the location of these line(s).

Wave band analysis

Wave band analysis includes filtering techniques to divide the measured longitudinal profile into separate wave bands. Most common is to use three bands covering short, medium and long wavelengths. This indicator is used in the UK and France.

Weighted longitudinal profile

The Weighted Longitudinal Profile (WLP) is the longitudinal pavement profile which has been weighted by a weighting function in the frequency domain. This is achieved by applying a fast Fourier transform (FFT) to the spatially defined profile data $H(x)$, applying the weighting factor $W(\Omega)$ to the resulting frequency-domain data, and then finally using an inverse fast Fourier transform to convert the weighted profile data back into the spatial domain. This is illustrated in...
The weighting function enhances small wavelengths and decreases large wavelengths in such a way that their respective power contents become measurable later by the same scale in the spatial domain.

The WLP is characterised by:

- $\sigma_{WLP}$: the standard deviation of the weighted profile $H_w(x)$;
- $\Delta WLP$: the range of variation, i.e. the difference between the maximum and the minimum value of the weighted profile $H_w(x)$.

For interpretation purposes the line $\Delta WLP = 6 \times \sigma_{WLP}$ defines two zones in the $\sigma_{WLP}$-$\Delta WLP$ graph (Illustration 8). Points below this line correspond with a wavy evenness; points above this line indicate a local unevenness. In section 9 a case study from Japan discusses how a more detailed study of these values may give an indication of the type of local distress.
Currently this indicator is used in Germany and Austria. They define a warning value when $\sigma_{WLP}$ is larger than 9 mm or $\Delta_{WLP}$ is larger than 54 mm, and a threshold value when $\sigma_{WLP}$ is larger than 13 mm or $\Delta_{WLP}$ is larger than 78 mm. The different zones are indicated in *illustration 9*.

*Illustration 9 - Warning and threshold values of WLP*
3. VEHICLE/ROAD INTERACTION CHARACTERISTICS

3.1. GENERAL

This section discusses the following four vehicle/road characteristics:

• surface texture;
• skid resistance;
• traffic noise;
• rolling resistance.

Road surface texture is the most important road surface feature affecting tyre/road interaction processes such as rolling resistance, tyre/road friction, exterior tyre/road noise, interior vehicle noise, ride quality and vehicle and tyre wear (illustration 1, page 4). Therefore, the description of texture is very important when trying to quantify road surface condition and/or its potential effects on safety, economy and environment.

3.2. SURFACE TEXTURE

3.2.1. Definition

In technical terms, road surface texture is a physical feature of a road surface describing its irregularities and deviation from a planar surface with horizontal dimensions ranging between 0 and 500 mm. Based on the wavelength of the irregularities, road surface texture can be divided into sub-groups (illustration 1, page 4):

• Microtexture – surface irregularities with horizontal dimensions ranging between 0 and 0.5 mm. Microtexture is produced by the surface properties (sharpness and harshness) of the individual aggregates or other particles of the surface which come in direct contact with the tyres. Microtexture is not directly measured, rather its effect on the friction between tyre and surface is measured (section 3.3);
• Macrotexture – surface irregularities with horizontal dimensions ranging between 0.5 and 50 mm. Macrotexture is related to aggregate size, the mixture design and laying (compaction) of the surfacing material. It has wavelengths in the same order of size as tyre tread elements in the tyre-road interface;
• Megatexture – surface irregularities with horizontal dimensions ranging between 50 and 500 mm. This type of texture has wavelengths in the same order of size as a tyre-road interface and is often created by potholes or corrugations (washboarding).

Surface texture with longer wavelengths than megatexture is referred to as evenness, and this is discussed in section 2.3. Macrotexture is commonly measured, and it is this subgroup of texture that is discussed further in this section.

Surface texture can be formed in different ways and differ in vertical direction though the values could be identical on a texture spectrum basis. Regarding different spatial variation, texture characteristic pattern, cavities in the surface, texture can be: periodic or random; isotropic or anisotropic; porous, open or closed.
Regarding the skewness, texture also can be described as *positive* or *negative*. Positive texture is formed by particles protruding above the plane of the surface, and negative texture is composed of voids below the plane of the road surface. A positive texture is generally provided by various types of surface dressings (including chip/sprayed seals) or special surfaces such as hot rolled asphalt, whilst a negative texture is often found in porous asphalt and thin surface materials.

### 3.2.2. Measurement methods

The most common used methods for road surface macrotexture measurements are the volumetric patch method and the profilometer method.

**Volumetric patch method**

The volumetric patch method is a manual method to measure Mean Texture Depth (MTD). A known volume of sand or glass beads is poured on a cleaned road surface and spread out to form a circular patch (*illustration 10a*). Once the used material is spread out to its limits, the average diameter of this patch is measured and mean texture depth calculated using a mathematical formula [6, 7]. When conducted by trained personnel, the method provides a direct measurement of surface texture, with good accuracy and repeatability, and is simple and uses low cost equipment. However, it requires a stationary operator and a traffic-free road, and so is not practical for large scale measurements.

**Profilometer method**

The Profilometer method is an automated method in which the profile of the surface is measured by scanning the road surface with certain type of sensor. Current designs of profilometers used in practice include sensors based on laser, light sectioning, needle tracer and ultrasonic technologies. The most commonly used are laser sensors which use triangulation to measure distance – a laser spot or line is projected onto the surface and the reflection from the surface is focused onto an optical detector (*illustration 10b*).

The distances measured by the laser are then used to calculate either Mean Profile Depth (MPD), or Sensor Measured Texture Depth (SMTD) which are used as measures of macrotexture. The difference between SMTD and MPD is the way that the height of the texture is estimated. SMTD measurement is essentially a root mean square (RMS) measure of the texture both above and below the mean level, whereas MPD measures the height of the highest peaks above the mean level. The measured texture profiles can be transferred into a spectrum by means of a Fast Fourier Transformation, and the indices MPD, ETD and RMS can also be generated to quantify the road surface (*section 3.2.3*).

Laser profilometers can be vehicle mounted or stationary. Stationary laser profilometer techniques are slow and require traffic control or complete lane closure, while vehicle mounted laser profilers can operate at highway speeds without disruption to the travelling public. Standards for measurement of the MPD with the profilometer method are readily available [8, 9, 10, 11].
Besides volumetric patch and profilometer methods, there are few less common technologies to measure road surface texture:

- **Circular Track Meter** [13], which uses a measurement principle similar to the volumetric patch method, except it uses lasers to measure the surface profile of a circle around a circumference. Measurement provides MPD and RMS values of the macrotexture profile.
- **Outflow Meter** [14], which is used to estimate surface drainage and macrotexture of non-porous pavements. The time for the water level to fall by a fixed amount is the outflow time. This parameter has high correlation with both MPD and MTD.
- Imaging technology is based on photographic images to assess road surface texture. High resolution and quality images are made by stereoscopic devices (measuring height, width, angularity, distribution and harshness of projections above the matrix, harshness of the matrix itself), Alternatively, 2D still cameras (measuring grey level variations, shadowing, luminance and viewing angle) can be used to quantify surface harshness or to reconstruct a 3D surface model.
- **3D laser profilers** are used to measure MPD and evaluate texture using digital model of the sand patch method. Road Porosity Index (RPI) is used and defined as a volume of the voids in the road surface that would be occupied by the sand (from the sand patch method) divided by a surface area. The digital sand patch model allows texture to be evaluated continuously over the complete road surface instead of measuring only a single point inside a wheel path.

Road surface microtexture is highly related to skid resistance, and skid resistance measurements (e.g. British Pendulum Number) provide information about microtexture levels. These are discussed in section 3.3.
3.2.3. Indicators

The most used indicators to quantify road surface texture are texture depth and profile depth.

Profile depth

Profile depth is the difference between the profile and a horizontal line through the highest peak (the peak level) within a distance along the surface. The distance along the surface is of the same order of length as the length of the tyre/road interface.

**MSD (Mean Segment Depth)** is the average value of the profile depth of a segment. For practical reasons, MSD is calculated as the difference between the arithmetic mean of the peak levels of the two baseline halves and the average level over the full baseline (*illustration 11*). **MPD (Mean Profile Depth)** is the average of the values of the **Mean Segment Depth** of the tested section. MPD is generally expressed, in millimetres.

![Illustration 11 - Illustration of the terms segment and mean segment depth (MSD)](source: modified from [15])

Texture depth

Texture depth is a distance between the textured road surface and a plane through the peak of the three highest particles within a surface area of the same order of a size as the tyre-pavement contact area. *Illustration 12* illustrates the texture of a pavement in the three-dimensional case and the term texture depth, which is the distance between an arbitrary point of the plane down to the surface perpendicular to the plane.

The mean texture depth parameter (MTD) is the quotient of a given volume of standardised material and the area of that material spread in a circular patch on the surface being tested. MTD is normally expressed in millimetres (mm) and is based on measurement using the volumetric patch method [6, 7].
Alongside the common MTD and MPD parameters, there are some other indicators to quantify texture, including measures based on texture amplitude spectral analysis of the texture [9, 15]:

- Estimated Texture Depth (ETD) is an estimate of the MTD from a measurement of MPD, by means of a transformation equation, e.g. \( \text{ETD} = 0.2 + 0.8 \text{MPD} \). ETD and MPD are expressed in millimetres;
- texture spectrum is obtained when a profile curve has been analysed by either digital or analogue filtering techniques in order to determine the magnitude of its spectral components at different wavelengths or spatial frequencies;
- texture wavelength is a quantity describing the horizontal dimension of the irregularities of a texture profile. The wavelengths can be represented physically as the various lengths of periodically repeated parts of the profile;
- mean absolute deviation of the profile height within evaluation length provides a measure for the profile depth;
- root mean square deviation of the profile height within evaluation length provides a measure for the texture depth;
- skewness of the surface profile is a measure for the asymmetry of the amplitude distribution. This indicates whether the profile curve exhibits a majority of peaks directed upwards (positive skew) or downwards (negative skew);
- kurtosis of the surface profile refers to the weighting of the tails of a distribution and is a measure of how flat or sharp it is in relation to a normal distribution. For example, a distribution with long and thick tails will have a high Kurtosis value.
3.3. Friction

3.3.1. Definition

Friction is defined as the resistance to relative motion between two bodies in contact. In measurement practice the term skid resistance is used and defined as the characterisation of the friction of a pavement surface when measured in accordance with a standardised method. Skid resistance is dependent upon characteristics of the tyre, the vertical load, surface wetness and the pavement material as well as the speed of travel.

3.3.2. Measurement methods

A variety of measurement methods have been developed to quantify friction. Measurement methods fall into four categories:

- longitudinal friction measurement methods (high speed measurement method);
- side force friction measurement methods (high speed measurement method);
- static or low speed friction measurement methods;
- other methods.

