Data Collection Technologies for Road Management

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1 Introduction

When considering the road infrastructure and its associated data, there are different types of data used for road management. Table 1.1 shows one data grouping from Paterson and Scullion (1990). This report focuses on the first four elements, which have two types of data:

- Inventory; and
- Condition.

Table 1.1: Road Management Data

Element	Aspects
Road Inventory	Network/Location Geometry Furniture/Appurtenances Environs
Pavement	Pavement Structure Pavement Condition
Structures	Structures Inventory Bridge Condition
Traffic	Volume Loadings Accidents
Finance	Unit Costs Budget Revenue
Activity	Projects Interventions Commitments
Resources	Institutional Materials Equipment

Source: Paterson and Scullion (1990)

Inventory data describe the physical elements of the road system. These do not change markedly over time. Condition data describe the condition of elements that can be expected to change over time.

There are a wide range of technologies available to the road manager for measuring attributes of the road network. The challenge is to select the appropriate equipment, given local conditions and the way in which the data are expected to be used.

The purpose of this report is to give an overview of the currently available technologies and to provide information that could assist managers in establishing an appropriate data collection program and procuring the appropriate equipment to collect the data.

The project includes a literature review and comprehensive survey of vendors and users, both of which were conducted in 2005. It is recognized that with the rapid developments in road data collection, some information provided in this project report may become outdated. To address this, we have developed a project web site:

www.road-management.info

This site enables vendors and others involved in road management to upload the latest information on equipment and general data collection issues. It is envisaged that this report will be reissued and refined on a bi-annual basis.

The report starts with a discussion of data collection requirements. This is then followed by separate discussions on pavements, bridges, and traffic data. The final chapter contains our recommendations for data collection.

2 Data Collection Issues

2.1 Introduction

Data collection is expensive. Each data item collected requires time, effort, and money to collect, store, retrieve, and use. The first rule of data collection is that data should never be collected because "it would be nice to have the data," or because "it might be useful someday."

This section addresses a number of issues that road managers face when determining exactly what their data requirements are and how to select the appropriate data collection technologies to meet those requirements.

2.2 Deciding What to Collect

Regarding road management data, the first question usually asked is, "What data should we collect?" Many agencies start by asking an internal team to compile a "data wish list." Other agencies first take inventory of their currently available data and try to implement road management systems using that data. Both approaches should be avoided. The real questions that should be asked are:

- What decisions do we need to make to manage the network?
- What data are needed to support these decisions?
- Can we afford to collect these data initially?
- Can we afford to keep the data current over a long time period?

Several agencies have become so mired in data collection that data collection appears to be an end in itself. Large sums of money are spent collecting data, with little to show in the form of more efficient and cost-effective decisions. Excessive data collection is probably one of the top five reasons road management systems (RMS)[1] are abandoned. The systems are seen as data intensive and too expensive to sustain. To avoid these misperceptions, Paterson and Scullion (1990) have provided approaches for deciding what data should be collected and how it should be collected:

- **Confirm whether the data are actually required.** A RMS is often used to assist in making management decisions. If the data does not have a bearing on either the RMS output or management decisions, it should not be collected. A common problem arises when agencies try to collect

[1] In this report the term 'road management system' (RMS) is used. This is often comprised of one or more applications such as a pavement management system (PMS), bridge management system (BMS), and traffic management system (TMS). The data collection principles presented here apply to all these individual sub-systems as well as other associated systems such as geographic information systems (GIS).

project-level data for network-level analyses (see below). This means that data are collected in a much more detailed manner than is required for analysis, thereby wasting time and money.

- **Consider the total cost.** With any RMS, the commitment is not for a one-time needs survey. Some inventory data need only to be collected once and require updating when there are changes in the network, such as new roads or realignments. However, some data changes rapidly, especially data on auxiliary information such as signs and markings. Implementation of a road management process is a commitment to a permanent change in the way roads are managed. This means that the data collected must be kept current -- this can be both difficult and expensive if excessive data are collected.
- **Minimize data collection.** Generally, the greatest temptation is to collect too much data, or in too much detail. When this proves to be unsustainable, data collection will cease, compromising the value of the RMS. If the data are not kept current, management decisions may be misguided and the RMS could become irrelevant to planning.

The guiding principles should always be:

- Collect only the data you need;
- Collect data to the lowest level of detail sufficient to make appropriate decisions; and,
- Collect data only when they are required.

When considering data collection methodologies, **pilot studies** are very useful. In the pilot implementation, all proposed data should be collected so as to determine the collection costs, as well as the appropriateness of the data collected.

Implementation can, and should, be incremental. Implementation should include considerations on what data to collect at each level and ensure that the data are kept current. A RMS should never be finished; as it matures and data collection processes change, other data elements can, and should, be added.

Data for collection may be considered as belonging to one of the following three levels:

- **Network-level data** should answer the general planning, programming, and policy decisions supported by the network-level RMS;
- **Project-level data** should support decisions about the best treatment to apply to a selected section of road. As these data are collected, they can be stored to create a more complete database over time. However, a method must be established to keep the data current; and,
- **Research-level data** should be established to collect detailed data on specific attributes to answer selected questions.

These differences are addressed in the following section on information quality levels.

2.3 Information Quality Levels (IQL)

As described in Bennett and Paterson (2000), imagine looking out of an airplane window, just as you are about to land. You recognize the landscape by a bend in the river, or the way a thread-like highway cuts through the landscape. The plane draws nearer, and you can make out your neighborhood, then your home, your car. You have been looking at the same spot throughout the descent, but the "information" available to you became enhanced. While from high above you had enough macro-level information to determine what town you were looking at, you needed a different kind of micro-level information to determine precisely where your car was. You have just experienced first hand the principle behind Information Quality Levels (IQL), introduced by Paterson and others in 1990.

IQL helps us structure road management information into different levels that correlate to the degree of sophistication required for decision making and methods for collecting and processing data. In IQL theory, very detailed data ('low-level data') can be condensed or aggregated into progressively simpler forms (higher-level data), as shown in Figure 2.1.

Five levels of road management have been identified for general use and are defined in Table 2.1. IQL-1 represents fundamental, research, laboratory, theoretical, or electronic data types, where numerous attributes may be measured or identified. IQL-2 represents a level of detail typical of many engineering analyses for a project-level decision. IQL-3 is a simpler level of detail, typically two or three attributes, which might be used for large production uses like network-level survey or where simpler data collection methods are appropriate. IQL-4 is a summary or a key attribute which has use in planning, senior management reports, or in low effort data collection. IQL-5 represents top level data such as key performance indicators, which typically might combine key attributes from several pieces of information. Still higher levels can be defined as necessary.

At IQL-1, pavement conditions are described by twenty or more attributes. At IQL-2, these would be reduced to 6-10 attributes, one, or two for each mode of distress. At IQL-3, the number of attributes is reduced to two to three, namely roughness, surface distress, and texture or skid resistance. At IQL-4, all of the lower-level attributes may be condensed into one attribute, "Pavement Condition" (or "state" or "quality"), which may be measured by class values (good, fair, poor) or by an index (*e.g.*, 0-10). An IQL-5 indicator would combine pavement quality with other measures such as structural adequacy, safety aspects, and traffic congestion—representing a higher order information, such as "road condition".

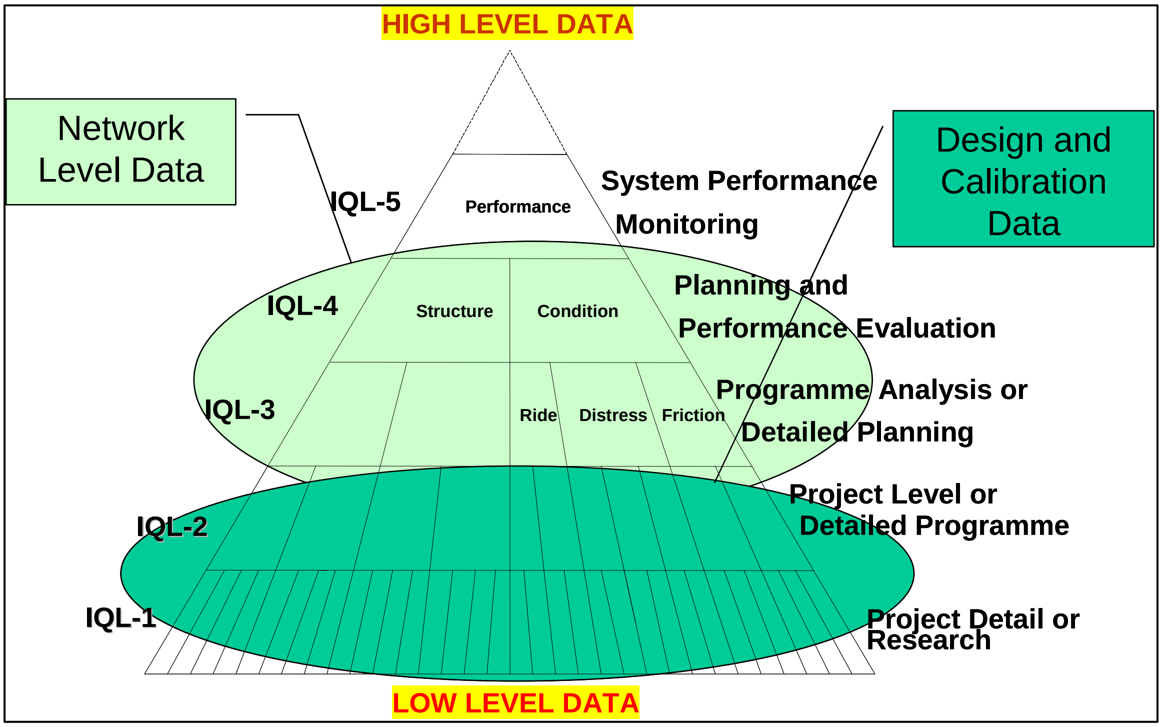


Figure 2.1: Information Quality Level Concept

Three observations that emerge from these definitions are:

- The higher the decision-level, the higher the IQL. Information at IQL-4 or IQL-5 is appropriate for performance indicators and road statistics that are of interest to senior management and the public, because they tend to be, or should be, easily understood without much technical background. At the project-level, however, the appropriate IQL depends much more on the standard of the project and the resources of the agency. For example, IQL-3 is usually sufficient for a rural road or a small local agency. For most agencies and main roads, IQL-2 is typical, but for expressways or high-level, well-funded agencies, IQL-1 may be used in some instances. The criterion to use in selecting the appropriate IQL is to ask, "Is the decision likely to be altered by having more detailed information?"

- Primary data collection at a low-level (detailed) IQL typically costs more and involves more sophisticated equipment than collection of higher IQL data. Thus, the IQL for primary data collection that is appropriate to a given agency and situation depends on the financial and physical resources, skills, cost, speed or productivity, degree of automation, complexity—all summed up in the need for the method to be sustainable for the intended purpose, such as the regular operation of a road management system.

- A higher level IQL often represents an aggregation or transformation of the lower level IQLs. When there is a specific rule or formula for conversion, say, from IQL-2 into IQL-3, then the information is reproducible and reliable. Thus, when the appropriate IQL is chosen, the data can be re-used through transformation to the higher IQLs as the decision-making moves up the project cycle – this avoids the need for repeating surveys and saves cost.

Table 2.1: Classification of Information by Quality and Detail

IQL	Amount of Detail
1	Most comprehensive level of detail, such as that which would be used as a reference benchmark for other measurement methods or in fundamental research. Would also be used in detailed field investigations for an in-depth diagnosis of problems, and for high-class project design. Normally used at project-level in special cases and unlikely to be used for network monitoring. Requires high level skill and institutional resources to support and utilize collection methods.
2	A level of detail sufficient for comprehensive programming models and for standard design methods. For planning, would be used only on sample coverage. Sufficient to distinguish the performance and economic returns of different technical options with practical differences in dimensions or materials. Standard acquisition methods for project-level data collection. Would usually require automated acquisition methods for network surveys and use for network-level programming. Requires reliable institutional support and resources.
3	Sufficient detail for planning models and standard programming models for full network coverage. For project design, would suit elementary methods such as catalogue-type with meager data needs and low-volume road/bridge design methods. Can be collected in network surveys by semi-automated methods or combined automated and manual methods.
4	The basic summary statistics of inventory, performance, and utilization that are of interest to providers and users. Suitable for the simplest planning and programming models, but for projects is suitable only for standardized designs of very low-volume roads. The simplest, most basic collection methods, either entirely manual or entirely semi-automated, provide direct but approximate measures and suit small or resource-poor agencies. Alternatively, the statistics may be computed from more detailed data.

Source: Bennett and Paterson (2000)

2.4 Sampling Intervals and Sectioning

All data are collected in one of two ways:

- **Point** data – data that exist at a single point in space, for example traffic signs, intersections, and potholes; or
- **Continuous** data - data that exist over a section of road, for example surface type or traffic volume between intersections.

The sampling interval is the frequency at which data are collected along the road. The sampling interval will have an impact on the cost of data collection and storage, as well as the usability of the data.

The proposed use of the data affects the sampling interval. Project level applications, such as detailed design of pavement overlays, requires sampling at a much more frequent interval than is required for network level analyses[1].

Dividing road data into analysis sections is a vital step in any RMS. This is because most, if not all, analyses are done using the concept of 'homogeneous sections,' wherein the sections are considered to have uniform/homogeneous attributes. The importance of creating proper analysis sections cannot be overemphasized. Without appropriate sections, it is impossible to establish the correct investment decisions for the network.

There are two stages to the sectioning process:

- Analyzing the attributes of the road network and breaking it into sections; and,

- Transforming the attribute data so that they adequately represent the road sections for the purposes of analysis.

As shown in Figure 2.2, there are three basic approaches to sectioning:

- **Fixed Length Sections** do not change over time. Fixed length sections are commonly used in conjunction with regular road markings, for example kilometer stones or between city blocks. The HDM-4 model recommends that sections "…must be matched by physical referencing **on the ground** … to facilitate future location of sections" (Kerali, *et al.*, 2000). While this is advantageous, it is not essential. Many RMS use fixed sectioning without ground markers.

- **Dynamic Sections** represent the other extreme. A road network's attributes are analyzed and analysis sections are created based on these attributes. Since attributes such as roughness can change from year-to-year, the sections will also change from year to year.

- **Static Sections** are created using dynamic sectioning principles but are treated as static for several years. This is usually the best approach as it combines the benefits of dynamic sectioning with the practical advantage of not having the section locations change too often.

Sections are created from data, usually via automated sectioning routines that use algorithms to evaluate data in the database and test the data against user-defined sectioning criteria. When the criteria are met, a new section is created. Bennett (2004) describes the different approaches to sectioning and provides detailed examples.

Agencies should do field verification of the analysis sections created using the sectioning algorithm as a part of their quality assurance process. The verification process will help identify any ambiguities in the sectioning methods used and errors in the data used in the sectioning process. It is not

[1] Alam *et al*. (2007) show how statistical techniques can be used to determine the optimum sampling interval for FWD measurements.

uncommon for inappropriate sections to arise due to errors in the source data.

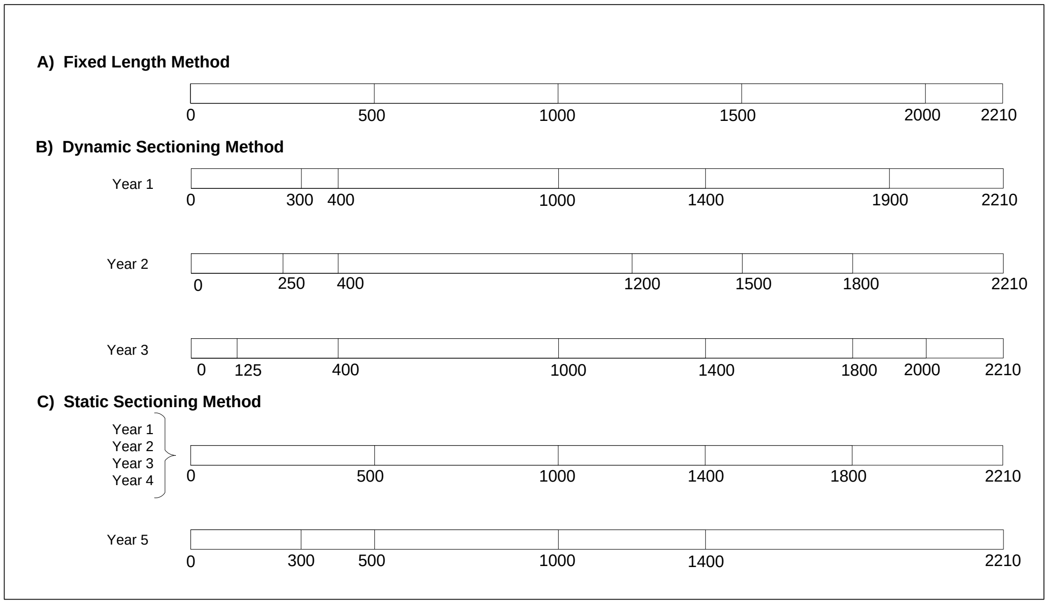


Figure 2.2: Comparison of Sectioning Methods

Unless the RMS operates on fixed sectioning principles and the data are stored at the same intervals as the analysis sections, it is necessary to transform the data in the RMS so that it corresponds to the analysis sections. As shown in Figure 2.3, transformations are usually done in two steps:

- First, the data are transformed from source data into what is called **smallest common denominator** sections. These are the smallest intervals that correspond to all data and the analysis sections.

- The smallest common denominator data are then amalgamated to represent the conditions of the analysis section.

An RMS with robust data sectioning and transformation processes provides a great deal of flexibility when it comes to data collection. It is possible to collect different types of data at a sampling interval that is appropriate for the particular data item. The alternative requires data to be carefully synchronized, which is difficult when the data are collected at different times.

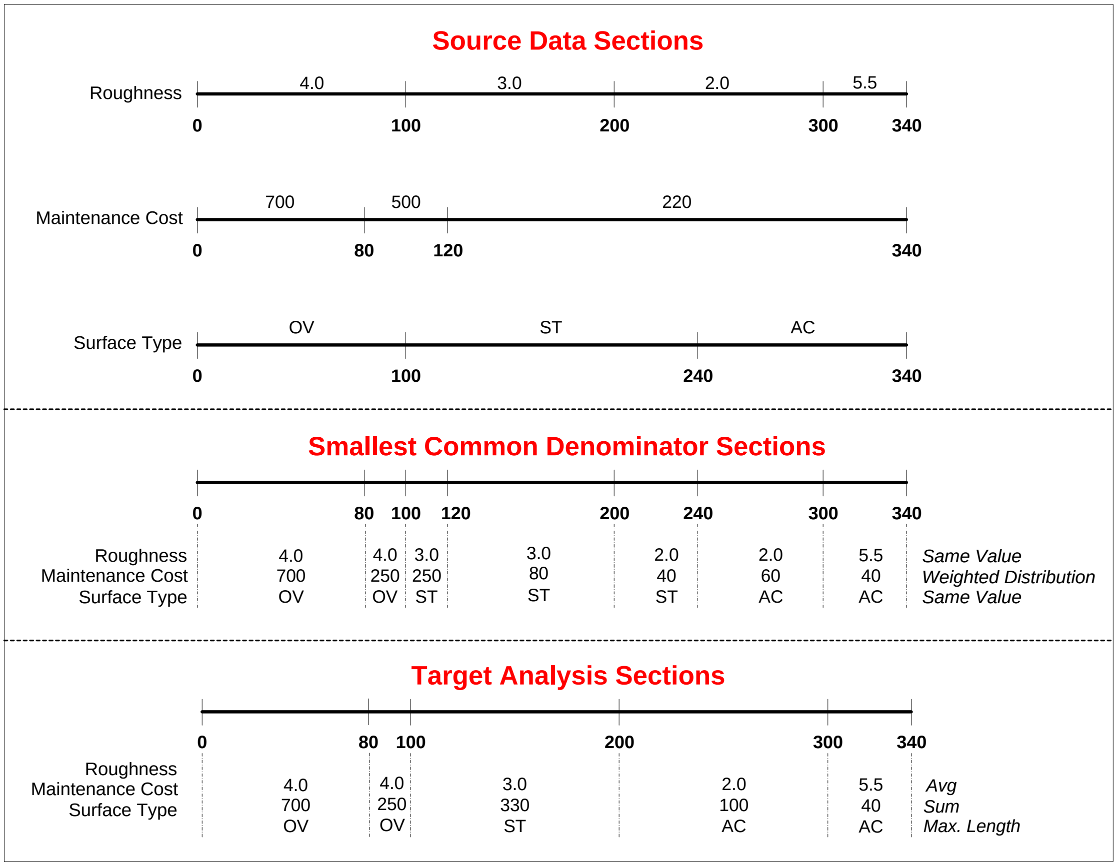


Figure 2.3: Example of Data Transformations

2.5 Survey Frequency

The frequency of surveys for monitoring road, bridge, or traffic conditions has an important bearing on the cost of surveys and the sustainability of data collection. Data should be collected only as frequently as is required to ensure proper management of the road network. The frequency can vary depending upon the data of interest:

- **Road inventory data** are typically collected in a once-off exercise. They are then updated when changes are made to the road. It is common to verify/update the data every five years or so.
- **Pavement condition data** are usually collected at different frequencies, depending on the road class. Main roads and major highways are monitored at frequent intervals, often 1-2 years, while minor roads may be monitored at 2 – 5 year intervals. The frequency needs to be sufficient to identify major changes which will influence road maintenance decisions.
- **Bridge condition data** tends to be collected in two cycles. Regular surveys are conducted at 1 – 2 year intervals for collecting general data

on bridge conditions. More intensive investigations are done at longer intervals, typically on the order of five years.

- **Traffic data** are usually collected through a set of permanent traffic count stations around the country, supplemented by short term counts (typically seven days for traffic volumes) at other locations.

3 Location Referencing

3.1 Introduction

Location referencing addresses the commonly asked questions "Where do I find it (e.g. a pavement section)?" and "Where am I?" The fundamental objective of referencing is to identify a location on a road. It is a means by which people can communicate the details of a location.

This section describes techniques and issues associated with location referencing, drawing heavily from HTC (2001).

Location referencing is the singularly most important consideration in conducting a survey. Unless the data are properly referenced, they will be of limited use in making management decisions. There are two key definitions associated with location referencing:

- The **location,** the point on the road; and,
- The **address,** a string of characters used in a management system that uniquely and unambiguously[1] define a location.

The location reference method is used in the field to ensure that the proper *address* is used to describe a *location* and that the proper *location* can be found using its *address*. The reference needs to be well documented and designed to accommodate all situations. In general, all location referencing methods have the following components:

- Identification of a known point (*e.g.*, kilometer post);
- Direction (*e.g.*, increasing or decreasing); and,
- Distance measurement (*i.e.*, a displacement or offset).

There are two common location referencing methods:

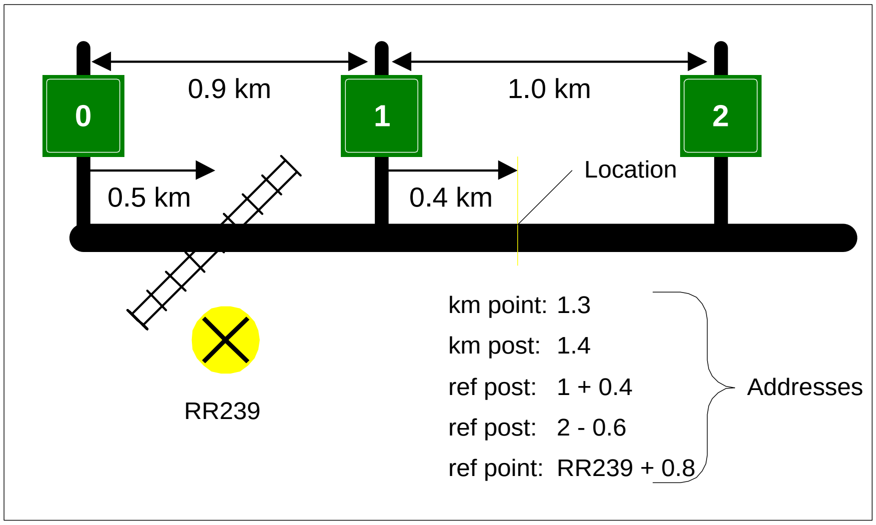
- **Linear**: gives an address consisting of a distance and direction from a known point, for example:

  Kilometer point (*e.g.*, 9.29)
  Kilometer post (*e.g.*, 9.29 with equations)
  Reference point (*e.g.*, xx + 0.29)
  Reference post (*e.g.*, xx + 0.29)

- **Spatial**: gives an address consisting of a set of coordinates. This is commonly done using Global Positioning System (GPS) data.

[1] Road names should not be used for referencing because road names are not unique. For example, there are over one hundred instances of 'Church Lane' as a street name in Hampshire County, U.K.

It needs to be recognized that one location can have many addresses. This is illustrated in Figure 3.1, which shows that the same location could be described by five different addresses.



Source: Deighton Associates Ltd.

Figure 3.1: Example of Various Addresses Applying to the Same Location

Links and nodes are a special implementation of a generic referencing system. The nodes refer to specific locations on the roads, and the links are unique segments connecting the nodes. Nearly any referencing method can be applied with a link-node system.

3.2 Linear Referencing

Linear referencing is the most commonly used referencing method for road data[1]. Unlike spatial referencing, it does not require any sophisticated technology and can be easily understood. McGhee (2004) notes that "discussions with maintenance personnel strongly suggest that [linear referencing] will be in use for working purposes well into the future."

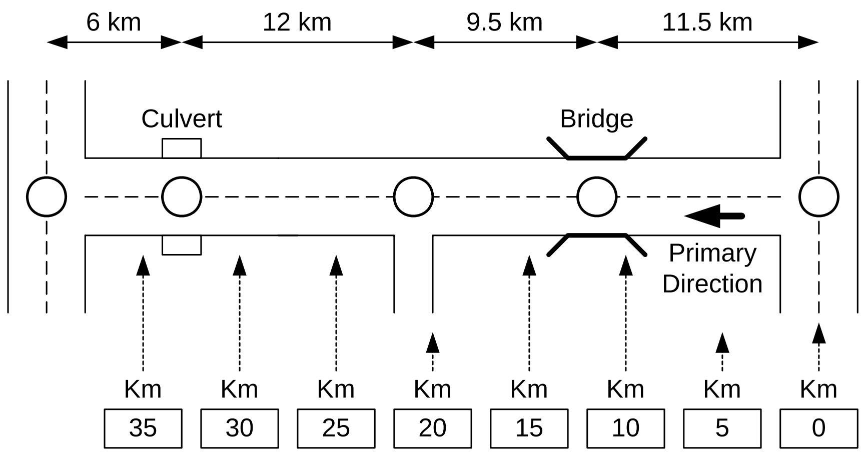
Most data collection technologies use linear referencing for recording data. The data are recorded between a start and an end point. The addresses are usually expressed relative to the start point and, ideally, intermediate points. The use of intermediate reference points improves the overall accuracy by limiting any accumulating error in the distance measurements. It is almost always necessary to 'rubber band'[2] the data at the end point. This is because

[1] McGhee (2004) reports that in almost every case, where spatial data is used it is recorded in conjunction with linear referencing data.
[2] Rubber banding of data is the process whereby the annual survey distance measurements are "stretched" or "shortened" so that they match the distance recorded in a previous survey.

no matter how well calibrated the odometer is, there will always be some margin of error which means that successive surveys will measure slightly different lengths each time. The surveyed lengths are increased or decreased to match the accepted length of the section, and the data adjusted accordingly.

As described above, there are four basic linear referencing methods used with highway data. These are described as follows.

The **kilometer post** or **milepost** method is probably the most commonly used method. The major difference between kilometer points and kilometer posts is that posts involve the use of physical posts, and signs placed at regular intervals along the road, usually every one kilometer[1].



Description	Address
Start of Road	0.0
Bridge	11.5
Intersection	21.0
Culvert	33.0
End of Road	39.0

Figure 3.2: Kilometer Post or Milepost Method

Kilometer posts are marked with a distance measurement, but the level of detail varies between countries. For example:

- New Zealand – signs show the distance from the start of a section, as defined by the last reference station. Reference stations are typically 15-20 km apart.

[1] Posts are never exactly 1 km apart. This may be due to operational limitations—for example, a driveway at the point where the km post should be—or to installation limitations. For example, the Transit New Zealand State Highway Marking Manual has a tolerance of +/-100 m for km posts which means that it is conceivable that they could be 800 m apart and still be within tolerance. In a survey in India it was found that over a 50 km section of road the km posts were all at 950 m intervals, indicating an improperly calibrated odometer in the original survey.

- The Philippines – signs show distances in relation to the zero km marker in Manila[1], distances to the next town, and the first letter in the name of the next town.
- India – signs show the distance from the start of the road, which may be as much as 50 km away.

Frequently, because of construction changes, kilometer posts do not indicate true kilometer points. When this occurs, an equation is often used to relate the kilometer post signed location with the true kilometer point.

Advantages of kilometer posts:

- Location information is readily understood by all users;
- Information is available for public use;
- Numerical sequence provides easy orientation; and;
- Distance between any two points is the difference between the 'from' and 'to' addresses;

Disadvantages of kilometer posts:

- Expensive to establish and maintain;
- May prove impossible to maintain consecutive numbering due to realignments;
- Must be accurately positioned during the initial survey. This is not always practical, for example, driveways may preclude the post from being placed in the correct location;
- Replacements must be placed in exactly the same location;
- All downstream signs must be moved if any changes are made to the road length. Chainage equations should be used for correcting distances to actual distance; and,
- The distance measurement displayed on a post is never the exact distance. This can lead to confusion amongst those using the posts as reference.

The **kilometer point** method uses the measured distance from a given or known point to the referenced location. The beginning point is often the beginning of the road or the point at which it enters a city or district. The address of any point along the road is the numerical value of the distance of the point from the beginning of the road (see Figure 3.3).

[1] The reference marker for **all** roads in the country, even those on other islands, is located in central Manila.

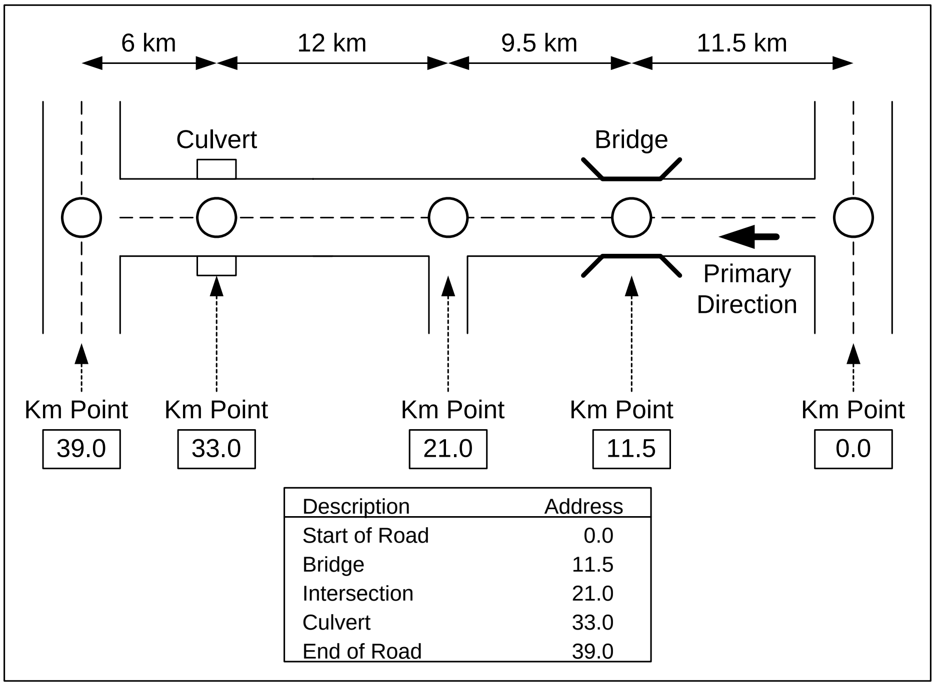


Figure 3.3: Kilometer Point Method

Advantages of kilometer points:

- There is no need to maintain regular reference posts or signs, since the displacement is measured from the start of the road (or the start reference point);
- The distance between any two points is simply the difference between the 'from' and 'to' addresses; and,
- They are easy to understand and calculate.

Disadvantages of kilometer points:

- Field workers need to measure from the kilometer point to get a reference. They must therefore know both where the route begins and the primary direction; and,
- Addresses are unstable. If roads are realigned, all of the points on roads beyond the kilometer point may change. While the effects can be minimized by having regular reference stations, it still creates the problem of reconciling historical data. For example, an accident at 15.38 one year could be 14.87 after a realignment.

The **reference post** method (see Figure 3.4) is similar to the kilometer post method, except the signs are not at regular intervals[1]. A sign or marker is placed next to the road with a unique identifier. This identifier may be a distance or just a number. Although a reference post never changes, the kilometer point associated with the post may change. As long as these distances are properly maintained, the method will be successful.

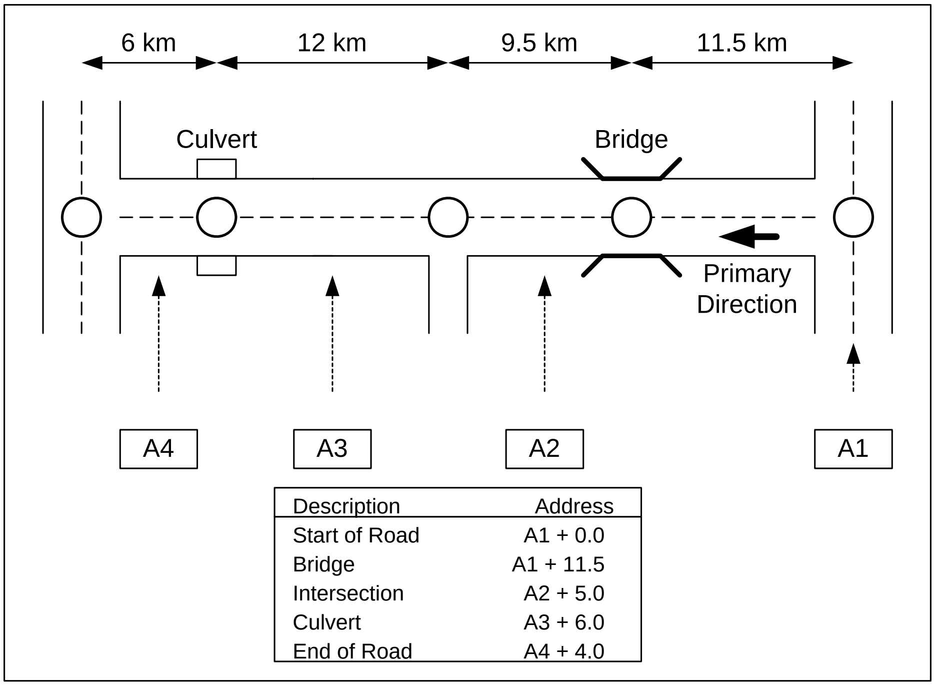


Figure 3.4: Reference Post Method

Events in the field are measured as a displacement from these posted references.

