THE DEVELOPMENT OF LOW-COST DUST AND ROAD ROUGHNESS MEASURING EQUIPMENT

D Jones
Division of Roads and Transport Technology, CSIR, PO Box 395, Pretoria, South Africa, 0001

Paper prepared for presentation at the
Road Construction Rehabilitation and Maintenance Session
of the 1997 XIIIth IRF World Meeting
Toronto, Ontario, Canada
ABSTRACT

Dust generation by vehicles on unsealed roads can cause serious air pollution, reduce visibility and the safety of motorists, pedestrians and workers and pose an overall hazard to health. Prior to the development of a road dust monitor, dust levels were either subjectively judged on a scale of one to five by the driver of the vehicle or by an observer at the roadside, or dust was collected in receptacles and then weighed. For obvious reasons, these methods are unacceptable for the monitoring of the effectiveness of dust palliatives or for the determination of acceptability criteria for dust on unsealed roads. A vehicle-mounted dust monitor was developed at the CSIR to quantify road dust levels. This dust monitor, which incorporates an infra-red measuring system, was developed in three phases over a four year period. A statically mounted system was developed for use on very rough roads, underground haul roads and sections where dust needs to be measured over extended periods.

Road roughness contributes significantly to vehicle operating costs and is therefore used to determine optimum maintenance intervals. Accurate measuring equipment is required for experimental work to develop deterioration models and to compare the performance of stabilised sections. In South Africa, a Linear Displacement Integrator (LDI) has been used for roughness measurements. However, this equipment is relatively expensive, vehicle dependant and generally unsuitable for accurately measuring short experimental sections. The CSIR therefore identified the need for a low-cost road roughness integrator (LORRI) for use in areas where it is not feasible to use an LDI. The LORRI incorporates a frame with front and rear wheels. A trailing arm with a measuring wheel is attached to the front wheel. A linear potentiometer connected between the frame and the trailing arm measures vertical movement and hence the road roughness. Speed and distance travelled is determined with a metal detection and sensor system. Data is processed on a data acquisition system and information is displayed and stored on a notebook computer. Repeatability tests and a comparison with an LDI were carried out on road surfaces of varying roughness. The repeatability of the measurements were considered acceptable and the comparison of the LORRI measurements with those of the LDI correlated well. The LORRI can be used where traditional equipment is not feasible nor cost-effective, for quality control of labour intensive and community based construction and maintenance and calibration of LDI equipment.

INTRODUCTION

South Africa has an extensive network of unsealed roads totalling more than 600000km. Most of these roads are dusty in the dry season while deterioration in the form of corrugations (washboarding), ravelling, potholing, rutting and exposure of stones contribute to reduced riding quality. Research into the development of performance related material specifications, dust control and the development of deterioration models for unsealed roads is continuing. The quality of the outputs of this research is dependent on the accuracy and repeatability of measurements taken over extended monitoring periods. In order to facilitate the gathering of this information, the Division of Roads and Transport Technology of the CSIR (Council for Scientific and Industrial Research) has developed a number of instruments. For unsealed roads, this instrumentation includes amongst others dust, riding quality and gravel loss measuring equipment as well as rapid compaction control and dynamic cone penetration devices.

In this paper, the development of the low-cost dust and road roughness measuring equipment is summarised.
DUST MONITORING EQUIPMENT

Literature Review

Although numerous references in the literature are made to the dust generated from unsealed roads, its measurement has not been widely reported. A number of techniques have, however, been developed to measure dust generated by moving vehicles at a single point on aggregate surfaced roads. These include the collection of dust in receptacles or measurement with electro-optical systems (1). The United States Forest Service has developed a vehicle-mounted infra-red dust measuring system for monitoring dust levels on forest roads. The equipment has not been widely used and is not commercially available (2).

Equipment Development

The need for an effective dust measuring device to provide reliable and repeatable values for quantifying dustiness was identified by the CSIR, when research projects in which the dustiness of different material types and the efficiency of various dust palliatives were initiated. The CSIR dust monitor was developed in three phases. A static dust monitor has also been developed.