Longitudinal friction measurement

This principle is based on measuring longitudinal friction from a braked measurement wheel travelling in a straight line. Longitudinal friction measurement devices represent reaction forces developed in the tyre/road contact area and aim to simulate tyre skidding or sliding over the surface process by controlling the slip rate. Longitudinal friction measurement devices are classified into the following types, based upon the testing tyre slip ratio [16]:

- Locked Wheel - Locked-wheel devices are installed on a trailer which is towed at a typical speed of 60 km/h (illustration 13a). A water film, typically of 0.5 mm thickness, is applied in front of the test tyre, the test tyre is lowered as necessary, and a braking system is forced to lock the tyre. The resistive drag force is measured and averaged for 1 to 3 seconds after the test wheel is fully locked. Measurements can be repeated after the wheel reaches a free rolling state again. Examples of locked wheel devices are SRT-3, locked wheel skid trailer, pavement friction tester (PFT) and ADHERA;

- fixed slip - Fixed-slip devices (illustration 13b) measure the rotational resistance of smooth tyres slipping at a constant slip speed, typically between 12 and 20 %. A 0.5 mm thick water film is applied in front of a retracting tyre mounted on a trailer or vehicle typically traveling at 60 km/h. Test tyre rotation is inhibited to a percentage of the vehicle speed either by a chain/belt mechanism or a hydraulic braking system. Wheel loads and frictional forces are measured by force transducers or tension and torque measuring devices. Data are typically collected every 25 to 125 mm and averaged 1 m intervals. Examples of fixed-slip devices are Roadway and runway friction testers (RFTs), Airport Surface Friction Tester (ASFT), Saab Friction Tester (SFT), GripTester, BV-11, and Road Analyzer and Recorder (ROAR);

- variable slip - Variable-slip devices (illustration 13c) measure friction as a function of slip between the wheel and the road surface. A 0.5 mm thick water film is applied in front of test wheel, which is allowed to rotate freely. The test wheel speed is reduced and the vehicle speed, travel distance, tyre rotational speed, wheel load, and frictional force are collected small
intervals, 2.5 mm or less. Examples of variable-slip devices are IMAG, Norsemeter RUNAR, ViaFriction, ROAR and SALTAR systems.

Illustration 13 - Examples of longitudinal friction measurement devices [16]

Side force friction measurement

This principle is based on measuring side-force friction for a vehicle travelling in a curve when the vehicle's front wheels are turned so that there is a difference between the vehicle direction and the rotation plane of the wheel. The induced angular difference is known as the slip angle. Side force friction measurement devices try to represent reaction forces developed in the tyre/road contact area and simulate angular tyre slipping over the surface process, by controlling slip angle. Side force friction measurement devices, measure pavement side friction or cornering force perpendicular to the direction of travel of one or two skewed tyres. Water is sprayed on the pavement surface and one or two skewed, free rotating wheels are pulled over the surface. Side force, tyre load, distance, and vehicle speed are recorded. Data is typically collected every 25 to 125 mm and averaged over 1 m intervals [16]. Examples of side-force friction devices are British Mu-Meter (illustration 14a), SCRIM (illustration 14b) and SKM.

Illustration 14 - Examples of side force friction measurement devices [16]
Stationary or low speed friction

These easily portable friction measurement devices are suitable for laboratory or localised use. Examples of stationary and low speed friction devices are the British Pendulum Skid Resistance Tester (illustration 15a), Dynamic Friction Tester (illustration 15b), VTI Portable Friction Tester and T2GO.

Other manual methods

Manual stopping distance measurement and deceleration rate measurements are less commonly used. Whilst these methods are simple to conduct, measurement repeatability is poor.

3.3.3. Indicators

A variety of measurements and indicators have been developed to quantify the friction. Summarised friction measurement methods has different indicators derived from the measurements [16].

Friction number (FN) or Skid number (SN)

These indicators are derived from longitudinal friction measurement devices (locked-wheel or fixed-slip). Resistive drag force and the wheel load applied to the pavement are used to compute the coefficient of friction. Variable-slip devices can provide:

- longitudinal slip friction number;
- peak slip friction number;
- critical slip ratio;
- slip ratio;
- slip to skid friction number;
- estimated friction number.
Side force indicators

Side force indicators are derived from side force friction measurement devices. The side force perpendicular to the plane of rotation is measured and averaged to compute the indicator, e.g. the Mu Number (MuN) from the British Mu-Meter, or the side force coefficient (SFC) from SCRIM systems.

**British Pendulum Number (BPN)**

Measured by the portable British Pendulum Skid Resistance Tester, the BPN is based on the pendulum swing height of the calibrated device. The BPN provides friction and microtexture indicators for any pavement, whether in the field or from laboratory analysis of cored or prepared samples. It is also used to evaluate the effect of wear on friction and texture.

**DFT number**

The Dynamic Friction Tester (DFT) produces a friction coefficient (DFT number) and a graph of the friction coefficient for different rotational speeds.

**Other indicators**

Other indicators are stopping distance number (SDN) or deceleration force. Both indicators can be expressed in terms of coefficients of friction using correlation functions.

**International Friction Index (IFI)**

As a result of an experiment conducted in the early 1990s, PIARC developed the IFI to compare and harmonise the various methods used to measure surface friction and texture [17]. The IFI is composed of two parameters: speed constant (Sp) and friction number at 60 km/h (F60).

3.4. TRAFFIC NOISE

3.4.1. Definition

Traffic noise is defined as the overall noise emitted by the traffic running on a road. Based on the origin of the noise, traffic noise can be subdivided into the following categories:

- power unit noise is generated by the vehicle engine, exhaust system, air intake, fans, transmission, etc.
- tyre/road noise is generated by the interaction between the tyres and the surface characteristics of the road.
- vehicle noise is the total noise from an individual vehicle. The two major components are power unit noise and tyre/road noise.

3.4.2. Measurement methods

Near-field measurement of tyre/road noise is measured by the close-proximity method [18], and far-field measurement of vehicle noise by the statistical pass-by method [19].
Close-proximity method (CPX)

The CPX method is designed for measurements of the tyre/road noise isolated from ambient conditions such as engine noise or aerodynamic noise at the car body. The CPX measurements are carried out continuously for complete road sections, thus the method is also suitable to characterise the homogeneity of the acoustic properties of road surfaces.

The CPX method is described in detail in an ISO standard [18]. State of the art CPX measurements are performed using a specially designed two-wheel trailer equipped with reference tyres. Measurement microphones are placed at well-defined positions, in close proximity to the tyre/road contact area and also both in front and behind the tyres to record the rolling noise (illustration 16).

(a) Trailer (source: Müller-BBM). (b) Tyre and measuring microphone / front position (source: Müller-BBM)

(c) Positions of the measuring microphones according to ISO/DIS 11819-2, top view. The height of all microphones above the road surface is 100 mm. [18]

Illustration 16 - Close proximity (CPX) method

For reproducible measurements using the CPX-method standard test tyres are defined [18]:

<table>
<thead>
<tr>
<th>tyre Pl: Uniroyal Tiger Paw</th>
<th>225/60 R16</th>
<th>used as the standard reference test tyre.</th>
</tr>
</thead>
<tbody>
<tr>
<td>tyre H1: AVON AV4</td>
<td>195/80 R14</td>
<td>used as a proxy for truck tyres.</td>
</tr>
</tbody>
</table>

Statistical pass-by method (SPB)

For SPB measurements a microphone is installed at a distance of 7.5 m to the middle of the traffic lane under investigation and at a height of 1.2 m above the top edge of the road surface as shown in (illustration 17 and illustration 18a) [19]. For each passing individual vehicle, the
maximum sound pressure level $L_{\text{max}}$ (in dB(A) units) and the vehicle speed $v$ are recorded. Additionally the road surface temperature, the air temperature and the wind speed at a height of approx. 2.4 m above the road surface are recorded.

Illustration 17 - Set-up for measurements according to the statistical pass-by method (SPB) [18]

A single measurement is considered valid according to the ISO standard if the sound pressure level before and after the pass-by of the vehicle under investigation is at least 6 dB below the maximum sound pressure level of the pass-by event $L_{\text{max}}$.

During the measurements, the vehicles are categorised as follows:

- passenger car: all passenger cars without trailer, no vans, SUVs, and cross-country vehicles;
- two-axle truck: truck without trailer with a rear axle with twin tyres, no buses;
- multi-axle truck: truck with a twin axle at the rear, with trailers or semitrailers, no buses.

Illustration 18 - Statistical passby (SPB) method
(source: Agency for Roads and Traffic, Belgium)
The measurement results are presented in the form of a graph wherein each point shows the maximum A-weighted sound pressure level of a vehicle passing with the associated velocity. A regression analysis allows estimation of average values for arbitrary velocities (illustration 18b).

3.4.3. Indicators

CPX measurements allow the determination of:

- close-Proximity Sound Index for passenger cars and light traffic (CPX\textsubscript{p}) - Index for comparison of road surfaces, which is based on the tyre/road sound levels of passenger car tyres;
- close-Proximity Sound Index for heavy vehicles (CPX\textsubscript{h}) - Index for comparison of road surfaces, which is based on the tyre/road sound levels of heavy vehicle tyres;
- close-Proximity Sound Index (CPXI) - Index composed of the weighted average of the CPX\textsubscript{p} and CPX\textsubscript{h}.

SPB results for the three vehicle categories can be combined to give a single index called the Statistical Pass-by Index (SPBI), which is typically used to quantify, and compare, the influence of road surfacings on the noise emitted by a mixed traffic stream.

In some countries SPB methods have been used to define the noise level generated by different pavement surfacings. These values are used in guidelines for traffic noise management. For example, in Germany, the RLS90, Guidelines for noise protection on roads [21], deals with noise reduction measures and methods for calculation for the quantitative representation of noise exposure. In the guidelines a non-corrugated mastic asphalt serves as a reference with an emission level of 85.2 dB(A) at a speed of 120 km/h for passenger cars. According to the 16\textsuperscript{th} federal emission control regulation (BImSchV) this value can be adjusted using the correction value \(D_{Stro}\) for less noisy road surfaces. RLS90 provides \(D_{Stro}\) values for a range of surface materials as shown in table 2.

<table>
<thead>
<tr>
<th>Surfacing</th>
<th>(D_{Stro})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone mastic asphalt 0/8 or 0/11</td>
<td>-2 dB(A)</td>
</tr>
<tr>
<td>Low noise mastic asphalt (Ver. B)</td>
<td>-2 dB(A)</td>
</tr>
<tr>
<td>Exposed aggregate concrete 0/8</td>
<td>-2 dB(A)</td>
</tr>
<tr>
<td>Porous asphalt 0/11</td>
<td>-4 dB(A)</td>
</tr>
<tr>
<td>Porous asphalt 0/8</td>
<td>-5 dB(A)</td>
</tr>
</tbody>
</table>

The implementation of acoustic measurements allow the classification of all road surfaces compared to this reference based on different indicators, e.g. it is planned to define a \(D_{Stro}\) value for thin asphalt layers with 5 mm maximum grain size DSH-V. The SPB method can be used to determine such new values of \(D_{Stro}\) by determining the average value of the A-weighted sound pressure level for the vehicle category “passenger cars” \(L_{pAF,max}\) at a velocity of 120 km/h. The difference between these new, measured values and the reference surfacing of the RLS 90 results in the \(D_{Stro}\) for the assessed surfacing.
3.5. ROLLING RESISTANCE

3.5.1. Definition

The movement of road vehicles requires that the power unit of the vehicles overcome driving resistance. The driving resistance is due to the following forces:

- rolling resistance;
- air resistance;
- inertial resistance;
- gradient resistance;
- side force resistance;
- transmission losses;
- losses from the use of auxiliary equipment;
- engine friction.

Rolling resistance is one of the most important functional properties of road pavements. It is applicable to the entire road network. Driving resistance and rolling resistance affects energy consumption and emissions from vehicles.

The measurement of rolling resistance is difficult and requires the use of advanced equipment and methods, operated by skilled and experienced staff. This implies that direct measurement of rolling resistance is only practical to do on selected parts of the road network. As rolling resistance is caused by an interaction between the tyre and road it is necessary to consider both factors. A less precise, but more practical way of examining rolling resistance for road management purposes has been developed, allowing estimation from road pavement parameters that in many cases already are collected for most of the road network, such as texture, evenness, stiffness and road topography.