A variation of the reference post method is to use **reference points** (see below). These are permanent roadside features, such as intersections or signs. The use of numbers instead of distances on the reference posts effectively makes them reference points.

Advantages of reference posts:

- Easy to use in the field;
- Easier to maintain than kilometer posts;
- Not necessary to measure from beginning of route—only necessary to measure from nearest post;
- Much less expensive to establish than kilometer posts, since the markers can be placed in the most appropriate locations and require fewer posts;

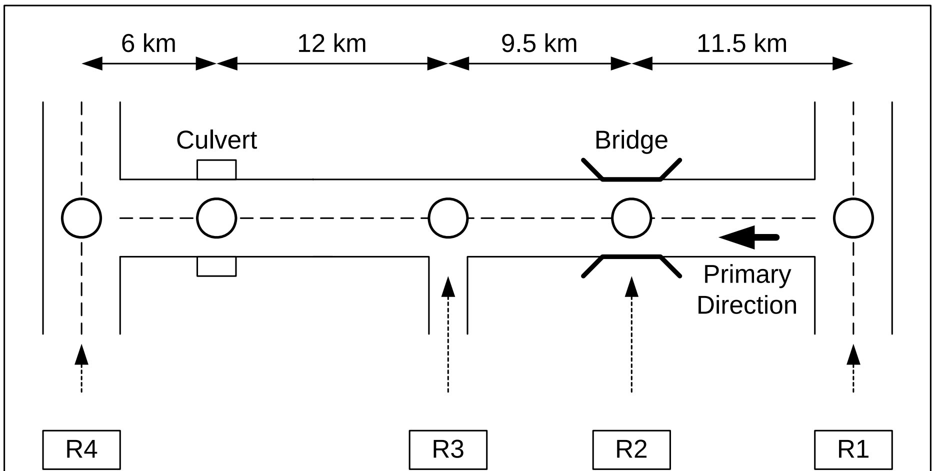
[1] Due to the inaccuracies in measurements, some consider that kilometer posts are actually reference posts since they are never exactly 1 km apart.

- A single set of signs can be used on overlapping routes;
- If any changes are made to the road length, there is no need to change all the other signs—only a short section of road is affected; and,
- A single set of posts applies to all routes on concurrent routes[1].

Disadvantages of reference posts:

- Location information is not clear to all users;
- Public generally not able to use information;
- Field crews need to carry with them information on distances if distances are not marked; and,
- Damaged signs must be replaced at the exact location.

Similar to the reference post method, the **reference point** method does not use signs but instead has regular identifier features, such as bridges, culverts, light posts, or intersections (Figure 3.5). Events in the field are measured as displacements from these posted references.



Description	Address
Start of Road	R1 + 0.0
Bridge	R2 + 0.0
Intersection	R3 + 0.0
Culvert	R3 + 12.0
End of Road	R4 + 0.0

Figure 3.5: Reference Point Method

[1] A concurrent route arises when one road section is assigned two different highway numbers. This is usually only for a short distance under special situations.

Advantages of reference points:

- Not necessary to measure from beginning of route—only necessary to measure from nearest point;
- Minimal maintenance requirements, since special posts are not used, only existing roadside objects;
- No need to change all the signs if any changes are made to the road length—only a short section of road is affected;
- Reference points apply to all routes on concurrent routes.

Disadvantages of reference points:

- Cumbersome to use in the field;
- Reference points may be spaced at very long intervals, particularly in rural areas;
- Location information is not clear to all users;
- The public, generally, is not able to use the information; and,
- Road crews need to know details on reference point locations and distances.

3.3 Spatial Referencing

Spatial referencing is accomplished using global positioning system (GPS) technologies. With GPS, data from four or more satellites are used to provide location information.

The accuracy of the 'raw' GPS data is typically +/- 10 meters, 95% of the time. Accuracy can be improved by using high quality GPS receivers and by employing a data correction method.

There are two types of data corrections that may be applied:

- **Real-time:** As GPS data are recorded, a correction signal is simultaneously received. The correction signal can be from a local transmitter or via a commercial service such as Starfire or Omnistar; or
- **Post-processing:** After the survey is completed, the GPS data are corrected by incorporating position data from a 'base station'.

Sub-meter accuracy can be achieved through corrections. MWH (2004) reports that with the Navcom Starfire, "maximum absolute variance from the survey mark was 26.9cm North (-6.5 to 20.4) and 28.9cm East (-20.1 to 80.8)." However, MWH (2004) noted that operational considerations are equally, if not more, important than the receiver accuracy:

> *"The main source of deviation from the true centerline is the path taken by the vehicle, which for safety reasons cannot always drive on the centerline. Additionally, the survey vehicles occasionally overtook very slow moving traffic (ox carts, livestock, bicycles, and motorbikes). Where these deviations were obvious the road centerline was straightened, but smaller deviations will remain as they are difficult to detect without a very detailed visual inspection. Taking all these factors into account, it could be concluded that the 95% road centerline data is accurate to less than 1m."*

GPS data are recorded using the WGS84 datum. It is usually necessary to project the data to a local datum to make it compatible with other spatially referenced data (*e.g.,* land records and aerial photographs). It is vital to ensure that the correct projection parameters are used with all spatial components – otherwise, errors can be significant. This is illustrated in Figure 3.6 from a survey in Samoa. Projection problems resulted in the road alignment data being shifted by 3-4 m in the N/S direction and 12-14 m in the E/W direction.

Figure 3.6: Example of Projection Problem with GPS Data

A common application of spatial data is to establish the road centerline. This is a nominal line that shows the location of the center of the road. It is usually captured by driving a vehicle with a GPS receiver along the road. There may be inertial navigation units to improve the accuracy of the GPS measurements.

As shown in Bennett (2003), there are several stages involved in creating the centerline, of which the field survey is just the first. Field data are required to be manually corrected to ensure that the network has the correct topology (*i.e.,* segments from intersecting roads meet at the same point; nodes and road segments intersect; nodes are in the centre of intersections). An example of these corrections is shown in Figure 3.7. It is also common to encounter obstacles in surveys that cause the vehicle to travel outside of its chosen path (*e.g.*, passing a stationary vehicle on the road). Such obstacles also need to be corrected, as shown in Figure 3.8.

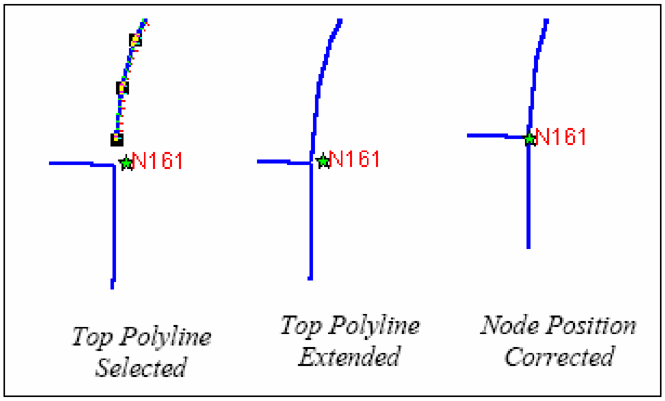


Figure 3.7: Example of Correcting Intersection Topology

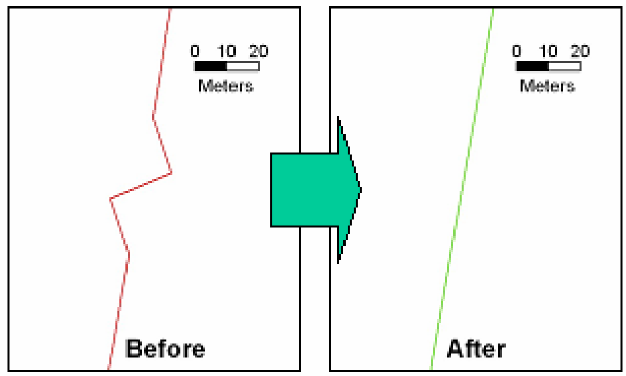
Figure 3.8: Example of Correcting for Path of Travel Interruptions

For a network survey of Cambodia, MWH (2004) compared the survey distance (in meters measured by the vehicle's distance measurement instrument) against the distance calculated from the GPS data. The GPS receiver used was a Navcom Starfire, which gave sub-meter accurate real-time positions. Any difference greater than $\pm$1% (10 meters/kilometer) was manually reviewed and corrected as necessary. This process is shown in Figure 3.9. MWH (2004) noted that:

> *"In total it was found that around **17%** of road segments had a discrepancy > 1%. After a manual validation of the data to remove GPS 'spikes' and gyro drift etc, this percentage was reduced to zero."*

As a final validation, MWH (2004) compared the measured road length against the calculated GIS road length for each link. About 75% of the 471 links had a discrepancy of less than ± 2 meters/kilometer (0.2%), with 95% ± 5 meters/kilometer and 100% ± 10 meters/kilometer. This shows the value of collecting GPS data in conjunction with distance measurements through an accurate odometer.

LRP_NUM	ROMDAS Length	GPS Length	Diff(m)	% Difference
0	1968	1968	0	-0.01%
1	41	40	1	0.05%
2	1932	1951	-19	-0.98%
3	1026	1024	2	0.09%
4	88	85	3	0.13%
5	3103	3115	-12	-0.61%
6	1192	1192	0	0.01%
7	1019	1019	0	0.01%
8	996	1007	-11	-0.55%
9	1105	1101	4	0.20%
10	2006	2028	-22	-1.10%



Source: MWH (2004)

Figure 3.9: Example of MWH Data Quality Management

4 Pavement Condition and Structure

4.1 Types of Evaluations

The road pavement must provide users with comfortable, safe, and efficient service, and it must possess sufficient structural capacity to support the combined effect of traffic loads and environmental conditions (de Solminihac, 2001).

To determine how a pavement is performing at a particular point in time and to predict how it will perform in the future, regular monitoring should be done to establish whether its three basic functions (provision of comfortable, safe, and efficient service) are being fulfilled.

The scope of a pavement evaluation is therefore to record pavement characteristics that describe its performance through several indices. Depending on which characteristic is being surveyed, a pavement evaluation can be classified as functional or structural.

- **Functional Evaluation:** A functional evaluation provides information about surface characteristics that directly affect users' safety and comfort, or serviceability. The main characteristics surveyed in a functional evaluation are skid resistance and surface texture in terms of safety, as well as roughness in terms of serviceability.
- **Structural Evaluation:** A structural evaluation provides information on whether the pavement structure is performing satisfactorily under traffic loading and environmental conditions. Surveyed characteristics may be related to structural performance, pavement distresses, and mechanical/structural properties. Note that several pavement distresses indirectly lead to functional problems such as asphalt pavement bleeding, which affects skid resistance, or faulting in jointed concrete pavements, which affects roughness.

Proper location referencing is essential for all surveys. Both structural and functional evaluations can only be successful when using an efficient and accurate referencing methodology. Typical referencing technologies include: distance measuring instruments (DMI), Global Positioning Systems (GPS) and video logging[1].

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[1] In the context of location referencing, video logging is used primarily to identify the location of assets and, to a lesser degree, their condition. Video monitoring of pavement surface condition is a different application of the technology and is considered separately.

4.2 Pavement Characteristics

The key pavement characteristics considered in an evaluation are:

- Roughness;
- Texture;
- Skid resistance;
- Mechanical/structural properties; and,
- Surface distress.

These characteristics are measured in the field through manual evaluations or using specialized equipment and are quantified by means of indicators or condition indices. Laboratory testing equipment such as that used for mix designs is not considered in this report.

A variety of survey equipment is available to measure pavement characteristics. Since different equipment types require different methodologies for evaluating pavement characteristics, different condition indexes are often available to quantify a given characteristic. Correlation equations and international indexes have been developed to standardize some attributes, thereby making measurements from different equipment, and sometimes technologies, comparable.

In Table 3.1, a simple scheme is presented correlating pavement functions with pavement characteristics for each evaluation type (Crespo del Río, 1991). Examples of indicators and indexes for each pavement characteristic are also presented.

4.2.1 Roughness

Pavement roughness is defined as "the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and pavement drainage," (ASTM E867-87). Roughness is primarily associated with serviceability; however, roughness is also related to structural deficiencies and accelerated pavement deterioration.

Roughness has a significant effect on vehicle operating costs, safety, comfort, and speed of travel. Studies have demonstrated that roughness is the primary criteria by which users judge pavement performance, and therefore, the condition of a highway system (Budras, 2001). The effects of roughness are also associated with pavement structure deterioration, particularly when amplitude-wavelengths are high, causing appreciable dynamic forces in excess of dynamic weight (FHWA, 1991).

Table 3.1: Pavement Functions and Characteristics by Evaluation Type

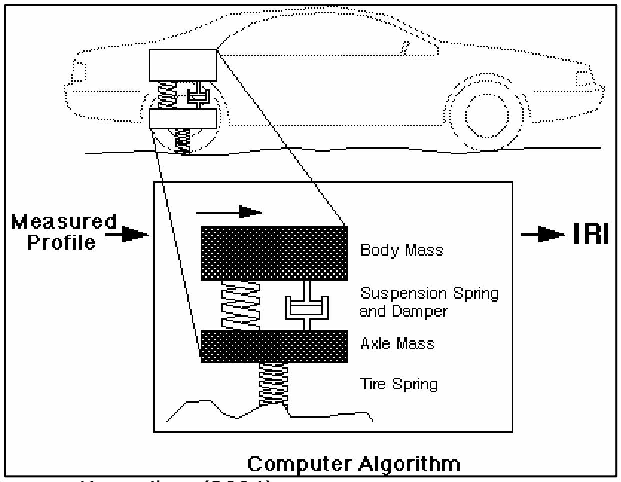
Evaluation Type	Pavement Function	Pavement Characteristics	Examples of Indicators and Indexes
Functional Evaluation	Serviceability	Roughness	IRI
			PSI
			QI
	Safety	Texture	Macrotexture
			Microtexture
		Skid Resistance	Skid Resistance Coefficient
			IFI
Structural Evaluation	Structural Capacity	Mechanical Properties	Deflections
		Pavement Distress	Cracking
			Surface Defects
			Profile Deformations
Referencing System		(Location of Pavement Characteristic Data)	

The first approach used to evaluate pavement roughness was a qualitative rating system, 'Present Serviceability Rating' (PSR), which later led to an objective quantitative index, the 'Present Serviceability Index' (PSI). Today, the most commonly used index is the 'International Roughness Index' (IRI), which is a standardized roughness measurement calculated using a mathematical simulation of a quarter-car (*i.e.*, a single wheel) traveling along the road profile at a speed of 50 km/h[1] (Figure 4.1).

The IRI was first presented by the World Bank in *Technical Paper Number 46* (Sayers et al., 1986), which suggested grouping various measuring methods into four classes, based on the ability of equipment providing precise IRI results. Later, ASTM developed the ASTM E 950-94 standard, which classified roughness measuring devices into four groups according to their accuracy and methodology used in IRI evaluations.

Although roughness measurements are perhaps the most 'mature' technologies, there is still work to be done in improving the measurement accuracies and repeatability. This was evidenced at the 2004 FHWA Profiler 'Round-up' which compared the results from 68 devices (35 high speed, 19 lightweight, 14 slow and walking speed) operating on the same twelve test sections.

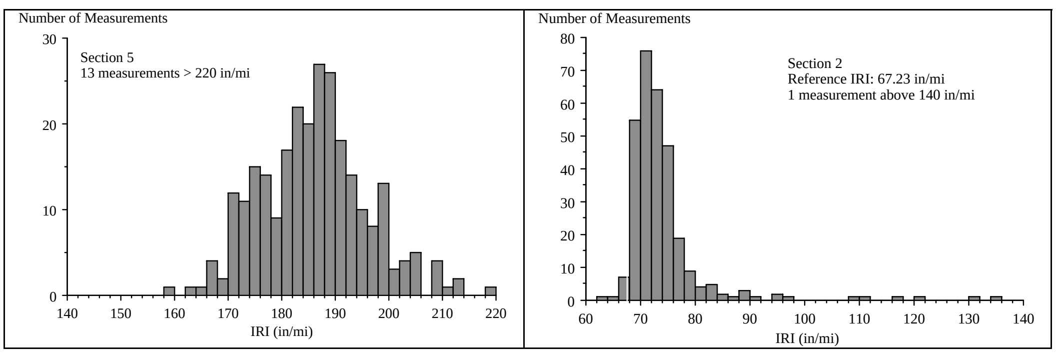
[1] There are also half-car and full-car simulation models available, as well as a truck simulation. All follow the same basic approach as the IRI—modelling how an idealized vehicle responds to the road profile—although the outputs are not directly comparable. For a full discussion on the development of the IRI and other information on roughness visit the 'Road Profiler User's Group' (RPUG) web site at www.rpug.com.



Source: Karamihas (2004)

Figure 4.1: Quarter-Car IRI Calculation

As shown in Figure 4.2, the performance of the different systems varied quite significantly. In some instances there was excellent agreement, whereas in others, there was a great deal of variability. Pavement texture often presented the biggest problem with the measurements.

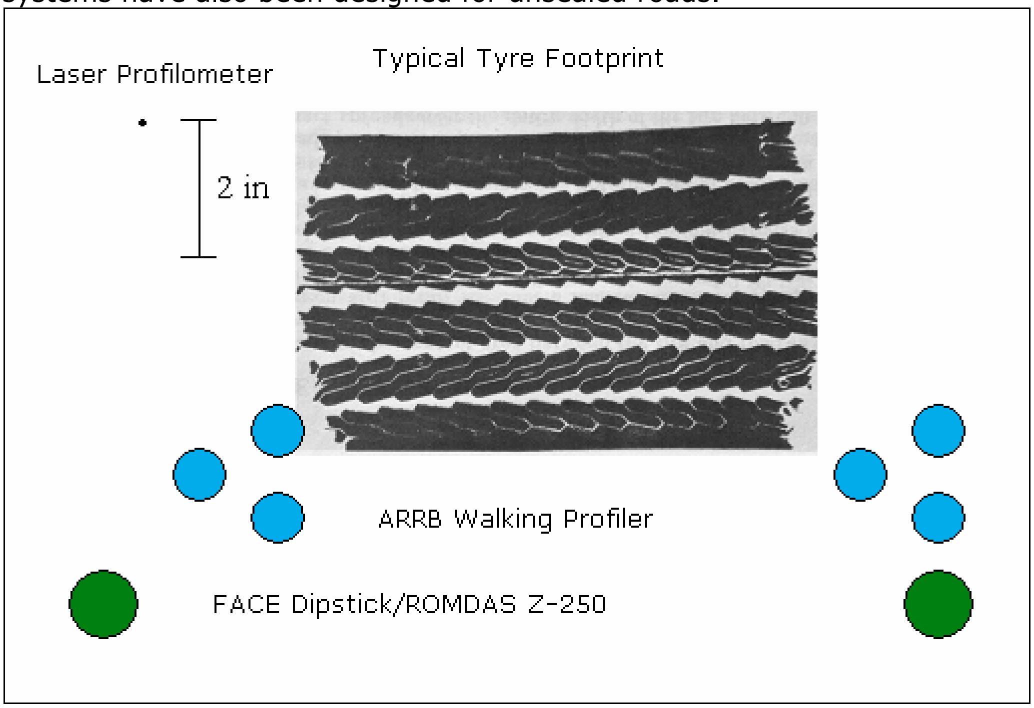


Source: Karamihas (2004)

Figure 4.2: Example of Range of Profiler Measurements from Comparative Study

Karamihas (2004) argues that the basic deficiency lies in the inability of the current measurement devices to replicate the footprint of a tire tread. This is illustrated in Figure 4.3, which compares the tire footprint with the footprints of different roughness measurement instruments. A laser profilometer has a very small point which measures at very short intervals along the road. Instruments such as the Dipstick/Z-250/ARRB Walking Profiler measure with larger footprints, but less frequently along the road. The footprint of a tire is not only larger than all of these, but it is also in continuous contact with the road surface.

Because of this situation, care must be taken when selecting a technology for measuring roughness. In some instances, simpler technologies such as response-type roughness meters may get better results than more sophisticated laser-based systems since they reflect the effects of the entire contact area of the tire with the pavement surface. When measuring unsealed roads, response-type meters are probably the most appropriate technology since they can handle very high roughnesses. Some accelerometer based systems have also been designed for unsealed roads.



Source: Karamihas (2004)

Figure 4.3: Comparison of Roughness Instrument Footprints

4.2.2 Texture

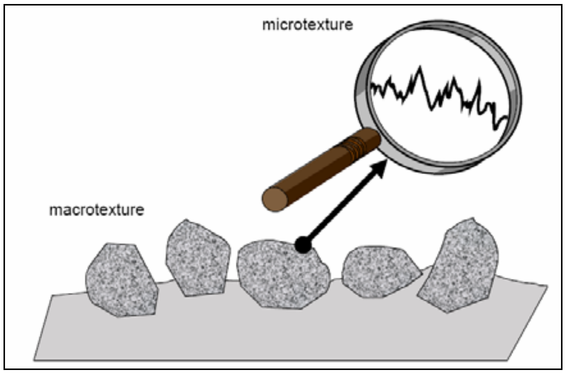
Pavement texture is primarily associated with safety conditions, user comfort, and road surroundings. In terms of safety, texture directly affects how well tires stick to pavement in wet conditions and indirectly affects skid resistance. Texture is also associated with noise emissions caused by traffic. From a pavement management perspective, texture depth is important since it can be controlled by maintenance activities and even trigger maintenance treatments.

There are three types of texture, classified according to profile wave-length: microtexture, macrotexture, and megatexture. As described below, road management focuses mainly on microtexture and macrotexture.

- **Microtexture** provides the adhesion between the rubber tires and the road surface and, as such, is vital to maintaining skid resistance.
- **Macrotexture** facilitates rapid drainage of the bulk of the water from the surface under vehicle tires and is represented by wavelengths between

0.5 mm and 0.5 cm. Figure 4.4 shows the difference between macrotexture and microtexture.

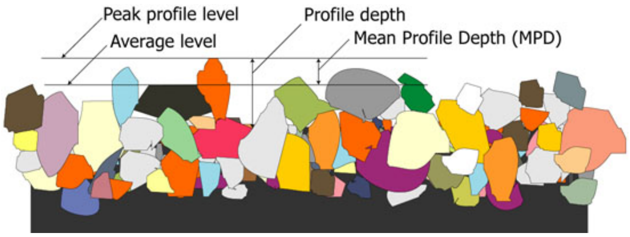
- **Megatexture** is commonly related to roughness, since it takes into account irregularities of significant wavelengths, between 0.5 cm to0.5 m. Megatexture prevents tires from having ideal contact with the road surface. The tire might "bounce" or "bump" over part of the megatexture, which means that adhesion is momentarily lost in parts of the tire/road interface. Megatexture is an unwanted surface feature, while micro-texture and macrotexture are both highly desirable.



Source: Crow (2003)

Figure 4.4: Microtexture vs. Macrotexture

High speed measurements of macrotexture are made using laser based systems. The measurements are reported in terms of either the 'mean profile depth' (MPD) or as the 'sensor measured texture depth' (SMTD). The MPD calculation is defined in the draft ISO standard ISO/DIS 13473 (see Figure 4.5). This requires very high performance systems. The SMTD is much simpler to measure, based on the variance around a regression line fitted to the data, but is not as robust as the MPD.



Source: Greenwood Engineering

Figure 4.5: Calculation of Mean Profile Depth

As pointed out by McGhee and Flintsch (2003), texture depth can be considered in terms of being 'positive' (such as that provided by the coarse surface of the pavement) or 'negative' (such as that provided by grooves cut into the pavement). While the MPD calculation would provide a much higher value for the positive textured surface than the negative surface, an SMTD calculation could give identical values, even though the 'positive texture', practically speaking, offers a much higher macrotexture. It is therefore necessary to carefully assess the SMTD predictions to ensure that they provide a correct reflection of the pavement surface.

4.2.3 Skid Resistance

Cenek (2004) gives the following description of skid resistance and the relationship of surface texture to skid resistance:

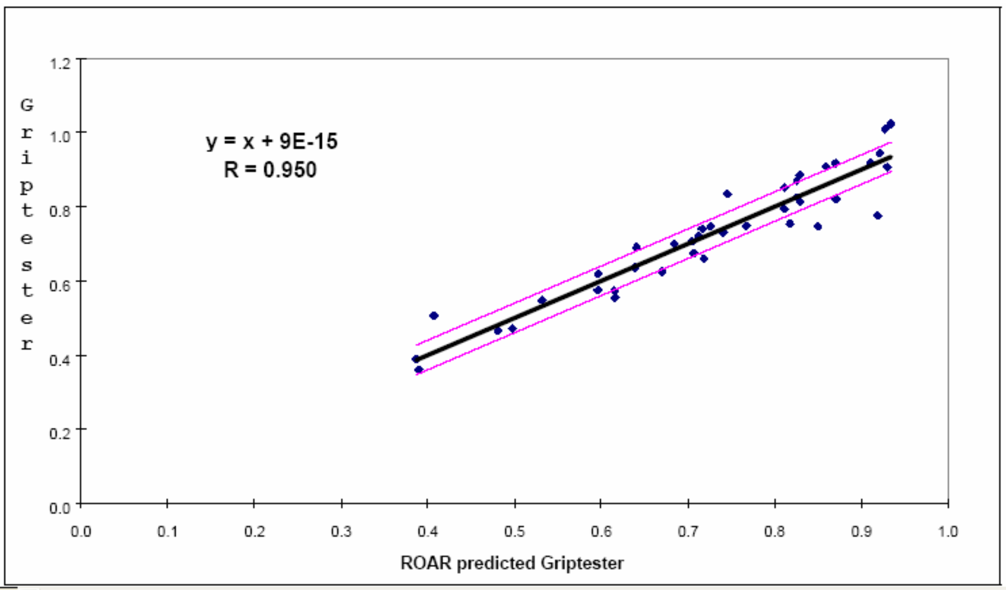
> A vehicle will skid when, in braking, accelerating, or maneuvering, the frictional "demand" exceeds the limiting friction force that can be generated at the tire/road interface. Therefore, **skid resistance** (or friction) may be defined as the limiting coefficient of friction between the tire and a road and is the ratio of the limiting horizontal frictional force that is resisting the braking, driving, and cornering forces to the vertical force acting on the tire due to the weight of the vehicle.

The skid resistance provided by a road is primarily a function of its surface texture. When microtexture comes into contact with the tire, an adhesive friction force (commonly referred to as "grip") is generated. Under wet conditions, microtexture penetrates the thin water film that remains between the tire and the road to establish direct contact with the moving tire. Macrotexture facilitates the drainage of water from the tire/road contact area.

Under wet conditions, microtexture dominates skid resistance at low speeds (less than 70 km/h). However, at high speeds (greater than 70 km/h), both microtexture and macrotexture are required to provide a high level of skid resistance. This is because at faster speeds, macrotexture is needed to allow surface water to escape and prevent partial or full aquaplaning. Therefore, macrotexture determines how quickly skid resistance in wet conditions decreases with speed. However, even at high speeds, microtexture remains the major influence, because a low level of microtexture will always lead to low skid resistance, regardless of the level of macrotexture. For this reason, and because the drainage function performed by macrotexture can be complemented by tire tread (which also facilitates the removal of water from the tire/road contact area), the skid resistance management of road networks tends to be dominated by microtexture considerations.

Skid resistance is measured by indirectly measuring the resistance of a test tire to wet pavement. Depending on driving direction and equipment displacement over pavement, a transverse or longitudinal skid resistance coefficient can be determined. The main difficulty is determining how to combine and compare measurements with different devices, since there is more than one type of skid resistance coefficient. To solve this limitation, the PIARC World Road Association published in 1995 the results of an experiment that compared and correlated texture and skid resistance measures. As a result, the 'International Friction Index' (IFI) was created, which defines a comprehensive friction reference scale associated with vehicle speed. For skid resistance determination, this methodology needs both skid resistance and texture measures related to equipment type and testing speed (PIARC, 1995). Unfortunately, the IFI has not proved to be as widely adopted as the roughness IRI since, as Crow (2003) points out, there are a number of issues with the way in which the value is calculated and there are deficiencies since it does not consider microtexture.

It is important to realize that irrespective of what technology is adopted, the results between systems are generally comparable. They will identify the locations where skid resistance is low compared to others where there are no skid resistance problems. An example of this between two portable devices is shown in Figure 4.6. However, Crow (2003) notes that overall there is "no consistent or precise direct correlation between the various ground friction vehicles". This especially arises when comparing different types of technologies (*e.g.* fixed wheel and slip). While the IFI was an attempt at overcoming this problem, more work is still required before an index similar to the roughness IRI is available.



Source: Norsemeter (2004)

Figure 4.6: Comparison of Griptester and ROAR Skid Resistance Measurements

4.2.4 Mechanical/Structural Properties

The structural capacity of a pavement denotes the ability of the pavement structure to support prevailing and projected traffic loads. Thus, a structural evaluation should assess pavement's overall capacity to perform satisfactorily under traffic loads with minimum deformation and distress (NCHRP, 1994).

The structural capacity of a pavement is usually determined through the evaluation of mechanical properties of each layer of the pavement structure, such as: elastic modulus, fatigue properties, deflection conditions, and residual tensile stresses. The two common methods for evaluating these parameters are coring, where pavement cores are studied in laboratory, or non-destructive tests done in the field. The bearing capacity of the pavement base layers and subgrade can also be estimated using a dynamic cone penetrometer.

Non-destructive methods evaluate pavement deflections produced by the elastic deformation generated by a known vibratory or static loading applied over pavement surface. Deflections mainly depend on type of pavement, pavement condition, temperature and type of load applied. The information used from deflection testing is the peak rebound deflection under the applied load and the curvature of the deflection basin. Figure 4.7 shows the principles of the falling-weight deflectometer (FWD). Deflection information is interpreted in order to determine pavement mechanical properties. A commonly used interpretation methodology is through the 'back-calculation' of the elastic modulii of the pavement structure[1].

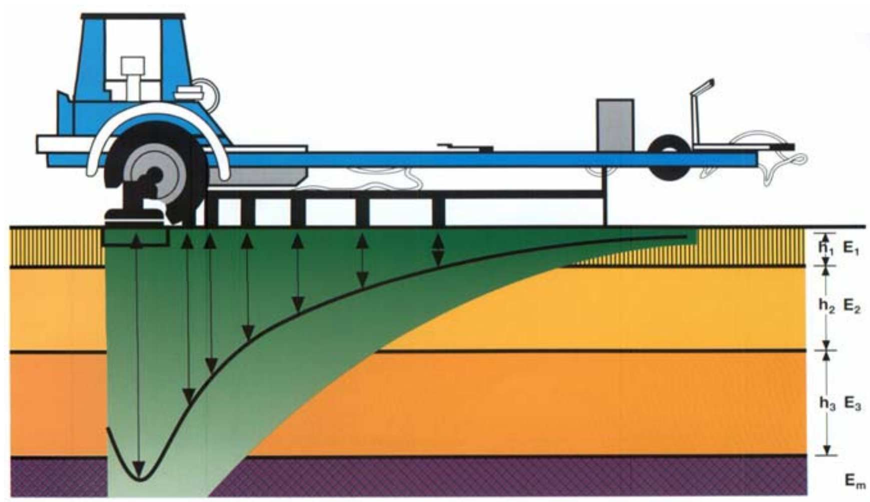


Figure 4.7: Example of Falling Weight Deflectometer Principles

4.2.5 Surface Distresses

Surface distresses reflect deterioration caused by traffic, environment and aging (AASHTO, 1990). Distress type, extent, and severity are indicators of pavement performance, related directly to structural capacity and indirectly to functional conditions.

Surface distress evaluations are generally performed manually, although automated crack detection is becoming more common. Important efforts have been made to standardize data collection methodologies, and while many countries have their own data collection manuals, there is general agreement on distress monitoring. What differs is the way the distresses are expressed (*e.g.*, length of distress versus area; area versus number) and the way the results are applied in the management process.

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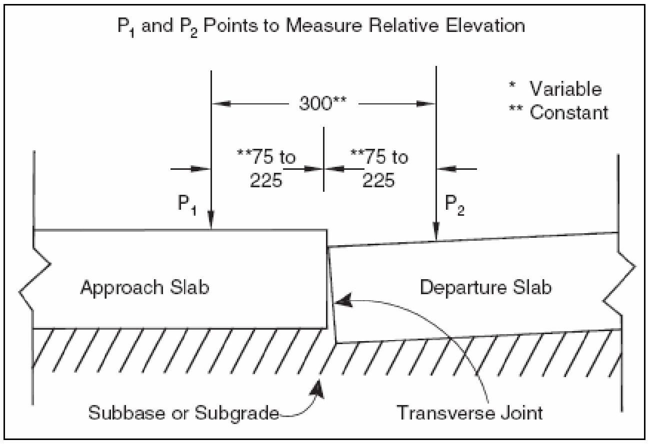
[1] Back-calculation uses the properties of the deflection bowl and layer thicknesses to estimate the elastic modulii of the pavement structure. Teng (2002) describes the three different methods for back-calculation: equivalent thickness; optimization; and iterative.

The Strategic Highway Research program developed a Distress Identification Manual for the Long-term Pavement Performance Project that is widely used, especially for project level surveys (FHWA, 2003). However, there is no standard approach for distress data collection similar to the roughness IRI, mainly because of the unique requirements of many road management systems (RMS).

Indicators evaluated in a surface distress evaluation are: cracking, surface defects, transverse and longitudinal profile deformations, and miscellaneous defects of the pavement. Cracking and surface defects vary between pavement types and are generally measured as a percentage of total surveyed area, as linear units, or as the number of defects. Along surface deformations, the most commonly observed are rutting in asphalt pavements, and faulting in concrete pavements. Both distresses are measured as the vertical deformation of the pavement with respect to pavement surface level, although differently. Faulting is a longitudinal deformation and is calculated either manually or with laser based systems from the elevation difference between two points (P1 and P2) as shown in Figure 4.8. Rut depth is calculated transversely as described in Section 4.3.9.



Source: McGhee (2004)

Figure 4.8: Calculation of Faulting

4.3 Data Collection Techniques

4.3.1 Introduction

Data collection equipment should ensure reliable, efficient, and secure pavement evaluation. Equipment can be divided into five classes, according to the type of pavement characteristic being evaluated: equipment for measuring location, geometry, serviceability, safety, and structural capacity.

Each equipment class is subdivided by equipment type according to collected data accuracy, type of data collected and methodology used to determine pavement characteristics. In Table 4.1, a summary of equipment types per class is presented. Summary tables describing general characteristics of each equipment class are presented in Appendix A.

Table 4.1: Measuring Equipment Types by Class

Function	Equipment Class	Types of Measuring Equipment
Location	Location Referencing	Digital DMI GPS Video Logging
Geometry	Geometry	GPS Inertial Navigation Units
Serviceability	Roughness	Class I: Precision Profiles ▪ Laser ▪ Manual Class II: Other Profilometer Methods Class III: IRI Estimates from Correlations Class IV: Subjective Ratings
Safety	Microtexture Macrotexture	Static Static Dynamic
	Skid Resistance	Static Dynamic
Structural Capacity	Mechanical Properties	Falling Weight Deflectometer Deflection Beams Dynamic Cone Penetrometer Clegg Hammer Laboratory Tests
	Surface Distress	Video Distress Analysis Visual Surveys Transverse Profilers

It is most cost effective to collect multiple pavement characteristics during a single pass of the data collection vehicle. Not only does this keep the survey costs down, but it also ensures that the data referencing is consistent. There are two broad approaches for achieving this:

- **Portable systems:** the systems can be installed in any vehicle and are designed to be modular and portable. Examples of these are the ROMDAS, Vizi-Road and the ARRB Hawkeye systems; and,
- **Dedicated vehicles:** vehicles with permanently installed instrumentation. Examples are the ARAN, Greenwood, HARRIS, WDM vehicles.

Portable systems suffice for the majority of applications and are usually less expensive[1]. Dedicated vehicles are required when using the most

[1] One important consideration in deciding between portable systems and dedicated vehicles is the availability of parts for the host vehicle. Many developing countries have restrictions on parts

sophisticated and data intensive instruments, for example, video detection of cracking.

4.3.2 Location Referencing

Location referencing is achieved using digital Distance Measuring Instruments (DMI) for linear referencing, and Global Positioning (GPS) receivers for spatial referencing. Video logging is included in location referencing as it is commonly used to determine the position of objects, although it is recognized that it is used for more than just referencing. Table 4.2 shows some examples of location referencing equipment.

Table 4.2: Examples of Location Referencing Equipment

CLASS	EQUIPMENT
Digital DMI	**Conventional digital DMI** (e.g. Nitestar, Halda) **Digital DMI integrated with other data** (e.g. ROMDAS System, ARAN System)
GPS	**Portable GPS** (e.g. Magellan, Garmin, LEICA, Trimble, Novatel) **GPS integrated with inertial systems** (e.g. Applanix, ARRB Gipsi-Trac)
Video Logging	**Analog imaging** (e.g. EVASIVA) **Digital imaging** (e.g. ARAN, ARRB Hawkeye, Mandli, Pavue, ROMDAS)

Digital DMI

Digital distance measuring instruments (DMI) are precision odometers that measure the linear traveled distance. There are two components: a pulse generator and a receiver. The pulse generator is attached to the vehicle's transmission, speedometer sensor, or to a wheel. It is calibrated against a known distance. The instruments must be periodically recalibrated, since the number of pulses/km changes as the tires wear on the vehicle. The accuracy of the measurements is proportional to the number of pulses per revolution of the pulse generator.

The type of instrument depends upon the application.

- **Standalone unit**: This is a digital display that shows the distance traveled (Figure 4.9). It is used with manual techniques to reference the pavement data. The operation is easy, needing only a simple calibration process in a field test each time a survey is done. Initial costs may vary between US $400 to US $2,000, and there are nearly no operational or maintenance costs.

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importation and other constraints that may affect vehicles brought in from overseas. It can be much more sustainable to mount portable equipment on a locally procured vehicle and accept a slightly lower level of data collection than to import a sophisticated data collection vehicle and find that it cannot be maintained.

- **Integrated systems**: The referencing is integrated as part of a larger data collection system, for example systems recording roughness and rut depths at the same time use linear referencing to locate the vehicle. Some systems (*e.g.*, ROMDAS) can also act in the same way as a stand-alone unit.

Figure 4.9: Digital DMI

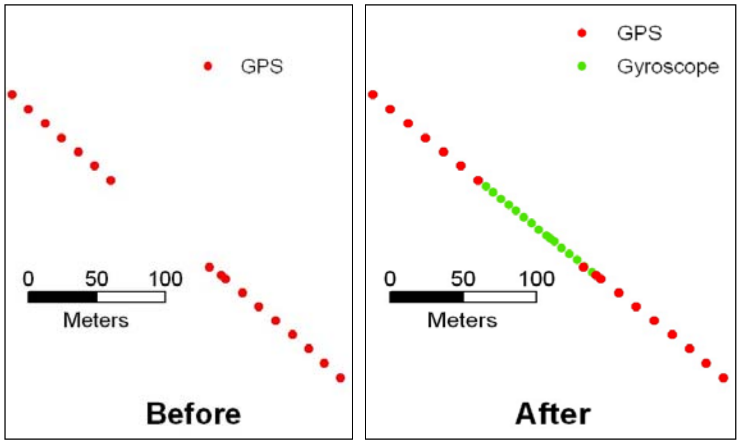
GPS

Portable GPS equipment can consist of hand-held units, luggable units, or GPS receivers integrated into hand-held PDAs or notebook computers. The receivers typically output the latitude, longitude, and elevation in WGS84 datum. The data can be manually recorded or logged automatically along with other data, usually the linear referencing.

There is a broad range of manufacturers and types of GPS equipment. Initial costs vary with accuracy and technology, ranging from US $150 to over US $5,000. Stand-alone GPS are inexpensive devices relative to other pavement survey equipment, since the initial costs are low and maintenance and operational costs are minimal.

GPS signals can be blocked by terrain (trees, hills, *etc.*) or urban buildings. The latter can also give inaccurate readings due to signal reflecting. Inertial navigation systems are therefore used to overcome this problem. These consist of one or more gyroscopes, to estimate the vehicle trajectory when the GPS signal is lost. Kalman filtering is often used to improve the accuracy of the estimates. Figure 4.10 is an example of how inertial systems are applied.

Inertial systems range from single integrated units with GPS (*e.g.*, Fibersense I2NS), to stand-alone GPS units with gyroscopes (*e.g.*, ROMDAS). Costing between US $3,000 and US $5,000, these are a useful complement to standalone GPS receivers. A special class of inertial systems are precision inertial navigation units, such as the Applanix POS LV or the ARRB TR Gipsi-Trac (costing approximately $50,000 or more). These are discussed in Section 4.3.3.



Source: MWH (2004)

Figure 4.10: Use of Gyroscope to Interpolate Missing GPS Data

Right-of-Way Video Logging

Video logging has for many years been a useful technology for identifying the location of roadside attributes and monitoring the road right-of-way. While systems were once based on films or analog video, most systems currently use digital technology to directly digitize the image and store it on a hard disk. The digitized images usually have the location of the image, in linear or spatial co-ordinates, superimposed on the image (see Figure 4.11). This makes it possible to reference the information in the image precisely, and is very useful when dealing with safeguard issues such as resettlement or the environment.

One issue with digital video logging is the size of the files. Since the cameras typically operate at 25 – 30 frames/second, storing all images results in very large files, even when using aggressive compression algorithms. A better approach is to sample the video at regular intervals along the road, usually every 5 – 10 m. This provides sufficient information for management purposes while not overloading the data storage system.

Most digital video logging systems record the linear or spatial location in conjunction with the frame number in a database. This makes it possible to quickly forward to any location on the road. A panoramic view can be obtained with the use of multiple cameras.

Video systems start with single camera systems with limited analysis software. These can be easily mounted in different types of vehicles. The more sophisticated systems have multiple cameras, often using stereoscopic principles, and offer precise positioning of data (*e.g.*, ARRB TR, Geo-3D, Mandli, Pavue, ROMDAS, and Roadware). While all digitized images can be analyzed to some degree, some multiple camera systems allow the use of photogrammetric techniques to precisely locate spatially any data that can be viewed in the image. This makes the video log a valuable tool for establishing a spatial data base.

Source: MWH New Zealand Ltd.

Figure 4.11: Example of Video Log with Referencing Information from Cambodia

In many instances video logs are recorded in conjunction with other data such as roughness, texture and rut depth. The combination of instrument data with the video image is very useful for confirming the true condition of the road.

There are many suppliers of video logging systems, and the prices for basic systems range from US $1,000 to US $8,000. The multi-camera and advanced systems can cost significantly more. Maintenance and operational costs of digital video systems are minimal since they are fully automated.

4.3.3 Road Geometry

Road geometry consists of the vertical and horizontal alignment, as well as the cross-fall. When combined with data on rut depths, this can be important data for safety management, since it can identify potential hydroplaning areas.

The vertical and horizontal alignments are often established using standard GPS systems, sometimes supplemented by inertial navigation units especially when there is a loss of GPS signal (see Section 4.3.2). For example, MWH (2004) collected GPS data on the Cambodia network. The rise and fall was determined by segmenting the links into 100m segments and assigning an elevation value to each link based on the average GPS elevation. The rise and fall are calculated by comparing the elevation of a segment to the previous segment. If the segment elevation was greater, then a value of 1 (rising) was assigned, and if the elevation was less, a value of -1 (falling) was assigned. The total number of rises or falls was then summed for each link. Cumulative rise and fall, expressed as m/km was calculated using an ESRI ArcView GIS (geographic information system) script. Horizontal curvature was calculated as an index from 0-100 by comparing the length of the road to the straight line distance between the start and the end points. The lower the index, the more curvature on the road.

The most accurate way of measuring the complete road geometry (including cross-fall) is through a precision inertial navigation unit with integrated GPS such as the Applanix POS LV or the ARRB TR Gipsi-Trac. These are used as stand-alone units or integrated with other instruments, such as video or roughness systems (*e.g.* ARAN, Geo-3D, and Mandli). The systems are able to render very accurate 3D maps of highways. For example, with samples every 10 mm, the Gipsi-Trac can measure gradient and cross-fall to 0.2% accuracy, and the horizontal/vertical curvature to 0.1 radian/km.

Crossfall is also estimated using accelerometers or inclinometers. However, the dynamic nature of vehicles makes this inaccurate. An improved approach is to use a transverse profiler to obtain an estimate of the shape of the pavement and then to calculate the cross-fall from this data and an inclinometer.

4.3.4 Roughness

Roughness measuring devices are classified by the ASTM E 950-94 standard into four groups according to their accuracy and methodology used to determine IRI. Class I devices incorporate precision profiles, Class II devices consider other profile methods, Class III devices use IRI estimates from correlation equations, and Class IV consider subjective ratings and uncalibrated measures. Table 4.3 gives some examples of the types of equipment in the different classes.

Table 4.3: Examples of Roughness Measuring Equipment

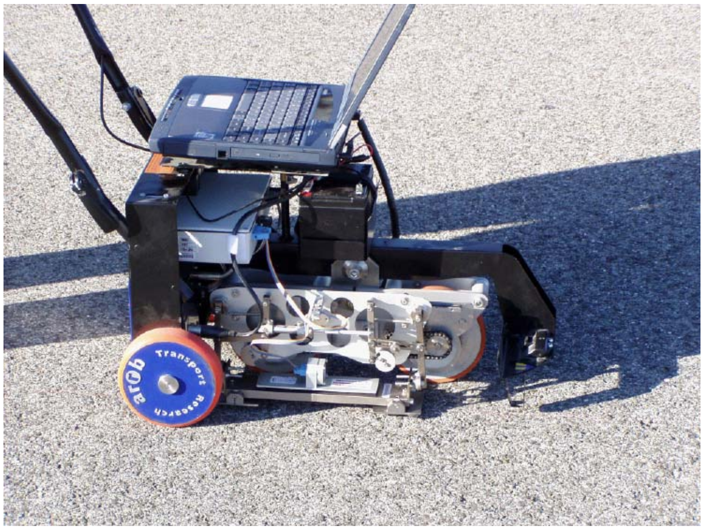
CLASS	EQUIPMENT
Class I Precision profiles	**Laser profilers:** Non-contact lightweight profiling devices and portable laser profilers **Manually operated devices:** e.g. TRL beam, Face Dipstick/ROMDAS Z-250, ARRB Walking Profiler
Class II Other profilometer methods	APL profilometer, profilographs (e.g., California, Rainhart), optical profilers, and inertial profilers (GMR)
Class III IRI estimates from correlation equations	Roadmaster, ROMDAS, Roughometer, TRL Bump Integrator, rolling straightedge.
Class IV Subjective ratings/uncalibrated measures	Key code rating systems, visual inspection, ride over section

As mentioned earlier, roughness measurements are usually expressed in terms of m/km IRI. Karamihas (2004), presenting the results of a comparative study between roughness measurements from different devices on the same roads, shows that there are a large number of different types of equipment on the market for measuring roughness.

Class I: Precision Profiles

This class is the highest accuracy standard for roughness measuring devices. The profile is measured as a series of closely spaced accurate elevation points in the wheelpath. The distance between points has to be short in order to achieve a high accuracy for describing the road profile. Some recommendations suggest that this distance should not be more than 0.25 m (Sayers et al., 1986).

Equipment included in this class can be divided into two broad groups, those using laser technology and manually operated equipment. Karamihas (2004) shows a variety of different equipment types falling into each group and some examples are shown in Figure 4.12 and Figure 4.13.



Source: Karamihas (2004)

Figure 4.12: ARRB Walking Profiler

Figure 4.13: Laser Profiler

There are substantial cost differences between different instruments. The initial costs of laser devices are higher than manually operated equipment: US $25,000 - $50,000 for a two wheelpath system, compared with as low as US $5,000 for a manual system. However, operational costs are low because laser profiler surveys are continuous and at traffic operational speeds. Manual systems are only practical for small surveys.

Class II: Other Profilometer Methods

This class considers dynamic profile measuring methods that determine profile elevations by either elevation data or summarizing statistics calculated from elevation data. The profile of one or both wheelpaths is measured with contact or non contact profilometers. Accuracy of these devices is dependant on the technology used, being less accurate than Class I.

Class III: IRI Estimates from Correlation Equations

Class III equipment include mechanical or electronic devices that indirectly evaluate pavement profiles. Measures obtained using these devices require calibration through correlations with standardized roughness values. Class III instruments are particularly useful for measuring very rough roads, especially those that are unpaved. They can record at very high levels of roughness and under conditions that could severely compromise the calibration of Class I and II instruments.

There are three types of Class III equipment:

- **Response-type road roughness measuring systems (RTRRMS)** measure the dynamic response of the vehicle to the road, either mechanically (see Figure 4.14) or by using accelerometers. Since the vehicle's response changes over time, the systems usually require recalibration. Accelerometer based systems (*e.g.*, Roadmaster, ARRB Roughometer) are easier to calibrate, but they do not give as accurate results as a well calibrated bump integrator (*e.g.*, CSIR LDI, ROMDAS, TRL Bump Integrator).

Figure 4.14: Bump Integrator Class III Roughness Meter

- **Rolling-straight edges** includes different types of profilographs, which sense displacements relative to a moving datum.
- **MERLIN** (Figure 4.15) is a manually operated instrument that is often used to calibrate RTRRMS. Consisting of a single wheel on a frame, it is moved along the road, and a probe attached to an arm is used to record the variability of the roughness along the road. This variability is correlated to the IRI. A major advantage to MERLIN is its low cost and the availability of plans enabling local manufacture.

Figure 4.15: TRL Merlin

The initial cost of these instruments is much lower than that of high precision devices. Operational costs depend on type of equipment used; however, performance is high since almost all are connected to survey vehicles that can measure near traffic operational speed. Maintenance costs are relatively low, but rigorous calibration processes may need to be performed as often as every 5,000 km (primarily for mechanical systems).

Class IV: Subjective Ratings and Uncalibrated Measures

This class is the least accurate. Subjective evaluations are produced by either driving over the section or conducting a visual inspection. Subjective evaluations such as these are usually adopted when higher accuracy is not essential or is not affordable. The operational costs may be relatively high when conducting a manual visual inspection, especially with regard to training in order to ensure that the ratings by different individuals are consistent. There are no maintenance costs or initial costs considered in this class.

4.3.5 Macrotexture

Since microtexture is measured through laboratory tests, the discussion here focuses on macrotexture. Macrotexture measuring devices are classified in two groups, dynamic and static. In Table 4.4, examples of texture measuring equipment are presented for each class. As discussed earlier, the dynamic texture depth is expressed in terms of MPD or SMTD. MPD requires much higher specification equipment and so the costs are usually higher.

Table 4.4: Examples of Macrotexture Measuring Equipment

CLASS	EQUIPMENT
Dynamic	Laser profilers, non-contact lightweight profiling devices and portable laser profilers (*e.g.*, RoadSTAR profiler, high speed texture system, WDM texture meter)
Static	Sand patch method, circular texture meter

Dynamic Measurements

Dynamic measurements use laser technology similar to those presented in Class I roughness. Often, the same equipment used to measure roughness can be used to measure texture and be mounted on a trailer (*e.g.*, WDM High Speed Texture System). In some instances, textures are measured in both the wheelpaths and between the wheelpaths. The difference in measurements gives an indication of the texture change occurring under traffic. A relatively low-cost manually operated slow-speed version was developed WDM (Figure 4.16). This uses a single laser to calculate the MPD.

Figure 4.16: WDM TM2 Texture Meter

Static Measurements

The most commonly used static texture method is the 'sand patch' or 'volumetric' method. This simple test is an approximate evaluation of surface macrotexture, indirectly evaluated through mean texture height. A known standardized volume of sand or glass beads is circularly placed over a pavement, and the mean height is measured. Differences in measured and initial volume diameter give an estimate of the texture depth.

Figure 4.17: Sand Patch Method

The volumetric method is inexpensive and does not need complex maintenance or calibration procedures but is very slow and not very accurate. According to Crow (2003) the differences reported for the same surface ranged from 100 to 350%.

An improvement over the sand patch method is the stationary laser profiler. This consists of a texture laser, similar to that used for dynamic measurements, which is manually positioned. The laser moves along the pavement using a motorized carriage. In Sweden, the laser is mounted on a vehicle that is stopped at each point of placement. The New Zealand approach (see Figure 4.18) is to have the laser texture meter completely portable.

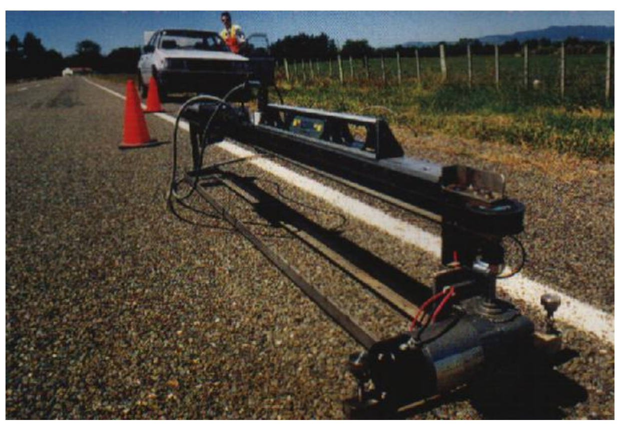


Figure 4.18: New Zealand Stationary Laser Texture Meter

A major disadvantage of static methods is the requirement to have traffic control—the traffic must be halted during the testing. Also, these methods only provide measurements at a single location instead of along a section, as is achieved with dynamic devices.

4.3.6 Skid Resistance

Skid resistance measuring equipment includes dynamic and static devices. In both cases, available equipment can measure transverse or longitudinal skid resistance. Table 4.5 presents examples of skid resistance measuring equipment.

Table 4.5: Examples of Skid Resistance Measuring Equipment

CLASS	EQUIPMENT
Dynamic Subdivided into trailer mounted and those embedded in a vehicle	**Trailer - Locked/partially Locked wheel:** Skiddometer, Sutt. Reibungsmesser, ASTM E-274 Trailer, Griptester, Norsemeter **Trailer - Transverse skid resistance**: ADHERA 2 **Vehicle mounted:** SCRIM, which measures transverse skid resistance
Static	British Pendulum tester (TRL), DF Tester, Rosan

Dynamic Measurements

Dynamic skid resistance measurements are made either by a locked/partially locked-wheel procedure or by a yawed-wheel method. Equipment can be sub-divided into two groups: vehicle mounted devices such as SCRIM and portable devices. The cost and operational characteristics are substantially different for both groups.

Source: Findlay Irvine

Trailer System - GripTester

Source: CEDEX

Vehicle System - SCRIM

Figure 4.19: Examples of Trailer and Vehicle Mounted Systems

Locked/partially locked trailers operate on the same principle. The trailer is towed at a standard speed. Water is applied to the pavement and a wheel on the trailer is partially or fully locked. The friction force between the wheel and the wet pavement is measured. An example of this equipment type is the ASTM E-274 Trailer.

Yawed-wheel equipment have the wheel at an angle to the direction of travel. The transverse skid coefficient is measured continuously over the section length. SCRIM (Sideway Force Coefficient Routine Investigation Machine) and MuMeter are typical examples of this type of equipment.

Partially locked wheel (*e.g.*, GripTester) and transverse skid (*e.g.*, SCRIM, ADHERA) provide continuous measurements of wheelpath skid resistance, whereas locked wheel devices (*e.g.*, KJ Law) can only give intermittent measurements typically of 2 seconds for each measurement before pausing. The locked wheel method has the disadvantage of shorter test tire life due to excessive wear in routine testing, and it generally can only be used on straight stretches of road.

The initial cost of trailer systems is commonly over US$ 50,000. However, vehicle mounted systems have significantly higher initial (> $250,000) and operating costs than trailer systems. Generally, skid resistance measuring devices cannot be operated with other equipment. Calibration is complex and costly, especially for vehicle mounted devices.

Static Measurements

The most commonly known static device for measuring skid resistance is the British Pendulum Tester. It is a portable and easy to use device comprising a rubber covered mass hanging by a pendulum. The tests are usually performed in accordance with ASTM Standard Method of Test E 303, or similar.

The pendulum is slid over the wet pavement from a known height. As a result of energy loss caused by the arm friction with the pavement, a skid number called the 'British Pendulum Number' (BPN) is obtained, which is correlated with a skid resistance coefficient. One disadvantage of the British Pendulum Tester is that its results can vary with the operator conducting the tests, particularly on coarse textured surfaces where differences in setting up the 130mm slide length can occur.

Figure 4.20: British Pendulum Tester

Static equipment is not as expensive as dynamic devices, having an initial cost between US$ 10,000 and US$ 30,000. However, since testing is static, they are not interoperable with other devices and operation is very slow. The use of static equipment also requires traffic control—the traffic must be halted during the testing—and the tests only provide measurements at a single location instead of along a section as is achieved with dynamic devices.

4.3.7 Mechanical/Structural Properties

Testing methods range from Falling Weight Deflectometers (FWD) to deflection beams. For both testing methods, mechanical/structural properties of pavements are measured indirectly through pavement deflections. Table 4.6 presents some examples of this equipment.

Assessing the pavement structural capacity is a challenge. Annex D describes some of the issues around this in detail and gives examples of the sampling intervals adopted in different countries.

Table 4.6: Examples of Mechanical/Structural Properties Measuring Equipment

CLASS	EQUIPMENT
Falling weight deflectometer: Traditional, light weight and vibratory deflectometers.	▪ Traditional FWD (*i.e.*, Carl Bro, Dynatest, JILS, KUAB). ▪ Light weight deflectometer (*e.g.*, Keros Prima 100, Loadman) ▪ Heavy weight deflectometer (HWD) (*e.g.*, Dynatest, Kuab) ▪ Multi depth deflectometers (MDD): CSIR Dynatest Dynamic deflection equipment: Dynaflect, Road rater, WES heavy vibrator
Deflection Beams	▪ Benkelman beam ▪ Road surface deflectometer (RSD) ▪ Lacroix deflectograph ▪ High speed deflectograph
Other Equipment	▪ GPR: Ground Penetrating Radar (IRIS from Penetradar, HiPAS from Zetica, Infrasense GPR System) ▪ Dynamic cone penetrometer (DCP) ▪ Clegg Hammer

Falling Weight Deflectometers (FWD)

FWDs are impulse loading devices that apply loadings with a frequency and magnitude very similar to that applied by heavy traffic. Sensors, or geophones, are used to measure deflections at several points of the deflection basin.

These devices vary according to load application systems, which can be vibratory or static impulses. They can be sub-divided into three groups: traditional FWD, Light Weight Deflectometers, and Heavy Weight Deflectometers (HWD).

The initial cost of this equipment is well over US$ 50,000. Measurements are usually performed independently from other pavement condition testing, as sampling is at individual points as opposed to continuous measurement.

Operationally, this method has several advantages compared to deflection beams, such as higher accuracy and faster sampling speed. However, this equipment needs skilled technicians to calibrate the instruments and analyze the data. The FWD output can be used for more detailed analyses than that from deflection beams.

Source: Dynatest Ltd.

Figure 4.21: Falling Weight Deflectometer

Source: JILS Ltd.

Figure 4.22: Vehicle Mounted FWD

In some instances FWDs have been mounted inside a vehicle instead of being towed by a trailer. There are advantages to having the FWD mounted in the vehicle in terms of portability and operational efficiency (*e.g.* it is easier to maneuver and has a smaller turning radius), but there can be disadvantages in terms of the alterations compromising the host vehicle's safety designs and potentially high noise levels for operators. It can also make the equipment servicing more difficult. Trailer mounted FWDs should therefore be preferred for most situations.

Heavy Weight Deflectometers (HWDs) operate in a similar principle to FWDs, except they have a much heavier load. They are used for very heavy pavements or airfields.

Light Weight Deflectometers (LWDs) such as the Keros Prima or Loadman (Figure 4.22) are portable units. Pidwerbesky (1997) compared the Loadman to Benkelman Beam and FWD and found reasonable correlations. However, the relationship between Benkelman Beam and Loadman data results were different than those found in India, which suggests that the results are pavement dependent.

Source: Al-Engineering Oy

Figure 4.23: Loadman

A vital consideration when assessing deflectometers is the software used to process the data. Manufacturers have their own software with proprietary algorithms. There are also some independent applications available. Teng (2002) describes the different approaches used for back-calculation of elastic modulii and some of the available software. Care needs to be taken to ensure that the predictions of the software, given the input data, are appropriate for the roads of interest. This often requires local calibration or adaptation.

Deflection Beams

This group considers all moving wheel approaches that measure pavement deflections, usually referred to as Benkelman Beams and deflectographs. A Benkelman Beam is a manually operated device that is placed on the road surface. Maximum rebound deflection is recorded while the test vehicle moves away. The device is easy to use and has low initial and operating costs; however, it is also very slow and not as accurate as FWDs.

Deflectographs are mobile versions of the Benkelman Beam. Two beams are placed in the rear of a heavy truck, and a special mechanism places the beams on the ground and moves them forward after each measurement is made. Initial and maintenance costs are fairly high; however, operation speed is higher than when testing with a Benkelman Beam, but generally less than 25 km/h.

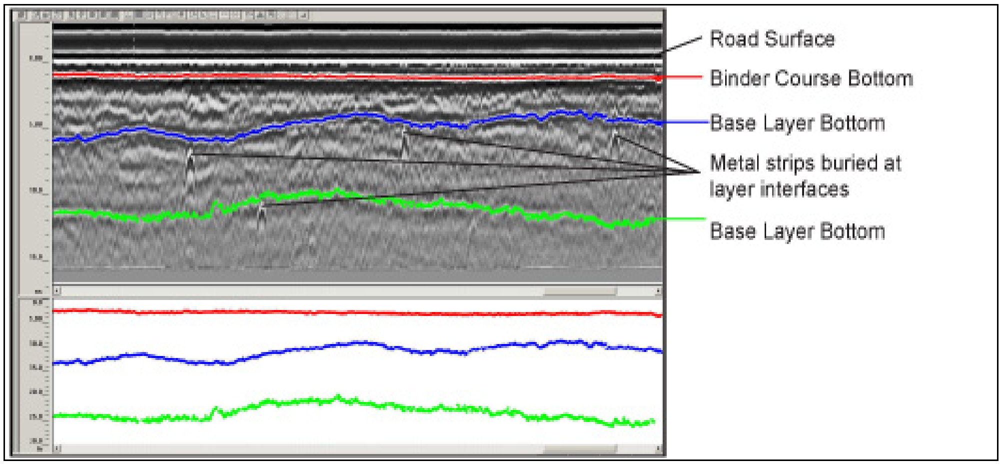
Figure 4.24: Benkelman Beam

Recent research in several countries has aimed at developing a high speed deflectograph. The objective is to replicate the stationary deflection measurements at high speeds. While still in the nascent stage, the most promising approach appears to be that developed in Denmark using laser doppler technology (Rasmussen, Krarup and Hildebrand, 2002). Very good correlations to the LCPC FLASH Deflectograph and traditional FWD results were found. The technology is still very expensive, but as it matures it can be anticipated to be more cost effective.

Ground Penetrating Radar (GPR)

Ground penetrating Radar is a pulse echo technique that uses radio waves to penetrate the pavement via wave energy transmission from a moving antenna. As energy travels through the pavement structure, echoes are created at boundaries of dissimilar materials. The strength of these echoes and the time it takes them to travel through the pavement can be used to calculate pavement layer thickness and other properties (FHWA, 2004). Figure 4.25 is an example of the data from a GPR and its interpretation.

Some of the most common applications in pavement mechanical and structural evaluation are: determining thicknesses of pavement layers for FWD back-analysis, freeze-thaw damage assessment, quality control of steel reinforcement bars, evaluation of subsurface condition, determining the existence and nature of joint spacing, full-depth asphalt patches detection, and evaluation of pavement voids and moisture accumulation. GPR systems can detect concrete pavement deterioration on exposed concrete pavements and on those with an asphalt riding surface. This technique is typically utilized for asphalt overlaid concrete pavements, where visual examination is not possible.



Source: GSSI Ltd.

Figure 4.25: Example of GPR Data and Interpretation

GPR measurements for pavement evaluation can be done manually or using vehicle mounted equipment (see Figure 4.26). Manual GPR systems are relatively low cost and tend to be used for project level data collection. These measurements are also useful for collecting pavement thickness data in conjunction with FWD surveys. Having pavement thickness data available during the FWD back-calculation analysis improves the accuracy of the elastic modulii estimates.

Manual System	**Vehicle Mounted System**
 Source: Mala Geoscience	 Source: GSSI

Figure 4.26: GPR Measurement Systems

Vehicle mounted systems can be used for both project level as well as network level surveys. With their rapid measurement speeds, it is possible to obtain a significant amount of layer thickness data on the road network. Unfortunately, very few road management systems can make adequate use of these data. For example, in Indonesia although continuous data were collected on the network, only the readings at the locations where FWD measurements were taken were actually used. It would have been more effective to use a lower cost (*e.g.* manual) method and only collect data at these locations.

Irrespective of whether the GPR data are collected manually or from a vehicle, it is necessary to calibrate the systems to local conditions prior to any survey commencement. Failure to do so can compromise the validity of the survey data. Similarly, it is important that staff be properly trained on data collection and interpretation to ensure useful results.

Dynamic Cone Penetrometer (DCP)

As described by TRL (1986), the DCP is an instrument designed for the rapid in-situ measurement of the structural properties of pavements constructed with unbound materials. Measurements can be made to a depth of 1200 mm. Where pavement layers have different strengths, the boundaries can be identified and the thickness of the layers determined to within about 10 mm.

The DCP consists of a shaft with an 8 kg hammer that drops from a height of 575 mm. The end of the shaft is fitted with a 60 degree cone with a 20 mm diameter. The instrument is operated by first digging a hole through the surface layer to the unbound layer. The instrument is held vertically and the hammer is allowed to drop. The number of hammer **blows** required for the cone to penetrate a certain distance is recorded. The DCP is usually operated manually; although a number of firms offer vehicle or trailer mounted systems (see Figure 4.27).

Source: Done and Samuel (2004)

Manual DCP

Source: Applied Research Associates

Trailer Mounted DCP

Figure 4.27: Examples of Manual and Trailer Mounted DCP Systems

Graphing the number of blows against distance clearly shows the boundaries between layers. Relationships exist between the DCP and the California Bearing Ratio (CBR), which is a measure of unbound layer strength. Software for analyzing DCP data is available from several suppliers, with a free application from http://www.transport-links.org/ukdcp/. The user's manual for this software also contains a number of relationships for converting the DCP data (Done and Samuel, 2004).

Clegg Impact Soil Tester (Clegg Hammer)

As described by the ASTM standard D 5874 entitled "Standard Test Method for Determination of the Impact Value (IV) of a Soil", the Clegg Hammer allows fast in-situ non-destructive checks of soil strength.

The Clegg Hammer consists of an instrumented compaction hammer operating within a vertical guide tube. The hammer is lifted by an operator to a measured height then released. It strikes the ground and decelerates at a rate determined by the ground stiffness. Measured units are Clegg Impact Values and design advances in recent years allow displayed outputs in terms of %CBR and Surface Modulus of the soil. Time and date stamped results can usually be stored within the recording unit.

Generally, two hammer weights are used: 4.5 kg and 20 kg. The 4.5 kg, 50mm diameter version is portable and allows rapid testing. It is also widely used to monitor trench reinstatement compaction quality as work proceeds. The 20 kg, 130mm diameter version is used for obtaining data for estimating traffic carrying potential of lightly surfaced trafficked roads. Estimated Benkelman Deflection and Surface Modulus of flexible pavements are available outputs.

Source: SD Instrumentation (UK)

4.5 kg Clegg **20 kg Clegg**

Source: Iteco, District Roads Support, Nepal

4.5 Kg Clegg Impact Soil Tester Use.

Figure 4.28: Clegg Hammer

4.3.8 Surface Distresses

Surface distress measurements cover a range of distresses, from potholing and cracking to surface deformations such as rutting. McGhee (2004) gives a good review of the automated pavement distress collection techniques and user experiences.

There are three groups of technologies used for recording these distresses. Manual techniques are based on surveyors visually observing distresses and then recording the data on paper or using some form of computerized technique. Imaging techniques involve taking photographs of the surface, either discretely or continuously, and then analyzing the images to report on the surface defects. Profilers use laser or acoustic techniques to measure deformations. Table 4.7 presents examples of distress measuring equipment. This section considers manual and imaging recording of surface distress data; rut depths are considered in the following section.

Table 4.7: Examples of Surface Distress Measuring Equipment

CLASS	DISTRESS	EQUIPMENT
Manual	Surface Defects	Paper forms Handheld data loggers Integrated systems (*e.g.*, ROMDAS, Vizi-road)
Analog and Digital Image	Cracking and Surface Defects	**Analog imaging:** Pasco RoadRecon, Gerpho, Roadware **Area scan digital image:** Samsung SDS, PAVUE, Pasco **Line scan digital image:** Waylink, Roadware, EVASIVA, International Cybernetics Corp.
Profilers	Rut Depths	**Laser profilers**: Acuity, AMSKAN, ARRB TR, Dynatest, Greenwood, INO, Roadware, ROMDAS **Ultrasonic Profilers**: Roadware, ROMDAS **Infrared Profilers**: PRORUT, SIRST

Manual Distress Recording

Manual distress recording is based upon visual observations of distress and recording the extent, severity, and location of the distress on either paper forms or using some type of data logging system. As described in Bennett and Paterson (2000), there is a range of methods used to describe surface defects. These can range from IQL III scores that summarize a range of defects to IQL I, which record precise information on the defects.