3.5.2. Measurement methods

There are established standard test methods available for testing tyre rolling resistance in laboratories (SAE and ISO [22] methods) but none for testing rolling resistance related to road pavements. It should be noted that most methods described below are in a development phase and are only mentioned here to give a view of the state of the art. The methods are currently being evaluated and assessed in the European project ROSANNE [23]. It has been shown that road pavement characteristics such as surface macrotexture (e.g. MPD) and evenness (e.g. IRI) clearly affect the rolling resistance. A range of other factors and road surface conditions, such as rutting, wetness (water depth) and snow cover also affect rolling resistance. There are currently two major methods under development to measure rolling resistance as it relates to pavement properties: the coastdown method and using a trailer with specified equipment (e.g. tyre) and set up. For surveys and long term road management purposes a third method is suggested using a model that can predict rolling resistance from road pavement data.
Coastdown method

This method measures all resistance contributions when the test vehicle is free rolling (clutch down, gear in neutral position), from a higher to a lower speed on a given road strip. The velocity is measured continuously along the road strip. The effect of air drag is eliminated by special calculations.

The trailer method

The trailer method uses a trailer equipped with a measuring wheel. The trailer is towed along the test section and the rolling resistance forces on the wheel are measured. The wheel uses a standard tyre with specified load and inflation, and the forces that have to be overcome to maintain a specific speed are measured. An alternative approach is to measure the forces needed by the towing vehicle to move the trailer, however the effect of the air drag on the trailer needs to be eliminated.

It is also possible to set up this method without a trailer. The wheel is then mounted in a truck or van as an extra non-powered wheel and the forces are measured in a similar way as in the trailer.

Rolling resistance prediction model

Probably the most practical method for long term road management purposes is to use a model that can estimate rolling resistance from road pavement data. This is done in many pavement assessment models such as the Highway Development & Management (HDM) [24]. The models are currently being improved and updated. Consideration of vehicle type and including many more road pavements characteristics, effects of wet and slushy roads and the transversal position of wheels is part of this development.

3.5.3. Indicators

Rolling resistance coefficient ($Cr$ or RRC – both terms are commonly used, ISO 28580 [22] uses $Cr$ the notation.), represents the characteristic of tyre/road rolling resistance. It is calculated as the rolling resistance force divided by the wheel load. The $Cr$ is dimensionless and a relative measure. It can be used to compare the effects of different tyres and pavement surfacings on the rolling resistance to wheel load. This coefficient typically ranges between 0.003 and 0.02 for modern tyres and pavement surfacings.
4. SURFACE DEFECTS

4.1.1. General

Surface distress data has usually been measured manually, based on visual assessment of distresses by trained personnel. There are three means by which the distress is observed:

- manual rating on foot – Detailed recoding of surface distresses is done for a small length of pavement. The technique can be very accurate, but is slow and requires closure of the road to allow safe access by the observer (illustration 19). Rating of observed defects using a pre-defined set of criteria are recorded using paper forms or a computer;
- windscreen rating – Observations are made whilst travelling over the entire length of pavement, or an entire network of pavements, usually at slower than normal traffic speeds. Rating of observed defects using a pre-defined set of criteria are recorded using paper forms or a computer;
- image rating – Observations are made using still images or video previously collected, over the entire length of pavement or network, by high resolution cameras mounted of a vehicle moving at traffic speed. Rating of observed defects using a pre-defined set of criteria are recorded by a trained technician using software – typically the same computer software used to display the images/video to the person doing the rating (illustration 20). This software allows the evaluator to detect defects on each image and to estimate, if necessary, the extent and severity of the defects. This technique has the advantage of being safer and less disruptive to the travelling public than manual and windscreen surveys. The rating personnel undertake their task in an office environment, and usually with software that allows images to be paused and examined in detail, providing more optimised environment for their task than a moving vehicle. The quality of the analysis is then dependent on the quality of the collected images, the functionality of the rating software, and the experience of the person doing the distress assessments.

Illustration 19 - Technician observing and rating defects using the manual method
(source: Ministry of Transport of Quebec)
In recent times software has been developed to automatically detect pavement cracks in collected still images or video. This is discussed in section 4.1.2.

More recently 2D and 3D laser systems have been developed that can accurately scan the surface of the pavement at normal traffic speeds. Whilst initially focussed on crack measurement, the processing of the collected data by automated software systems is an ongoing area of development, with the number of distress types that can be detected increasing as development continues. This is also discussed in section 4.1.2.

A wide number of indicators of surface distress has been developed, often tailored for specific regional climate, budget and policy conditions.

Some organisations consider repaired distresses as defects in their own right, whereas others do not. Poorly repaired defects are usually considered to be distressed.

4.1.2. Cracking

Definition

A surface crack is a narrow width fracture or discontinuity in the pavement surface material (illustration 21).

Illustration 20 - Technician observing and rating defects using the image rating
(source: ARRB Group)

Illustration 21 - Cracking [1]
Measurement methods

The main way of measuring severity of cracking is to measure crack width and the extent of the area affected by cracking. The type of cracking (longitudinal, transverse, block, crocodile/alligator etc.) is also commonly recorded, as this information assist in diagnosing the cause of the cracking. Detection of cracks is typically conducted by trained personnel using the image rating method discussed in section 4.1.1, or by using automatic software processing of collected images. The WiseCrax software shown in illustration 22 is an example of this type of automated measurement approach.

![Illustration 22 - WiseCrax automated crack detection software](source: Fugro Roadware)

More recently laser and line-scan cameras have been used in place of traditional photographic or video images as source data to automatic crack detection processing software. Some of these systems are able to measure other surface distresses, including transverse profile (section 2.2).

3D laser measuring system

This measuring technique can be conducted at traffic speed, utilising transverse profile measurements collected at spacings of 1 to 5 mm.

The main advantage of these systems is that there is no human factor in the survey and in the analysis. The analysis is fully automatic and is based on well-documented classification and severity levels for each crack detected. Generally, the data is post-processed at the office.

Systems can operate 24 hours per day as long as the pavement is dry and clean. The main disadvantages of the systems are the cost, the high quantity of data produced and the long processing times. Those systems can output 800 MB per kilometre and they can process about 5 km/h for a survey done at 100 km/h.
The laser crack measurement system (LCMS) sensors manufactured by Pavemetrics (www.pavemetrics.com) measure transverse profiles with the following characteristics:

- 4 meters wide transverse profile;
- 4,000 points per profile;
- 1 profile every 1 to 5 mm at 100 km/h (programmable);
- accuracy of 0.5 mm in elevation.

The LCMS sensors and processing software can be incorporated into survey vehicles (Illustration 23) and processing systems manufactured by other companies. In addition to cracking, the following distress and condition types can also be measured by the combination of the accurate recording of the pavement surface and the detection algorithms programmed into the processing software:

- ruts (depth and type);
- potholes / local unevenness / depression;
- delamination;
- ravelling;
- edge break;
- bleeding;
- spalling;
- patching;
- polishing;
- joints;
- pavement imaging.

Illustration 23 - Ministry of transport of Quebec, survey vehicle showing two lcms sensors mounted on rea
(source: Ministry of Transport of Quebec)
Illustration 24 - Example of crack detection from the LCMS system
(source: Ministry of Transport of Quebec)

2D Line scan cameras (2D)

The Pavemetrics manufactured Laser Road Imaging System (LRIS) combines high speed/high resolution linescan cameras and high power laser line projectors that are aligned in a symmetrically crossed optical configuration. The two cameras and lasers are configured to 4 m wide road sections with 1 mm resolution (4,000 pixel) or 0.5 mm (8,000 pixel option) at speeds of up to 100 km/h.

The Appareil Multifonction d'Auscultation des Chaussées (AMAC) system (Illustration 25) produced by VECTRA in France (http://vectrafrance.com/vectra-ingenierie-routiere) uses a similar coupling of linescan camera and laser projection to acquire high resolution images not dependent on lighting conditions. Profiles are taken across a 3.9 m width, and the system can detect cracks to a resolution of 2 mm wide and 1 m long.

Illustration 25 - AMAC system incorporating linescan cameras for crack detection
(source: VECTRA)
RoadCrack (illustration 26) is a real-time automatic crack measurement system that was initially developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the Roads and Maritime Services of New South Wales (RMS NSW, formerly the Roads and Traffic Authority, NSW) and was recently upgraded by ARRB Group (www.arrb.com.au). The system utilises a bank of four adjacent modules that are aligned across the pavement, each fitted with a high resolution line scan camera and its own lighting system. The system has been in operation since the mid-1990s and has collected over 20,000 km of cracking data across the RMS road network each year. Over this time, the results have been found to be repeatable at highway speeds on all surfaces, including coarsely textured chip/sprayed seals [27, 28]. The system is unique in that it can automatically classify and measure cracks in real-time, with widths down to 1 mm.

Illustration 26 - Roadcrack crack detection system, trailer and lighting
(source: ARRB Group)

Indicators

A wide number of indicators of cracking distress have been developed. One indicator is the ratio of the total cumulated lengths/areas of all the cracks measured and the corresponding measurement surface area. Another common system is the type/severity/extent approach, as demonstrated in table 3.

<table>
<thead>
<tr>
<th>Cracking type</th>
<th>Severity categories</th>
<th>Name</th>
<th>Width range</th>
<th>Extent categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td></td>
<td>Fine</td>
<td>≤ 1 mm</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>1 mm – 3 mm</td>
<td>1 % – 5 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide</td>
<td>&gt; 3 mm</td>
<td>5 % – 10 %</td>
</tr>
<tr>
<td>Transverse</td>
<td></td>
<td>Spalled</td>
<td>&gt; 3 mm and spalled</td>
<td>10 % – 25 %</td>
</tr>
<tr>
<td>Block</td>
<td></td>
<td></td>
<td></td>
<td>&gt; 1 %</td>
</tr>
<tr>
<td>Crocodile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irregular</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3 - EXAMPLE OF TYPE/SEVERITY/EXTENT CRACKING INDICATORS
4.1.3. Potholes / local unevenness / depressions

Definition

A pothole is a localised deterioration of the pavement surface resulting from breakdown and loss of the surface material, in a relatively short time, leaving a steep depression. Typical potholes have a depth of at least 30 mm, and an area equivalent to a diameter between 10 cm and 1 m.

It should be noted that this type of defect is usually repaired shortly after its appearance, in accordance with local maintenance practices.

Illustration 27 - Potholes [26]

Possible causes of potholes are:

- presence of significant, mainly crocodile/alligator type, cracking of the surfacing, coupled with fast traffic;
- localised failure of supporting granular base or foundation;
- inadequate thickness of the wearing coating;
- highly stressed by heavy traffic.

Note: The pothole is often the final manifestation of a combination of different problems.

Measurement methods

Manual measurement methods typically determine the area and number of potholes within a defined section. Manual detection methods are typically used to initiate repairs. Periodic measurement can be done automatically using 3D laser systems or by visual surveys.
Indicators

A common indicator used is the ratio between the number and/or area of potholes and the surface of the surveyed section area.

4.1.4. Delamination

Definition
Delamination is the separation of the wearing course from the sound underlying pavement layer.

Possible delamination causes are:

- poor adhesion of the wearing course with the underlying layer (e.g.: lack of tack coat, chemical incompatibility between the layers, presence of dirt);
- inadequate thickness of the surface layer;
- high traffic loads.

Illustration 28 - Delamination [26]

Measurement methods.