With the advent of low cost PDAs, many organizations have transferred their paper based methods to electronic methods. This has major advantages since it allows for improved quality assurance on the data. By integrating GPS receivers into the PDA, the location referencing of the data is significantly improved.

Systems such as Vizi-road and ROMDAS are used to visually record distress data while driving along the road. Observers use computer keyboards to record the data. The observations are integrated with the positions of other measurements, such as roughness and rut depth. In some instances, the data can also be superimposed on the video logging images.

Analog and Digital Imaging

Analog and digital imaging is used to record and quantify cracking and surface distresses. The systems consist of an imaging unit that records either still or continuous images of the pavement (either on film or digitally) and a means for analyzing the images (either manually or automatically). The initial cost of this equipment is high, over US $50,000, and if supplemental lighting is used the costs can be in excess of US $200,000.

An important advantage of automated systems is their repeatability. By eliminating the manual element of distress identification, one can obtain consistent and repeatable measurements of the distresses.

Analog systems have been used for some time to record pavement data. The trend now is to digitize the analog images. For example, the U.S. LTPP data are in the process of being converted from analog to digital images. Traditionally, analog was preferred to digital due to the higher resolution of analog images (2 mm pixels). However, current digital technology offers resolutions of 1mm so the majority of systems are based on digital cameras.

There are two types of digital cameras used for distress recording: **area scanning** and **line scanning**. Most systems use area scanning cameras, in which a charged couple device (CCD) matrix (usually rectangular in form) of pixels provides a view of an object that contains both length and width. With a line scan camera, the CCD contains only a single row of pixels. Line scanning offers the most precise images and potentially eliminates the need for supplemental lighting.

The resolution of the camera determines the size of the distress that can be observed. For example, a 1300 pixel camera can identify 3mm wide cracks; a 2048 pixel camera 2 mm; and a 4096 pixel camera 1 mm (8 bit or 256 grey-scales). The size of the images is proportional to the number of pixels. Each 2048 pixel image is 1.6 GB, compared to 6.6 GB for 4096 pixels. Advanced compression techniques could reduce image size to 70 MB or 280 MB respectively; however, the data storage requirements of digital imaging are significant, even with the best compression.

As described by Wang (2004), it is not straightforward to analyze digital images for crack identification. Even visual inspections with different surveyors may not yield agreed upon results for cracking. One issue is that all systems available for automated crack detection are based upon proprietary algorithms. Experience has shown that these algorithms can often reliably identify cracking on certain types of pavements—specifically those upon which the algorithms were developed. However, when trying to apply the algorithms to new types of pavements, the results have been less than stellar. It is therefore important that a validation exercise be done when implementing automated distress identification systems to identify any limitations with the system.

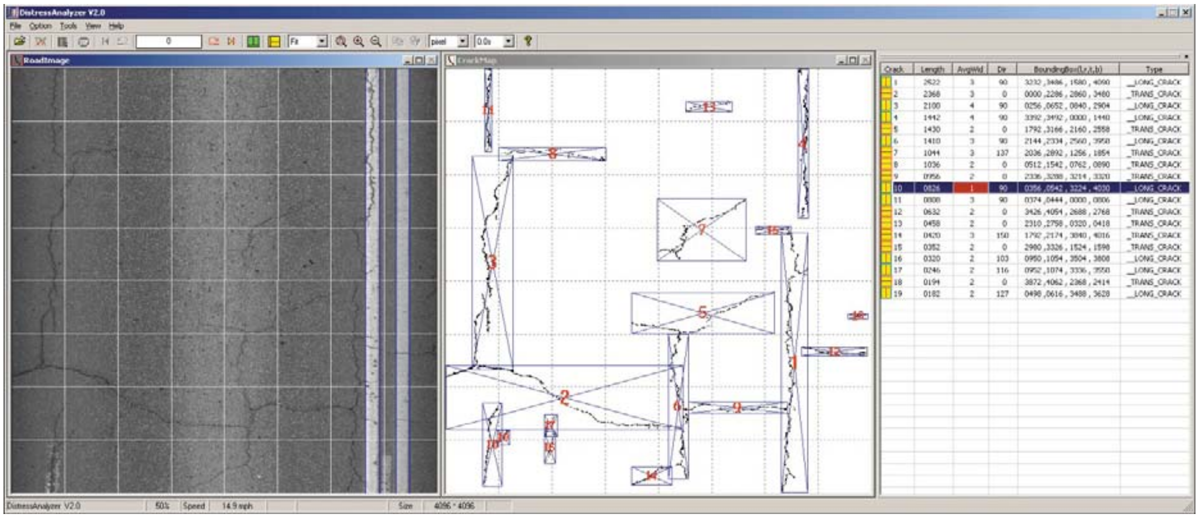
Distress recording systems have very similar designs. They consist of one or more cameras suspended above the road. They are often mounted on long arms to give them better panoramic views. Lights are often used to illuminate pavement surfaces, since this improves the quality of the images and thus the accuracy of the automated crack detection. Figure 4.29 is an example of a typical data collection vehicle. It is common to collect additional data along with video imaging, for example roughness and rut depth.

Source: Wang (2004)

Figure 4.29: Digital Imaging for surface distress

McGhee (2004) describes how images are processed using manual, semi-automated, or fully-automated techniques. Both manual and semi-automated require human intervention. The amount of intervention can vary significantly between systems. Fully-automated systems identify and quantify distresses through either no or very minimal human involvement. WiseCrax from Roadware is the most commonly used application, but there are several alternatives available using different algorithms and approaches.

The most sophisticated systems create crack maps that show the precise location, severity, and extent of cracking. These can be used to determine summary statistics on cracking. Figure 4.30 is an example of such software. An alternative approach, as described by Lee (2004), is to break the image into a number of 'tiles' and estimate the cracking from these. This approach is far less computer intensive than the crack mapping approach and has been shown to yield reasonable results for many road management applications.



Source: Wang (2004)

Figure 4.30: Example of Automated Crack Analysis

McGhee (2004) describes the current situation with regard to automated distress analysis as follows:

> *"The whole process of automated distress data reduction from images is evolving and is extremely complex, with significant technical demands, from the points of view of both equipment and personnel."*

It can be anticipated that as the industry matures over the next few years, the situation will improve. Those considering implementing automated distress analysis need to carefully assess the technological requirements as well as their institutional capacities for managing the process. There have been many successful implementations of automated distress analysis; however equally, there have been unsuccessful implementations.

4.3.9 Rut Depths

Rut depths are measured either manually, by placing a straight-edge (usually 1.2 or 2.0 m) across the rut and measuring the height difference to the pavement, or using a profiler. Profilers operate by having sensors record the elevation of a sensor relative to the pavement. From these, transverse profiles are established. The data are then analyzed to determine the extent of rutting. Figure 4.31 is an example of an ultrasonic transverse profiler.

Figure 4.31: Ultrasonic Transverse Profiler

There are four technologies used for estimating rut depths:

- **Ultrasonic**. Ultrasonic sensors are the lowest cost sensors and are used in systems like ARAN and ROMDAS. These have sensors at approximately 100 mm intervals that measure 3 m or more across the pavement. While older systems sampled only every 2.5 – 5 m along the road, new high speed systems sample at intervals similar to lasers.
- **Point Lasers**. Point lasers give the elevation at a point. The number of lasers varies, with systems such as the Greenwood profilometer having as many as 40 lasers. Much faster than ultrasonics, these record the transverse profile at intervals as close as every 10 mm along the road.
- **Scanning Lasers**. These lasers measure what is almost a continuous profile. An example of such a system is the Phoenix Science 'Ladar' which samples a 3.5 m pavement width from a single scanning laser mounted 2.3 m above the ground. Nine hundred and fifty points are sampled across the transverse profile, every 25 mm along the pavement.
- **Optical Imaging**. This method uses digitized images of the transverse profile that are analyzed to estimate rut depths. These images may be produced using various photographic techniques, often supplemented by lasers. An example of such a system is the INO rut system that uses two lasers to project lines to the pavements and a special camera to measure deformations of the laser line.

Ultrasonic and point laser profilers have their own unique configurations for the positioning of the elevation sensors. Figure 4.32 shows the positioning for the ARRB TR multilaser profiler, where the sensors are positioned at different spacing. By comparison, the ARAN ultrasonic profiler has sensors at 100 mm equal spacing.

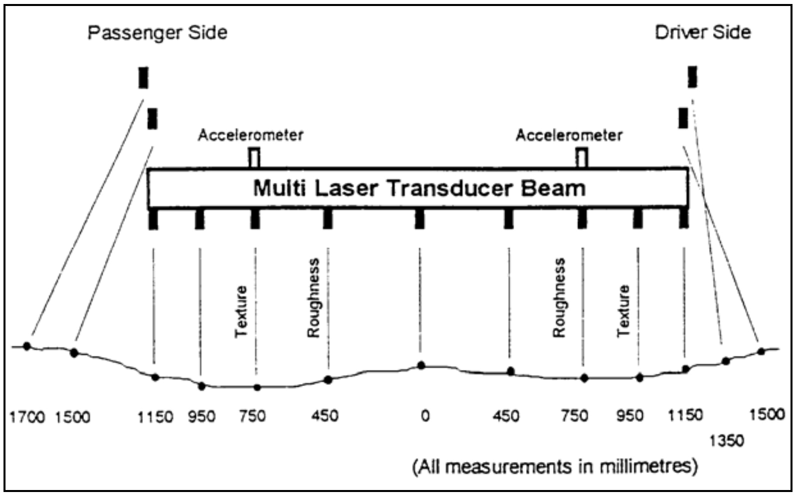


Figure 4.32 ARRB TR Multilaser Profilometer Laser Positioning

Irrespective of the technology or the sensor spacing used, the analytical approach is similar for all technologies. The elevations of each sensor result in the transverse profile being established. The data are analyzed to determine the rut depths.

There are three basic algorithms used for calculating rut depths.

- The **straight-edge** model emulates the manual method of placing a straight-edge across the pavement. Figure 4.33 is an example of the straight-edge model.

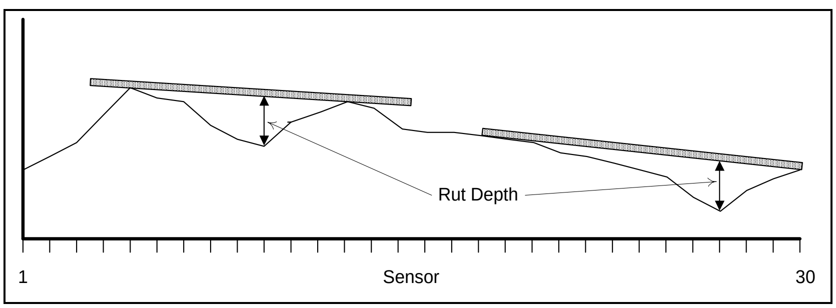


Figure 4.33 Example of Straight-Edge Simulation

- The **wire model** is popular since it is very fast in performing its calculations. Figure 4.34 is an example of the wire model calculations. Unlike the straight-edge, the wire model expresses the rut depth based on a wire 'stretched' over the high points. The distance to the pavement from the wire is calculated, and the highest values constitute the rut depth.

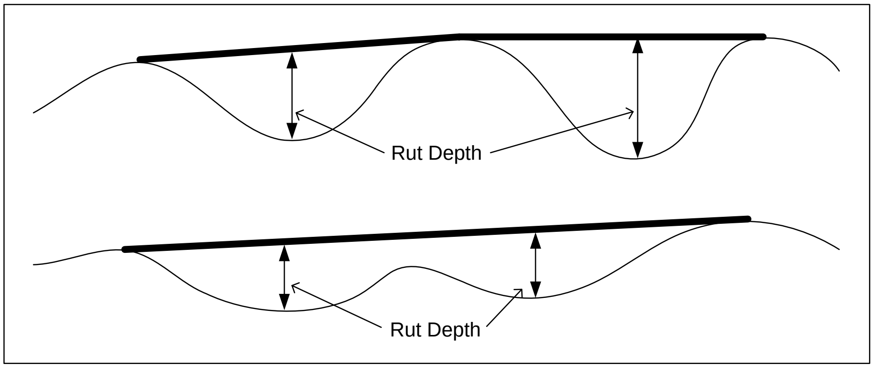


Figure 4.34 Example of Wire Model

- **Pseudo-ruts** are defined as the difference (in mm) between the high and the low points. It is used on systems with only a limited number of sensors, generally based on the South Dakota profilometer.

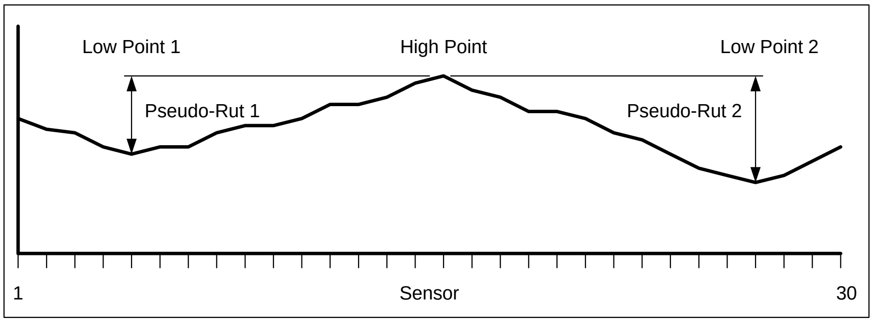


Figure 4.35 Definition of Pseudo-Ruts

Discrete sampling from ultrasonic and point laser profilers also results in differences in rut measurements between profilers. Figure 4.36 shows a hypothetical example of two different systems measuring the same profile. Each results in different high and low point elevations and, thus, different estimates of rut depths. This is where approaches such as scanning lasers have a major advantage: they sample the entire pavement width and therefore capture the critical information for calculating rut depth.

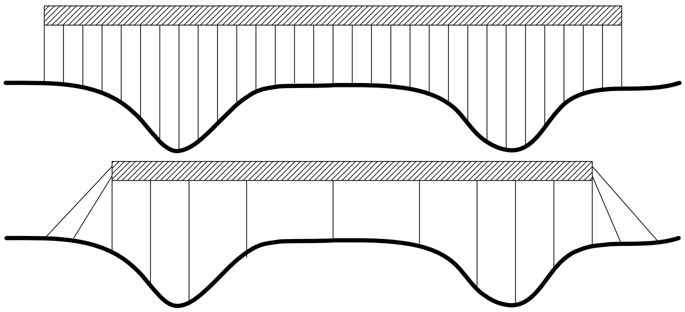


Figure 4.36: Example of Sampling Between Profilers

Because of the sampling issue shown in Figure 4.36, there will always be a bias towards underestimating the true rut depth with most profilers. Bennett and Wang (2002) showed that the error is proportional to the number of sensors and that "with less than approximately 15 sensors, there can be a significant under-estimation of the true rut depth. It is notable that even with 60 sensors, the rut depth would still be underestimated by approximately 1 mm."

Even though profiler methods may comprise different manufacturers, different numbers of sensors, and varying sensor configurations, there is generally good agreement between profiling methods when it comes to estimating the rut depth. Bennett and Wang (2002) used a computer simulation to test the implications of rut depths calculated from different profiler configurations. As shown in Figure 4.37, there were very good correlations between the various instrument configurations tested. This means that it is possible to use different equipment for surveys as long as correlation studies are done to develop transfer functions between the measurements.

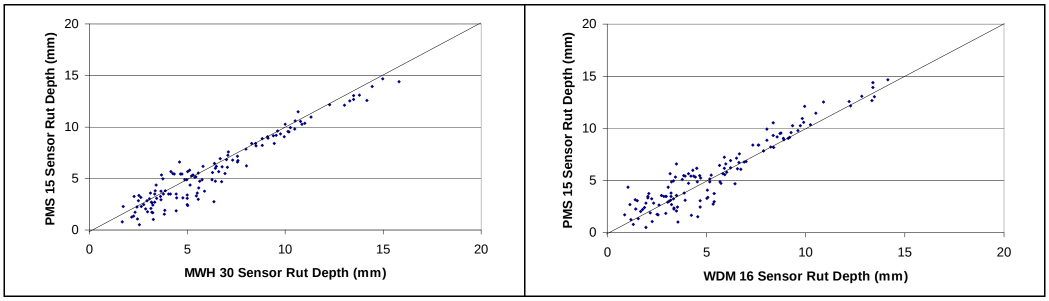


Figure 4.37: Correlations Between Different Profiler Configurations

The costs of profilers vary significantly between technologies. Acoustic profilers are the least expensive and start at approximately $25,000. Laser profilers typically cost approximately $10,000 for each laser sensor. Scanning lasers and the more sophisticated imaging systems typically start at approximately $75,000 and go upwards.

4.4 Technology Suitability Ranking and Cost/Performance Matrix

4.4.1 Suitability Evaluation Forms

With the range of equipment available for collecting pavement data, it is useful to be able to assess the relative merits of different equipment against one another. Having determined the general class type of equipment, the specific offerings from different manufacturers can then be evaluated in detail.

For the purpose of this report, an investigation was made on the relative merits at a very high level to gain an indication of what types of equipment are preferable under certain circumstances. It is not intended to replace detailed surveys of the offerings of different suppliers.

Data were gathered for this exercise by the research team and the equipment was assessed in terms of two criteria:

- **Cost:** both the initial and the ongoing maintenance costs; and,
- **Operational Considerations:** factors such as the portability, ease of assembly, *etc*.

A survey was conducted of the literature as well as of equipment manufacturers and users. The survey considered three components: general information on equipment, cost evaluation, and operational evaluation.

Cost Evaluation (CE)

The cost evaluation considered initial, operational and maintenance costs. Data were obtained from literature review and complemented with questionnaires submitted by manufacturers and users.

In questionnaires, operational costs were quantified in terms of US$/day and maintenance costs in US$/year. However, as costs need to be compared to operational characteristics of equipment, a five level scale was defined. Table 4.8 presents cost ranges per scale level for initial and operational/ maintenance costs.

Table 4.8: Evaluation Criteria for Initial and Operational/Maintenance Costs

Scale Level	Initial Cost $USD	Annual Operational/Maintenance Cost ($USD)
1	> $50,000	> $5,000
2	$10,000 - $50,000	$1,000 - $5,000
3	$ 3,000 - $10,000	$ 300 - $1,000
4	$ 1,000 - $ 3,000	$ 100 - $ 300
5	< $1,000	< $100

Operational Evaluation (OE)

The operational evaluation considered nine characteristics related to equipment performance when capturing and processing collected data. These nine operational characteristics were: ease of assembly and installation, ease of operation, ease of calibration and maintenance, accuracy for intended IQL, ease of data collection and processing, interoperability with other equipment, robustness of equipment, data collection speed and portability.

Operational characteristics were quantified in a five-level scale. Table 4.9 to Table 4.12 present the evaluation criteria used per characteristic, considering that almost all characteristics can only be assessed using subjective qualitative criterion.

Table 4.9: Evaluation Criteria for Ease of Assembly, Installation, Operation, Calibration, and Maintenance

Scale Level	Ease of Assembly, Installation, Operation, Calibration and Maintenance
1	**Very Difficult:** A great amount of resources, professional experience and qualification is needed
2	**Difficult:** Resources, professional experience and qualification is needed
3	**Moderate Difficulty:** Resources and technical experience are needed.
4	**Easy:** Some resources and experience are needed
5	**Very Easy:** Little resources and experience are needed

Table 4.10: Accuracy for IQL

Scale Level	Accuracy for IQL
1	Least Accurate, poor approximations of condition data
2	Evaluations determined from correlations or indirect evaluations with low accuracy
3	Evaluations determined from correlations or indirect evaluations with reasonable accuracy
4	Equipment with fairly high accuracy
5	Precision equipment with very high accuracy

Table 4.11: Evaluation Criteria for Ease of Data Collection / Processing and Data Collection Speed

Scale Level	Ease of Data Collection and Processing	Data Collection Speed
1	**Manual:** Both, data processing and collection are done manually	Slow: Static Measuring with no continuous measuring.
2	**Semi-Manual:** Some software and devices are used to facilitate data collection and processing	10 to 20 km/hr
3	**Semi-Automatic:** Automatic data collection, processing done by operator using typical database software	20 to 40 km/hr
4	**Almost Automatic:** Automatic data collection, processing software managed by operator	40 to 80 km/hr
5	**Automatic:** Automatic data collection, processing using automatic analysis software	Fast: Over 80 km/hr

Table 4.12: Evaluation Criteria for Equipment Interoperability, Robustness, and Portability

Scale Level	Interoperability	Robustness	Portability
1	Open	Not Robust	Not Portable
2-4	Operability is possible with some equipment	Some caution with non robust pieces	Portable under special conditions
5	Closed	Robust	Portable

4.4.2 Suitability Index Calculation

The suitability index was determined by a linear equation that included cost and operational characteristics. Each component was assigned a weight, related to its importance on cost and operation of equipment. The Cost Evaluation (CE) was assigned a weight of 30% for All Roads and Expressways, 40% for Urban and Rural Roads and 50% for Unsealed Roads. Operational Evaluation (OE) was assigned a weight of 70% for All Roads and Expressways, 60% for Urban and Rural Roads and 50% for Unsealed Roads. This difference in weights between pavement classes is attributed to the fact that operational characteristics of equipment may be more significant in roads having a higher standard than the costs of acquiring and operating the equipments. On the other hand roads of lower standards should focus on lower cost technologies. The data used for the calculations for different road types is presented in Appendix A.

Equation 1 is the linear relation used for determining the Suitability Index. Equations 2 and 3 denote the linear relation of each characteristic with cost and operational evaluations.

$$SI = a*CE + b*OE \quad (1)$$

$$CE = (IC + OMC) \quad (2)$$

$$OE = c*AI + d*P + e*CP + f*I + g*R + h*O + i*CM + j*A + k*S) \quad (3)$$

Where: SI is the Suitability Index
- CE is the Cost Evaluation
- OE is the Operational Evaluation
- IC is the Initial Cost
- OMC is the Operational and Maintenance Cost
- AI is the Ease of Assembly and Installation
- P is the Portability
- CP is the Ease of Data Collection and Processing
- I is the Interoperability
- R is the Robustness
- O is the Ease of Operation
- CM is the Ease of Calibration and Maintenance
- A is the Accuracy for IQL
- S is the Data Collection Speed
- a to k constants typical for each road class (Table 4.13)

Constants a to k were estimated for each road class considering the relative incidence of each variable over the Suitability Index. Values were obtained after a sensibility analysis performed for each road type and from the discussion of results between the research team. First, a mean value per constant was estimated for All Roads. Having this value as a basis, constants were adapted considering the relative cost and operational weight for each road type. The main criteria considered were:

- **Expressways:** Need high operational performance, especially high accuracy with high data collection speeds. For this, more expensive equipment is required.
- **Urban Roads:** Equipment cost tends to be more significant than in All Roads and Expressways, constant "a" increase to 0.4. Operational issues are focused on higher performance in assembly, installation, calibration, and portability. This is mainly because measurements are made with spatial and maneuver limitations.
- **Rural Areas:** The main difference to All Roads is that equipment cost tends to be more significant, constant "a" increase to 0.4. Operational performance has a lower weight, however, constants "c" to "k" maintain their relative weight.
- **Unsealed Roads:** Cost evaluation and operational evaluation have the same weight (0.5). Cheaper equipments can be used as operational performance is not so relevant. Accuracy and data collection speed can be lower, however, robustness and portability are essential as survey conditions are tougher than in paved roads.

Table 4.13: Constants a to k per Road Class

		Constants per Road Class				
	Constant Name	All Roads	Expressways	Urban Roads	Rural Roads	Unsealed Roads
Cost Evaluation (C,E)	**a**	**0.30**	**0.30**	**0.40**	**0.40**	**0.50**
Initial	-	0.50	0.50	0.50	0.50	0.50
Operation & Maintenance	-	0.50	0.50	0.50	0.50	0.50
Operational Evaluation (O,E)	**b**	**0.70**	**0.70**	**0.60**	**0.60**	**0.50**
Assembly/Installation	c	0.05	0.05	0.10	0.05	0.05
Operation	d	0.15	0.10	0.15	0.15	0.10
Calibration & Maintenance	e	0.15	0.10	0.20	0.15	0.10
Accuracy for IQL	f	0.15	0.20	0.10	0.15	0.05
Data Collection/Processing	g	0.10	0.10	0.10	0.10	0.10
Interoperability	h	0.10	0.10	0.10	0.10	0.05
Robustness	i	0.10	0.10	0.10	0.10	0.30
Data Collection Speed	j	0.15	0.20	0.05	0.15	0.05
Portability	k	0.05	0.05	0.10	0.05	0.20

The Suitability Index values range from a potential minimum of 1 to a potential maximum of 5; 1 indicating high cost and low operational performance and 5 low cost and high operational performance. The calculations for each equipment type are presented in Appendix A.

4.4.3 Suitability Ranking

Table 4.14 presents the suitability index values calculated in descending order for Expressways. Here, the higher the ranking, the better the equipment is in terms of its cost and operational performance for that road class. Suitability Rankings for Expressways, Urban Roads, Rural Roads, and Unsealed Roads are presented in Annex C.

The results indicate that survey referencing and geometry systems are the most cost effective and operationally useful equipment for road management. However, it must be noted that referencing equipment does not measure pavement condition.

The best technologies for measuring pavement condition are those that balance cost and performance. They are relatively accurate, simple to operate and maintain. Often, they cost much less than more sophisticated technologies for measuring the same characteristic (*e.g.*, Class III roughness vs. Class I roughness).

Low-performing equipment are expensive devices that use very specific technologies and usually perform measurements through static sampling or dynamic testing with low operational performance. This is the case of Falling Weight Deflectometer (FWD), deflection beams, and dynamic skid resistance evaluation (SCRIM). Although accuracy and robustness of this equipment is high, maintenance and calibration is not trivial, since the equipment requires experienced people and significant expenses to operate them. Since sampling is so specific and in many cases static, the equipment cannot be operated simultaneously with other devices.

Table 4.14: Suitability Ranking for All Roads and Expressways

Suitability Ranking: All Roads	
Equipment Type	**Suitability Ranking**
Referencing- Digital DMI	4.62
Referencing- GPS	4.29
Geometry GPS With INU	4.01
Macrotexture- Dynamic Low-Speed	3.88
Referencing- Video	3.82
Geometry Precision INU	3.76
Roughness- Class III	3.60
Macrotexture- Static	3.57
Macrotexture- Dynamic High Speed	3.51
Roughness- Class I Manual	3.50
Roughness- Class II	3.41
Rut Depth Profilers	3.41
Surface Distress Imaging	3.31
Roughness- Class IV	3.30
Skid Resistance- Dynamic (Trailer)	3.24
Skid Resistance- Static	3.12
Deflections- Beams	3.07
Roughness- Class I Laser	2.91
Deflections- Portable FWD	2.71
Ground Penetrating Radar- Dynamic	2.69
Ground Penetrating Radar- Static	2.61
Deflections- Trailer FWD	2.55
Skid Resistance- Dynamic (Vehicle)	2.23

The ability to measure multiple attributes at once, for example a system measuring roughness, texture, video logging, GPS, *etc*., offers economies of scale and should be preferred to single function systems. It should be emphasized that the most cost-effective systems are usually portable and can be installed in any vehicle rather than in a dedicated vehicle. This applies to all types of data collection equipment.

4.4.4 Cost / Performance Matrix

A subjective assessment of the relative cost to performance of different types of equipment for All Roads, Expressways, Urban Roads, Rural Roads and Unsealed Roads is given in Table 4.15 to Table 4.19. It should be noted that the performance considers more than just the ability to measure an attribute accurately, it also reflects practical considerations, such as ease of operation, flexibility, data processing requirements, *etc*. The matrix does not include these types of multi-function vehicles, since their ratings would vary depending upon cost and functionality.

As a general rule, if an agency has budgetary restrictions, equipment selected for pavement data collection should be located in the right bottom boxes shaded in the matrix (cost ranging between 3 to 5 and operational performance from 3 to 5). Of course, specialized needs that require specialized equipment may necessitate going out of that area. Agencies with limited budgets or technical skills should focus on the 4 – 5 areas of the matrix.

Table 4.15: Cost/Performance Trade-off Matrix for All Roads

	Operational Performance					
	Scale	**1 (Low performance)**	**2**	**3**	**4**	**5 (High performance)**
Equipment Global Cost	**1 (High cost)**			• Skid Resistance Dynamic - Vehicle	• Imaging for Surface Distress	
	2			• Ground Penetrating Radar – Dynamic • FWD - Trailer	• Macrotexture – Dynamic High Speed • Precision INU for Geometry • Roughness – Class I (Laser)	
	3			• Deflection Beams • FWD - Portable • Ground Penetrating Radar – Static • Skid Resistance – Dynamic Trailer	• GPS with INU • Macrotexture – Dynamic Low Speed • Rut Depth Profilers • Roughness – Class II	
	4		• Roughness- Class IV	• Roughness – Class I (Manual) • Skid Resistance – Static	• Video Logging • Roughness – Class III	• GPS
	5 (Low cost)			• Macrotexture – Static		• Digital DMI

Table 4.16: Cost / Performance Trade-off Matrix for Express Roads

	Operational Performance					
Equipment Global Cost	**Scale**	**1 (Low performance)**	**2**	**3**	**4**	**5 (High performance)**
	1 (High cost)			• Skid Resistance Dynamic - Vehicle		
	2			• Ground Penetrating Radar – Dynamic • FWD - Trailer	• Macrotexture – Dynamic High Speed • Roughness – Class I (Laser)	
	3			• Deflection Beams • FWD - Portable • Ground Penetrating Radar – Static	• Macrotexture – Dynamic Low Speed • Imaging for Surface Distress • Rut Depth Profilers • Roughness – Class II • Precision INU for Geometry • Roughness – Class III • Skid Resistance – Dynamic Trailer	
	4			• Roughness – Class I (Manual) • Skid Resistance – Static • Roughness-Class IV	• GPS with INU	
	5 (Low cost)			• Macrotexture – Static	• GPS • Video Logging	• Digital DMI

Table 4.17: Cost/Performance Trade-off Matrix for Urban Roads

		Operational Performance				
Equipment Global Cost	**Scale**	**1 (Low performance)**	**2**	**3**	**4**	**5 (High performance)**
	1 (High cost)		• Skid Resistance Dynamic - Vehicle			
	2			• Ground Penetrating Radar – Dynamic • FWD - Trailer • Roughness – Class I (Laser)	• Macrotexture – Dynamic High Speed	
	3			• Deflection Beams • FWD - Portable • Ground Penetrating Radar – Static	• Macrotexture – Dynamic Low Speed • Rut Depth Profilers • Roughness – Class II • Precision INU for Geometry • Roughness – Class III • Imaging for Surface Distress • Skid Resistance – Dynamic Trailer	
	4			• Skid Resistance – Static • Roughness-Class IV	• Video Logging • GPS with INU • Roughness – Class I (Manual)	
	5 (Low cost)				• Digital DMI • GPS • Macrotexture – Static	

Table 4.18: Cost / Performance Trade-off Matrix for Rural Roads

	Operational Performance					
Equipment Global Cost	**Scale**	**1 (Low performance)**	**2**	**3**	**4**	**5 (High performance)**
	1 (High cost)			• Skid Resistance Dynamic - Vehicle		
	2			• Ground Penetrating Radar – Dynamic • Roughness – Class I (Laser) • FWD - Trailer	• Macrotexture – Dynamic High Speed	
	3			• Deflection Beams • FWD - Portable • Ground Penetrating Radar – Static	• Macrotexture – Dynamic Low Speed • Rut Depth Profilers • Roughness – Class II • Precision INU for Geometry • Roughness – Class III • Imaging for Surface Distress • Skid Resistance – Dynamic Trailer	
	4			• Skid Resistance – Static • Roughness- Class IV	• Video Logging • GPS with INU • Roughness – Class I (Manual)	
	5 (Low cost)			• Macrotexture – Static	• Digital DMI • GPS	

Table 4.19: Cost / Performance Trade-off Matrix for Unsealed Roads

		Operational Performance				
Equipment Global Cost	Scale	1 (Low performance)	2	3	4	5 (High performance)
	1 (High cost)					
	2			• Ground Penetrating Radar – Dynamic	• FWD - Trailer	
	3			• Ground Penetrating Radar – Static • Imaging for Surface Distress	• Roughness – Class III	
	4			• Roughness- Class IV	• Video Logging • FWD – Portable • Dynamic Cone Penetrometer	
	5 (Low cost)				• Digital DMI • GPS	

5 Bridge Data Collection

5.1 Introduction

Bridges are one of the most critical infrastructure components in the transportation network. They are structures that provide passage over a gap or a barrier, such as water, canyon, or a roadway. To properly perform their functions, bridges must provide:

- Sufficient structural (load-carrying) capacity to resist any combination of dead and living loads (e.g., weight, traffic, impact, wind, temperature, earthquake, and settlement);
- Good level of service to users to ensure ride quality and traffic capacity; and
- Appropriate safety facilities to ensure proper bridge use.

Bridges suffer structural and functional deterioration as a result of structural damage and/or material degradation. Because the transportation network is extremely important for a country’s economic and social development, bridge performance is attracting more and more attention. Periodic evaluation of bridge condition is necessary for estimating how a bridge is performing at a certain point in its life, predicting how the bridge will perform in the future, and managing bridge assets at the network level.

Data collected from bridge condition assessments are used to support decisions regarding future bridge management strategies, such as maintenance, repair, and rehabilitation. Data collection is, therefore, a critical step in the bridge management decision-making process. Sufficient, quality data is the first step towards making correct decisions. The data collection techniques discussed in this report only include those necessary to obtain physical (functional or structural) conditions of bridges or bridge components.

Data collection technologies used on bridges varies significantly from place to place due to differences in economic and technology levels. While there is a lot of information about the procedures and equipment used in developed countries, little could be found on bridge data collection practices in developing countries. The lack of information from developing countries is, to some extent, understandable because the in-service transportation infrastructure in these areas is often relatively less extensive and newer. Even in developed countries, such as the U.S., little emphasis was given to inspection and maintenance of bridges before the 1960s. However, today there is widespread recognition of the importance of monitoring the condition of bridge assets due to the significant disruptions that accompany bridge failures. Even in many developing countries, which do not have a history of asset management, there is a commitment to monitoring the condition of the bridge stock.

5.2 Bridge Inspection Procedures

Periodic bridge inspections provide appropriate and timely information for the planning and application of maintenance operations, which are expected to slow bridge deterioration and extend the service life of bridges. They may help minimize the volume of repair works, contribute to the reduction of repair costs, and provide valuable information on performance of materials and quality of designs.