As for potholes (section 4.1.3)

Indicators.

As for potholes (section 4.1.3)
4.1.5. Ravelling

Definition

Ravelling is a progressive loss of pavement material, mainly caused by stripping (separation of bituminous film from aggregate particles). Ravelling can be also be known as fretting.

The main possible causes of ravelling are:

- hardening of the bituminous binder due to ageing;
- spillage of materials resulting in degradation of the binder;
- bad adhesion between bitumen and aggregates;
- defect on the asphalt mix during coating.

Measurement methods.

Measured using manual methods, the dimensions of the area concerned are recorded.

Indicators.

A ratio of the area affected and the total surface area can be used as an indicator.

4.1.6. Edge break

Definition

Edge break occurs when the edge of surface material is fretted, broken or irregular.

Measurement methods

Edge break is typically measured using visual surveys or using optical reading devices (3D laser systems).

Indicators

Typical indicators are the ratio between the affected surface area and the total surface area, or
the length of effected area.

4.1.7. Bleeding

Definition

Bleeding results from the movement of bituminous binder to the surface resulting in a reduction in surface macrotexture.

The possible causes of bleeding are:

- excess of bituminous binder;
- quality of the binder;
- high temperatures;
- inadequate voids in asphalt;
- embedment of aggregate.

Measurement methods

Bleeding is identified by visual surveys or by large decreases in surface macrotexture (section 3.2) or using optical reading devices (3D laser systems). Point lasers can also be used to identify bleeding by specifying a minimum texture level.

Indicators

The ratio between the effected surface area and the total surface area can be used as an indicator. Length of affected area can also be used.

4.1.8. Spalling

Definition

Spalling is the crumbling, cracking, or breaking of a concrete slab, particularly at edges, joints or cracks.
Measurement methods

The only measurement method is a visual inspection leading to the determination of the total length effected.

Indicators

The spalled area is typically used as an indicator.

4.1.9. Patching

Definition

Patching is the localised repair of previously damaged pavement. Patching corresponds to an area where localised repairing works have been done on the existing pavement.

Some organisations consider patches as defects in their own right, whereas others do not. Poorly repaired patches are usually considered to be distressed.

Illustration 33 - Patching [26]

Measurement methods

Area of length of patched road is determined from visual surveys or using optical reading devices (3D laser systems).

Indicators

The total patched area is commonly used as an indicator. The ratio of the patched area and the total area is also used.

4.1.10. Polishing

Definition

Polishing is the decrease in microtexture of surface aggregates due to the passage of traffic.

Possible causes polishing are:

• poor abrasive properties of aggregate;
• high traffic volumes.
Measurement methods

Surface friction measurements (section 3.3) are used to detect regions affected by polishing.

Indicators

Refer section 3.3.
5. STRUCTURAL CONDITION

5.1. DEFINITION

The definition of pavement deflection is a vertical deformation due to a load, measured at the surface.

Pavement deflection is commonly used as an indicator of the strength of the pavement structure. Deflection measurement techniques are generally used in preference to destructive methods for assessing strength due to the lower costs of non-destructive deflection testing, reduced need for lane closure and traffic control during testing, and the lack of damage done to the pavement. These benefits enable a higher number of tests to be conducted than would occur using destructive methods such as excavating inspection pits or trenches.

The application of a load to a surface results in a deflection of the pavement surface, with the magnitude of the deflection generally decreasing with increasing distance from the applied load. The resulting shape is typically called a deflection bowl, and is shown schematically in illustration 35. A commonly used convention is to denote the surface deflection at a location using the letter with a subscript indicating the longitudinal distance of the location from the point of maximum deflection. Thus denotes the maximum deflection recorded, and the deflection 300 mm from the point at which was recorded.

5.1.1. Measurement methods

A variety of devices are used to measure pavement deflection, and these devices use a range of load application methods. A given pavement’s deflection response to a load will depend upon the composition of the pavement, the magnitude of the load applied, and also the nature by which the load is applied. An absolute one-to-one correspondence between different deflection measuring technologies cannot be reasonably expected to exist for all pavements. However, high degrees of correlation are generally observed.

Benkelman beam

The Benkelman Beam was developed by A.C. Benkelman in the 1950s (illustration 36). Testing is conducted by apply a rolling wheel load using a dual-tyred single axle (usually loaded with
8.2 tonne). The deflection is measured using a pivoted beam, with the measurement tip placed between the dual-tyres of the axle in the wheelpath of interest. The loading vehicle is slowly driven away from the beam and the resulting movement of the beam is recorded at the pivot. Simple geometry is used to determine the deflection at the tip of the beam that corresponds to the displacement recorded. The original design used a dial gauge to display the displacement and required an observer to manually record the test reading. It is only practical to measure the maximum deflection response using such systems. Subsequent design modifications continually record the displacement which, when coupled with continuous measurement of the distance that the load vehicle has travelled, allows the measuring of a full deflection bowl.

Illustration 36 - Benkelman Beams in use

Pavement deflection testing using Benkelman Beam is a slow, labour intensive process, and is not practical for testing long lengths of road, nor for conducting testing with small intervals between tests. Accordingly the use of Benkelman Beam testing for network level condition surveys is considered impractical.

Deflectograph

Deflectograph devices provide a means of automating Benkelman Beam type testing. A variety of Deflectograph devices have been developed over the last four decades using the sample basic operating principals. The measuring system is integrated with the loading vehicle into a single device (Illustration 37). Deflection measuring beams, one for each wheelpath, are mounted on a reference frame. The testing sequence begins with the frame being placed on the road surface with the tips of the measuring beams between the load axle dual-tyres. The frame remains on the surface as the vehicle slowly drives forward, and the displacement response and the travelled distance are both recorded, the frame is then mechanically lifted from the surface, or dragged along it, and then placed for the next test. Such systems allow for deflection bowls to be measured at spacings of approximately 5 metres, whilst the vehicle is smoothly driven along the test road. In many Deflectograph designs measurement beams are oriented so that the loading wheel travels towards the beam. The length of the sensor frame and movement mechanism is constrained by the length of the loading vehicle, and as a result Deflectographs are unable to measure a full deflection bowl. Deflections located further from the load cannot be recorded, and the length of the recorded bowl is dependent upon individual Deflectograph designs.
The speed of Deflectograph testing is limited by both the speed with which the mechanical movement of the frame can be practically undertaken, and with the time taken by the displacement measuring sensors to stabilise to a null reading after movement of the frame. Testing speeds of 2 – 5 km / h are typical. The automated nature of Deflectograph testing makes the devices suitable for small network level testing as well as project level investigations. The slow travelling speed of the vehicle necessitates the use of moving traffic control systems to provide safety to both the vehicle operators and other road users.

Many bespoke Deflectographs have been developed by individual road agencies. The Lacroix Deflectograph was the first commercially available system, based on the 1950s design of MJ Lacroix of the Ponts et Chaussées à Périgueux in Dordogne, France. Most Deflectographs in use today are derivatives of the original Lacroix design. Within France the Lacroix design has been refined over the years and the current system, the Flash Deflectograph, is commercially available from VECTRA (www.vectra.fr). WDM (www.wdm.co.uk) have commercialised a Deflectograph design developed in the 1970s in the UK, based on the Lacroix concept.

Developed by France’s Centre Expérimental de Recherches et d’Études du Bâtiment et des Travaux Public (CEBTP), the Curviometer is not based upon Lacroix’s Deflectograph design. The system design has been progressively updated since its inception in the 1970s. Like a Deflectograph the system integrates the measurement sensors into the load application vehicle. As seen in illustration 38, geophones or accelerometers are fixed to a 15 metre long looped chain that is continuously being placed on the road surface between the dual-tyres of the loaded axle. The three sensors evenly spaced along the loop enable the measurement of a full deflection bowl every 5 metres of distance travelled. The significant advantage of the Curviometer is that the device allows higher testing speeds, with a typical speed of 18 km/h. A disadvantage of the system results from the long length of chain that lies on the road surface; testing must be halted, and the chain lifted, when travelling through curves or turns.
The device is well suited to conducting network level surveys, as well as project level investigations, although the slow travelling speed, in comparison to normal traffic speeds, does necessitate additional traffic control measures.

Although the Curviameter is not currently used in France, the Belgian Road Research Centre (www.brcc.be) and Spain-based Euroconsult (www.euroconsult.es) routinely conduct network level surveys with Curviameter systems. Euroconsult manufacture new systems.

**Falling Weight Deflectometer**

Unlike the previously discussed deflection measurement systems Falling Weight Deflectometers (FWDs) do not measure the deflection response of a pavement to a rolling wheel load. Developed in Scandinavia from the late 1960s, FWD testing involves the application of a dynamic load induced by a falling mass applying a force to a static plate in contact with the road surface. Geophones located within the load plate, and at varying distances offset from the load measure pavement surface responses. From these responses the deflection of the road surface is then derived.

As the generation of the load is by the falling mass and not as a result of a large gravimetric mass used by other deflection devices, FWD systems are comparatively light weight. FWD equipment is generally mounted on trailers (Illustration 39) which can be towed by light commercial vehicles or passenger vehicles suitable for towing heavy trailers or caravans. Some FWD manufactures offer systems which integrate the FWD load and sensors into the vehicle itself, negating the use of a trailer.
Whilst the load applied to the pavement is dynamic, FWD tests are conducted whilst the equipment is stationary. The high precision of the geophone sensors used, and the application of repeated load drops at the same test location allows the accurate measurement of both applied load and deflection response. By careful selection of rubber materials used on the load plate and for the buffers which absorb the impact of the falling weight, FWD designs aim to develop a load pulse of similar width and magnitude to the idealisation of the load applied by a vehicle travelling at normal traffic speeds. As a result FWD equipment is perceived by some practitioners as the most accurate of deflection measuring systems. Others argue that the applied load is not the same as the rolling wheel load applied by traffic vehicles.

As FWD testing is conducted whilst the system is stationary, traffic control is required for the safety of the operator and travelling public. The spacing between adjacent FWD tests is arbitrary. Whilst testing at spacings of 1 metre or less is used in research applications, more common spacings are 5, 10 or 20 metres in project level applications. Network level testing with FWD equipment has been conducted, however budget constraints usually result in spacings between tests of several hundred metres.

FWDs are commercially available from Dynatest (www.dynatest.com), Grontmij|Carl Bro (www.pavement-consultants.com) and Kuab (www.kuab.se).

Measurement at traffic speed methods

For time efficient collection of deflection data at network levels high collection speeds are necessary. Ideally collecting data whilst travelling at the general traffic speed on the road would allow both the most efficient collection of data, but also negate the need for many, if not all, additional traffic control requirements. All of the above deflection measurement technologies utilise sensors that are in physical contact with the pavement surface. The use of such sensors limits the number of tests that can be conducted in a given period of time using static systems like the Benkelman Beam or FWD. Similarly continuous measurement systems, such as Curviamètre and Deflectographs, are limited in the speed at which they can travel.
In recent years, new deflection methods have been explored that use non-contact sensors, such as lasers, to record the response of the pavement surface without making physical contact with the surface. Considerable research and development work has been undertaken to date, however only two systems have emerged that appear mature enough to be considered ready for adoption.

FHWA Rolling Wheel Deflectometer

The US Federal Highways Administration (FHWA) has developed and extensively tested a prototype Rolling Wheel Deflectometer (RWD). Developed under contract by ARA (www.ara.com/Projects/p_RWD.html) the RWD uses laser sensors to record the longitudinal profile of the road surface in front of a loaded axle, and also between the dual-tyres of the loaded axle. By subtracting successive readings the deflection of the road profile can be determined. The system is limited to the measurement of the road deflection immediately under the applied load. However data can be collected at near highway speeds of up to 80 km/h.