Bridge structures should be inspected at reasonable time intervals depending on the scope of the particular type of inspection. According to the practices in the U.S. and European countries, bridge inspections can be divided into two basic groups:

- **Routine Inspections** are regularly scheduled, intermediate-level inspections consisting of sufficient observations and measurements to determine the structural and functional condition of the bridge. They also identify any developing problems or changes from a previously recorded condition. This kind of inspection can be carried out by skilled maintenance personnel or technicians. Only in the case of very complex bridge structures would an inspection team of highly qualified experts be required. All defects must be recorded and the condition of the structure must be evaluated in an appropriate manner. The frequency of routine inspections is normally from one to two years, according to local inspection specifications.
- **In-Depth Inspections** are scheduled or unscheduled close-up inspections of bridges to assess the structural damage resulting from external causes. They also detect any deficiencies not readily visible in routine inspections. Such inspections are usually carried out by bridge engineers or experts. All parts of the bridge should be checked by close inspection of each bridge element. The frequency of the major inspection depends on both local specifications and bridge conditions, but usually should be less than 5 years. Examples of these tests include: deck permeability; concrete cover depth; internal cracking; and position of bearings, deflections, settlements, and joint openings.

5.3 Bridge Component Inspection and Available Technologies

Currently, bridge data collection is component-specific. Visual inspections are normally used for all bridge components, but other applicable physical inspection techniques vary with the material of bridge components.

The use of data loggers and digital cameras can significantly improve the quality of data collected with visual inspections. These allow for control over the data entered and the application of various validation rules. MWH (2004) used custom designed software on iPAQ PDAs for bridge surveys in Cambodia. Figure 5.1 is an example of their data entry forms.

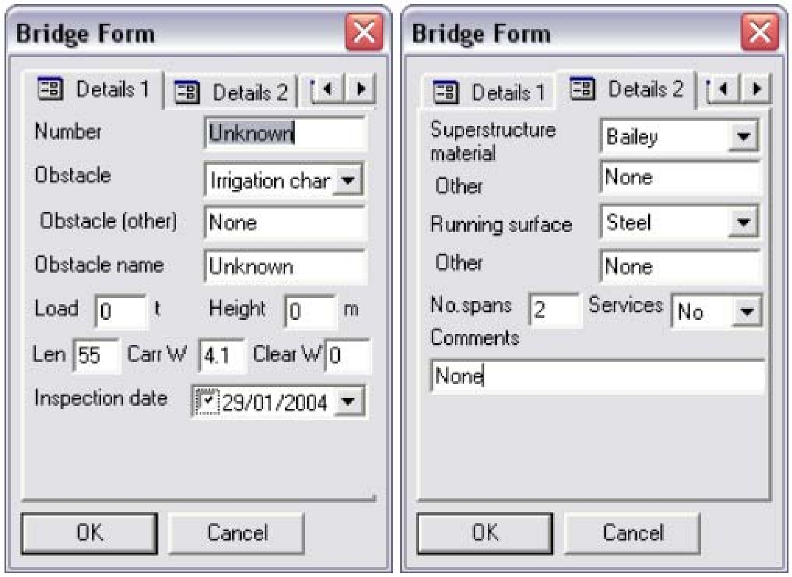


Figure 5.1: Cambodia Bridge Inspection Data Logging

5.3.1 Timber Members

Common damage in timber members is caused by fungi, parasites, and chemical attack. Deterioration of timber can also be caused by fire, impact or collisions, abrasion or mechanical wear, overstress, and weathering or warping.

Timber members can be inspected by both visual and physical examination. The hammer-sounding method is a simple non-destructive method. Tapping on the outside surface of the member with a hammer detects hollow areas, indicating internal decay. There are a few advanced non-destructive and destructive techniques available. Two of the most commonly used destructive tests are boring or drilling and probing. The main non-destructive test available for timber is ultrasonic testing to measure crack and flaw size.

5.3.2 Concrete Members

Common concrete member defects include cracking, scaling, delamination, spalling[1], efflorescence[2], pop-out, wear or abrasion, collision damage, scour, and overloading. The inspection of concrete also includes both visual and physical examination. Two of the primary deteriorations noted by visual inspections are cracks and rust strains. Core sampling is a commonly used destructive technique for concrete inspection. Hammer sounding and chain drag are two common non-destructive methods to detect unsound concrete areas and delaminations. The hammer sounding method is impractical for the evaluation of larger surface areas. For larger surface areas, chain drag can be

[1] Spalling is when sections of concrete break away from the slab. It can be caused by improperly cured concrete or exposure to road salt.

[2] Efflorescence is a white powdery appearing deposit. It may appear from a "light haze " to a very heavy "blooming". It may also be due to water soluble salts, deposited as moisture evaporates, on the exterior of brick or concrete. It is caused by water travelling through the concrete member.

used to evaluate the integrity of the concrete with reasonable accuracy. Chain drag surveys of decks are not totally accurate, but they are quick and inexpensive[1]. Other advanced non-destructive inspection techniques are:

- Delamination detection machinery to identify the delaminated deck surface;
- Copper sulfate electrode to estimate the likelihood of corrosion;
- Nuclear methods to determine corrosion activity;
- Infrared thermography to detect deck deterioration, although this technique is relatively coarse;
- Ground penetrating radar (GPR) to determine the position of reinforcement and delamination;
- Pachometer (magnetic testing equipment) to determine the position of reinforcement;
- Rebound and penetration tests to predict concrete strength; and
- Lab test to verify penetration and concentration of chloride ions.

5.3.3 Steel and Iron Members

Common steel and iron member defects include corrosion, cracks, permanent deformation, and overstress. Visual inspection is still the major method for these members, particularly for surface defects. There are also several destructive and non-destructive techniques available for steel inspection. Some of the non-destructive techniques used in steel bridges are:

- Acoustic emissions testing to monitor and identify growing cracks;
- Computer tomography to identify interior defects;
- Dye penetration to define the size of the surface flaws and cracks in welded section; and
- Ultrasonic testing to detect cracks in flat and smooth members.

5.4 Bridge Data Collection Equipment

Bridge data collection is mostly based on visual inspection and the use of handheld tools. The quality of the inspections is therefore governed by the

[1] The method involves a technician dragging a chain across the surface of a bridge deck and listening for significant changes in the tone, which corresponds to the frequency content of the response. "Hollow" sounding responses that depend on the geometry of the bridge deck and the distress are indicative of delaminated areas, while sound concrete produces consistent sounding responses with different frequency content. Due to the variety of frequency responses that can be produced by different distress and bridge deck geometries, the test is carried out using the qualitative judgment of the technician conducting the test. More details could be found in ASTM D 4580-86.

training and skills of the inspection staff and the accessibility that the inspector has to all elements of the bridge.

Special access equipment is often necessary to reach some bridge elements, particularly when they cannot be directly observed from the bridge deck, as is the case for the deck bottom, piers standing in water, girders, etc. Accurate assessment of these hard-to-access components is important, and in many cases crucial, in establishing the overall condition of the bridge. The first group of equipment to be discussed in this chapter consists of the bridge access devices.

Ground Penetrating Radar (GPR) is used to locate reinforcement and delaminations and thus detect deterioration of the bridge decks and rigid pavement concrete slabs. GPR is also used on flexible pavements to estimate the asphalt layer thickness, locate air voids and moisture, and predict undersurface distresses (see Section 4.3.7).

There are an increasing number of non-destructive technologies to enhance bridge data collection processes. Compared with visual inspections, non-destructive data collection technologies have the advantage of producing detailed and consistent outputs, causing the least disturbance of evaluated member, and providing faster and larger coverage. The major non-destructive inspection techniques and equipment are discussed later in the document.

5.4.1 Bridge Access Technologies

Bridge inspections present some challenges for inspectors to safely access the desired parts of the bridge components. Whenever possible, it is preferred that bridge data collection be conducted from downside because this eliminates or minimizes the need for traffic control on the bridge. Most small bridges can be accessed from lower places without great efforts, but for most large bridges it is usually necessary to take advantage of access equipment to protect inspectors and assist data collection. Sometimes a ladder is sufficient, while other times more versatile equipment is necessary. Common access equipment are ladders, boats or barges, floats, scaffolds, man-lifts, snoopers, and aerial buckets. These main types of access equipment are discussed below (after White *et al*., 1992).

- **Hydraulic lifts** (Figure 5.2) are versatile pieces of equipment used in bridge inspection and are usually mounted on vehicles or boats. Their advantages include high mobility and regular range of movement. They can be transported easily from site to site by the vehicles or boats. Furthermore, the inspector's platform may be moved to positions underneath the bridge deck in order to allow inspection of bridge superstructure components. Because of the ease of operation, time and money are usually saved by using a hydraulic lift. Disadvantages of the hydraulic lift include high initial cost, blocking of traffic underneath the bridge, professional personnel required to operate it, and difficulty in reaching areas over water on truck-mounted lifts.

Figure 5.2. Hydraulic Lift

- **Snooper-type trucks** (Figure 5.3) are another type of under-deck inspection platform, which have most of the advantages of hydraulic lift equipment and even more versatility. A boom system is designed to go under the superstructure for inspection while the mounted truck is on the deck. The units can have a bucket or a platform for the inspector(s). The snooper arm of such access equipment could be crooked to reach more areas without moving the mounted truck. The boom system could be also mounted on boats to avoid blocking surface traffic. The disadvantages of snooper trucks are high initial costs (even higher than most hydraulic lifts), the need for professional personnel for their operation, and potential blockage of traffic.

Figure 5.3. Snooper-type Truck

- Besides those specially designed bridge access devices, a **boat** or **barge** can be used as a platform from which to do substructure inspections, such as measuring scour with a leaded line, pole, or electronic device. They may act as a platform from which to climb so as to reach and inspect the tops of various components, such as dolphins. Larger boats may have scaffolding or a frame construction to facilitate easier and safer inspection of those bridge elements under the deck portion. The main problem of using boats as access equipment is the safety of inspectors because boats are not designed for bridge inspections.

- **Scaffolds** are temporary structures to support the inspector and inspection equipment. When constructing the scaffold framework, it is important to make sure the framework is anchored securely and is strong enough to support the intended load. Scaffolds always require considerable time to construct and take down. Some types of scaffolds may be floated under a bridge and raised with a block and tackle, which increases their construction efficiency and operational flexibility.

- **Diving equipment** may be required for inspections of underwater components. The diving equipment could be of many different types, from scuba to the type of equipment that requires a source of surface air. Professional personnel are required to operate diving and inspection equipment simultaneously.

In most developing countries, visual inspections are still the main, if not the only, method for collecting in-service bridge condition data. Therefore, inspector safety and inspection accessibility are major concerns. The selection of bridge access equipment should be based on local bridge types. For small bridges over water, boats could provide sufficient accessibility most of the time. For flyover type bridges, vehicle-mounted hydraulic lifts could better secure inspectors and assist inspections. For high elevation bridges, like viaducts to provide accessibility to the bottom side of bridges, snooper type access equipment is the only choice most of the time. Both the initial costs and maintenance costs of snooper type access equipment are higher than those of hydraulic lifts. Renting the equipment could diminish the cost problem if there is no regular demand for snooper type equipment. Because of the ease of transportation, rental services are offered by many manufacturers or agencies with such equipment.

5.4.2 Non-destructive Testing (NDT) Technologies

After a bridge is visually inspected for its overall and component conditions, it is often necessary to carry out non-destructive testing (NDT) in order to further extend the diagnostic process and get in-depth assessment results if it is suspected that the bridge has been weakened in some way. Normally, the objectives of NDT are:

- To evaluate the physical quality of the materials; and

- To determine the position and extent of hidden defects, elements, and material boundaries.

NDT technologies may be employed to gain more extensive and/or in-depth information about a potentially critical condition discovered by visual or manual inspections. Some of the sophisticated technologies for data collection include strength method, sonic, ultrasonic, magnetic, electrical, nuclear, infrared thermography, radar, and radiographic methods.

Table 5.1 and Table 5.2 (AASHTO, 2000) compare the various non-destructive technologies in terms of their capability of detecting defects in concrete and steel components. The main technologies are discussed in the following sections (after AASHTO, 2000, and Ryall, 2001).

Concrete Strength Testing

For concrete bridge components, especially for compressive load-carrying components, concrete compressive strength is one of the main indicators of component conditions. Sufficient compressive strength provides required support for the bridge under design conditions. However, this cannot be measured directly in the field. Two NDT technologies, rebound and penetration tests, are the main methods of predicting the concrete strength by assessing the surface hardness.

Table 5.1: NDT Method Performance in Concrete Component Inspection (AASHTO, 2000)

	Capability of Concrete Defect Detection					
Method based on	**Cracking**	**Scaling**	**Corrosion**	**Wear and Abrasion**	**Chemical Attack**	**Voids in Grout**
Strength	N	N	P	N	P	N
Sonic	F	N	G[3]	N	N	N
Ultrasonic	G	N	F	N	P	N
Magnetic	N	N	F	N	N	N
Electrical	N	N	G	N	N	N
Nuclear	N	N	F	N	N	N
Thermography	N	G[1]	G[2]	N	N	N
Ground Penetrating Radar	N	G[2]	G[3]	N	N	N
Radiography	F	N	F	N	N	F

Notes: 1/ G = Good; F = Fair; P = Poor; N = Not suitable
2/ Beneath bituminous surfacings
3/ Detects delamination

Table 5.2: NDT Method Performance in Steel Component Inspection (AASHTO, 2000)

Method based on	Capability of Steel Defect Detection[1]									
	Minute Surface Cracks	Deeper Surface Cracks	Internal Cracks	Fatigue Cracks	Internal Voids	Porosity and Slag in Welds	Thickness	Stress Corrosion	Blistering	Corrosion Pits
Radiography	N	F[4]	F[2]	P	G	G	F	F	P	G
Magnetic particle										
(A.C.) Wet	G	G	N	G	N	N	N	G	N	N
Dry	F	G	N	G	N	N	N	F	N	P
Eddy Current	F	G	N	N	N	P	P	N	N	N
Dye Penetrants	F	G	N	G	N	N	N	G	N	F
Ultrasonic[5]	P	G	G	G	G	F	G	F	F	P

Notes: 1/ G = Good; F = Fair; P = Poor; N = Not suitable
2/ Beneath bituminous surfacings
3/ Detects delamination
4/ If beam is parallel to cracks
5/ Capability varies with equipment and operating mode

- A **rebound hammer** is a self-contained unit that consists of a spring-loaded mass and an impact plunger that is held vertically or horizontally against the smooth surface of concrete components. During strength testing, the mass strikes the free end of the plunger and rebounds. The impact energy is well-defined, and the rebound of the hammer mass is dependent on the hardness of the concrete. The extent of rebound gives an indication of the strength of the concrete at the surface position tested. One limitation is that rebound tests are considered usable only on relatively new (less than one-year-old) concrete.

- The **penetration resistance** utilizes a probe device to drive a steel probe into the concrete using a constant amount of energy supplied by a precise powder charge. The length of the probe's projection from the concrete component is measured. A corresponding concrete strength is given based on the average of measurements.

Rebound and penetration tests are mostly comparative techniques because the absolute value depends on the local variations in the surface properties due to the presence of voids or aggregate particles. A number of measurements are required in the same location from which the mean and standard deviation values can be determined. Another limitation of such technologies is that only the surface of the concrete is checked; actual strength can only be determined by other means.

Sonic Test

Sonic testing, which is also called the stress wave propagation method, is effective for detecting internal flaws in concrete components, such as cracking, delaminations, and air voids. Sonic testing is based on the use of stress waves (sonic waves). Surface impacts, like hammer blows, create impulses that project into concrete. The travel time of the stress wave between the transmitter and receiver is measured. The speed of the stress wave is pre-determined using the modulus of elasticity, the mass density, and Poisson's ratio. With time and speed, specimen thickness can be determined and hence the presence of internal defects.

The limitation of sonic testing is that it can only be applied on small areas and cannot provide a global picture of bridge components. It can tell unsound concrete from sound concrete and is frequently used to detect delaminations or other fractures, but it is just a qualitative test. The technique is impractical for evaluating vertical areas, like abutments, and is not efficient for large surface areas, like concrete decks.

Chain drags, sounding rods, or hammers are frequently used for detecting delaminations on horizontal surfaces, such as decks or tops of piers. Portable automatic methods have been developed for bridge decks. The equipment usually consists of a tapping device, a sonic receiver, and a signal interpreter. The accuracy of all kinds of sonic tests decreases when used on an asphalt-covered deck.

Ultrasonic Testing

Ultrasonic tests are capable of locating both surface and subsurface defects in metal or concrete components, including cracks, slag, and delamination. Such tests measure the travel time of ultrasonic waves passing from the transmitter through the component to a receiver and then calculate the pulse velocity. Because the speed of the stress wave is related to the modulus of elasticity, the mass density, and Poisson's ratio, it is possible to assess the quality of the component, metal, or concrete.

The principles of ultrasonic tests are similar to sonic tests. The difference is that the pulses are of different frequencies. Ultrasonic waves have a much higher frequency than sonic waves. Pulses with higher frequency can produce signals with higher resolution, but have a reduced penetration capacity. For concrete components with reinforcing bars, the accuracy of ultrasonic testing is even lower because reinforced concrete is a heterogeneous material. The travel velocities of ultrasonic waves in steel and concrete are very different, requiring more complexity in the signal processing and interpretation of final outputs.

Ultrasonic test equipment is currently well-suited for locating possible defects during bridge inspections. Modern equipment is relatively lightweight and portable. It is simple to operate, has a high level of accuracy and stability, and its signals can be accurately interpreted.

Magnetic Testing

The main application of magnetic testing technologies is to determine the position of reinforcements in concrete bridge components. Magnetic testing technologies involve the magnetic properties of the reinforcement and the response of the hydrogen nuclei to such fields. Because of the need to control the magnetic field, electromagnets are used in most devices. The device produces a magnetic field between the two poles of a probe, and the intensity of the magnetic field is proportional to the cube of the distance from the pole faces. When a reinforcing bar is present, the magnetic field distorts; the degree of distortion is a function of the bar diameter and its distance from the probe.

Although concrete cover depths are not defects, inadequate cover is often related to corrosion-induced deterioration. Therefore, the inspection of reinforcement location is important in corrosion control.

Modern magnetic testing equipment, known as cover meters or pachometers, are portable and battery-operated. They are specially designed to detect the position of reinforcement and measure the depth of concrete cover. In general, the devices can measure cover within 6 mm (0.25 in.) in the range of 0 to 76 mm (3 in.). The results are satisfactory for lightly reinforced components, but for heavily reinforced components or where large steel members are nearby, it is not possible to obtain reliable results.

Electrical Testing

Electrical methods for inspection of concrete bridge components include resistance and potential measurements. One popular potential measurement technology is the 'Half-Cell' test, which is commonly used on bridge decks to determine the probability of active corrosion. Corrosion of reinforcement produces a corrosion cell caused by difference in electrical potential. This potential difference can be detected by placing a copper-copper sulfate half-cell on the surface of the concrete and measuring the potential differences between the half-cell and steel reinforcement. It is generally agreed that the half-cell potential measurements can be interpreted as follows:

- Less than -0.20 volts indicates a 90 percent probability of no corrosion;
- Between -0.20 and -0.35 volts, corrosion activity is uncertain; and
- Higher negative value than -0.35 volts is indicative of greater than 90 percent probability that corrosion is occurring.

If positive readings are obtained, it usually means that insufficient moisture is available in the concrete and the readings are not valid. These tests do not indicate the rate of corrosion, and the measurements only reflect the potential for corrosion at the time of measurement.

Infrared Thermography

The concept behind infrared thermography is that subsurface distresses affect the heat flow through material and thus cause different temperatures to show on the surface. Water or air voids inside bridge components always show up with distresses and definitely affect the surface temperature. Therefore, using infrared thermography equipment, one can identify the area with excess moisture or air voids below the surface, which has a high potential to have distresses. The limitation of this technique is that it is mainly a qualitative rather than a quantitative test.

Infrared thermography has been found to be a useful supplemental test for detecting delaminations in concrete bridge decks. Delaminations and other discontinuities interrupt the heat transfer through the concrete, and these discontinuities cause a higher surface temperature during periods of heating than the surrounding concrete and the reverse situation during periods of cooling. The differences in surface temperature can be measured using sensitive infrared detection systems. The equipment can record and identify areas of delamination below the surface by the differences in surface temperature.

Magnetic Particle (Steel Components Only)

Magnetic particle testing technology is limited to detecting surface or near-surface defects. Since the studied component has to be magnetized, only magnetic materials may be examined using this method. In field applications, the studied area is locally magnetized using two current-carrying copper prods. A circular magnetic field between them is generated and component defects transverse to the field are detected by using iron powder.

The advantages of this method are its relative portability, minimum skills required to perform it, and its ability to detect even tight cracks. Of course, it is limited to the orientation of defects. In some applications, it has the additional limitation that it leaves the component in a magnetized condition, which may cause some problems in future treatments, such as welding. It is possible to demagnetize the area examined by this method, but this is time consuming and adds to the cost.

Ground Penetrating Radar

GPR technology was discussed earlier under pavement surveys (see Section 4.3.7). For bridge surveys, GPR can be used to locate reinforcement and delaminations and thus detect deterioration of bridge decks and rigid pavement concrete slabs. GPR technology also has the important potential to examine the condition of the top flange of box beams that otherwise are inaccessible.

5.4.3 Digital Imaging

Digital imaging can be regarded as a type of enhanced and subjective visual inspection. Therefore the collected data from visual inspection do not always provide an accurate assessment of the condition of bridges or bridge components. Visual inspection is also slow, qualitative, and potentially hazardous for the inspectors.

Digital imaging technology is a promising fast data collection approach to overcome many of these disadvantages and provide accurate and global raw information of bridge conditions. Current digital imaging technologies are sufficient to record high-resolution video images with relatively low costs. One potential enhancement of digital imaging technology is automatic identification of surface distresses; however, as discussed under pavements in Section 4.3.8, this technology is still in its early days. An important limitation of image surveys is that access to some parts of a bridge can be difficult, such as the bottom side of the deck and the tops of piers.

5.4.4 Application in Developing Countries

The survey conducted as part of this project indicated that manual evaluations are the main method used for bridge evaluation in developing countries. However, non-destructive testing (NDT) techniques are attracting more attention in bridge inspections. More detailed and in-depth assessments can be obtained through NDT techniques compared to subjective visual inspections therefore they offer many advantages. However, for developing countries, the major limitations are available budgets and availability of properly trained personnel.

Although NDT technologies can provide more reliable information about bridges compared with visual inspection, the visual inspection produces rating information about the global bridge condition and can generally be done much faster. Thus, many countries would benefit from simply:

- Committing to regular visual inspections to a high standard; and
- Ensuring that those conducting the inspections are properly trained.

In the absence of regular, systematic visual inspections, no technology will add much value to the bridge management process.

Regular inspections can be supplemented by technology. To assist in selecting the most appropriate technology a suitability ranking was defined based on the manufacturers' (and users') assessment of the following equipment characteristics:

- Assembly/Installation: 5 = easy, 1 = difficult
- Operation & Maintenance: 5 = easy, 1 = difficult
- Calibration: 5 = easy, 1 = difficult
- Data Collection/Processing: 5 = automatic, 1 = manual
- Interoperability: 5 = open, 1 = closed
- Robustness: 5 = robust, 1 = not robust
- Data Collection Speed: 5 = fast, 1 = slow, N/A
- Portability: 5 = portable, 1 = not portable

An average operability rating was produced by averaging the main score in the above listed categories from the survey. It must be emphasized that a very limited number of responses were received, probably due to the scarce use of these technologies in developing countries, so the ranking should only be viewed in a very general way. The responses are summarized in Table 5.3.

Table 5.3. Survey Based Suitability Ranking for Bridge Evaluation Technologies

Technology	Assembly / Installation	Operation & Maintenance	Calibration	Data Collection / Processing	Interoperability	Robustness	Data Collection Speed	Portability	Average
Ultrasonic	5	5	5	1	1	5	5	5	4.0
Electrical	5	5	5	2	1	4	4.5	5	3.9
Digital Imaging	3.5	4.5	3.5	3	1	4	4	3	3.3
GPR	3	3	2	3	1	3	3	1	2.7
Infrared Ther.	1	1	1	3	1	1	3	1	1.7

The results clearly show that ultrasonic and electrical testing equipment offers the greatest advantages, and infrared thermography the lowest. These two technologies are not expensive – typically in the range of US $2,000 – US $6,500, with annual operating costs of US $500 or less.

6 Traffic Data Collection

6.1 Introduction

Traffic data are collected to monitor the use and performance of the roadway system. These data could be used in a variety of management and research areas. Table 6.1 (FHWA, 2001) gives some examples of the application area relative to data types.

Table 6.1: Traffic Data versus Highway Activities

Highway Activity	Traffic Counting	Vehicle Classification	Truck Weighing
Engineering	Highway Geometry	Pavement Design	Structural Design
Economic Analysis	Benefit of Highway Improvements	Cost of Vehicle Operation	Benefit of Truck Climbing Lane
Finance	Estimates of Road Revenue	Highway Cost Allocation	Weight Distance Taxes
Legislation	Selection of Highway Routes	Speed Limits and Oversize Vehicle Policy	Permit Policy for Overweight Vehicles
Maintenance	Selecting the Timing of Maintenance	Selection of Maintenance Activities	Design of Maintenance Actions
Operations	Signal Timing	Development of Control Strategies	Designation of Truck Routes
Planning	Location and Design of Highway Systems	Forecasts of Travel by Vehicle Type	Resurfacing Forecasts
Environmental Analysis	Air Quality Analysis	Forecasts of Emissions by Type of Vehicle	Noise Studies, NOX Emissions
Safety	Design of Traffic Control Systems and Accident Rates	Safety Conflicts Due to Vehicle Mix and Accident Rates	Posting of Bridges for Load Limits
Statistics	Average Daily Traffic	Travel by Vehicle Type	Weight Distance Traveled
Private Sector	Location of Service Areas	Marketing Keyed to Particular Vehicle Types	Trends in Freight Movement

Source: FHWA (2001)

This report only discusses the collection technologies for three categories of traffic data: volume, vehicle classification, and truck weights. Besides these three data types, a variety of other traffic characteristics, such as vehicle speeds and vehicle occupancies, can also be monitored. Although these characteristics are not directly related to road management, they could supplement traffic volume and vehicle classification for transportation management activities, such as network planning and highway system design and improvement.

As illustrated in Table 6.2, different users in an organization require different traffic data. This highlights the need to carefully consider data needs throughout the organization prior to commencing any procurement of traffic equipment.

Table 6.2: Example of Traffic Data Needs

User		Purpose	Data Needs
Within Agency	Research	Research	AADT Speed/5 min Traffic Volume/5 min, Peak Hour
	ITS Division	Real-time Traffic Control/Management	AADT Incidents Speed Travel Time Traffic Volume Vehicle Classification
	Transit Division	Manage Commuter Line Provide Instant Data on Conditions; Congestion; and Signal Timing.	Speed/15 min Traffic Volume/Hourly, Real Time Turning Movement/Pear Times Vehicle Classification
	Planning	Long Range Planning HOV Analysis Capacity Analysis	Traffic Volume/Hourly Peak Hour Volume/ Dir. Split Ramp Volumes Vehicle Classification
	Traffic/Safety	Safety Studies	AADT/AWDT Density/15 min Speed Traffic Volume Vehicle Classification Turning Movement/15 min
	Traffic Statistics	Traffic Statistic and Reporting	AADT Traffic Volume/15 min Vehicle Classification/Length, Axle
	Maintenance	Road Maintenance	AADT Traffic Volume
Outside Agency	Other Government Associations	Planning Signal Coordination Incident Analysis Congestion Analysis	Speed Traffic Volume Turning Movement Ramp Metering
	County	Maintenance Signal Design	AADT Travel Time Turning Movement
	City	Maintenance Signal Design	AADT Travel Time Turning Movement
	Transit Authority	Route Performance Analysis Scheduling Evaluation and Planning	Speed/15min Incidents/Accidents Traffic Volume/Hourly, by lane Vehicle Classification
	University	Research	AADT Speed/5min Traffic Volume/5min Turning Movement/5min

Source: Martin *et al.*, (2003)

To efficiently support decisions for the highway system, traffic data collection programs must have the capability of identifying changes in traffic patterns in the studied areas. In general, to monitor traffic at a network level a data collection plan may consist of:

- A modest number of permanent, continuously operating, data collection sites; and
- A large number of short-duration data collection efforts.

The permanent data collection sites provide knowledge of seasonal and day-of-the-week trends, while short-duration monitoring provides the geographic coverage needed to understand traffic characteristics on individual roadways as well as on specific segments of those roadways.

Pavement design can have special data requirements. Cambridge Systematics, *et al*. (2005) describe traffic data collection and analysis for mechanistic pavement design. The latest methods require information on the axle load spectrum instead of equivalent standard axles, so this introduces additional demands in terms of data collection equipment. Software for analyzing traffic data and producing traffic data inputs required for the AASHTO 2002 mechanistic designs can be downloaded from http://trb.org/news/blurb_detail.asp?id=4403. The outputs are of use for other design procedures as well.

The following sections discuss the collection technologies for traffic counting and vehicle classification as well as weighing trucks. In all cases, the traffic data collection system is composed of one or more sensors and a data collection unit and these are addressed separately.

Box 6.1: Travel Times and Journey Speeds

This report does not specifically cover the issue of travel time and journey speeds over links, except insofar as it is measured using in-place technologies such as loops and other similar detectors. Lin, *et al.* (2005) gives a good summary of the different approaches in use.

Traditional monitoring using in-place technologies is being supplemented by probe vehicles wherein a moving vehicle is monitored as it travels through the network. This provides near real-time data on network condition between the locations of the detectors. An emerging technology probe vehicle monitoring is through the analysis of cell phone signals. The signal patterns of cell phones are monitored anonymously and used to determine the speed of vehicles as they travel through the network. This provides a real-time update to the traffic flow situation on the network, often for segments of only a few hundred meters. Since the data are collected continuously with little latency, changes in network travel conditions can be quickly identified. It can be anticipated that probe vehicle technology will change rapidly in the next few years and augment traditional data collection approaches.

6.2 Vehicle Classifications

A key element of most traffic data collection systems is the ability to classify traffic. The counting strategy may be simple—for example short or long vehicles—or it may be complex, based on the number of axles and the distances between axles. The latter is the most common and is used with any system that records individual axles. Two detectors are required to classify traffic accurately, based on the time of observation of each axle.

As an example of how this is done, consider a two-axle vehicle that is detected by two detectors at a distance D meters apart. At each detector there are two values for the cumulative time (in s) when each axle of the vehicle is observed:

Detector 1	Axle 1: t11	Axle 2: t12
Detector 2	Axle 1: t21	Axle 2: t22

VEL1 =(t21 – t11)/D   VEL2 = (t22 – t12)/D

SPACING1 = (t12 - t11) VEL1   SPACING2 = (t22 - t21) VEL2

The values for VEL1 and VEL2 represent the velocity of axle 1 and the velocity of axle 2 (in m/s). The spacings are the distances between axle 1 and axle 2 in m, based on these velocities. These values are usually very similar, with the differences due to timing errors in the detectors. It is common practice to average the values or else to adopt only one. The combination of the number of axles and the spacings between each axle are used to classify the vehicle.

Table 6.3 is an example of an axle-based classification system. There are many different systems available, based on the specific vehicle fleets used in different countries. When procuring equipment it is important that the classification system used is appropriate otherwise the results will be incorrect. It is therefore also essential to validate any automatic classification system prior to its full deployment.

Traffic **counters** count the total number of axles. This is divided by a factor representing the average number of axles per vehicle to convert the measurement to the number of vehicles. **Classifiers** count each individual axle and apply a classification system such as in Table 6.3 to classify each individual vehicle. They will also usually record the speed. For this reason, classifiers are generally preferable to counters since they provide much more information for relatively little cost. Table 6.4 compares the various portable and permanent vehicle classification technologies (Hallenbeck and Weinblatt 2004). Those using axle based classifications will usually give the most reliable classifications.

Table 6.3: Example of Axle Based Classification System

Classification	Vehicle	Number/Spacing of Axles
21	Cycle or Motorcycle	0 0
22	Car or Light Van	0 0
23	Short Two Axle Truck	0 0
24	Long Two Axle Truck	0 0
25	Very Long Two Axle Truck or Two Axle Bus	0 0
29	Other Two Axle Vehicle	
31	Car or Light Van Towing One Axle	0 0 - 0
32	Two Axle Truck Towing One Axle	0 0 - 0
33	Two Axle Rigid Truck	0 0 0
34	Two Axle Twin Steer Rigid Truck	0 0 0
35	Two Axle Articulated Truck	0 0 - 0
36	Three Axle Bus	0 0 0
39	Other Three Axle Vehicle	
41	Car or Light Van Towing Three Axle	0 0 - 0 0
42	Two Axle Truck Towing Three Axle	0 0 - 0 0
43	Three Axle Truck Towing One Axle	0 0 0 - 0
44	Three Axle Twin Steer Towing One Axle	0 0 0 - 0
45	Four Axle Twin Steer Rigid Truck	0 0 0 0
46	Four Axle Articulated 'A' Train	0 0 - 0 0
47	Four Axle Articulated 'B' Train	0 0 0 - 0
49	Other Four Axle Vehicle	
51	Two Axle Truck Towing Three Axle	0 0 - 0 0 0
52	Three Axle Twin Steer Towing Two Axle	0 0 0 - 0 0
53	Four Axle Twin Steer Towing One Axle	0 0 0 0 - 0
54	Three Axle Rigid Truck Towing Two Axle	0 0 0 - 0 0
55	Five Axle Articulated 'A' Train	0 0 - 0 0 0
56	Five Axle Articulated 'B' Train	0 0 0 - 0 0
59	Other Five Axle Vehicle	
61	Two Axle Truck Towing Four Axle	0 0 - 0 0 0 0
62	Three Axle Truck Towing Three Axle	0 0 0 - 0 0 0
63	Three Axle Twin Steer Towing Three Axle	0 0 0 - 0 0 0
64	Four Axle Twin Steer Towing Two Axle	0 0 0 0 - 0 0
65	Six Axle Articulated 'B' Train	0 0 0 - 0 0 0
69	Other Six Axle Vehicle	
71	Three Axle Towing Four Axle	0 0 0 - 0 0 0 0
72	Three Axle Twin Steer Towing Four Axle	0 0 0 - 0 0 0 0
73	Four Axle Twin Steer Towing Three Axle	0 0 0 0 - 0 0 0
79	Other Seven Axle Vehicle	
81	Four Axle Twin Steer towing Four Axle	0 0 0 0 - 0 0 0 0
89	Other Eight Axle Vehicle	
91	All Nine Axle Vehicles	
10	All vehicles with more than Nine Axles	
99	Vehicles that could not be classified	

6.3 Traffic Sensor Types

Sensor technologies are the core of traffic data collection. There are two main categories of sensors used in traffic data collection equipment: intrusive and non-intrusive (Skszek, 2001). From another perspective, the sensors can be classified as permanent or portable. Table 6.5 provides an overview of the data collected by the various technologies available.

Intrusive sensors are those that involve placement of the sensors on top of, or in, the lane to be monitored. They represent the most common sensors used today, including inductive loops, piezo-electric sensors, and pneumatic rubber road tubes. Conversely, non-intrusive sensors, such as passive acoustic sensors and video image detection devices, do not interfere with traffic flow either during installation or operation. Besides these two major categories, modern off-road technologies use probe vehicles to obtain traffic information[1].

Table 6.4: Classification Technology Comparison

Sensor Technology		Data Types	Lanes/ Sensor
Short-duration	Inductive Loops	Length Based	1 per pair
	Road Tubes	Axle based	1 per pair
	Magnetometer	Length Based	1 per sensor
	Piezo sensors	Axle based	1 per pair
	Side-fired Radar	Length Based	Multiple
Permanent	In. Loop (conventional)	Length Based	1 per pair
	In. Loop (undercarriage)	Various	1 per pair
	Magnetometer	Length Based	1 per pair
	Piezoelectric Cable	Axle based	1 per pair
	Fiber-Optic Cables	Axle based	1 per pair
	Infrared	Length or Height based	1 per array
	Side-fired Radar	Length Based	Multiple
	Overhead Radar	Length Based	1 per sensor
	Ultrasonic	Length Based	1 per pair
	Acoustic	Length Based	1 per pair
	Video (Trip wire)	Length Based	Multiple
	Video (Object analysis)	Various	Multiple

Source: Hallenbeck and Weinblatt, (2004)

Figure 6.1 shows a summary of the main sensor technologies used in traffic systems. It should be noted that this is an evolving field, and new technologies are added frequently. A brief description of each technology is presented in the following sections.

6.3.1 Intrusive Sensors

Inductive Loops

An inductive loop (Figure 6.2) is a wire embedded on (usually only for temporary counts) or in the roadway, generally in a square configuration. The loop utilizes the principle that a magnetic field introduced near an electrical conductor induces an electrical current. In the case of traffic monitoring, a large metal vehicle acts as the magnetic field and the inductive loop as the electrical conductor. The counter unit at the roadside records the signals generated.

[1] Probe vehicles are an outcome of the ITS effort. Vehicles are equipped with sensors which monitor traffic conditions, for example the average speed or stop/start conditions. This information is transmitted on a regular basis to receivers adjacent to the road where it is tabulated and further transmitted to information systems.

Table 6.5: Sensor Technology Data Type

Sensor Technology		Count	Speed	Classification	Occupancy	Presence	Weight
Intrusive Devices	Inductive Loop	√	√	√	√	√	
	Passive magnetic	√	√	√	√	√	
	Pneumatic Road Tubes	√	√	√			
	Piezoelectric Sensor	√	√	√		√	√
	WIM - Bending Plate						√
	WIM - Capacitive Weigh Mat						√
	WIM - Hydraulic Load Cells						√
	WIM – Piezoelectric Sensor						√
Non-Intrusive Devices	Active infrared	√	√	√			
	Passive infrared	√	√	√	√	√	
	Microwave Radar	√	√	√	√	√	
	Ultrasonic	√				√	
	Passive Acoustic	√	√	√	√	√	
	Video Image Detection	√	√	√	√	√	

Source: Martin *et al.*, (2003)
Notes: 1/ WIM systems are typically operated with loops or other detectors to collect count, speed, and classification data.

Unlike many other sensors, inclement weather will not generally affect the performance of inductive loops. However, there is potential damage to sensors caused by snow removal equipment. For those embedded in flexible pavements, high temperatures may cause the material to shift and thus lead inductive loops to fail. Traffic load-caused stress and temperature also affect the performance of inductive loops.

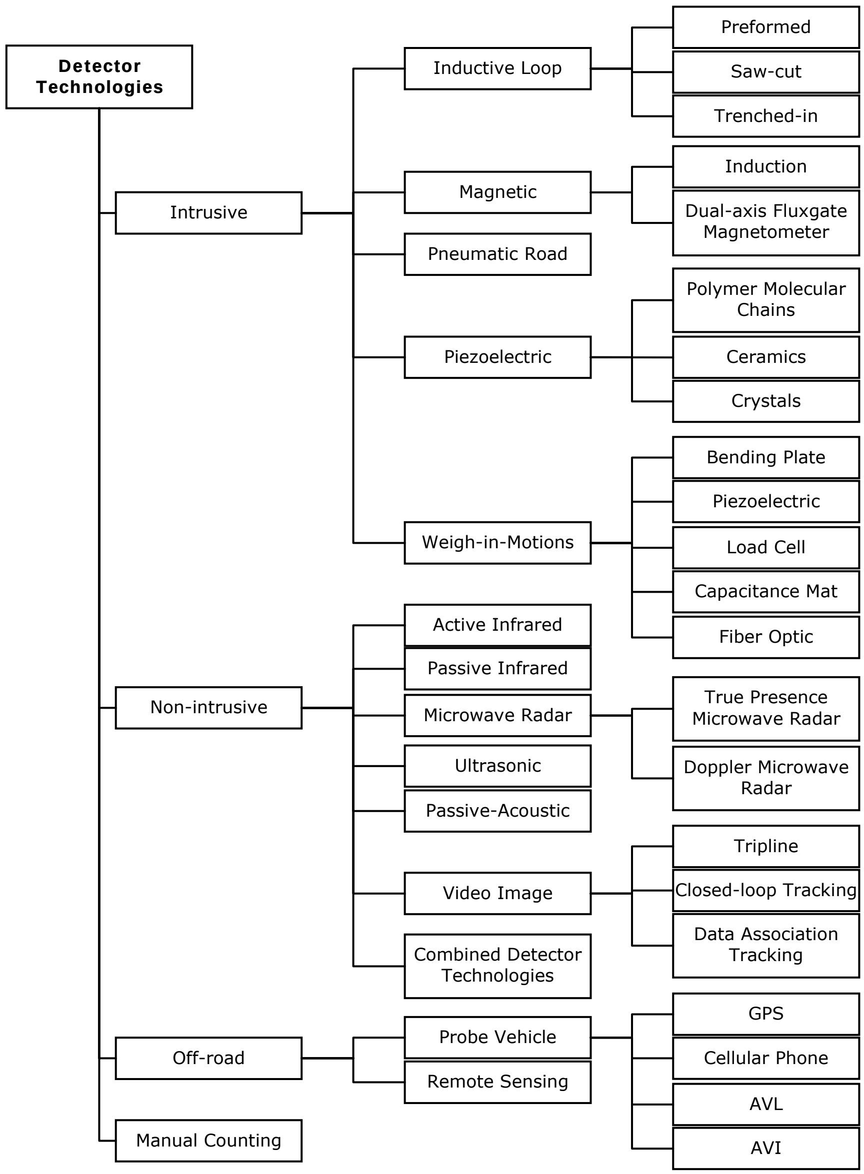


Figure 6.1: Traffic Monitoring Technology Family Map (Martin *et al.*, 2003)

Passive Magnetic

Passive magnetic devices (or magnetometers) detect the disruption in the earth's natural magnetic field caused by the movement of a vehicle through the detection area. In order to detect this change, the device must be relatively close to the vehicles, usually directly below. This limits most applications to installation under or on top of the pavement, although some testing has been done with roadside devices in locations where they can be mounted within a few feet of the roadway. Magnetic sensors can be used to collect count, speed, and simple classification data. One advantage of magnetic detectors is that they are not affected by inclement weather.

Figure 6.2: Inductive Loops

Pneumatic Road Tubes

A pneumatic road tube is a hollow rubber tube placed across the roadway that is used to detect vehicles by the change in air pressure generated when a vehicle tire passes over the tube. An air switch records the change in pressure as a vehicle axle. Axle counts can be converted to count, speed, and/or classification depending on how the road tube configuration is structured.

The performances of pneumatic road tubes are subject to weather, temperature, and traffic conditions. Their use is not viable in snow. The air switches on road tubes are also sensitive to temperature. Road tubes may have difficulty in detecting vehicles in low speed flows.

A specialist application of road tubes is in counting bicycles. As described in MWH (2002), it was found that road tubes were able to reliably count bicycles under a range of conditions. It was usually necessary to ensure that the tubes were 'calibrated' to the counter, and some manufacturers supply special tubes for this purpose.

Piezo-Electric Sensors

Piezo-electric sensors are usually mounted in a groove that is cut into the roadway surface within the traffic lane. The sensors gather data by converting mechanical energy into electrical energy. Mechanical deformation of the piezo-electric material causes a change in the surface charge density of the material so that a change in voltage appears between the electrodes. The amplitude and frequency of the signal is directly proportional to the degree of deformation. When the force of the vehicle axle is removed, the output voltage is of opposite polarity. The change in polarity results in an alternating output voltage. This change in voltage can be used to detect and record weight-in-motion, vehicle count and classification, and speed data.

Bending Plates

Bending plate technology (Figure 6.3) is used for collecting weigh-in-motion data. It is usually combined with other sensors, such as loops, to gather data on vehicle speeds and classifications.

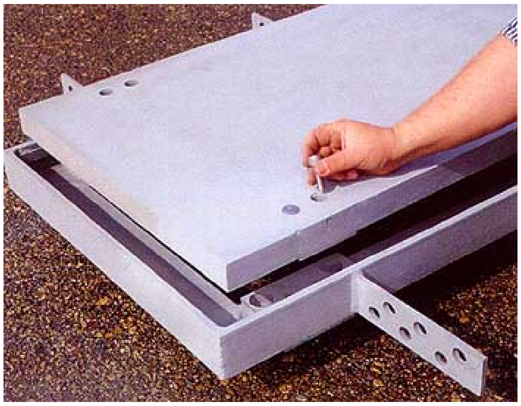


Figure 6.3: Bending Plate

The device typically consists of a weighing pad attached to a metal frame installed into the monitored lane. A vehicle passes over the metal frame causing it to bend slightly. Strain gauge weighing elements measure the strain on the metal plate induced by the vehicle passing over it. This yields a weight based on wheel/axle loads on each of two scales installed in a lane.

Load Cells

Hydraulic load cells are also used for weight-in-motion. The load cell is an oil-filled piston that is placed between two steel plates. The steel plates are permanently mounted in the pavement, flush with the wearing surface. The hydraulic load cell interprets the load passing over by measuring the hydraulic pressure change in the cell as it deforms with the plate it is connected to. This pressure change is proportional to the load passing over and is converted into a dynamic load.

Figure 6.4: Load Cell WIM

Capacitive Weigh Mats

Capacitive weigh mats/pads (Figure 6.5) are used for weigh-in-motion. They are constructed of two or three steel plates, placed parallel to each other, and separated at known distances by a synthetic dielectric material, typically rubber with known elastic properties. The capacitance of the mat is integrated into an oscillatory circuit with a given frequency controlled by an electronic device. As a vehicle passes over the sensor, the wheel load causes compression of the sensor, which in turn results in a change in the oscillating frequency of the tuned circuit. The magnitude of the change in frequency is then interpreted as a weight.

Figure 6.5: Capacitive Weigh Mat

Fiber-Optic Sensors

Fiber-optic sensors are a new technology used for weight-in-motion that promise to offer high reliability at low costs; however, this technology is still in the experimental phase.

6.3.2 Non-Intrusive Sensors

Video Image Detection

Video image detection devices use a microprocessor to analyze the video image input from a camera (Figure 6.6). Two techniques, trip line and tracking, are used to record traffic data. Trip line techniques monitor specific zones on the roadway to detect the presence of a vehicle. Video tracking techniques employ algorithms to identify and track vehicles as they pass through the field of view. The mounting height is related to the desired lane coverage, usually 35 to 60 feet above the roadway. Video detection devices are capable of recording count, speed, and classification data. This technology is affected by penetration, wind, temperature, and light conditions.

Source: Traficon

Figure 6.6: Video Image Analysis

Active Infrared

Active infrared devices emit a laser beam at the road surface and measure the time for the reflected signal to return to the device. When a vehicle moves into the path of the laser beam, the time it takes for the signal to return is reduced. The reduction in time indicates the presence of a vehicle. Both active and passive infrared devices can be used to record count, speed, and classification data. Active infrared detectors are affected by inclement weather because the short wavelength cannot penetrate snow and rain.

Passive Infrared

Passive infrared devices detect the presence of vehicles by measuring the infrared energy radiating from the detection zone. A vehicle will always have a temperature that contrasts the background environment. The infrared energy naturally emanating from the road surface is compared to the energy radiated when a vehicle is present. Because the roadway may generate either more or less radiation than a vehicle, the contrast in heat energy is detected. The possibility of interference with other devices is minimized because the technology is completely passive. Passive infrared detectors are typically mounted directly over the lane of traffic on a gantry, overpass, or bridge, or alternatively on a roadside pole. Passive infrared detectors are not affected by inclement weather.

Microwave Radar

Radar is capable of detecting distant objects and determining their position and speed. With vehicle detection, a device directs high frequency radio waves—either a pulsed, frequency-modulated, or phase-modulated signal—at the roadway to determine the time delay of the return signals, thereby calculating the distance to the detected vehicle. Radar devices are capable of sensing the presence of stationary vehicles. They are insensitive to weather and provide day and night operation. Electromagnetic interference may occur when the radar equipment is placed close to other high-power radars. This technology is capable of recording count, speed, and simple classification.

Ultrasonic and Passive Acoustic

Ultrasonic devices emit pulses of ultrasonic sound energy and measure the time for the signal to return to the device. The sound energy hits a passing vehicle and is reflected back to the detection device. The return of the sound energy in less time than the normal road surface background time is used to indicate the presence of a vehicle. Ultrasonic sensors are generally placed over the lane of traffic to be monitored.

Passive acoustic devices utilize sound waves in a different manner. These systems consist of a series of microphones aimed at the traffic stream. The device detects the sound from a vehicle passing through the detection zone. It then compares the sound to a set of sonic signatures pre-programmed to identify various classes of vehicles. The primary source of sound is the noise generated by the contact between the tire and road surface. These devices are best used in a side-fire position, pointed at the tire track in a lane of traffic to collect count, speed, and classification data. The problem with passive acoustic detectors is that they are affected by snow and low temperatures.

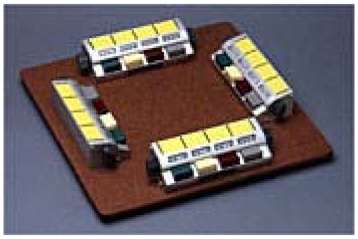
Off-roadway Technologies

Probe vehicle and remote sensing are two new off-roadway technologies. They use vehicle or aerial/satellite images to obtain traffic information. Probe vehicles show some advantages for collecting travel time data. The theory is that with sufficient vehicles transmitting real-time information on roadway conditions, traffic management systems will be able to provide travelers with information and will improve the overall traffic flow. Remote sensing is still in the very early stages of development.

Manual Observation

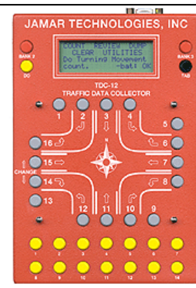
Manual observation involves detection of vehicles with the human eye and hand recording count and/or classification information. Hand-held devices are available for on-site recording of information gathered by one or more individuals observing traffic. Often called 'deonominators' or 'tally boards', they are available as manual or electronic systems (see Figure 6.7). Electronic systems have the advantage of enabling more detailed analyses, but are significantly more expensive to purchase than simple manual systems.

Most manual surveys are done at single points. An alternative approach, which gives the average volume on a link, is to conduct a **moving traffic survey**. As a vehicle travels along the road it notes the number and (optionally) type of vehicles traveling in the opposite direction. From these, an estimate of the ADT can be calculated using the equation:



Source: The Denominator Co.

Manual



Source: Jamar Tech.

Electronic

Figure 6.7: Manual and Electronic Survey Systems

$$X = \frac{C}{L} \frac{1}{\frac{1}{So} + \frac{1}{Sr}}$$

Where X is the oncoming flow rate in veh/h;
So is the average oncoming vehicle speed in km/h;
Sr is the speed of the survey vehicle in km/h;
L is the distance traveled by the survey vehicle in km; and,
C is the number of vehicles counted traveling in the opposite direction in veh.

If the survey vehicle travels at the same speed as the oncoming traffic, and it is assumed that there are no speed differences between classes, the above expression reduces to:

$$X = \frac{C}{L} \frac{Sr}{2}$$

Since the duration of the survey is given by t = L/S_r, this can be expressed as:

$$X = \frac{C}{2\,t}$$

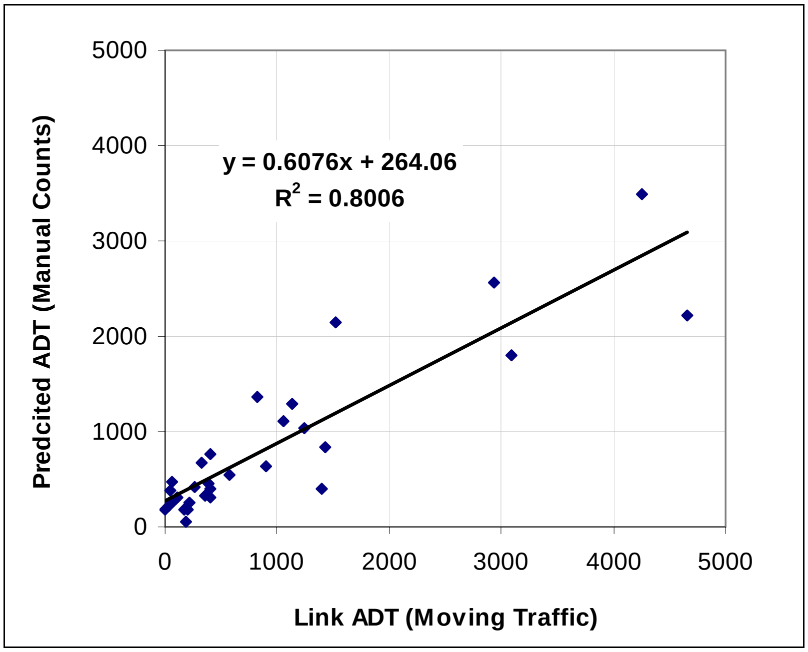
We assume that the ADT is twice the flow in the opposing direction so the ADT is given as:

$$ADT = \frac{C}{t}$$

Or, for different survey vehicle speeds to oncoming traffic:

$$ADT = \frac{C}{L} \frac{2}{\frac{1}{So} + \frac{1}{Sr}}$$

MWH (2004) used ROMDAS to record the time of each vehicle's observation in a Cambodia network survey. The data were adjusted using calibration factors based on the time of day and on manual counts from 31 locations. As shown in Figure 6.8, the moving traffic counts had a good correlation with the observed traffic counts, although the intercept of 264 may have resulted in an overestimation on low-volume roads.



Source: MWH (2004)

Figure 6.8: Moving Traffic Survey Calibration from Cambodia

6.4 Traffic Counting and Vehicle Classification Technologies

The discussion above presented a range of traffic counting and vehicle classification technologies. There are advantages and disadvantages to each. For example, as shown in Table 6.6, weather and traffic conditions affect different technologies in different ways.

The advantages and disadvantages of different traffic counting and classification technologies are compared in Table 6.7. These are based on the analysis presented in Martin *et al.* (2003) and Skszek (2001).

Table 6.6: Impacts of Environmental and Traffic Conditions (after Martin, *et al.*, 2003)

Sensor Technology	Environmental				Traffic	
	Penetration	Wind	Temp.[1]	Light	High	Low
Inductive Loop	√[2]	√		√	√	√
Passive magnetic	√[2]	√	√	√	√	√
Pneumatic Tubes	√[2]	√		√		√
Active infrared		√	√	√	√	√
Passive infrared	√	√	√	√	√	√
Radar	√[3]	√	√	√	[4]	√
Ultrasonic	√	√	√	√	√	√
Passive Acoustic		√		√		√
Video Detection[5]					√	√

Notes: √ - affected
1/The temperatures are extremely low or high and each detector device has its own operating temperature range.
2/They possibly may be damaged by snow removal equipment.
3/Some vendor claims that rain and snow less than 10mm should not hinder detection capabilities.
4/Doppler microwave is not good at stop-and-go conditions.
5/Video detection systems are incorporating a variety of new features to reduce the impacts of environmental factors on detection accuracy, such as image stabilization algorithm, sun location, night reflections, contrast losses, etc.

6.5 Truck Weighing Technology

Vehicle weighing systems are used to obtain the distribution of axle loads for each truck type. Trucks are weighed either at static weight stations, on portable scales, or using weigh-in-motion (WIM). Section 6.3 described typical WIM sensors. WIM stations can be operated for a short period of time (one to two days) or for longer periods (seven days or more) to determine daily variations. The frequency of surveys, the number of stations, the sample of the network, and the sample of the traffic dictate the quality level of the information (Paterson and Scullion, 1990). TRL (2004) is an excellent guide on all aspects of planning and executing axle load surveys.

Vehicle and axle weighing systems can be characterized as static or dynamic and each are discussed in the following sections.

Table 6.7: Sensor Technology Comparison

Technology		Advantages	Disadvantages
Intrusive Devices	Inductive Loop	• Flexible design to satisfy large variety of applications • Mature, well-understood technology • Lower equip. costs compared to non-intrusive devices • Provides basic traffic parameters (e.g., volume, speed) • High frequency models provide classification data • Operability in harsh environment	• Disruption of traffic (lane closure) for installation and repair • Pavement cut potentially decreasing pavement life • Sensor installation may be compromised in old pavements • Multiple detectors usually required for a given location • Prone to installation errors that lead to high maintenance • Susceptible to damage by heavy vehicles and road repairs • Maintenance requirement/potentially short life expectancy
	Passive Magnetic	• Can be used where loops are not feasible (e.g., bridge decks) • Less susceptible than loops to stresses of traffic • Some models transmit data over wireless RF link • Less disruption to traffic flow than inductive loop	• Simple/very limited traffic classifications • Installation and maintenance require lane closure • Some models have small detection zones • Cannot detect stopped vehicles • Pavement cut potentially decreasing the life of the pavement (if not surface mounted)
	Piezoelectric Sensor	• Well supported by vendor community • Ease of deployment in low-volume conditions and when measurement lane is accessible from a shoulder • Reliable	• Installation requires working within the traffic lane • If placed on road surface, may be displaced / loss of data • If imbedded in roadway, requires disruption of road surface • Sensor installation may be compromised in old pavements • Susceptible to system failure and heavy maintenance • Weather conditions can interfere with performance
	Pneumatic Road Tubes	• Quick installation for temporary data recording • Low power usage • Low cost • Simple to maintain	• May become displaced resulting in loss of data • Installation requires working within the traffic lane • Inaccurate axle counting when traffic volume is high • Temperature sensitivity of the air switch • Not suitable with snow due to plowing • Tubes may be cut by vandalism or traffic wear • Often not suitable for multi-lane roads

Technology		Advantages	Disadvantages
Non-Intrusive Devices	Video Image Detection	• Monitors multiple lanes and multiple zones/lane • Easy to add and modify detection zones • Rich array of data available • Provides wide-area detection when information gathered at one camera • Location can be linked to another	• Overhead inst. requires the presence of existing structure • Weather conditions that obstruct view of traffic can interfere with performance (i.e., snow, fog, sun glare, etc.) • Large vehicles can mask trailing smaller vehicles
	Passive/Active Infrared	• Active sensor transmits multiple beams for accurate measurement of vehicle position, speed, and class • Multizone passive sensors measure speed • Multiple lane operation available	• Lane coverage limited to one to two lanes • Active: generally limited to the same range in inclement weather as can be seen with the human eye; classification based on vehicle height (not length) • Passive: performance degraded by heavy rain or snow
	Radar	• Generally insensitive to inclement weather • Direct measurement of speed • Multiple lane operation available	• Roadside inst. limited to only long and short vehicle classes • Antenna beam width and transmitted waveform must be suitable for application • Overhead inst. requires the presence of existing structure • Doppler sensors cannot detect stopped vehicles • Doppler sensors perform ineffectively at intersections as counters
	Ultrasonic	• Multiple lane operation available • Easy installation	• Large pulse repetition periods may degrade occupancy measurement at moderate to high speeds • Performance may be degraded by variations in temperature and air turbulence
	Passive Acoustic	• Passive detection • Insensitive to precipitation • Multiple lane operation available	• Cold temperatures affect data accuracy • Signal processing of energy received requires removal of extraneous background sound and acoustic signature • Calibration can be difficult

6.5.1 Static Scales

Static systems use either portable scales or permanent platform scales:

- **Portable scales** are wheel pads that weigh one or more wheels at a time. To avoid distortion arising from tilting the vehicle, dummy pads are usually placed to keep the vehicle on a level plane.
- **Permanent scales** come in a variety of sizes. Some are half, and some are full-vehicle-width, allowing either half the axle or a whole axle to be weighed at once. They range from 0.5 m up to 15 m in length. The larger platforms are generally segmented into three independent scales each capable of weighing a portion of a vehicle. Some use strain-gauged load cells as sensors.

Figure 6.9: Static Weigh Scales

The primary advantage of static scales is their very high accuracy, with a typical precision of 3 to 5 percent, which makes them admissible for load enforcement purposes. However, the main disadvantages of static weighing are safety, delays, and avoidance problems. The queue of trucks waiting to be weighed is a safety hazard, and the delays to users are costly and frustrating. Avoidance by trucks, which either take alternative routes or avoid driving while the weigh station is in operation, is exacerbated by the delays and the high visibility of the static weighing operation. Usually only a sample of trucks can be drawn from the traffic stream in medium or high volumes of traffic, which can introduce a significant sampling error. If the weighing is being conducted for load enforcement purposes, then only vehicles that appear to be fully loaded or overloaded are stopped for weighing. Thus, such data show a bias in the loading spectrum.

6.5.2 Weight-in-Motion

Of all the traffic monitoring activities, WIM technology requires the most sophisticated data collection sensors, the most controlled operating environment (strong, smooth, level pavement or bridges in good condition), and the most costly equipment set up and calibration.

Unlike static scales, WIM systems provide continuous traffic data without interrupting the traffic flow. When combined with other sensors WIM can provide traffic volumes, axle weights for various vehicle classifications, and vehicle speeds. In addition, they permit measuring a large sample (a full sample for systems that are reliable at highway speeds) of vehicles during the duration of the survey. Thus they provide a comprehensive picture of traffic loading, which is valuable for pavement and bridge design as well as management purposes. WIM technology is quickly becoming one of the most widely used forms of traffic data collection. While some WIM systems are only used for permanent continuous monitoring sites, others, such as the capacitive mats and some piezoelectric sensors, are designed for portable applications.

Figure 6.10: Capacitance Pad WIM – Permanent Site

There are numerous types of WIM systems available. The systems differ in the type of sensors they use, the software that processes the data, the set-up of each, and countless other variations. Each type of system has its own advantages and disadvantages.

Most WIM systems have the following elements: the roadway component, computer component, signalization component, and tracking component (Siegel, 2003). The types of components used and the way the components are set up are generally what make the various available systems unique. The type of system an agency chooses to use and types of components involved in that system are generally determined by the type of data that one would want to collect with the system and how these data would be used (McCall and Vodrazka, 1997).

The ASTM E1318-92 specification entitled "A Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test

Method" is the first attempt at a North American specification for WIM systems. It classifies WIM systems into four types:

- **Type I** – high accuracy data collection systems (typically bending plate scale type WIM);
- **Type II** – lower cost data collection systems (typically piezoelectric scale type WIM);
- **Type III** – systems for use in a sorting application at weigh station entrance ramps (bending plate or deep pit load cell type WIM) at speeds from 15 to 50 mph;
- **Type IV** – low-speed WIM.

Table 6.8 shows the ASTM performance standards for each WIM type. The costs of WIM systems vary significantly depending on the type. Thus, standards must be very carefully selected based on the data needs.

Table 6.8: ASTM Defined WIM Type Accuracy

WIM Type	Single Axle	Axle Group	Gross Vehicle Weight
I	20%	15%	10%
II	30%	20%	15%
III	15%	10%	6%
IV	-	-	-

Another important factor when comparing WIM technologies is the effort required to install the sensors, in particular with regard to traffic disruption. Table 6.9 compares the installation requirements for both short-duration and permanent classification technologies.

Table 6.9: WIM Technology Comparisons

Sensor Technology	Installation Requirements	Traffic Disruption
Bending Plate	Moderate frame installation	Moderate
Piezoelectric Cable	Narrow slot	Short
Piezopolymer Film	Narrow slot or portable	Short
Piezoquartz	Narrow slot	Short-Moderate
Hydraulic Load Cell	Deep pit	Long
Capacitance mat	Portable or moderate frame	Short-Moderate
Fiber-Optic Cables	Narrow slot	Short
Bridge WIM	Weight sensors under bridge	Short
Subsurface Strain Gauge	Deep pit	Long
Multi-Sensor WIM	Multiple narrow slot	Moderate

Source: Hallenbeck and Weinblatt (2004)

In general terms, portable WIM accuracies vary depending on the following considerations:

- Evenness of the ground approaching the weighing area. The evenness around the weighing area, and after the weighing area, impacts the accuracy. The latter has to be the length of the longest vehicle, as weighing is performed axle by axle. The evenness of the ground prior to the weighing site affects the vehicle suspension oscillation and this in turn affects the Impact Factor (ratio of dynamic weight to static weight). The levels of the ground immediately adjacent to the weighing system effect the way tandem and triple axles behave when they are weighed.
- Whether the system is a high or low speed weighbridge. High speed systems using piezoelectric sensors, on a good quality site, will provide a coefficient of variation (COV) in the region of 7%, although this depends upon the number of WIM sensors and assumes effective temperature compensation. A minimum of two sensors are required, and it should be noted that more than four sensors do not result in better accuracies. If the system is a low speed WIM, then the accuracies obtained are around 1% COV depending upon the surface profiles and quality of the recording electronics.
- If piezosensors are used for high speed weighing (HSWIM), temperature compensation is required as the results are variable and drift with temperature. During the 1990s this was not considered effective and many HSWIM systems struggled to achieve COV's better than 15%.
- The quality of the actual recording electronics is important. For HSWIM, a sufficiently fast scanning rate is required in order to record the axle pulse as it passes over each sensor. The weight is a product of axle speed and area under the pulse shape.
- For low speed weighing (LSWIM), an effective algorithm is required to ensure the middle part of the weighbridge or weigh beam is taken for axle weight recording. An averaging algorithm to filter out oscillations is often used to increase accuracy and minimize the COV.
- Portable HSWIM and LSWIM are fraught with difficulties unless the weighing system is made level with the surrounding ground. In the case of portable weigh pads, or a portable weigh beam for LSWIM measurements, it is important to ensure that all adjacent axles are kept at the same height. Use of the system in pre-cast pits helps to achieve good results, near 5% COV.

6.6 Selecting the Traffic Monitoring Technology

Each of the technologies discussed so far has its advantages and disadvantages for collecting traffic data. Under the right conditions, most of the technologies are reliable. However, if used incorrectly, any of these technologies can perform very poorly. As a consequence, operating more than one type of traffic monitoring technology is helpful to ensure successful data collection.

In 1990, the FHWA published the "Traffic Detector Handbook" to help transportation engineers and technicians in planning, designing, installing, and maintaining traffic detectors (Kell et al., 1990). However, due to the state of practice at the time, only inductive loops and magnetic detectors were discussed in the handbook.

The Office of Highway Policy Information at FHWA published their "Traffic Monitoring Guide" (FHWA, 2001). The guide recommends a program structure for traffic volume counting, vehicle classification and truck weight measurements. Also, the guide describes specific traffic monitoring requirements, quality assurance, and data formats. The collected data are mainly used in pavement management and traffic operations. Besides the FHWA guide, AASHTO has Guidelines for Traffic Data Programs providing recommendations for traffic data collection for common traffic monitoring practice (AASHTO 1992).

Martin *et al.* (2003) proposed a framework to help select detector technologies for traffic monitoring. The framework is comprised of a series of questions. By answering the questions, a detector technology is evaluated on its data types, installation conditions, costs, data accuracy requirements, reliability, ease of installation and maintenance, power and data communication, and field experience. The technology should be selected based on all the above issues.

As an example, Table 6.10 presents a table proposed by Hallenbeck and Weinblatt (2004) for selecting traffic monitoring and weighing equipment. The process considers the following three different types of information to reach the final decision:

- Data collection needs of users;
- Data handling requirements and capabilities of the highway agency; and
- Characteristics of available makes or models of equipment (*e.g.*, cost, reliability, and data provided)

Although several guides are available, it seems that there still are no comprehensive and systematic procedures on detector device selection.

6.7 Application in Developing Countries

Traffic counting technologies are used routinely in many developing countries, with manual traffic counts being the primary method. Vehicle classification and weigh-in-motion (WIM) technologies are less common but are beginning to be used, especially in privatized projects.

Table 6.10: Technology Selection Analysis Sheet

Technology/Vendor/Model: ______________________________________

Subject Area	Issues/Concerns	Technology Vendor Review Comments
Equipment Capability		
Type of Data Collected • WIM • Classification		
Type of Vehicle Classes Measured • 13 FHWA axle-based classes • Vehicle lengths only • Other (total number allowed)		
Desired/Required Sensor Location • In pavement • On pavement • Non-intrusive	Can sensor be placed? • Condition of pavement, planned pavement maintenance, and repair? • Traffic volumes • Availability of overhead structures or poles	
Count Duration • Portable (Several days) • Permanent	• Seasonal changes? (In traffic generators?) • Correlation with permanent sites, reliability of measurements?	
Output from Device • Level of aggregation • Specific • Quality-control metrics available for analysis of device output	• Can be polled from central source, or only from the site? • Flexibility of output formats • Availability of standardized formats (NTCIP? Other?)	
Site Conditions		
Operating Environment • Temperature range and daily variation • Visibility constraints (fog, mist, dust) • Snow (loss of lane lines) • Free-flow or congested traffic (including other acceleration / deceleration conditions)		
Number of Lanes • Are all lanes next to a shoulder?	• Number of sensors required • Number of sets of electronics required	
Is Power Available?	Can device run off solar panels?	
Are Communications Available? • Telephone, DSL, wireless • Other	Bandwidth required from device • Frequency of communications	
General		
Technology Price	Total Cost = Sensor Cost × Number of Sensors + cost of Electronics	
Staff Training to Install, Operate, and Maintain the Devices		
Equipment Needed to Install, Operate, and Maintain the Device		
Published Accuracy Achieved with the Technology	Has the technology been used previously?	
Previous Experience with this Technology/Vendor	Vendor support offered/available	

Source: Hallenbeck and Weinblatt (2004)

A survey-based suitability rating similar to the ones used for pavement and bridge technologies was also undertaken for traffic data collection technologies. However, in this case, the response was very limited and did not cover the full spectrum of available technologies. Thus information from other available sources is also presented in this section. The following criteria and scales were defined for the technology rating:

- Assembly/Installation: 5 = easy, 1 = difficult
- Operation & Maintenance: 5 = easy, 1 = difficult
- Calibration: 5 = easy, 1 = difficult
- Data Collection/Processing: 5 = automatic, 1 = manual
- Interoperability: 5 = open, 1 = closed
- Robustness: 5 = robust, 1 = not robust
- Data Collection Speed: 5 = fast, 4, 3, 2, 1 = slow, N/A
- Portability: 5 = portable, 4, 3, 2, 1 = not portable

Because there are a large number of possible combinations of data acquisition and sensor technologies, it is hard to evaluate the combined technologies. Despite this limitation, Table 6.11 gives an evaluation based on very limited responses received in the survey. Since the suitability rankings were based on these limited responses, information for traffic monitoring technology compiled from available literature (Martin *et al*, 2003; Skszek, 2001) and the survey in this project is presented in Table 6.12.