Only a single device has been constructed to date (illustration 40).

Further information, including extensive research reports, are available from the FHWA (http://www.fhwa.dot.gov/pavement/management/rwd/).

[Image: Illustration 40 - FHWA rolling wheel deflectometer (source: federal highways administration)]

Greenwood Traffic Speed Deflectometer

Developed in conjunction with the Danish Road Directorate, the Greenwood Engineering (www.greenwood.dk) Traffic Speed Deflectometer is the first commercially available device able to measure pavement deflection at traffic speeds. First generation design Traffic Speed Deflectometer (TSD) devices are widely used in Denmark (Danish Road Directorate) and the UK (Highways England), and second-generation devices are now used in Italy (ANAS), Poland (Road and Bridge Research Institute - IBDiM), China (Research Institute of Highways), South Africa (SANRAL) and Australia (ARRB Group).
Central to the design of the TSD is the use of Doppler lasers that measure the velocity at which the road surface moves whilst being subjected to load. Each Doppler laser measures the instantaneous velocity of the road surface, and therefore comparisons between adjacent lasers are not needed to determine the deflection change resulting from the application of load. Significantly, the maximum deflection cannot be directly measured as, by definition, the velocity at this point would be nil.

Multiple Doppler sensors can be spaced along a beam, enabling the pavement response at offsets away from the load to be recorded. Currently alternative methods of generating a deflection bowl similar to that recorded by Deflectograph, Curviamètre and FWD devices are being explored.

By enabling the collection of pavement deflection data at up to 100 km/h, although systems are currently operating closer to 80 km/h, the TSD can provide continuous deflection data at network level. TSD data can be used to identify local areas of pavement discontinuity that can be subsequently investigate using traditional project level tools. However, most current TSD owners are hopeful that TSD data will prove to be of suitable accuracy to use in some project level analyses.
### 5.1.2. Indicators

The most common, and oldest, pavement deflection indicator is the maximum deflection response of the pavement to the applied load. This is used in a variety of ways:

- as an indicator of variability in construction quality;
- as a specification limit in construction works;
- as a consideration to aid in the selection of appropriate rehabilitation treatment types;
- as an input into structural overlay design procedures;
- as an indication of changing structural condition with the passage of time.

Other deflection bowl parameters are used to provide additional insight. Some agencies use single bowl parameters, e.g. common use in Australia of as an indicator of subgrade condition, or derived parameters such as pavement curvature that are related to the amount of flexure experienced in the upper, particularly asphalt, layers of a pavement. The curvature parameter $D_0 - D_{500}$ is commonly used – often termed SCI300. In some countries with relatively thin asphalt pavement, the curvature function is defined as $D_0 - D_{200}$. The radius of curvature of the deflection bowl is also used.

Full deflections bowls can be used in back-calculation processing in order to estimate the properties of in situ materials, of known thicknesses. In these calculations, response-to-load (usually layered linear-elastic) pavement calculations are conducted with the modulus properties of the pavement layers adjusted in an iterative manner in order to calculate a deflection bowl that best matches the measured bowl.

Deflection results can also be used as predictors of other pavement structural indices. The most commonly used one is the structural number of the pavement. A range of different correlations between structural number and deflections results have been determined for different pavement types and deflection measuring equipment [30]. The final report of the COST 354 project [31] suggests that the residual service life should be used as a structural indicator.
6. IMPORTANCE OF MANAGING DATA QUALITY

6.1. BACKGROUND

As described in the introduction, road pavements comprise a major component of public infrastructure, and are designed to have long service lives delivering safe, smooth, all-weather access for people and goods. Sound asset management practices require regular assessment of the condition of this infrastructure, to ensure that it is meeting the needs of the travelling public, and in assessing what remedial works are necessary to ensure that established levels of service can be achieved.

Tools to improve pavement management, planning and maintenance are continuously developed. Almost since the first road was built, means of judging the quality has been needed. The development of monitoring techniques has progressed from pure visual inspections to today’s highly sophisticated computerised multifunction systems. The challenges regarding the functionality of those systems are continuously increasing, and the requirements as to what data should be collected changes with time. The constant demands on higher operational efficiency drives the development of multifunction systems that are able to obtain many different condition parameters in a single pass, and the optimisation of techniques to use the least expensive sensors capable of achieving the precision required.

Profilometers are examples of such dedicated tools that are used to reliably monitor the condition or status of the road pavement. A business segment has gradually grown up with a large number of companies offering profilometers of different types and functionality. In the introduction a variety of uses for condition data are listed. These can be divided into three important categories for the data quality aspects:

- long term planning: knowledge of the condition of an entire road network including trend analysis and prognoses;
- object and project monitoring: support in the daily construction and maintenance;
- contracts: performance control of contractors.

These categories and the relationships between them is illustrated in illustration 42. It is important to remember that data from monitoring systems are used in all levels, either as a direct parameter or part of a more complex indicator.
Key performance indicators [32, 33] are built up from monitored information combined with static asset data as well as inclusion of policies and required standards as can be seen in illustration 43.

Illustration 42 - Categories of condition data usage
(source: VTI, Sweden)

Illustration 43 - Performance indicators and parameters
(source: VTI, Sweden)
6.2. OVERALL QUALITY REQUIREMENTS

The required quality of data depends upon the use of the data. The same technical parameter can be used to form indicators at different levels, and thus have different requirements of precision. In some cases, the technical parameter can be used as is (i.e. standalone).

When used as a parameter supporting performance indicators on the higher level, the quality requirement must consider the importance of long-term robustness e.g. when used as a benchmark between years. The quality requirements for profilometer data for long term planning have to be well known and high. One reason can be seen in illustration 44, which includes a deviation in condition for one year in a series of data. The question arises as to whether this is an actual change in the pavement condition or an error in the monitoring system. This curve is probably a more realistic example of a condition trend collected over time curve than the smooth and gradual lines often illustrated.

Illustration 44 - Road condition trend with uncertainties
(source: VTI, Sweden)
6.3. QUALITY APPROVAL (QA) PROCEDURES

The cradle to the grave process regarding road condition measurement can be divided into four parts expressing major risk sources of error, see illustration 45. A valid indicator must be specified and used. The indicator must be measureable and reliably implemented into the software and hardware. The operator of the measuring equipment as well as the user of the data and the data manager must be skilled enough. Defining and specifying the data is important [34].

Illustration 45 - Major sources of uncertainty
(source: VTI, Sweden)

Many countries have introduced quality approval procedures. Unfortunately, many of these focus largely on the sensors and the equipment. Based on both experience and tests [35, 36, 37], a major source of error can be related to the behaviour and processes used by the human operator. As shown above many more risk sources needs to be included. Considering the main responsibilities for quality, three levels of control can be defined:

- **sensor control**: the responsibility of the equipment manufacturer and the operator;
- **application control**, meaning signal filtering, the implementation of technical parameter calculation, etc.: the responsibility of the operator and measurement service provider;
- **total function control**: the responsibility of the client/road owner.

It is suggested that this third total function control should include quality control procedures conducted before, during and after measurement. The road owner having their road network monitored must be sure that they can get the required data in the right format and in the required time. As total function control is the responsibility of the road owner, it is recommended that all processes shown in illustration 45 be undertaken on a small section of collected data before committing resources to collection of data for the large networks.

Part of any quality assurance procedure is to understand the reliability of the monitoring method. Reliability consists of three major parameters (illustration 46):

- **repeatability**: how repeatable the measurements are, using repeated tests using the same equipment/operator;
- **reproducibility**: the repeatability using different equipment/operators;
- **validity**: how comparable the result is to the true value, in practise represented by a reference value.
6.4. CONCLUSIONS

To conclude it should be remembered that it is the use and purpose to which technical parameters and indicators are to be put that should drive the specification of the quality requirements. Long-term monitoring needs as high a quality, or even higher quality, than short term object/project level monitoring. Monitoring to be used in performance control of contractors must also be of the highest quality.

The major source of uncertainty is the human interaction/operator and location of data not the sensors [4]. The sensors are almost always very reliable and robust. Section 7 describes quality procedures in more detail. This is followed in section 8 by a specific case study of procedures from Quebec in Canada.
7. QUALITY MANAGEMENT: VERIFICATION AND VALIDATION

7.1. QUALITY CONTROL

The purpose of quality control is to ensure that data gathered on the road network are reliable, usable and are collected at minimum cost.

As discussed in section 6 there are many different stages of the data collection and use process at which the quality of data needs to be assessed and controlled. This section describes three main areas where quality assurance processes are undertaken.

The first is the control of equipment and sensors dedicated to the data collection. This is when all checks and calibrations are carried out. The second area relates to the process of data collection itself. It is within this control that it is ensured that the locating of collected data to points on the road network, the optimal speed of survey, the environment, etc. all meet the established standards required by the road owner. Finally, the last area of control is directly connected to the data itself.

7.2. QUALITY CONTROL OF SENSORS AND EQUIPMENT

7.2.1. Sensors

Quality control of sensors is done via regular calibration and monitoring over time. The calibration must always be carried out according to the recommendations of manufacturer using procedures and reference tools that should be provided with the device (Illustration 47). These reference tools, e.g. forms of known dimensions, must have a unique identifier (to enable traceability) and if applicable be carefully stored so as to avoid any physical alteration.

Tracking of the calibration of the sensors with time provides the ability to detect any excessive drift in the sensors. With this information a proactive approach can be implemented to remove or repair any sensor that fails the calibration to the established standard. This information also provides the opportunity to gradually adjust the calibration schedule. For example, if a calibration is performed weekly, and it is observed that the unit had not drifted for several months, it might be possible to extend the time between these calibrations in order to achieve a more optimal schedule.

Illustration 47 - Reference form for the calibration of laser sensor on a road profilometer
(source: Ministry of Transport of Quebec)
Calibrations and verifications of the sensors must be made regularly or according to the schedule recommended by the manufacturer in order to detect all defects or drifts. An important point while performing a sensor calibration is to know the state of it prior to the calibration. Therefore, it is strongly recommended before doing any physical adjustments or modification to the calibration values, to know if the sensor it currently respecting the limits imposed by the standards. Doing so will allow the documentation of any drift of the sensor (resulting from accidental or natural causes) and will provide all the necessary information to select the best course of action to take regarding data gathered since the last calibration (e.g. deciding to reject that data).

Some systems require a lot of time to calibrate or must be sent to the manufacturer for them to carry out the calibration. However for these systems periodic checks can still be made between undertakings of the more onerous full calibration process. For example, in the case of 3D laser sensors, this verification may be carried out by measuring the shape and size of a reference surface (illustration 48). Any deviation of the measurement that does not respect the precision stated by the manufacturer will indicate that it is time to calibrate the sensors. Another example might be to conduct a survey on a reference site (road section) whose parameters are known. The comparison of the results between the survey and the baseline data serves as a form of validation.

Illustration 48 - Reference surface for a 3d laser system
(source: Ministry of Transport of Quebec)

7.2.2. Equipment

After the sensors are properly calibrated, the next stage is to qualify/validate the equipment which, by definition, is the grouping of one or more sensors that allow automatic or semi-automatic collection of pavement surface characteristics. Such validations will allow checking of the entire equipment in a real environment, i.e. on reference road sections.

Two types of validation are possible. The first is more comprehensive and generally would be undertaken before the beginning of a season of surveying in order to qualify the survey equipment. All the survey systems are evaluated in detail on a small number of sites that are very well documented. Once the device is qualified, a detailed validation will be performed on a large number of sites, speeds and runs. This validation will provide assurance that the equipment produces good results on the entire range of monitored defects.
The second type of validation will be performed periodically throughout the season of survey. It will consist of a smaller number of sites and runs. These second validations will detect any drifts of the equipment and will provide all the necessary information to determine the point in time from which the unit has become defective or out of calibration. In the event that the equipment does not meet the minimal criteria, the survey must be stopped immediately and the equipment has to be technically reviewed in order to find and rectify the source of the error.

Established well-documented reference sites (measured with reference devices, *illustration 49*) are needed to validate or qualify the survey equipment. The surveys conducted by the equipment on these sites will enable comparisons and correlations between different systems to be made, as well as comparisons to the established references. Some standards can also be used to qualify a system, for example, the ASTM-E950 standard [38] is commonly used for the qualification of laser road profilometers. Regardless of whether an international or locally developed standard is used, it will be necessary to put in place reference sites respecting those standards. In addition, sites must be representative of the condition of the roads that will be surveyed.

*Illustration 49 - Measuring rutting on reference site using laser rut reference bar device*  
(source: Ministry of Transport of Quebec)

Each of the reference sites will be selected based on the defects present as well as their consistency throughout their length. It is important for a site to be homogeneous as to avoid major gaps between the values. For example, a site selected to validate ruts measurement will have ruts depth of same size and same shape along its entire length. This will ensure the stability of the equipment and if there are deviations observed, it they will be easier to explain. In addition, the number of sites needed to validate equipment will be determined by the range of values observed throughout the network to be surveyed.

Ideally a reference site can be used to validate several equipment components. For example a reference section can be simultaneously used to validate texture and profile. This situation is desirable and will reduce the time required for the validation or qualification and the costs associated with that operation.
It is important to note that due to the large number of survey runs to be done on the reference sites, factors such as the safety and the permitted speed must be taken into account when selecting sites in order not to endanger the lives of the operators and users of the road. In addition, the length of the reference tracks should be limited to avoid distance shifts caused by the accuracy of the odometer present on the equipment.

In some cases where it is very difficult to establish a reference site, it will be necessary to artificially build sections of roads. These artificial sites are quite expensive and very difficult to put in place, but they have the benefit of not physically changing over time. For example, the use of these types of sites are recommended for the validation of automated crack measurement device. This type of site will allow the measurement of the repeatability of equipment and the evaluation of bias (deviation from the reference) can be easily determined due to the high accuracy to which the reference constructed crack (**Illustration 50**) can be measured.

**Illustration 50 - Cracking reference sites**  
(source: Ministry of Transport of Quebec)

The number of survey runs necessary as well as the speed at which those runs should be carried out can be driven either by a well-established standard or can be determined locally. The decision will take into account the type of validation (qualification, detailed or periodical validation). The number of runs must be statistically significant. Usually a minimum of 5 or 6 runs for each speed is recommended. With respect to the speed at which the runs should be made, a rule of thumb is to look at the speeds at which the network survey measurements will be carried out. Increments of 25 to 30 km/h starting from the lowest speed provide a good range – e.g. 50, 75 and 100 km/h. In addition, all recommendations of the manufacturer must be taken into account (e.g. minimum and maximum speeds at which the equipment can operate). Exactly locating the start of the run is also important in order to ensure the synchronisation between each runs.

Finally, it is important to have good communication with the department responsible for road maintenance. It is not uncommon for a reference site to be scheduled for maintenance. To avoid losing a reference site during the survey season, it is advised that contact be made with personnel responsible for maintenance planning before doing any detailed characterisation of a site.
7.2.3. Acceptability thresholds

The thresholds or levels of acceptability with which a piece of equipment must comply can be variable depending on the type of surveys that equipment must perform. Thus, more permissive criteria can be adopted in the case of network data collections while they will be more severe in the case of surveys for accepting maintenance work. Moreover, these criteria must be respected in qualification as well as during the various validations throughout the season.

Different thresholds should be established for each of the identified defects. These thresholds will establish the level of acceptability with respect to repeatability as well as for bias (deviation from the reference).

Existing standards (e.g. ASTM-E950 [38]) may serve as a basis for establishing these thresholds. In absence of a standard, previous survey experience can help guide decisions. Additionally, the technical specifications from the manufacturer of the equipment can be used as starting point for the establishment of thresholds.

7.3. QUALITY CONTROL OF NETWORK DATA COLLECTION

Before the beginning of the survey season, and as specified in the previous section, it is necessary to carry out equipment qualification (whether equipment is operated by the road owner or by an external service provider). In addition, periodically or after a predefined number of kilometres of survey kilometres (e.g. 1000 km), a validation of the equipment must be made. The number of kilometres between checks must be practical.

Additionally, the modus operandi of the equipment plays an important role on the quality of the collected data. This operation must be well framed by a detailed procedure. Starting from those procedures, the operating personnel must be well informed about the control of the equipment and also about the hardware and software limits.

In no specific order, the most common errors are:

- minimum or maximum speed limits exceeded;
- sudden speed changes;
- exceeding the equipment physical limits and operational environment;
- presence of water on the pavement (laser sensors);
- sensor operational temperature range exceeded;
- poor reference information;
- bad location on the road network;
- bad surveyed line (i.e. in the wrong lane);
- bad position in the surveyed line (i.e. in the wrong transverse location within the lane);
- bad position in a curve;
- road detour undocumented (area of work, accident, etc.), including line change;
- lack of documentation of the events that can impact the quality of the data (logbook);
- loss of computer files or corrupted files during the data transfer;
- misidentification of the data (e.g. incorrect file name);
- length of the run too long. Cumulative distance error (odometer).
As can be seen from this list, a major source of error is related to the physical location of the survey. Poorly localised data has no value, even if it meets all other quality criteria.

The use of the location by GPS technology can help, but for most cases these coordinates must be converted to a linear positioning system and the accuracy of GPS systems does not permit, for example, the discerning between a lane and a ramp access merging.

Therefore strong surveying protocols should be put in place. These must be mastered and understood by the operators of the equipment. These protocols will describe all possible situations and explain the necessary actions to be taken. In addition, protocols must be refined and will get improved as new situations are encountered. Such an approach will progressively reduce ambiguities.

Regular meetings should be scheduled between the equipment operators and the management team to allow feedback on the operational mode and to solve problematic situations.

It is strongly recommended that the operators keep a logbook indicating all events that have an impact on the quality of the data. Whether it is for a road detour imposed by a road maintenance site or an unplanned lane changes, the journal should reflect what happens along the way. This will help the people who will have to process and validate the data (and to invalidate it if necessary).

### 7.4. QUALITY CONTROL OF THE DATA

Once the data is collected, it must be processed, verified, and validated in order to be certain that when it is uploaded into a database or pavement management system it has a high quality.

#### 7.4.1 Data processing

The data processing phase comprises the conversion of the raw data into interpretable data. Processing software and computer systems perform this task.

At this level, the only quality control that is exercised is to verify that all the files coming from the equipment have been processed without problem and they were consistent and readable. If a file is corrupted, a request should be made to the operators to provide a new copy of the file. To perform this operation, it is necessary that all the data files in the equipment are never deleted until they have been processed successfully. At this point the files present in the equipment may be erased. When the second copy of the file is also corrupted, then a request to repeat data collection should be made to the operators.

#### 7.4.2 Data verification

The verification of the processed data phase exists to ensure that values or indices characterising the road surface are well within the ranges of valid values. All values out of range should be detected and explained. The analysis of any non-compliance will be mainly based on the study of the operator logs which should indicate any problems or incidents during the survey. In addition, the video images recorded at the same time (if available) can provide assistance.

If several files do not pass the verification step, an analysis of the condition of the equipment (calibration of sensors, etc.) should be undertaken in order to detect any defect. Furthermore, the determination of the exact moment when the equipment started to produce bad data is needed. This will help to identify all sections of road which must be surveyed again.
7.4.3 Data validation

Data validation is performed by a statistical analysis of trends in condition data parameters over the years, considering possible progressive degradation of pavement condition. This is conducted for each road surface characteristic.

To reduce the number of cases where differences are unexplained (often seen as improvements in condition), it is necessary to have access to information about road works carried out since the last collection. Thus, a good part of the unexplained road surface characteristic improvements observed can be explained. However for the cases where road maintenance was not performed, consulting operator logs and video (if available) can help find explanations for these differences.

The same process should be applied upon detection of unexplained sudden road surface deterioration. The causes of these sudden damages are very varied. Whether it is for a reason of operation of the equipment (lane change, etc.) or for an increase in the number of heavy vehicles in the segment of road in question, it is important to find the cause. In the former case the data is invalid, in the latter the data is valid.

If unexplained differences between the expected value and the one obtained during the survey remain, local network managers may be able to provide explanations and to assist in validating the data. Where no explanation can be found, the data should be rejected and, if necessary, new data collection should be scheduled.

Illustration 51 summarises the entire validation process.
CONCLUDING REMARKS

This report has summarised the current state of the art regarding the collection of road condition and road/vehicle interaction data, providing an overview of current practice and emerging technologies.

As well as providing documentation of the range of road condition and road/vehicle interaction parameters that are routinely being measured by road owners the world, it is hoped that the report has demonstrated, albeit implicitly, that parameters, methods of measurement and derived indicators are being developed on an ongoing basis. As such, the utility of this document is expected to diminish with the passage of time as more efficient systems become widely available.

New system developments in sensors capable of measuring large numbers of different surface condition conditions and defects are encouraging, as is the evolving development in technologies for collecting closely spaced pavement deflection data at normal traffic speeds. One of the challenges that these technologies face is the speed with which such data can utilised by pavement engineers and network managers.

The report has focussed heavily upon quality management processes for data collection and processing. The authors make no apology for this, as their experience has convinced them that rigorous and continual attention must be spent in ensuring that collected data is accurate and appropriate for decision makes to use. It is all too easy to spend excessive effort checking for changes in stable sensors on condition monitoring equipment at the expense of focussing enough effort on survey and operator protocols, data processing and overall data validity.
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<tr>
<th>TERM</th>
<th>DEFINITION</th>
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<tbody>
<tr>
<td>ABS</td>
<td>Anti-lock braking system</td>
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<td>BPN</td>
<td>British pendulum number</td>
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<td>CAN</td>
<td>Controller area network</td>
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<tr>
<td>CEN</td>
<td>Comité européen de normalisation (European Committee for Standardisation)</td>
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<td>CPX</td>
<td>Close proximity (method)</td>
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<td>ETD</td>
<td>Estimated texture depth</td>
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<td>FCD</td>
<td>Floating car data</td>
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<td>FEHRL</td>
<td>Forum of Europeans Highway Research Laboratories</td>
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<td>FFT</td>
<td>Fast Fourier transform</td>
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<td>FN</td>
<td>Friction number</td>
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<td>FWD</td>
<td>Falling weight deflectometer</td>
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<td>IRI</td>
<td>International roughness index</td>
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<td>LCMS</td>
<td>Laser crack measurement system</td>
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<td>MPD</td>
<td>Mean profile depth</td>
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<td>Mean texture depth</td>
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<td>Road porosity index</td>
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<td>RWD</td>
<td>Rolling wheel deflectometer</td>
</tr>
<tr>
<td>SMPD</td>
<td>Sensor measured profile depth</td>
</tr>
<tr>
<td>SMTD</td>
<td>Sensor measured texture depth</td>
</tr>
<tr>
<td>SN</td>
<td>Skid number</td>
</tr>
<tr>
<td>SPB</td>
<td>Statistical pass-by (method)</td>
</tr>
<tr>
<td>SPBI</td>
<td>Statistical pass-by index</td>
</tr>
<tr>
<td>TCS</td>
<td>Traction control system</td>
</tr>
<tr>
<td>TSD</td>
<td>Traffic speed deflectometer</td>
</tr>
<tr>
<td>WLP</td>
<td>Weighted longitudinal profile</td>
</tr>
</tbody>
</table>
APPENDIX – CASE STUDIES

CASE STUDY 1

QUALITY CONTROL OF ROAD SURFACE CHARACTERISTICS DATA
(CANADA-QUEBEC)

The province of Quebec in Canada has nearly 26,000 km of road network spread over the whole of its territory. This territory is divided into 14 territorial sectors each having between 1,000 and 3,000 km of road network.