Table 6.13 presents a summary of the average initial acquisition and maintenance costs for the various traffic monitoring technologies evaluated in this report. The results are presented for the survey conducted in this project as well as from the available literature. It should be noted that the costs reported in the survey usually included estimated installation costs. The wide variations in values show that it is important for full cost analyses to be done prior to the acquisition of any equipment, especially since the costs can vary markedly between vendors.

Hallenbeck and Weinblatt (2004) provide a comparative analysis of the four most-used WIM technologies. The main parameters considered are costs and performance. A summary of their findings is presented in Table 6.14.

Table 6.11: Survey-based Suitability Ranking for Traffic Data Collection Technologies

Sensor Technology	Assembly / Installation	Operation & Maintenance	Calibration	Data Collection / Processing	Interoperability	Robustness	Portability	Average
Traffic Counters								
Induction Loops	1.3	4.0	3.7	4.7	3.0	4.0	1.0	3.1
Piezo-electric	3.0	3.3	3.7	4.7	2.7	2.5	2.8	3.2
Pneumatic Tube	4.3	2.8	4.0	3.7	3.0	2.5	4.3	3.5
Digital Imaging	3.0	3.3	3.0	3.5	2.3	4.3	2.7	3.2
Radar	3.8	3.3	3.3	4.0	2.0	3.8	3.5	3.4
Vehicle Classification								
Piezo-electric	3.3	3.3	3.7	4.7	3.0	2.8	2.8	3.5
Quartz	3.0	3.0	4.0	4.0	2.0	2.0	4.0	3.1
Magnetic	3.0	3.5	3.0	4.0	1.5	3.7	3.0	3.1
Weigh-in-Motion								
Bending Plate	2.0	3.5	3.0	3.5	2.5	4.0	1.0	2.8
Load Cell	3.0	4.0	3.0	3.5	2.5	4.0	3.0	3.3
Strain Gauges	2.0	4.0	3.0	4.0	2.5	4.0	1.5	3.0
Capacitance Pads	4.0	5.0	3.0	4.0	1.0	2.0	5.0	3.4
Piezoelectric	3.3	3.0	3.0	4.3	2.0	2.5	3.0	3.0

Table 6.12: Traffic Counting and Classification Technology Comparison

Sensor Technology	Count Accuracy: Low Volume[1]	Count Accuracy: High Volume[1]	Speed Accuracy[1]	Classification Accuracy[1]	Ease of Installation[2]	Ease of Calibration[2]	Maintenance Requirement[3]	Average
Induction Loops	3.3	4.7	4.0	4.0	1.7	2.5	3.0	3.3
Magnetic	3.0	4.0	2.0	2.5	2.5	3.0	3.5	2.9
Pneumatic Tube	4.7	3.0	4.0	3.7	4.3	4.5	2.7	3.8
Active infrared	4.0	3.5	4.0	3.0	4.0	4.0	3.0	3.6
Passive infrared	3.5	3.5	4.0	3.0	4.0	4.0	3.0	3.6
Radar	3.5	3.5	4.5	4.0	4.0	4.0	3.0	3.8
Passive acoustic	4.0	3.0	4.0	3.0	4.0	4.0	3.0	3.6
Ultrasonic	4.0	3.0	4.0	3.0	4.0	4.0	3.0	3.6
Video image	5.0	4.7	4.5	4.5	3.7	3.0	3.7	4.1

Notes:
(1) 5 = Excellent (<5%); 3 = Fair (<10%); and 1 = Poor (>10%)

(2) 5 = Easy; and 1 = Difficult
(3) 5 = Low; and 1 = High

Table 6.13: Approximate Costs for Traffic Data Collection Technologies (US$)

Sensor Technology	Service Life (yr)	Initial Costs		Maint. Costs (Survey)	Annual Costs[1]	
		Survey	Literature[2]		Survey	Literature[2]
Induction Loops	5~29	$2,400~ $14,000	$500~ $1,000	$50~ $1,880	$1,683	$250 ~ $750
Magnetic	2	$1,450	$900~ $1,100	$70	$795	$230
Pneumatic Tube	9	$2,000	$1,000	$100	$322	
Piezo-electric	5~10	$4,000~ $6,500	$2,500	$50~ $400	$900	$7,350
Quartz	10	$6,500	$17,000	$350	$1,000	$10,100
Bending Plate	10	$5,000	$10,000	$100	$600	$7,900
Load Cell	5	$12,000	$39,000	$2,400	$4,800	$8,800
Capacitance Pads	15	$28,570		$1,143	$3,048	
Strain Gauges	10	$25,000		$350	$2,850	
Active infrared			$6000~ $7500			$1,200
Passive infrared			$700~ $1400			$250~ $375
Radar	10	$2,500	$400~ $1,000	$50	$300	$100~ $355
Ultrasonic		$400~ $600				
Passive acoustic		$3000~ $5000				$285
Digital Imaging	3	$20,000	$4000~ $15000	$6,000	$12,667	$250~ $500

Notes:
(1) Annualized costs of device, installation, maintenance, and operations
(2) Martin *et al*, (2003); Skszek (2001); Hallenbeck and Weinblatt (2004)

Table 6.14: WIM Equipment Costs Comparison (Hallenbeck and Weinblatt, 2004)

	Site Cost Consideration	Piezo	Piezo Quartz	Bending Plate	Load Cell
	Performance [1]	± 10%	± 5%	± 5%	± 3%
Acquisition	Sensor Costs/ Lane	$2,500	$17,000	$10,000	$39,000
	Roadside Electronics	$7,500	$8,500	$8,000	$8,000
	Roadside Cabinet	$3,500	$3,500	$3,500	$3,500
Installation	Labor and materials	$6,500	$12,000	$13,500	$20,800
	Traffic control	0.5 days	1 day	2 days	3+ days
	Calibration	$2,600	$2,600	$2,600	$2,600
Total Initial Costs/lane		$22,600	$29,000	$21,500	$50,500
Recurr.	Site Maintenance	$4,750	$7,500	$5,300	$6,200
	Recalibration	$2,600	$2,600	$2,600	$2,600
Annual Recurring Costs/Lane		$7,350	$10,100	$7,900	$8,800

Notes: [1] Percent Error on GVW at Highway Speed

7 PROCURING EQUIPMENT

7.1 Introduction

The procurement of data collection equipment represents a major challenge for many organizations. However, there are certain fundamental principles that can be followed to simplify procurement.

When developing specifications, they should be based on the **functional** requirements—specifically, what data are required to be collected, at what resolution and what frequency. For example, if the objective is to measure the road roughness the specification should indicate that:

(i) the roughness is to be measured using a Class I profilometer compatible with an established standard (e.g. ASTM E1274-03);
(ii) the measurements should be made in two wheelpaths (say) 1.65 m apart;
(iii) the distance must be measured with an accuracy of 0.1% of the true distance;
(iv) the roughness is to be expressed in terms of m/km IRI, summarized to (say) 25 m intervals.

With this basic requirement, a set of **minimum** technical specifications that would be required to meet the requirement need to be defined. For example, the minimum speed of the lasers is 16 kHz; the minimum resolution of the accelerometer is 5µG, *etc*. It is important that only the key specifications are included so that vendors are not restricted.

By having a functional specification combined with the minimum technical requirements to meet that specification, one opens up competition for vendors to provide a range of equipment.

7.2 Validation

Whenever any equipment is procured, upon delivery it must be **validated**. The purpose of the equipment validation is confirm the equipment, how it will be used, how the data are processed, and outputs meet the required standard, while maintaining consistency between different data collection equipment. It also ensures that the data produced by the equipment can be imported and used by the Agency's RMS.

Validation also demonstrates that the equipment can operate under the expected conditions of the network. Therefore in addition to meeting the equipment specification detailed above, each equipment type must also meet the validation requirements detailed below.

There are two issues addressed during the validation process—calibration and validation:

- **Calibration** of the equipment confirms that measurements can achieve a measurable/specified tolerance. Calibration does not confirm that the equipment can measure the required parameter from a moving vehicle. Data is filtered and processed to achieve the desired output.

- **Validation** demonstrates that the survey equipment can be operated by local surveyors on roads that are characteristic of their particular network, and provide meaningful data of sufficient accuracy to meet its intended use. Validation therefore confirms that the data capture, associated filtering and data processing work on the client's network.

An important part of all validation exercises is a field trial. Once the equipment is calibrated and validated, it should be used to undertake a minimum of 100 km of surveys. The data from these surveys should be processed and entered into the Agency's RMS. Depending upon the design of the RMS, it may be necessary to modify either the RMS or to have the equipment supplier produce a custom data format. Only once the equipment is calibrated, validated, and shown to be fully functional in the field trial should the client accept the equipment from the vendor.

Validation is done by testing the survey equipment against a reference measurement. This is done by measuring sections of roads with the reference instrument, and then the same sections with the survey equipment.

For example, with roughness calibration the reference calibration equipment must be compatible with ASTM standard E950 (2004) 'Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference', Class I.

The survey equipment should make at least five repeat runs over each of the validation sections at 4 nominal speeds of 25, 50, 75, and 100km/hour or within the limits specified by the manufacturer. The results must be averaged to give the profile at each of the nominated speeds.

The line of best fit between the reference measurement and the survey equipment using least squares regression is then established:

$$RM = SE \times A + B$$

Where:

RM	is the measurement from the reference equipment
SE	is the measurement the survey equipment
A	is the slope of line of best fit
B	is the intercept of line of best fit (regression offset)

The equipment is considered validated when ***A* and *B*, *and R*^{2}** (the coefficient of determination) are within the specified parameter ranges detailed in Table 2 below for all sites combined.

Repeatability – this is the expected standard deviation of measurements obtained in repeat tests, using the same survey equipment on a single randomly selected road. The standard deviation of measurement on each segment must be within the tolerance defined for the different surface types from the mean for each of the 5 repeat runs.

Assuming a normal distribution then the 95% confidence intervals for the roughness is given by $data \pm t\frac{s}{\sqrt{n}}$.

The error limit is defined by $-\beta = t\,\frac{s}{\sqrt{n}}$.

Where:

data	is the data measured by the instrument (e.g. IRI m/km, mm rut depth, etc.)
s	is the standard deviation of the data in the same measurement units
n	is the number of runs
t	is 2.776. This is the critical value for the t Distribution for a Critical t Confidence Interval of 95%

The equipment is considered to be repeatable when β is within the specified percentage of the mean. Table 7.1 gives recommended validation limits for roads in good to fair condition (e.g., IRI<5m/km). If the roads are in poor condition then the tolerances may be relaxed.

Table 7.1: Validation Limits

Parameter	Slope (A)	Intercept (B)	Correlation R^2	Acceptance Limit β
Roughness	0.98–1.02	0.05IRI	0.99–1.00	$\leq$ 0.030 IRI
Response Type Roughness	Not Applicable	0.5IRI	0.93–1.00	$\leq$ 0.30 IRI
Rutting	0.98–1.02	0.2mm	0.97–1.000	$\leq$ 0.050 RD
Texture	0.98–1.02	0.05mm	0.98–1.00	$\leq$ 0.030 MPD

Specific guidance on how to undertake validation studies is given in the Generic Specifications for Data Collection, described in Section 7.3 below.

7.3 Generic Specifications for Data Collection

To assist with procurement, a set of generic specifications have been prepared covering the following technologies:

- Road data collection using a multi-function vehicle (pavement roughness, rutting, texture, skid resistance, road geometry, crack detection using video logging, and right-of-way (ROW) video)
- Pavement strength using a falling weight deflectometer
- Pavement structure using ground penetrating radar
- Weigh-in-motion and traffic counting

The specifications can be downloaded from www.road-management.info and www.worldbank.org/transport.

The specifications were prepared with inputs from specialists in several countries and feedback from vendors. They are meant to be **the basis** for final specifications which reflect the local requirements and operating conditions. Each specification contains comments to guide the user on issues associated with the data to be measured, as well as recommended minimum criteria to be included in the specification. An example is given in Figure 7.1.

3.2	**Roughness – Response Type Roughness**	**Yes**
	These are the minimum requirements for the use of response-type roughness meters. This consists of a mechanical or accelerometer based instrument which measures the response of the vehicle chassis or axle to the road. The data are then processed to establish the IRI, often via a calibration equation. **The preferred measuring system will measure roughness in each wheel path using two sensors. A single measurement location (one wheel path or the centre of the axle) may be utilized provided the equipment can satisfy the validation criteria detailed below.** **Note: Specifications for the two most common systems are detailed below, however, alternative systems may be included as long as they meet the validation criterion detailed in Chapter 4.**	
	Motion Encoder Bump Integrator Type Systems: (e.g., CSIR LDI, ROMDAS BI, TRL BI) ☐ No of Wheel paths — 2/1 *<select as required>* ☐ Minimum Measuring Range — 0.8mm ☐ Resolution — 1.0mm **Accelerometer Type Systems:** (e.g., AL-Engineering Roadman, ARRB Roughometer) ☐ No of Wheel paths — 2/1 *<select as required>* ☐ Minimum Measuring Range — ±2G ☐ Resolution — 10mG ☐ Minimum Bandwidth — DC - 100Hz	

Figure 7.1: Example of Generic Specification

As described in Section 7.2, an important element of the specifications is the need to **validate** the equipment upon receipt. This is because operating conditions are different between countries, and it is essential to ensure that the equipment operates correctly in the local setting. The specifications contain a recommended validation methodology and validation criteria based on experience from several developed and developing countries. Users can be confident that if equipment pass the validation they will provide suitable data for use in road management.

8 Conclusions

8.1 Implications for Developing Countries

Based on our literature review and the surveys conducted in the project it is clear that many developing countries have adopted, or are in the process of adopting, sophisticated data collection equipment. Many transportation agencies in developing countries are grappling with the cost/performance dilemma: on one hand, they recognize the need to improve data collection accuracy and increase the extent of surveys on their networks, but on the other hand, funding is often a major limitation which limits their activities.

This project observed that there are roughly two groups of developing countries:

- those that have succeeded in improving data collection by incorporating high-quality measuring equipment; and
- poorer countries that lack sufficient private and public investment to afford measuring devices for pavement condition surveys.

The latter countries tend to use manual methods and, in some instances, inexpensive and/or low performing equipment. Since manual labor is cheaper in these countries, maintenance and operational costs of manual equipment and methodologies are affordable.

Not surprisingly, countries that employ manual methodologies and low-quality equipment often find it difficult to justify investments in their road networks compared to others. Some automated technologies, that are well-known for being accurate and relatively inexpensive, have better cost/operational performance than traditional manual methodologies. Adopting these could significantly enhance the quality and, potentially, extent of data collection at a relatively modest cost. The following sections describe the recommendations for collecting pavement, bridge, and traffic data. However, some general conclusions can be drawn.

- **Data collection is expensive.** It is essential that the road agency only collects the data which are required for its management purposes. This data should be collected at a frequency and a level which is appropriate for the decisions they are to be used for.
- **Dynamic measuring devices** for surface distress evaluation, roughness evaluation and, in some instances, texture measurement are strongly recommended for use in developing countries. Portable equipment can be installed in local vehicles and can be used to collect a range of data through a single pass of a multi-functional vehicle. Data should be properly referenced by using a good referencing system, which ideally combines more than one reference technology. Where practical, video logging may be desirable.

- **Bridge surveys** should be regularly programmed and use of manual techniques supplemented by key specialist equipment as required.
- **Traffic surveys** should be done with a combination of permanent automatic sites and temporary counts, either manual or automatic. Weigh-in-motion is desirable on key links in the road network. Where practical, traffic classifiers should be used in preference to traffic counters since classifiers will also report speeds and the individual vehicle classes for little additional cost.

In selecting any technology careful consideration needs to be given to (i) the initial cost, (ii) ongoing costs, and (iii) the ability of the agency to sustain the technology. It is often better to adopt less sophisticated technologies if they are more likely to be sustained given the agency's institutional and staffing arrangements.

8.2 Location Referencing

Prior to investing in any data collection technology it is essential to have a robust location referencing system. Without this, the data collected cannot be used to their full potential. Experience has shown that a linear location referencing system with appropriate ground markers will give accurate position data in the field. GPS is a useful technology for collecting data, but most data are still collected using a distance measuring instrument. Video logging offers many benefits to the agency when it comes to confirming the location of key assets and should be considered where practical.

8.3 Pavement Data Collection

There are a wide range of technologies available for collecting pavement data. These range from low to high cost, and from very precise to approximate measurements. The challenge is to select the appropriate technology given the data needs and the operating environment.

Experience has shown that many countries have not been able to sustain state-of-the art equipment. This is usually for one or more of the following reasons:

- The operating costs, especially spare parts for the technologies, are very high and cannot be met from regular budgets;
- The equipment has been mounted in a vehicle which has been imported to the country specifically for this purpose and it is difficult to maintain the vehicle and to obtain parts for it;
- Equipment needs to be returned overseas for recalibration; and/or
- The staff who were trained to use the equipment have left their positions and either the positions have not been filled, or there is no budget for training of new staff.

For this reason it is important that the overall suitability of the technology be considered. This consists of not just the initial cost, but the ongoing operating costs and the technological demands that it will place on the staff to operate.

The suitability matrix established in this project suggests that most agencies should be aiming at technologies in the range of 3 - 5 for cost and 3 – 5 for operational performance. In less developed countries, or those in the early stages of pavement management system development, preference should be given for equipment in the cost range of 4 – 5.

It should be emphasized that this operational performance is more than the ability to collect data accurately and precisely. It includes factors such as the overall usability. The most expensive and precise technologies often fall outside of this range of the matrix. There are always instances when these technologies are appropriate; however, they need to be very carefully assessed for their long term viability. Several countries have adopted such technologies, and found them unsustainable after a few years.

While many countries still use manual systems for condition data collection, this project has found that low cost automated technologies can have a higher cost/performance ratio. This is because it is very difficult to ensure quality with manual techniques while investments of approximately $10,000 can provide any agency with objectively quantified data.

The available equipment can be broadly classified as portable or installed in a dedicated host vehicle by its manufacturer. It is generally preferable to procure portable or trailer mounted equipment since this enables the agency to use a locally available vehicle for the surveys. Not only is portable equipment usually less expensive, but the costs of importing and maintaining imported vehicles can be prohibitive. Experience has shown that it is best for the agency to assign a specific vehicle for surveys otherwise it may not be available when required for data collection.

Urban data collection presents specific challenges. Most technologies are developed for collecting data at a constant speed. The stop/start conditions in urban areas make that impossible. Some instruments, such as laser profilometers, have difficulty measuring at low speeds and so the specifications need to be carefully considered prior to procurement. This can also be an issue in rural areas; for example in India one project found that approximately 30 percent of the data were not usable due to the profilometer traveling below 50 km/h. Skid resistance in urban areas can be a particular challenge since the systems are generally not designed for turning corners.

In terms of what to collect, road roughness is one of the primary attributes used for road management. When supplemented by visual distress data, managers can make sensible investment decisions. Other data, such as rut depth, texture, and friction will improve the quality of the decisions. Where possible these data should be collected by a single multi-function vehicle. This ensures consistent location referencing and also simplifies data processing. Pavement strength and composition data are important for project level decisions, less so at the network level.

8.4 Bridge Data Collection

Conducting regular surveys of bridge condition is the singularly most important data collection exercise that any agency can do. Bridge failures have a significant negative impact on the network and for that reason it is vital that the agency have current information on the condition of its bridge stock. Because of this, in a number of countries where budgets are constrained the policy is to cut back on pavement and traffic data collection and prioritize bridges. This is a sensible prioritization.

While there are a range of technologies available for bridge surveys, the best investment a road agency can make is to enhance visual surveys. This is done by (i) adopting a comprehensive and sensible bridge data collection guide; (ii) implementing robust quality assurance procedures; (iii) providing extensive, and regular, training for staff; and, (iv) conducting regular surveys. Certain low cost technologies will enhance the surveys, such as ultrasonic and electric testing, but the main focus should be on improved visual surveys. Accessibility equipment can save significant time and enhance the quality of the data collected by providing access to otherwise hard to reach areas of the bridge.

8.5 Traffic Data Collection

The appropriate traffic data technology depends upon the type of survey to be conducted. In general, traffic classifiers are preferable to simple counters since the additional data they can supply are usually worth the small additional cost. However, it is essential that the vehicle classification system be appropriate for the vehicle fleet in the country and this must be checked prior to procurement or made a condition of acceptance.

The selection of technology should consider a range of factors, but the following general guidelines will usually apply:

- **Permanent traffic count stations** usually consist of a traffic counter/classifier and a permanent detector such as an inductance loop. An alternative is to use video technology. Video has the disadvantage of requiring infrastructure for transmitting the signal but has advantages since the maintenance requirements are often lower. It is not unusual for loops to be replaced approximately every three years.

- **Temporary traffic counts** are usually best done with pneumatic traffic counters/classifier. If the surveys are to be done on a regular basis, it may be appropriate to install loops. This is important on multilane roads where pneumatic tubes are often not viable. Magnetic counters are very portable and easy to install but they do not have the same accuracy as an axle detector system. Temporary counts can be supplemented by moving traffic surveys. These are very approximate estimates and the data are best put into bands as opposed to treated as absolute values.

- **Weigh-in-motion** technology depends upon the accuracy required. For most road management applications, low-cost piezo-electric sensors will provide data of sufficient accuracy. Portable data collection can be done using capacitance pads or surface mounted piezo-electric cables.

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ANNEX A: Pavement Data Collection Equipment Details

EQUIPMENT CLASS	SURVEY REFERENCING EQUIPMENTS		
Eq. Type / **Eq. Characteristics**	**Digital DMI**	**GPS**	**Video**
Parameters it measures	Linear Distance	Geographical reference, linear distance and altitude	2D Analog or digital image referenced to Digital DMI or GPS.
Initial cost range (USD), transport and taxes not included	350-800 (costs vary depending on whether vehicle installation kit is included or not)	200-3,000 (costs vary depending on precision, if it is fixed or handheld and mapping capability)	4,000-10,000
Operating cost range (USD/km)	0-0.5 (fuel consumption)	0-0.5 (fuel consumption)	0-1 (fuel consumption and labor cost)
Annual maintenance cost range (USD/year)	0-100	0-100	0-100
Average performance (km/day)	Rural: 400-700, Urban: 50-200	Rural: 400-700, Urban: 50-200	Rural: 400-700, Urban: 50-200
Staff needed for operation	1 driver or 1 operator working with other survey instruments.	1 driver or 1 operator working with other survey instruments.	1 driver and 1 operator. In multipurpose vehicles the same operator can work simultaneously with other survey instruments.
Training needed for operation	Very Low	Low	Low to medium, general knowledge on image capture and filming.
Calibration issues	Calibration is typical to each survey vehicle as it depends on wheel radius and pressure. Performed in a known length test field. Calibration tests should be done frequently.	Not needed. Some high precision equipment needs specific calibration.	Not needed. Needs connection with calibrated Digital DMI or GPS. It is recommended to use a horizontal reference in the image coordinated with the DMI or GPS reference.
Alternative equipment	GPS, but usually presents lower precision.	Digital DMI for linear distance reference and altitude measuring devices.	Panoramic Photographs, Analog, or Digital System for distress survey.
Target IQL level	IQL-1	IQL-1	IQL-1
Suitability to HDM-4 application	Needed to reference survey data in a road network	Geographical reference is not needed, linear distance is needed to reference survey data in a road network	Not needed.
Major Brands	Applanix, ARRB, Data Collection Limited, Jamartech, Nitestar, SSI	Applanix, ARRB, Data Collection Limited, Garmin, Magellan, SSI, Trimble	ARRB, Data Collection Limited, Jai, Samsung, Sony

EQUIPMENT CLASS	PAVEMENT ROUGHNESS SURVEY				
Eq. Type / Eq. Characteristics	Class I (Laser)	Class I (Manual)	Class II	Class III (RTRRMS)	Class III (MERLIN)
Parameters it measures	IRI in meters per kilometer (m/km)	Profile mean difference which can then be correlated to IRI (m/km) measures.	Quarter Index (QI), IRI in meters per kilometer (m/km)	Quarter Index (QI), IRI in meters per kilometer (m/km)	Maximum Deviation of Measured Histogram, the total roughness is then converted to IRI (m/km) using correlation equations
Initial cost range (USD), transport and taxes not included	70,000-100,000	8,000-15,000	40,000-60,000	30,000-50,000	100-150
Operating cost range (USD/km)	0.5-1 (fuel consumption and labor cost)	1-2 (labor cost, depending on frequency and number of measures per point)	0.5-1 (fuel consumption and labor cost)	0.5-1 (fuel consumption and labor cost)	0.5-1 (fuel consumption and labor cost)
Annual maintenance cost range (USD/year)	500-1,000	50-150	500-800	400-600	400-600
Average performance (km/lane/day)	Rural: 400-700, Urban: 50-200	Rural: 5-10, Urban: 5-10 (depending on frequency and number of measures per point)	Rural: 300-500, Urban: 50-100	Rural: 300-500, Urban: 50-100	Rural: 300-500, Urban: 50-100
Staff needed for operation	1 driver and 1 operator. In multipurpose vehicles the same operator can measure simultaneously with the same instrument other distresses such as rut depth, macrotexture, concrete faulting, etc.	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.	1 driver and 1 operator.	1 driver and 1 operator.	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.
Training needed for operation	Medium to high. Needs skills on software operation, data base analysis, and mechanical knowledge on laser operation.	Medium. Needs skills on equipment operation and data base analysis.	Medium to High. Needs skills on equipment operation, data base analysis and some mechanical knowledge.	Medium to High. Needs skills on equipment operation, data base analysis and some mechanical knowledge.	Medium to High. Needs skills on equipment operation, data base analysis and some mechanical knowledge.

EQUIPMENT CLASS	PAVEMENT ROUGHNESS SURVEY (Continued)				
Eq. Type / Eq. Characteristics	Class I (Laser)	Class I (Manual)	Class II	Class III (RTRRMS)	Class III (MERLIN)
Calibration issues	Sensors and accelerometer to be calibrated by user. Sensors are calibrated by means of special calibration metal sheets provided by manufacturer. Sensor alignment to be calibrated for a local slope angle of 40º. Sensor frequency and wave length to be checked periodically.	Depth measured by the equipment to be calibrated by user generally by means of special calibration metal sheets provided by manufacturer.	Calibration similar to that of Class I devices, depending on the technology used.	Generally user calibrates equipments in test fields, with different known roughness levels.	The amplification of roughness measures done by the beam has to be measured before each survey. Deviation measures are then corrected using the calibration number obtained.
Alternative equipment	Class I manual devices, but with lower performance. Class II or Class III devices, but with lower accuracy.	Class I laser devices. Class II or Class III devices, but with lower accuracy.	Class I devices, which present higher accuracy. Class III devices, but with lower accuracy.	Class I and Class II devices in paved roads. Specially recommended on Non-paved roads.	Class I and Class II devices in paved roads. Specially recommended on Non-paved roads.
Target IQL level	IQL-I	IQL-I	IQL-II	IQL-I	IQL-II
Suitability to HDM-4 application	High suitability, because of its accuracy and high performance. HDM-4 is very sensible to roughness data.	Suitable because of its high accuracy, however, low performance has to be considered when evaluating at network level. HDM-4 is very sensible to roughness data.	Suitable, but less accurate than Class I Devices.	Suitable, but less accurate than Class I Devices. Specially recommended to consider roughness input data for non-paved roads.	Suitable, but less accurate than Class I Devices. Specially recommended to consider roughness input data for non-paved roads.
Major Brands	ARRB, Data Collection Limited, Dynatest, Greenwood, Roadware, SSI	ARRB, Data Collection Limited, Face	Amskan, ARRB, Dynatest, SSI	ARRB, Data Collection Limited	CNS Farnell, Data Collection Limited

EQUIPMENT CLASS	PAVEMENT DISTRESSES SURVEY	
Eq. Type / Eq. Characteristics	**Analog & Digital Image**	**Profilers**
Parameters it measures	Distresses measured in units, length or area captured in a 2D image. E.g.: Cracking, raveling, patching, potholes, bleeding, joint and crack spalling.	Distresses measured vertically as a distance, such as asphalt rutting and faulting in concrete pavements.
Initial cost range (USD), transport and taxes not included	30,000-60,000 (costs depend on type of technology used and illumination system)	70,000-100,000
Operating cost range (USD/km)	0.5-1 (fuel consumption and labor cost)	0.5-1 (fuel consumption and labor cost)
Annual maintenance cost range (USD/year)	300-600	500-1,000
Average performance (km/lane/day)	Rural: 200-500, Urban: 50-150	Rural: 400-700, Urban: 50-200
Staff needed for operation	1 driver and 1 operator. In multipurpose vehicles the same operator can work simultaneously with other survey instruments.	1 driver and 1 operator. In multipurpose vehicles the same operator can work simultaneously with other survey instruments. IRI and macrotexture can be measured simultaneously with some laser technologies.
Training needed for operation	Medium to High, depending on image capturing and processing technology used. Needs skills on software operation, data base analysis, general knowledge on optics and distress analysis.	Medium to high. Needs skills on software operation, data base analysis, and mechanical knowledge on laser operation.
Calibration issues	Image size, focus, and focal distance need to be checked before starting survey. Intensity and homogeneity of illuminance needs to be calibrated. DMI has to be calibrated as images are referenced to the linear distance from the starting point of a survey.	For laser profilers by means of a special calibration surface having a known mean profile. According to ISO 13473-3 standard, the accuracy of the calibration surface, in relation its theoretical profile, shall be at least 0.05 mm vertically. Sensor alignment shall also be calibrated for a local slope angle of 40º. Sensor frequency and wave length shall also be calibrated.
Alternative equipment	The only recommended alternative is manual distress identification. These technologies are not recommended for surveying distresses that are measured vertically.	The only recommended alternative is manual distress identification.
Target IQL level	IQL-1	IQL-1
Suitability to HDM-4 application	High suitability, as surface distresses such as cracking, raveling, potholes, and joint spalling, are considered as input data in distress models for concrete and asphalt pavements.	High suitability, because of its accuracy and high performance. Rutting and Faulting are input data in distress models for asphalt and concrete pavements.
Major Brands	Altasecure, Amskan, ARRB, Data Collection Limited, GIE Technologies, Mandli, Pavex Consulting, Roadware, Samsung, Waylink,	ARRB, Data Collection Limited, Dynatest, Greenwood, Roadware, SSI

EQUIPMENT CLASS	MECHANICAL / STRUCTURAL CAPACITY SURVEY				
Eq.Type / Eq. Characteristics	Falling Weight Deflectometer (FWD)	Light Falling Weight Deflectometer	Deflection Beams	Ground Penetrating Radar	Dynamic Cone Penetrometer
Parameters it measures	Maximum deflection produced by dynamic loads applied over the pavement's surface, characterization of the deflection basin as deflections are measured under each sensor and load pulses. Usually the elastic modulus of each layer is estimated under back calculation using Boussinesq Theory assuming layers' homogeneity.	Maximum deflection produced by a dynamic load (peak method), load pulses, and an estimation of the elastic modulus of the pavement obtained under Boussinesq Theory, assuming layers' homogeneity.	Vertical surface deflection produced by a vehicle's load.	Pavement layer thickness determined by wave energy transmission.	Thickness of unbound layers and structural capacity of soils can be obtained indirectly by correlating depth penetrated by the DCP to the number of hammer blows.
Initial cost range (USD), transport and taxes not included	300,000-500,000	14,000-20,000	300-500	200,000-400,000	800-1,000
Operating cost range (USD / km)	1-2 (fuel consumption and labor cost, depending on frequency and number of measures per point)	1-2 (labor cost, depending on frequency and number of measures per point)	1-2 (fuel consumption and labor cost, depending on frequency and number of measures per point)	1-2 (at higher speeds costs are higher)	0-1 (labor cost)
Annual maintenance cost range (USD / year)	500-1,000	50-200	50-200	500-800	50-100
Average performance (km / lane / day)	Rural: 5-10, Urban: 2-4 (depending on frequency and number of measures per point)	Rural: 6-15, Urban: 2-5 (depending on frequency and number of measures per point)	Rural: 3-5, Urban: 2-3 (depending on frequency and number of measures per point)	Rural: 300-400, Urban: 50-200 (depending on survey speed)	Rural: 3-5, Urban: 2-3 (depending on frequency, number of measures per point and soil stiffness)
Staff needed for operation	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.	1 driver and 1 operator.	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.
Training needed for operation	Medium to high, mechanical knowledge and data processing is needed. Training on the equipment operation procedure and for data interpretation is required.	Low, general knowledge on data processing	Low to medium, both driver and operator should have training on the measuring procedure.	Medium to high, mechanical knowledge and data processing is needed. Training on the equipment operation procedure and for data interpretation is required.	Low, is a simple test where no data base analysis nor equipment operational skills are needed

EQUIPMENT CLASS	MECHANICAL / STRUCTURAL CAPACITY SURVEY (continued)				
Eq. Type / **Eq. Characteristics**	**Falling Weight Deflectometer (FWD)**	**Light Falling Weight Deflectometer**	**Deflection Beams**	**Ground Penetrating Radar**	**Dynamic Cone Penetrometer**
Calibration issues	User to check periodically load system and geophones. Mechanical calibration of parts performed by manufacturer	Mechanical calibration of parts performed by manufacturer	No calibration is needed, just check device alignment and that it is in good conditions.		No calibration is needed, just check that the device is in good conditions.
Alternative equipment	Light falling weight deflectometer, Benkelman Beam, Lacroix deflectograph, ground penetrating radar and laboratory tests.	FWD, Benkelman Beam, Lacroix deflectograph, ground penetrating radar and laboratory tests.	FWD, Light falling weight deflectometer, ground penetrating radar and laboratory tests.	FWD, Light falling weight deflectometer, Benkelman Beam, Lacroix deflectograph and laboratory tests.	Laboratory tests.
Target IQL level	IQL-1	IQL-1	IQL-1	IQL-1	IQL-1
Suitability to HDM-4 application	High suitability, deflection measured by FWD can be used as an input data in HDM-4 to estimate the structural capacity of the pavement	High suitability, deflection measured by LFWD can be used as an input data in HDM-4 to estimate the structural capacity of the pavement	Suitable, deflections measured by Benkelman Beam or Lacroix deflectograph can be used as an input data in HDM-4 to estimate the structural capacity of the pavement. However, accuracy of measures is lower than FWD.	Can be used, as layer thickness can be used to estimate the structural capacity of the pavement.	Only suitable for unbound materials, not for paved roads.
Major Brands	Carl Bro, Dynatest, KWAB	Carl Bro, Dynatest	Generally homemade	GSSI Ltd., Mala Geoscience, OKM GmbH	CNS Farnell, CSIR South Africa