In order to optimally manage the investments necessary for maintenance and the development of its network, the Ministère des Transports du Québec (MTQ) must know the state of its network. To do this, the MTQ developed multifunctional monitoring equipment. This equipment allows, in a single pass and at the prevailing traffic speed, measuring of longitudinal profile, rutting, cracking, surface macrotexture as well as the recording of video images.

The MTQ carries out 95% of the annual surveys itself. Acquisition of the remaining part is carried out by private firms equipped with similar monitoring equipment to that of the MTQ and complying with the MTQ’s quality plan acceptance criteria. Acquisition plans ensure that each year the MTQ examines approximately 20,000 km of network comprising all of its 7,300 km of superior network (network with a major economic impact) and half of the remaining network.

The collected data, having an impact both on the level of investment and on the choice of interventions, must be reliable. To ensure this the MTQ has implemented a quality plan control that is as much about the quality and reliability of equipment as about the software used to process and capture the data.

Having the quality plan in place allows the production of homogeneous data throughout the territory. That data can then be used to establish the scenarios for intervention. This case study details this quality plan [39, 40].

Illustration 52 - Road condition survey equipment
(source: Ministry of Transport of Quebec)
Step 1: Systems and software validations

Systems and software validation is performed once a year at the beginning of the survey campaign or when a change or a repair is done to one of the systems or software.

The calibration of the sensors is performed according to the manufacturer’s recommendations. If the sensor meets the requirements, a certificate of compliance is issued. This step can be performed by an employee of the MTQ or by the manufacturer of the system. It is important to note that each of the sensors must have a unique identifier to ensure traceability.

Regarding the data acquisition software, version numbers are entered in a register and all the documentation recording which operators are allowed to perform surveys is constantly updated. In addition, before the start of the season, a series of data gathering is conducted in order to ensure the files produced by the different systems comply with requirements. These files are subsequently passed into the automated data processing engines in order to validate the entire chain of production.

Finally, for the data processing software, all of these are validated with the help of known data sets. The results obtained, are kept for the purpose of traceability. If deviations are observed, specialists find the cause so that computer programmers can perform the necessary corrections to the software.

Step 2: Selection and preparation of the reference sites

To qualify and validate equipment, several references sites are necessary, as summarised in table 4.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Number of sites</th>
<th>Length (m)</th>
<th>Usage</th>
<th>Commentary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal profile</td>
<td>1</td>
<td>400</td>
<td>Profiler Qualification</td>
<td>ASTM-E950 IRI &lt; 1.0 m/km</td>
</tr>
<tr>
<td>Cracks</td>
<td>1</td>
<td>380</td>
<td>LCMS Qualification</td>
<td>Artificial cracks (illustration 53) Saw cracks Aluminium casting Width 1 to 5 mm Different length and orientation Different crack severity and pattern</td>
</tr>
<tr>
<td>Longitudinal profile</td>
<td>11</td>
<td>400</td>
<td>Periodic validation of the systems</td>
<td>IRI between 1.0 and 6.0 m/km Rut depth between 0 and 25 mm Different rut shape Different textures</td>
</tr>
<tr>
<td>Cracks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rut</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macro texture</td>
<td>14</td>
<td>2,000</td>
<td>Verification of the drift of all systems</td>
<td>Measured at the beginning and end of a survey campaign One site per survey campaign</td>
</tr>
<tr>
<td>Longitudinal profile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rut</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macro texture</td>
<td>Min. 4</td>
<td>1,000</td>
<td>Distance measurement instrument calibration</td>
<td>Length measured accurately (+/- 1 cm)</td>
</tr>
</tbody>
</table>

Reference sites are characterised with the help of reference equipment, e.g. Dipstick or SurPro for longitudinal profiles, rut reference bar for transverse profile (illustration 54).
Step 3: Equipment qualification

The qualification of the equipment is carried out once a year before the start of the campaign of surveying of the road network. All raw data produced by systems is then processed in order to ensure the compliance to the standards and criteria summarised in table 5.
### Table 5 - Reference Measure and Criteria for Survey Systems

<table>
<thead>
<tr>
<th>Equipment (System)</th>
<th>Measure</th>
<th>Reference</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profiler</td>
<td>Longitudinal profile</td>
<td>Measure with SurPro*</td>
<td>ASTM-E950 standard</td>
</tr>
<tr>
<td></td>
<td>Texture</td>
<td>Measure with TM2*</td>
<td>Correlation over 90%</td>
</tr>
<tr>
<td></td>
<td>Cracks</td>
<td>Artificial cracks site</td>
<td>90 % of detection for longitudinal and diagonal over 75 % or more of the length of the reference site.</td>
</tr>
<tr>
<td>LCMS (Laser Cracks Measuring System)</td>
<td>Transverse profile</td>
<td>Laser reference system</td>
<td>Severity: 90 % of the detected cracks with a good evaluation</td>
</tr>
<tr>
<td></td>
<td>Texture</td>
<td>Measure with TM2*</td>
<td>Repeatability: &lt;= 0.09 m/m²</td>
</tr>
<tr>
<td></td>
<td>Longitudinal profile</td>
<td>Measure with SurPro*</td>
<td>Work on progress to establish the criteria</td>
</tr>
<tr>
<td></td>
<td>Road surface and general views</td>
<td>Reference grid</td>
<td>View should fit with the reference grid (angle and zoom)</td>
</tr>
<tr>
<td>Video logging</td>
<td>Distance and speed</td>
<td>Reference kilometre</td>
<td>Repeatability &lt; 0.1 % on measured distance</td>
</tr>
<tr>
<td>Distance measuring system (DMI)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- TM2: Micro texture measuring device produce by WDM
- SurPro: Longitudinal profile measuring device produce by ICC

The acquisition equipment being assessed for qualification must undertake a total of 15 passes on each of the reference sites. These data allow assessment of bias and repeatability of the equipment. All eligibility criteria must be met before proceeding to the next step.

**Step 4: Equipment validation**

This step is performed repeatedly throughout the campaign. Following qualification of the previous step, a first validation is performed before officially beginning the season of surveys. Subsequently, a validation is performed at the end surveying each territory’s network campaign or every 2,000 km for territories that have more than 2,000 km of network under their responsibility.

For these validations, a total of 6 runs is made throughout the 12 reference sites tracks (1 site is used for qualification of equipment, and 11 sites are for ongoing validation). The bias, repeatability, distribution and reproducibility are then calculated. If one of the systems does not meet the established criteria, then a second validation is made upon verification of the system. Compliance with the criteria is absolutely necessary in order to begin or continue the campaign.

**Step 5: Equipment drift verification**

When the acquisition equipment arrives in a territory, the unit performs 5 consecutive runs on a site measuring 2 km in length and having moderate surface defects. These surveys are used to determine the status of the equipment at the beginning of the surveys.

When all the entire network of the territory has been surveyed, 3 new runs are performed on the same 2 km site. These passages can detect any drift of systems between the beginning and end of survey dates.
Step 6: Verification and validation of the data and detection of out of range values

The verification phase of the processed data exists to ensure that values or indices characterising the road surface are well within the ranges of valid values. All values out of range should be detected and explained. This is undertaken using the process described in section 7.4.2.

Data validation is performed by a statistical analysis of trends over the years, and follows the approached described in section 7.4.3.

General remarks

The qualification of equipment operators is one of the most important things ensured. Operators are provided with detailed and updated documentation and pass through an ongoing training program. Operators must rely on up-to-date and easy to understand reference material. In addition, experience and specialised resources must be available throughout the campaign of to support operators.

The support of resources skilled in statistical analysis is absolutely necessary. Whether in the establishment of acceptance criteria or in the monitoring of the behaviour of systems, the presence of resources able to process and especially apply judgment on the validity and quality of the data reduce the risk of misinterpretation and thereby increases the quality of the diagnosis on the equipment’s condition and the quality of the data.

It is desirable that technical resources (computer science, electronic, mechanical, etc.) knowing equipment systems are available throughout the campaign in order to minimise time lost to equipment faults. Moreover, when equipment is not in the field for surveys (off season), these resources perform all preventive maintenance as well as all desired adjustments or improvements to the systems.
CASE STUDY 2

POTENTIAL FOR WEIGHTED LONGITUDINAL PROFILE DATA TO PRIORITISE LOCALISED DISTRESSES FOR REPAIR (JAPAN)

It is not easy for road operators to objectively classify the type and severity of localised road surface distress and thus to determine appropriate budget allocations for remedies. For example, it is hard to compare severity of a crack-propagated roadway section and an impulsive bridge-joint section. This is mainly because different unit dimensions are used – cracking is usually measured in area-percentage with no dimension, while joint faulting is measured in difference in height by millimetre. Furthermore, since such localised distress takes place intermittently, it is difficult to justify which part of the roadway to prioritise to repair.

Since road profile is related to any distress of the road surface, waveband analysis of the profile might be an option to help develop prioritisation. This case study summarises a trial of applying the Weighted Longitudinal Profile [41] theory on Japanese data.

The Weighted Longitudinal Profile (WLP), as introduced in section 2.3, is used to characterise longitudinal evenness [42]. A sensitivity analysis of the WLP method on whether it can classify specific distress types on the road surface, was conducted using longitudinal profile data on the Japanese toll expressways operated by NEXCO. In order to easily assess the sensitivity, the laser-sensor based data were selected from those with the International Roughness Index (IRI) 3.5 m/km or higher, where it would be expected that road surface would be more distressed. The data were then classified into several distress groups such as culvert box type, bridge joint, concrete joint, cracking and patching, as shown in illustration 55. As illustrated in illustration 56, the maximum height (ΔWLP) and standard deviation (σWLP) components of WLP were then calculated for every identified data and on a 100 m basis.

Illustration 55 - Distress classification [41]
Illustration 56 - Maximum height and standard deviation of weighted longitudinal profile [1]

Illustration 57 plots the total distress data on the relation between $\sigma WLP$ and $\Delta WLP$. Generally, it can be seen that there is a trend of $\sigma WLP$ increasing with increasing $\Delta WLP$ (as was noted by others [41]). However, there could be some additional trends when the data is examined for each distress group.

Illustration 58 shows the WLP data for each distress type. Interestingly each distress type group shows its own pattern between $\sigma WLP$ and $\Delta WLP$. For example, the culvert box distress group has a good correlation with wavy pattern, as the slope of regression exceeds 1/6 which is a boundary deemed as irregular pattern [42]. The bridge joint and concrete joint groups show a correlation with close to irregularity, while the patching is closer to a transient pattern, as the slope of regression is steadily reducing. In culvert box sites, upper three data at sites #222b, #219a and #221a were located in between two consecutive boxes, and the remaining data from a single box. The bridge joint data shows a correlation, regardless of askew angles of the joints. The patching data shows a better result if the relation is not forced through the origin point.
From a practical point of view, ΔWLP can generally represent the magnitude of weighted distress at every 100 meter, regardless of the type of distress. In this sense, it is possible to roughly but directly compare, for instance, the severity of a bridge-joint leading 100-meter section and another patching dominant section in terms of ΔWLP. This is significant because such a direct comparison has never been achievable due to different dimensions used in distress measurement.

For example, it might be considered that a 100-meter section with ΔWLP of 100 mm caused by patching is more distressed than sections with a bridge-joint induced ΔWLP of 50 mm. If there is a substantial difference in the ΔWLP of sections with different distresses, it might be possible to prioritise the repair of the sections based upon those ΔWLP differences. However, it is not suggested that such comparisons could be made between sections with closer ΔWLP values. In must also be remembered that ΔWLP and σWLP values alone cannot distinguish distress type.

As discussed in section 2.3.3, threshold ΔWLP and σWLP values could be established to trigger repair works. Such thresholds could be separately established for each distress mode as shown in illustration 58 – e.g. 100 mm of ΔWLP could be set for repairing bridge-joint sections, and 50 mm for patching sections.

In conclusion, all distress data can be generally evaluated in a simple relation between σWLP and ΔWLP, which may greatly assist in decision making.
CASE STUDY 3

USING COLLECTED ROUGHNESS DATA TO DEVELOP ACCEPTABILITY LIMITS FOR NEW CONSTRUCTION (SAUDI ARABIA)

INTRODUCTION

The International Roughness Index (IRI) is a measure used in pavement evaluation by The Ministry of Transport of Saudi Arabia (MOT) and is used as an acceptance measurement at the handing over of delivered projects. IRI provides a measure of pavement surface condition that has international consistency and comparability and is realistic and practical. Roughness is considered as one of the main factors when it comes to rating the highways all over the world.

There is no internationally uniform specification for acceptable limits of IRI. In the past the MOT has adopted its own limits. These limits were specified in project contract documents, and several contractors were found to be unable to conform to these specifications. Subsequently the MOT held a workshop to discuss the opinions of the contractors, consultants and experts in the Ministry. After the workshop, MOT decided to allow higher limits for acceptance.

Through the previous two years, lots of IRI data has been collected at the handing over of MOT projects. The projects were from different road classifications. This case study summaries how the MOT was able to draw conclusions and recommendations regarding the old limits and to establish new limits of acceptable IRI values. In doing so, it was important to understand the gap between the aspirations of the MOT and the ability of the contractors to accomplish the works.

Work was focused on the comparison of the measurements done for handed over MOT projects during the previous two years. This comparison showed to what extend the contractors satisfied the MOT specification requirements.

METHODOLOGY

Data was extracted from the Maintenance Department database. The analysed data was the 100 m average IRI results for the handed over projects throughout a two year period. This data was collected by using the ARRB Group Hawkeye 2000 system owned by MOT (illustration 59). The data was then distributed and classified according to the adopted MOT classification. After that, it was statistically analysed and compared with MOT old and new specifications.
ANALYSIS OF THE RESULTS

The gathered IRI data for the all regions of the Kingdom of Saudi Arabia was grouped into three categories:

• values for all road types;
• values for expressways and dual roads;
• values for agricultural roads and maintenance projects.

Analyses were undertaken to determine the number of projects that met the old specification limits. The old limits did not distinguish between road types, and it was apparent that the IRI values of the handed over projects were dependent upon the type of road project. New specifications limits were established, based on what was generally achievable by an appropriate proportion of contractors, and these limits were divided into road categories. The old and new specification limits are shown in table 6.

<table>
<thead>
<tr>
<th>Penalty</th>
<th>Old</th>
<th>New: Expressways &amp; dual roads</th>
<th>New: Agricultural roads and maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>No deduction</td>
<td>IRI ≤ 1.2</td>
<td>IRI ≤ 1.6</td>
<td>IRI ≤ 2</td>
</tr>
<tr>
<td>10 % deduction</td>
<td>1.2 ≤ IRI &lt; 1.4</td>
<td>1.6 ≤ IRI &lt; 1.8</td>
<td>2.0 ≤ IRI &lt; 2.2</td>
</tr>
<tr>
<td>20 % deduction</td>
<td>1.4 ≤ IRI &lt; 1.6</td>
<td>1.8 ≤ IRI &lt; 2.0</td>
<td>2.2 ≤ IRI &lt; 2.4</td>
</tr>
<tr>
<td>Rejected</td>
<td>IRI &gt; 1.6</td>
<td>IRI &gt; 2.0</td>
<td>IRI &gt; 2.4</td>
</tr>
</tbody>
</table>
DISCUSSION AND CONCLUSION

Using the old IRI limits only 31 out of 359 projects (8.6%) passed the specifications. While 68 (18.9%) of the projects were accepted with 10% deduction, and 82 projects (22.9%) were accepted with 20% deduction. The rejected projects totalled 178 (49.6%).

The new specifications gave two limits for acceptance. One is for expressways and dual roads and other for agricultural and maintenance roads. Using these new limits, 230 out of 359 projects (64.1%) passed the specifications. While 60 (16.7%) of the projects would be accepted with a 10% deduction, and 30 projects (8.3%) accepted with 20% deduction. The rejected projects were 39 (10.9%). This data is shown in illustration 60 and illustration 61.

Since adoption of the new limits, the feedback from site supervisors is that riding quality of projects has improved.

The major findings of this research are that the new specifications look more reasonable than previous ones. Since more than 64% of the contractors were able to get the limits without penalties, the MOT could consider higher penalties to be applied for non-conformance with the new specifications.
The quality of work is still acceptable with the new specifications. The study showed savings from the non-conformance with the old specifications. Having access to this type of data would allow future studies to examine the change in contractor pricing and the saving for the Ministry due to this specification change, and further studies could be done separately for each region, and even for each contractor.
CASE STUDY 4

USE OF PROBE VEHICLES

INTRODUCTION

Road owners carry out surveys on a regular basis to determine the condition of their road network. This might be once a year up to once every five years. Dedicated equipment measures profiles to calculate longitudinal roughness and transverse evenness, skid resistance, texture or surface defects such as potholes or cracks.

In recent years, several research projects have been carried out to look at using probe vehicles to gather information on the road condition. In this context probe vehicles are vehicles equipped with relevant sensors that produce floating car data (FCD). Originally probe vehicles were ordinary cars which have a GPS (as part of an occupant’s smartphone, the inbuilt navigation devices, etc.) that sends traffic flow information to a central point which gets redistributed to other road users. As more sensors have been incorporated into vehicles, the potential use of probe-vehicles is being explored for pavement engineering and asset management purposes.

PROBE VEHICLES

Modern standard cars are equipped with 50 or more sensors, some of which might be utilised to get information on road condition. Cars have several systems to aid the driver. Some systems that might be used for road condition monitoring are given in table 7.

<table>
<thead>
<tr>
<th>Car system</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic stabilisation programme:</td>
<td></td>
</tr>
<tr>
<td>- Traction Control System (TCS)</td>
<td>Wheel speed sensor</td>
</tr>
<tr>
<td>- Anti-lock Braking System (ABS)</td>
<td></td>
</tr>
<tr>
<td>Active suspension</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>Parking assist system</td>
<td>Camera</td>
</tr>
<tr>
<td>Navigation</td>
<td>Global positioning system (GPS)</td>
</tr>
<tr>
<td>Temperature control</td>
<td>(Outside) Temperature sensor</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>Fuel level sensor</td>
</tr>
</tbody>
</table>

These systems are connected via a controller area network (CAN), which is a protocol for sensors to communicate without the need of a central computer. It is possible to connect to the so called CAN bus to get access to the data from all the sensors, via an on-board diagnostics (OBD) connector. This allows the connection via Bluetooth or a USB cable to a smartphone, laptop or data logger where the CAN bus data is stored or maybe even pre-processed.
SURFACE CHARACTERISTICS

Ride quality / roughness

The obvious characteristic to get from FCD is ride quality. Internationally the most widely used parameter to characterise ride quality or roughness is IRI. IRI is calculated from a quarter car travelling along a measured profile. Research has shown a good correlation between IRI and the output of the accelerometer in a car.

One point to pay attention to are the parameters of an actual car, compared with the golden car assumed in the IRI model. Each car has its own suspension and chassis characteristics, making comparison between the FCD of different cars difficult.

Friction and slipperiness

Electronic stability control/program systems can be used to evaluate the skid resistance of the road surface, especially in winter conditions. The activation of a traction control system or anti-lock braking system is an indication as to whether the surface is slippery or not. Also, analysis of the braking deceleration curve can give information about the braking distance and hence of the friction condition of the road.

Bearing capacity

In cold regions, freeze-thaw cycles in spring result in soft roads with reduced bearing capacity. Using the FCD of lateral vibrations when driving along a curve, can provide information about the bearing capacity of gravel roads.

POTENTIAL USE

The use of FCD can be an inexpensive alternative for some traditional expensive network surveys. For some (local) road owners this might be a viable alternative means of obtaining some indicators of roughness or friction. However, these means will not be able to replace those dedicated vehicles. Currently, some important surface characteristics cannot be measured with probe vehicles, such as cracking, bearing capacity of paved roads, rutting and surface macrotexture.

A more interesting use is the interaction with the road user, following the example of the original traffic flow application. If a group of probe vehicles collect e.g. information on slipperiness, this can be sent back to other road users and, if necessary, activate a warning system inside the car.

CHALLENGES

Research projects are still in the proof of concept phase and not yet widely operational.

One of the biggest challenge to overcome is the processing of the data. The data sent by hundreds or thousands of probe vehicles has to be processed with a sound statistical basis. Additionally, the quality of the data is a big concern. The sensors in standard cars are not calibrated in the same way as traditional road condition monitoring sensors and different cars may use sensors
with a different accuracy. Sending FCD to a central point may have to rely on the availability of different communication networks, as encountered in other projects examining connected vehicle/infrastructure systems.

The other challenge has to do with reading the CAN bus. The CAN bus data is not standardised across different car brands, making it difficult to make a generic tool to read and process the relevant data. This may be solved by using a well selected, more or less homogeneous fleet of probe vehicles, e.g. taxis, postal vans, busses, etc.

**RESEARCH PROJECTS**

Several research projects deal with the possibilities of probe vehicles. The following is a non-exhaustive list of current research projects:

- INTRO, FEHRL project: Intelligent Roads, [http://intro.fehrl.org](http://intro.fehrl.org)
- TRIMM, FEHRL project: Tomorrow’s road infrastructure monitoring & management, Task 4.5 Monitoring functionality, [http://trimm.fehrl.org](http://trimm.fehrl.org)
- Mobi-Roma, EraNet-Road project: Mobile Observation Methods for Road Maintenance Assessments, [http://www.mobiroma.eu](http://www.mobiroma.eu)
- SRIS project: Real-time warnings for slippery road conditions, [http://www.sris.nu](http://www.sris.nu)
- Sensovo, VIM project: Sensors on vehicles, [http://www.vim.be](http://www.vim.be)
- CVI-UTC, Connected Vehicle/Infrastructure, University Transportation Center project: [http://www.cvi-utc.org](http://www.cvi-utc.org)
- CVIS, Cooperative Vehicle-Infrastructure systems, [http://www.cvisproject.org](http://www.cvisproject.org)