EQUIPMENT CLASS	PAVEMENT TEXTURE TESTING	
Eq. Type / Eq. Characteristics	**Static (Sand Patch Method)**	**Dynamic (Laser)**
Parameters it measures	Mean texture depth of a known volume of sand or crystal granules, distributed over the pavement with a known diameter circle.	Mean profile depth (under ISO standard) or Sensor measure texture depth
Initial cost range (USD), transport and taxes not included	400-700	70,000-100,000
Operating cost range (USD/km)	0,5-1 (labor cost)	0,5-1 (fuel consumption and labor cost)
Annual maintenance cost range (USD/year)	0-30	500-1,000
Average performance (km/lane/day)	Rural: 5-10, Urban: 2-4 (depending on frequency and number of measures per point)	Rural: 400-700, Urban: 50-200
Staff needed for operation	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.	1 driver and 1 operator. In multipurpose vehicles the same operator can work simultaneously with other survey instruments. IRI and macrotexture can be measured simultaneously with some laser technologies.
Training needed for operation	Low, is a simple test where no data base analysis nor equipment operational skills are needed	Medium to high. Needs skills on software operation, data base analysis, and mechanical knowledge on laser operation.
Calibration issues	No calibration is needed, rather than controlling sand volume and circle diameter during measurements.	By means of a special calibration surface having a known mean profile. According to ISO 13473-3 standard, the accuracy of the calibration surface, in relation its theoretical profile, shall be at least 0.05 mm vertically. Sensor alignment shall also be calibrated for a local slope angle of 40º. Sensor frequency and wave length shall also be calibrated.
Alternative equipment	Laser profiler measures	Sand patch method, but has low accuracy and performance
Target IQL level	IQL-2	IQL-1
Suitability to HDM-4 application	Suitable, but with some limitations because of its low accuracy. Texture is an input data for asphalt distress models; however, friction models still have to be improved in HDM-4 v. 2.	High suitability, because of its accuracy and high performance. Texture is an input data for asphalt distress models; however, friction models still have to be improved in HDM-4 v. 2.
Major Brands	WDM, homemade	ARRB, Data Collection Limited, Dynatest, Greenwood, Roadware, SSI

EQUIPMENT CLASS	PAVEMENT SKID RESISTANCE TESTING		
Eq. Type / Eq. Characteristics	**Static (British Pendulum Tester)**	**Dynamic (Scrim)**	**Dynamic (Others)**
Parameters it measures	British pendulum number, which can then be correlated to skid resistance measures.	Transverse skid resistance measured by a blocked wheel	Longitudinal skid resistance measured by partially blocked (grip tester) or blocked wheel
Initial cost range (USD), transport and taxes not included	2,500-3,500	600,000 - 800,000	40,000-60,000
Operating cost range (USD/km)	0,5-1 (labor cost)	1-2 (fuel consumption and labor cost)	0.5-1 (fuel consumption and labor cost)
Annual maintenance cost range (USD/year)	200-300	800-1,000	500-700
Average performance (km/lane/day)	Rural: 5-10, Urban: 2-4 (depending on frequency and number of measures per point)	Rural: 100-200, Urban: 50-100 (depends on water tank capacity)	Rural: 100-200, Urban: 50-100 (depends on water tank capacity)
Staff needed for operation	1 operator working with the equipment, 1 or 2 operators in charge of safety conditions.	1 operator and 1 driver	1 operator and 1 driver
Training needed for operation	Medium to low, general knowledge on equipment operation.	High. Needs skills on software operation, data base analysis, and mechanical knowledge on the equipment operation and calibration.	Medium to High. Needs skills on software operation, data base analysis, and mechanical knowledge on the equipment operation.
Calibration issues	Mechanical calibration performed by manufacturer. Operator needs to check pavement temperature and surveyed surface length during each measure.	Mechanical calibration performed by manufacturer, water flow calibration, vertical load sensor calibration, temperature and texture measuring devices need special calibration	Mechanical calibration performed by manufacturer, water flow calibration.
Alternative equipment	SCRIM, Griptester, Mu-meter	Griptester, Mu-meter	SCRIM
Target IQL level	IQL-1	IQL-1	IQL-1
Suitability to HDM-4 application	No	Suitable, measures at 50 km/hr are input data in asphalt pavements models.	Suitable, need to be harmonized to SCRIM measures at 50 km/hr as input data in asphalt pavements models.
Major Brands	Mastrad	WDM	Dynatest, Findlay Irvine, Norsemeter

ANNEX B: Suitability Index Rankings - Equipment

All Roads Suitability Index for Survey Referencing Equipment and Pavement Roughness Survey

	Eq. Type / Weight	Location Referencing			Geometry		Roughness				
		Digital DMI	**GPS**	**Video**	**GPS With INU**	**Precision INU**	**Class I Laser**	**Class I Manual**	**Class II**	**Class III**	**Class IV**
Cost Evaluation (C.E)	**0.30**	**5.00**	**4.50**	**3.50**	**3.50**	**2.50**	**2.00**	**3.50**	**2.50**	**3.00**	**4.00**
Initial	0.50	5.0	4.0	3.0	3.0	1.0	1.0	3.0	2.0	3.0	5.0
Operation & Maintenance	0.50	5.0	5.0	4.0	4.0	4.0	3.0	4.0	3.0	3.0	3.0
Operational Evaluation (O.E)	**0.70**	**4.45**	**4.20**	**3.95**	**4.23**	**4.30**	**3.30**	**3.50**	**3.80**	**3.85**	**3.00**
Assembly/Installation	0.05	5.0	4.0	4.0	4.0	4.0	2.0	4.0	3.0	4.0	4.0
Operation	0.15	5.0	4.0	4.0	4.0	4.0	3.0	4.0	4.0	4.0	4.0
Calibration & Maintenance	0.15	4.0	4.0	4.0	4.0	4.0	2.0	5.0	3.0	3.0	2.0
Accuracy for IQL	0.15	5.0	4.0	3.0	4.5	5.0	5.0	5.0	4.0	3.0	1.0
Data Collection/Processing	0.10	5.0	5.0	4.0	5.0	5.0	5.0	1.0	5.0	5.0	2.0
Interoperability	0.10	3.0	3.0	3.0	3.0	3.0	1.0	4.0	3.0	3.0	5.0
Robustness	0.10	3.0	4.0	4.0	4.0	4.0	2.0	3.0	3.0	4.0	5.0
Data Collection Speed	0.15	5.0	5.0	5.0	5.0	5.0	5.0	1.0	5.0	5.0	2.0
Portability	0.05	5.0	5.0	5.0	4.0	4.0	3.0	5.0	3.0	4.0	5.0
Suitability Index = 0.3*CE+0.7*OE		**4.62**	**4.29**	**3.82**	**4.01**	**3.76**	**2.91**	**3.50**	**3.41**	**3.60**	**3.30**

All Roads Suitability Index for Mechanical/Structural Capacity Testing and Pavement Distress Survey

		Deflections			Ground Penetrating Radar		Surface Distress Imaging	Rut Depth Profilers
	Eq. Type / Weight	Portable FWD	Trailer FWD	Deflection Beams	Static	Dynamic		
Cost Evaluation (CE)	**0.30**	**2.50**	**1.50**	**3.00**	**2.50**	**1.50**	**2.50**	**2.50**
Initial	0.50	2.0	1.0	3.0	2.0	1.0	1.0	2.0
Operation & Maintenance	0.50	3.0	2.0	3.0	3.0	2.0	4.0	3.0
Operational Evaluation (OE)	**0.70**	**2.80**	**3.00**	**3.10**	**2.65**	**3.20**	**3.65**	**3.80**
Assembly/Installation	0.05	5.0	5.0	3.0	4.0	3.0	2.0	3.0
Operation	0.15	3.0	3.0	3.0	2.0	3.0	4.0	4.0
Calibration & Maintenance	0.15	4.0	2.0	4.0	3.0	2.0	4.0	3.0
Accuracy for IQL	0.15	2.0	5.0	3.0	4.0	4.0	4.0	4.0
Data Collection/Processing	0.10	2.0	3.0	3.0	2.0	4.0	4.0	4.0
Interoperability	0.10	1.0	1.0	3.0	1.0	1.0	2.0	3.0
Robustness	0.10	5.0	4.0	5.0	4.0	3.0	4.0	4.0
Data Collection Speed	0.15	1.0	2.0	1.0	1.0	5.0	4.0	5.0
Portability	0.05	5.0	3.0	4.0	5.0	3.0	3.0	3.0
Suitability Index = 0.3*CE+0.7*OE		**2.71**	**2.55**	**3.07**	**2.61**	**2.69**	**3.31**	**3.41**

All Roads Suitability Index for Pavement Macrotexture and Skid Resistance

		Macrotexture			Skid Resistance		
	Eq. Type / Weight	Static	Dynamic Low-Speed	Dynamic High Speed	Static	Dynamic (Vehicle)	Dynamic (Trailer)
Cost Evaluation (CE)	**0.30**	**5.00**	**3.00**	**2.00**	**3.50**	**1.00**	**2.50**
Initial	0.50	5	2	1	3	1	2
Operation & Maintenance	0.50	5	4	3	4	1	3
Operational Evaluation (OE)	**0.70**	**2.95**	**4.25**	**4.15**	**2.95**	**2.75**	**3.55**
Assembly/Installation	0.05	5.0	4.0	3.0	5.0	3.0	4.0
Operation	0.15	4.0	4.0	4.0	3.0	2.0	3.0
Calibration & Maintenance	0.15	4.0	4.0	3.0	5.0	1.0	4.0
Accuracy for IQL	0.15	2.0	5.0	5.0	4.0	4.0	4.0
Data Collection/Processing	0.10	1.0	4.0	4.0	1.0	4.0	4.0
Interoperability	0.10	5.0	5.0	5.0	1.0	1.0	2.0
Robustness	0.10	2.0	5.0	4.0	3.0	4.0	3.0
Data Collection Speed	0.15	1.0	3.0	5.0	1.0	4.0	4.0
Portability	0.05	5.0	5.0	3.0	5.0	1.0	4.0
Suitability Index = 0.3*CE+0.7*OE		**3.57**	**3.88**	**3.51**	**3.12**	**2.23**	**3.24**

Expressways Suitability Index for Survey Referencing Equipment and Pavement Roughness Survey

		Location Referencing			Geometry		Roughness				
	Eq. Weight / Type	Digital DMI	GPS	Video	GPS With INU	Precision INU	Class I Laser	Class I Manual	Class II	Class III	Class IV
Cost Evaluation (C.E)	**0.3**	**5.00**	**4.50**	**3.50**	**3.50**	**2.50**	**2.00**	**3.50**	**2.50**	**3.00**	**4.00**
Initial	0.5	5	4	3	3	1	1	3	2	3	5
Operation & Maintenance	0.5	5	5	4	4	4	3	4	3	3	3
Operational Evaluation (O.E)	**0.7**	**4.50**	**4.25**	**3.95**	**4.30**	**4.40**	**3.55**	**3.35**	**3.90**	**3.90**	**2.85**
Assembly/Installation	0.05	5	4	4	4	4	2	4	3	4	4
Operation	0.10	5	4	4	4	4	3	4	4	4	4
Calibration & Maintenance	0.10	4	4	4	4	4	2	5	3	3	2
Accuracy for IQL	0.20	5	4	3	4.5	5	5	5	4	3	1
Data Collection/Processing	0.10	5	5	4	5	5	5	1	5	5	2
Interoperability	0.10	3	3	3	3	3	1	4	3	3	5
Robustness	0.10	3	4	4	4	4	2	3	3	4	5
Data Collection Speed	0.20	5	5	5	5	5	5	1	5	5	2
Portability	0.05	5	5	5	4	4	3	5	3	4	5
Suitability Index = 0.3*CE+0.7*OE		**4.65**	**4.33**	**3.82**	**4.06**	**3.83**	**3.09**	**3.40**	**3.48**	**3.63**	**3.20**

Expressways Suitability Index for Mechanical/Structural Capacity Testing and Pavement Distress Survey

		Deflections			Ground Penetrating Radar		Surface Distress Imaging	Rut Depth Profilers
	Eq. Weight \ Type	Portable FWD	Trailer FWD	Deflection Beams	Static	Dynamic		
Cost Evaluation (CE)	**0.3**	**2.50**	**1.50**	**3.00**	**2.50**	**1.50**	**2.50**	**2.50**
Initial	0.5	2	1	3	2	1	1	2
Operation & Maintenance	0.5	3	2	3	3	2	4	3
Operational Evaluation (OE)	**0.7**	**2.60**	**3.10**	**2.95**	**2.65**	**3.40**	**3.65**	**3.90**
Assembly/Installation	0.05	5	5	3	4	3	2	3
Operation	0.10	3	3	3	2	3	4	4
Calibration & Maintenance	0.10	4	2	4	3	2	4	3
Accuracy for IQL	0.20	2	5	3	4	4	4	4
Data Collection/Processing	0.10	2	3	3	2	4	4	4
Interoperability	0.10	1	1	3	1	1	2	3
Robustness	0.10	5	4	5	4	3	4	4
Data Collection Speed	0.20	1	2	1	1	5	4	5
Portability	0.05	5	3	4	5	3	3	3
Suitability Index =0.3*CE+0.7*OE		**2.57**	**2.62**	**2.97**	**2.61**	**2.83**	**3.31**	**3.48**

Expressways Suitability Index for Pavement Macrotexture and Skid Resistance

		Macrotexture			Skid Resistance		
	Eq. Weight / Type	Static	Dynamic Low-Speed	Dynamic High Speed	Static	Dynamic (Vehicle)	Dynamic (Trailer)
Cost Evaluation (CE)	**0.30**	**5.00**	**3.00**	**2.00**	**3.50**	**1.00**	**2.50**
Initial	0.5	5	2	1	3	1	2
Operation & Maintenance	0.5	5	4	3	4	1	3
Operational Evaluation (OE)	**0.7**	**2.70**	**4.25**	**4.30**	**2.80**	**3.00**	**3.60**
Assembly/Installation	0.05	5	4	3	5	3	4
Operation	0.10	4	4	4	3	2	3
Calibration & Maintenance	0.10	4	4	3	5	1	4
Accuracy for IQL	0.20	2	5	5	4	4	4
Data Collection/Processing	0.10	1	4	4	1	4	4
Interoperability	0.10	5	5	5	1	1	2
Robustness	0.10	2	5	4	3	4	3
Data Collection Speed	0.20	1	3	5	1	4	4
Portability	0.05	5	5	3	5	1	4
Suitability Index = 0.3*CE+0.7*OE		**3.39**	**3.88**	**3.61**	**3.01**	**2.40**	**3.27**

Urban Roads Suitability Index for Survey Referencing Equipment and Pavement Roughness Survey

		Location Referencing			Geometry		Roughness				
	Eq. Type / Weight	Digital DMI	GPS	Video	GPS With INU	Precision INU	Class I Laser	Class I Manual	Class II	Class III	Class IV
Cost Evaluation (C.E)	**0.40**	**5.00**	**4.50**	**3.50**	**3.50**	**2.50**	**2.00**	**3.50**	**2.50**	**3.00**	**4.00**
Initial	0.50	5	4	3	3	1	1	3	2	3	5
Operation & Maintenance	0.50	5	5	4	4	4	3	4	3	3	3
Operational Evaluation (O.E)	**0.60**	**4.40**	**4.15**	**3.95**	**4.10**	**4.15**	**2.90**	**3.85**	**3.55**	**3.75**	**3.30**
Assembly/Installation	0.10	5	4	4	4	4	2	4	3	4	4
Operation	0.15	5	4	4	4	4	3	4	4	4	4
Calibration & Maintenance	0.20	4	4	4	4	4	2	5	3	3	2
Accuracy for IQL	0.10	5	4	3	4.5	5	5	5	4	3	1
Data Collection/Processing	0.10	5	5	4	5	5	5	1	5	5	2
Interoperability	0.10	3	3	3	3	3	1	4	3	3	5
Robustness	0.10	3	4	4	4	4	2	3	3	4	5
Data Collection Speed	0.05	5	5	5	5	5	5	1	5	5	2
Portability	0.10	5	5	5	4	4	3	5	3	4	5
Suitability Index = 0.4*C.E.+0.6*O.E.		**4.64**	**4.29**	**3.77**	**3.86**	**3.49**	**2.54**	**3.71**	**3.13**	**3.45**	**3.58**

Urban Roads Suitability Index for Mechanical/Structural Capacity Testing and Pavement Distress Survey

	Eq. Weight / Type	Deflections: Portable FWD	Deflections: Trailer FWD	Deflections: Deflection Beams	Ground Penetrating Radar: Static	Ground Penetrating Radar: Dynamic	Surface Distress Imaging	Rut Depth Profilers
Cost Evaluation (CE)	**0.40**	**2.50**	**1.50**	**3.00**	**2.50**	**1.50**	**2.50**	**2.50**
Initial	0.50	2	1	3	2	1	1	2
Operation & Maintenance	0.50	3	2	3	3	2	4	3
Operational Evaluation (OE)	**0.60**	**3.30**	**3.05**	**3.40**	**2.95**	**2.90**	**3.50**	**3.55**
Assembly/Installation	0.10	5	5	3	4	3	2	3
Operation	0.15	3	3	3	2	3	4	4
Calibration & Maintenance	0.20	4	2	4	3	2	4	3
Accuracy for IQL	0.10	2	5	3	4	4	4	4
Data Collection/Processing	0.10	2	3	3	2	4	4	4
Interoperability	0.10	1	1	3	1	1	2	3
Robustness	0.10	5	4	5	4	3	4	4
Data Collection Speed	0.05	1	2	1	1	5	4	5
Portability	0.10	5	3	4	5	3	3	3
Suitability Index = 0.4*C.E.+0.6*O.E.		**2.98**	**2.43**	**3.24**	**2.77**	**2.34**	**3.10**	**3.13**

Urban Roads Suitability Index for Pavement Macrotexture and Skid Resistance

		Macrotexture			Skid Resistance		
	Type / Eq. Weight	Static	Dynamic Low-Speed	Dynamic High Speed	Static	Dynamic (Vehicle)	Dynamic (Trailer)
Cost Evaluation (CE)	**0.40**	**5.00**	**3.00**	**2.00**	**3.50**	**1.00**	**2.50**
Initial	0.50	5	2	1	3	1	2
Operation & Maintenance	0.50	5	4	3	4	1	3
Operational Evaluation (OE)	**0.60**	**3.45**	**4.35**	**3.85**	**3.40**	**2.40**	**3.55**
Assembly/Installation	0.10	5	4	3	5	3	4
Operation	0.15	4	4	4	3	2	3
Calibration & Maintenance	0.20	4	4	3	5	1	4
Accuracy for IQL	0.10	2	5	5	4	4	4
Data Collection/Processing	0.10	1	4	4	1	4	4
Interoperability	0.10	5	5	5	1	1	2
Robustness	0.10	2	5	4	3	4	3
Data Collection Speed	0.05	1	3	5	1	4	4
Portability	0.10	5	5	3	5	1	4
Suitability Index = 0.4*C.E.+0.6*O.E.		**4.07**	**3.81**	**3.11**	**3.44**	**1.84**	**3.13**

Rural Roads Suitability Index for Survey Referencing Equipment and Pavement Roughness Survey

		Location Referencing			Geometry		Roughness				
	Eq. Type / Weight	Digital DMI	GPS	Video	GPS With INU	Precision INU	Class I Laser	Class I Manual	Class II	Class III	Class IV
Cost Evaluation (C.E)	**0.40**	**5.00**	**4.50**	**3.50**	**3.50**	**2.50**	**2.00**	**3.50**	**2.50**	**3.00**	**4.00**
Initial	0.50	5	4	3	3	1	1	3	2	3	5
Operation & Maintenance	0.50	5	5	4	4	4	3	4	3	3	3
Operational Evaluation (O.E)	**0.60**	**4.45**	**4.20**	**3.95**	**4.23**	**4.30**	**3.30**	**3.50**	**3.80**	**3.85**	**3.00**
Assembly/Installation	0.05	5	4	4	4	4	2	4	3	4	4
Operation	0.15	5	4	4	4	4	3	4	4	4	4
Calibration & Maintenance	0.15	4	4	4	4	4	2	5	3	3	2
Accuracy for IQL	0.15	5	4	3	4.5	5	5	5	4	3	1
Data Collection/Processing	0.10	5	5	4	5	5	5	1	5	5	2
Interoperability	0.10	3	3	3	3	3	1	4	3	3	5
Robustness	0.10	3	4	4	4	4	2	3	3	4	5
Data Collection Speed	0.15	5	5	5	5	5	5	1	5	5	2
Portability	0.05	5	5	5	4	4	3	5	3	4	5
Suitability Index = 0.4*C.E.+0.6*O.E.		**4.67**	**4.32**	**3.77**	**3.94**	**3.58**	**2.78**	**3.50**	**3.28**	**3.51**	**3.40**

Rural Roads Suitability Index for Mechanical/Structural Capacity Testing and Pavement Distress Survey

	Eq. Type Weight	Deflections			Ground Penetrating Radar		Surface Distress Imaging	Rut Depth Profilers
		Portable FWD	Trailer FWD	Deflection Beams	Static	Dynamic		
Cost Evaluation (CE)	**0.40**	**2.50**	**1.50**	**3.00**	**2.50**	**1.50**	**2.50**	**2.50**
Initial	0.50	2	1	3	2	1	1	2
Operation & Maintenance	0.50	3	2	3	3	2	4	3
Operational Evaluation (OE)	**0.60**	**2.80**	**3.00**	**3.10**	**2.65**	**3.20**	**3.65**	**3.80**
Assembly/Installation	0.05	5	5	3	4	3	2	3
Operation	0.15	3	3	3	2	3	4	4
Calibration & Maintenance	0.15	4	2	4	3	2	4	3
Accuracy for IQL	0.15	2	5	3	4	4	4	4
Data Collection/Processing	0.10	2	3	3	2	4	4	4
Interoperability	0.10	1	1	3	1	1	2	3
Robustness	0.10	5	4	5	4	3	4	4
Data Collection Speed	0.15	1	2	1	1	5	4	5
Portability	0.05	5	3	4	5	3	3	3
Suitability Index = 0.4*C.E.+0.6*O.E.		**2.68**	**2.40**	**3.06**	**2.59**	**2.52**	**3.19**	**3.28**

Rural Roads Suitability Index for Pavement Macrotexture and Skid Resistance

	Eq. Weight / Type	Macrotexture			Skid Resistance		
		Static	Dynamic Low-Speed	Dynamic High Speed	Static	Dynamic (Vehicle)	Dynamic (Trailer)
Cost Evaluation (CE)	**0.40**	**5.00**	**3.00**	**2.00**	**3.50**	**1.00**	**2.50**
Initial	0.50	5	2	1	3	1	2
Operation & Maintenance	0.50	5	4	3	4	1	3
Operational Evaluation (OE)	**0.60**	**2.95**	**4.25**	**4.15**	**2.95**	**2.75**	**3.55**
Assembly/Installation	0.05	5	4	3	5	3	4
Operation	0.15	4	4	4	3	2	3
Calibration & Maintenance	0.15	4	4	3	5	1	4
Accuracy for IQL	0.15	2	5	5	4	4	4
Data Collection/Processing	0.10	1	4	4	1	4	4
Interoperability	0.10	5	5	5	1	1	2
Robustness	0.10	2	5	4	3	4	3
Data Collection Speed	0.15	1	3	5	1	4	4
Portability	0.05	5	5	3	5	1	4
Suitability Index = 0.4*C.E.+0.6*O.E.		**3.77**	**3.75**	**3.29**	**3.17**	**2.05**	**3.13**

Unsealed Roads Suitability Index for Survey Referencing Equipment and Pavement Roughness Survey

	Eq. Type / Weight	Survey Referencing Equipment: Digital DMI	Survey Referencing Equipment: GPS	Survey Referencing Equipment: Video	Pavement Roughness Survey: Class III	Pavement Roughness Survey: Class IV
Cost Evaluation (C.E)	**0.5**	**5.00**	**4.50**	**3.50**	**2.50**	**4.00**
Initial	0.5	5	4	3	2	5
Operation & Maintenance	0.5	5	5	4	3	3
Operational Evaluation (O.E)	**0.5**	**4.30**	**4.40**	**4.25**	**3.70**	**2.70**
Assembly/Installation	0.05	5	4	4	3	4
Operation	0.1	5	4	4	3	4
Calibration & Maintenance	0.1	4	4	4	2	2
Accuracy for IQL	0.05	5	4	3	3	2
Data Collection/Processing	0.1	5	5	4	4	1
Interoperability	0.05	5	5	5	5	1
Robustness	0.3	3	4	4	4	2
Data Collection Speed	0.05	5	5	5	5	1
Portability	0.2	5	5	5	4	5
Suitability Index = 0.5*C.E.+0.5*O.E.		**4.65**	**4.45**	**3.88**	**3.10**	**3.35**

Unsealed Roads Suitability Index for Mechanical/Structural Capacity Testing and Pavement Distress Survey

		Mechanical/Structural Capacity Testing					Pavement Distress Survey
	Eq. Weight / Type	Trailer FWD	Portable FWD	Dynamic Cone Penetrometer	GPR Static	GPR Dynamic	Analog & Digital Image*
Cost Evaluation (C.E)	**0.5**	**2.00**	**3.50**	**4.00**	**2.50**	**1.50**	**3.00**
Initial	0.5	1	3	4	2	1	2
Operation & Maintenance	0.5	3	4	4	3	2	4
Operational Evaluation (O.E)	**0.5**	**3.50**	**3.95**	**4.30**	**3.40**	**3.05**	**3.45**
Assembly/Installation	0.05	5	5	5	4	3	2
Operation	0.1	3	4	5	2	3	4
Calibration & Maintenance	0.1	2	4	4	3	2	5
Accuracy for IQL	0.05	4	4	4	4	4	3
Data Collection/Processing	0.1	3	3	3	2	4	4
Interoperability	0.05	1	1	1	1	1	4
Robustness	0.3	5	4	5	4	3	3
Data Collection Speed	0.05	2	3	2	1	5	4
Portability	0.2	3	5	5	5	3	3
Suitability Index = 0.5*C.E.+0.5*O.E.		**2.75**	**3.73**	**4.15**	**2.95**	**2.28**	**3.23**

ANNEX C: Suitability Index Rankings - Roads

Suitability Ranking for Expressways, Urban Roads and Rural Roads

Suitability Ranking: Expressways		Suitability Ranking: Urban Roads		Suitability Ranking: Rural Roads	
Equipment Type	Suitability Ranking	Equipment Type	Suitability Ranking	Equipment Type	Suitability Ranking
Referencing- Digital DMI	4.67	Referencing- Digital DMI	4.64	Referencing- Digital DMI	4.65
Referencing- GPS	4.32	Referencing- GPS	4.29	Referencing- GPS	4.33
Geometry GPS With INU	3.94	Macrotexture- Static	4.07	Geometry GPS With INU	4.06
Referencing- Video	3.77	Geometry GPS With INU	3.86	Macrotexture- Dynamic Low-Speed	3.88
Macrotexture- Static	3.77	Macrotexture- Dynamic Low-Speed	3.81	Geometry Precision INU	3.83
Macrotexture- Dynamic Low-Speed	3.75	Referencing- Video	3.77	Referencing- Video	3.82
Geometry Precision INU	3.58	Roughness- Class I Manual	3.71	Roughness- Class III	3.63
Roughness- Class III	3.51	Roughness- Class IV	3.58	Macrotexture- Dynamic High Speed	3.61
Roughness- Class I Manual	3.50	Geometry Precision INU	3.49	Roughness- Class II	3.48
Roughness- Class IV	3.40	Roughness- Class III	3.45	Rut Depth Profilers	3.48
Macrotexture- Dynamic High Speed	3.29	Skid Resistance- Static	3.44	Roughness- Class I Manual	3.40
Roughness- Class II	3.28	Deflections- Beams	3.24	Macrotexture- Static	3.39
Rut Depth Profilers	3.28	Roughness- Class II	3.13	Surface Distress Imaging	3.31
Surface Distress Imaging	3.19	Rut Depth Profilers	3.13	Skid Resistance- Dynamic (Trailer)	3.27
Skid Resistance- Static	3.17	Skid Resistance- Dynamic (Trailer)	3.13	Roughness- Class IV	3.20
Skid Resistance- Dynamic (Trailer)	3.13	Macrotexture- Dynamic High Speed	3.11	Roughness- Class I Laser	3.09
Deflections- Beams	3.06	Surface Distress Imaging	3.10	Skid Resistance- Static	3.01
Roughness- Class I Laser	2.78	Deflections- Portable FWD	2.98	Deflections- Beams	2.97
Deflections- Portable FWD	2.68	Ground Penetrating Radar- Static	2.77	Ground Penetrating Radar- Dynamic	2.83
Ground Penetrating Radar- Static	2.59	Roughness- Class I Laser	2.54	Deflections- Trailer FWD	2.62
Ground Penetrating Radar- Dynamic	2.52	Deflections- Trailer FWD	2.43	Ground Penetrating Radar- Static	2.61
Deflections- Trailer FWD	2.40	Ground Penetrating Radar- Dynamic	2.34	Deflections- Portable FWD	2.57
Skid Resistance- Dynamic (Vehicle)	2.05	Skid Resistance- Dynamic (Vehicle)	1.84	Skid Resistance- Dynamic (Vehicle)	2.40

Suitability Ranking for Unsealed Roads

Suitability Ranking: Unsealed Roads	
Equipment Type	**Suitability Ranking**
Digital DMI	4.65
GPS	4.45
DCP	4.15
Reference- Video	3.88
Light FWD	3.73
Roughness - Class IV	3.35
Roughness - Class III	3.10
FWD	2.75
GPR	2.48

ANNEX D: Assessing Pavement Structural Capacity

Assessment of pavement structural capacity is one of the main challenges that developing countries face in managing their pavements. Most developed and developing countries use non-destructive testing methods to evaluate the structural capacity of their pavements. In the late 1980s and early 1990s the main methodologies used were based on deflection beam systems, such as Benkelman Beams and Lacroix Deflectometers. During the late 1990s these technologies were replaced by Falling Weight Deflectometers (FWDs), in their standard and heavy weight version. For unsealed roads and granular layers, many countries also use basic penetrating devices, such as the Dynamic Cone Penetrometer, light weight deflectometers, or pit testing complemented by laboratory tests.

In general terms, more advanced pavement management countries use FWDs while less developed countries assess pavement structural capacity by laboratory testing or use low cost deflection systems, such as the Benkelman Beam. This makes testing performance much lower, and hence, network level assessment almost unpractical. Often, the public sector own one or two FWDs to survey the primary network, while private consultancy companies own FWDs to assess concessioned roads and complement the structural evaluations performed in the rest of the public network.

Even though non-destructive and high precision devices are available in many developing countries, many of the evaluations are performed only at project level. This is mainly because of lack of funding to perform systematic evaluations to the network and lack of high performance equipments required for the assessment of the network. However, in countries having private and concession systems, project level assessments are periodically performed, for maintenance needs or because it is demanded by their contractors. In some countries, these roads represent an important portion of the primary network so even though it is not a network policy, structural evaluations are performed regularly.

The main applications of non-destructive devices in developing countries are:

- Project level evaluations, in public and concessioned roads, for the assessment of pavement sections presenting structural distresses. These evaluations are performed either by public agencies or consultancy companies. This is the main application of FWDs available in developing countries.

- Construction reception control of new pavements, mainly demanded by public agencies to contractors. This is typical in countries with more advanced pavement management, where more efficient and high performance equipments are available. For example, in Chile this type of assessment is required by the Ministry of Public Works through highway standards (MOP, 2003) and in almost all construction contracts. Evaluations are mainly performed with FWDs, owned by the public and private sector.

- Some public agencies are starting to evaluate their primary network yearly, using FWDs. For example, Colombia (INVIAS, 2004), started a five year pavement structural assessment plan applied at network level for the main roads. A similar approach was used in Argentina during the mid 1980s, using Benkelman Beams and Lacroix Deflectometer (Tagle et al., 1983).

- Assessment of the design of rehabilitation projects, such as asphalt overlays. FWDs are used to determine the effective structural capacity of the existing pavement in order to design the asphalt overlay.

- Quality Control during construction of new pavements developed at research level. De Solminihac et al. (2004) evaluated the use of FWDs in new asphalt pavements during construction. The main findings of the research recommended a control methodology based mainly on center normalized deflections, evaluating every layer. This type of evaluation was found to be very useful to identify local spots with poor performance during construction. As a complement to this research, some ongoing studies are being performed in developing countries for the characterization of the non-elastic behavior of unbound materials combining finite elements and the use of FWD and Light Weight Deflectometer.

The frequency and spacing between surveys is not standardized for any of the non-destructive evaluations. ASTM Standard D4695-03 discusses sampling in detail. The testing frequency will depend on the equipments' performance and the purpose of the study. Generally, FWD assessments performed at project level are performed at a rate of five to ten points per kilometer per lane. With deflection beams fewer points are evaluated per kilometer as performance is low. Table D.1 shows the reported intervals adopted in countries for project and network level surveys.

Alam *et al.* (2007) used statistical techniques to assess the viability of changing the State of Virginia's network level evaluation protocol requiring 10 tests per mile, at four drop levels, with three repetitions at each drop level. The results of this study document that network level testing at 10 points per mile could be reduced to three points per mile and the four FWD drop levels reduced to only one drop level, with two repetitions without statistically compromising the quality of the data collected. This shows the need to carefully consider any testing program so as to minimize the data collection intervals while not compromising the quality of the data.

As an alternative method to non-destructive tests, developing countries use laboratory testing or subjective evaluations derived from field inspections. Typically, new pavement design is performed using the AASHTO 93 methodology. This method estimates the structural capacity of pavements when no testing device is available. Structural capacity under this method is estimated knowing each layers depth, and assuming a structural coefficient recommended by AASHTO for each layer in case no laboratory test is available to evaluate it.

Table D1: Intervals Adopted for FWD Measurements in Different Countries

Country	Type of Roads	Number of Measurements per km by Type of Survey		Comments
		Project Level	Network Level	
Australia	Highways	50-100	1-10	Tests per km per carriageway for network level survey;
Australia	Cities	6-10		Minimum three measurements; beginning, middle and end of each block.
Cambodia	All	5-20	2-10	Follow ASTM D4695-03
Denmark	All	40 (20 each direction)	10 (5 each direction)	All points are placed in the outer (near-roadside) wheelpath. Points in one direction are placed midway between points in the opposite direction (i.e. giving a "zig-zag" pattern).
Denmark	Borough	10	10	Min 4 points per road
Denmark	County	10	10	Only in special cases is the interval reduced
Denmark	State	10	10	Only in special cases is the interval reduced.
Fiji	Highways		2	
Indonesia	Highways		2	
New Zealand	Motorways/ Highways	20	5	Project level is for dTIMS calibration Note no of measurements are per lane
Nicaragua	Highway	4		Proof/check of design
Various	Highways	20	5	Alternate lanes
Sweden	All	20		According to Swedish Road Administration standard
Sweden	Cities	50		Standard adopted by Ramboll RST in Sweden
Zambia	Highways	2		Used for design
Zambia	Major Highways	5		Used for confirmation of design