Phase I

The design of the Phase I dust monitor was based on that of an instrument developed by the United States Forest Service, which measures the dust generated by one of the rear wheels of a vehicle (2). The instrument consisted of a duct, containing an infra-red transducer and receiver, which was positioned behind the right hand rear wheel of the monitoring vehicle. The duct was attached to a length of steel tubing which was in turn bolted to a standard towbar plate on the vehicle. Data was processed and displayed on an instrument panel mounted near the driver. On completion of initial testing, the Phase I dust monitor was found to be too dependent on the aerodynamics of the vehicle to which it was attached, and the results obtained were not considered to be sufficiently accurate for southern African needs (1).

Phase II

Since the Phase I instrument was not considered suitable, an entirely new design was developed. The Phase II dust monitor consists of a frame-work which is attached to the tow-bar of a monitoring vehicle. An infra-red transducer and a reflector strip are mounted on opposite sides within the frame-work. An instrument panel with an indicating meter and printer is mounted near the driver. This dust monitor enables dust to be measured across the entire width of the monitoring vehicle. The transducer contains a light-sending and receiving unit from which an infra-red light beam shines onto a reflector positioned on the opposite side of the frame-work. The reflected light is in turn detected by the receiver. As the moving vehicle generates dust from the gravel road surface, the infra-red light beam is scattered, thus reducing the amount of light reflected back to the receiver. The level of opacity is ascertained from this reduced light level and converted to a voltage output which is integrated over 100 metre lengths of road and then displayed on the read-out unit. Measurements by the Phase II dust monitor are displayed on a scale of 1 to 250. A reading of 250 would be obtained for no dust (ie total light transmission), while a reading of 1 signifies total absorption of light (1).

Extensive monitoring with the Phase II instrument over a period of four years resulted in the identification of a number of problems (1):
the design required the fitting of distance and speed sensors to the wheel rim and chassis of the vehicle. Some customising was thus often necessary, depending on the vehicle to which the instrument was fitted, and transferability between vehicles was thus limited.

- the transducer and receiver could be affected by incident light at certain times of the day. However, studies revealed that in such instances, a reading of 000 or 001 was recorded, and that normal readings were not affected;
- the instrument could only be used on a moving vehicle and could not be used statically;
- the reflectors required regular cleaning owing to dust build-up on the plastic reflectors resulting from static electricity;
- the measuring scale of 1 to 250 was considered to be too wide for reporting purposes and for calculating average levels on certain roads, and
- as the instrument package could not store data, further analysis on a computer was not possible.

Phase III

The Phase III dust monitor was developed to overcome the problems described above. It consists of a horizontal steel square tube which is bolted to a standard vehicle towbar. The transmitter and receiver are attached to two vertical square tubes which are attached to each end of the main support. The transmitter and receiver are protected by a stone guard. The wiring from the transmitter and receiver is connected to the back of the monitor with clips and is joined in a plug in the centre of the instrument. Data are processed by a serial port data acquisition system (SPORTDAC) and displayed and stored on a notebook computer (Figure 1) (1).

![FIGURE 1: Phase III Dust Monitor](image)

The transmitter consists of a pulsed near infra-red source with a controlled power output. The infra-red beam is directed towards the receiver on the opposite side of the framework. Light energy reaching the photo-sensors is amplified and passed through a bandpass filter which is tuned to the transmitted frequency. This reduces the effect of ambient light on the detector. The resulting signal is rectified, amplified and then passed to the output measuring device which indicates the amount of light reaching the receiver. Zero obscuration (ie no dust) is calibrated as full scale while a zero reading indicates full obscuration. To further reduce the effects of ambient light, the receiving detector was fitted with an auto-biasing arrangement. The biasing circuitry derives its output from the prevailing ambient lighting and, since it uses a long time constant, is immune to slow changing light fluctuations, without reducing the reaction to the high frequency pulsed source used for the obscuration measurement (1).
The SPORTDAC is a low cost eight channel data acquisition system which is attached to a notebook computer via one of the serial ports. The system was developed for field applications where power restrictions dictate the use of notebook or laptop computers, which seldom have the space to accommodate conventional expansion boards used by standard data loggers. The SPORTDAC can accept four internal personality modules which act as signal conditioners. The remaining four channels are used for high level pre-processed signals from external signal conditioning equipment, such as the dust monitor. The control of channel selection and sampling rate is managed by the software that is written for each individual application. Power for the unit is derived from an internal rechargeable sealed lead acid battery with a built-in charger or from an external 12 volt battery. Final processing, display and storage of information are done on a 386 or higher notebook computer. Appropriate software was written and compiled to accept baseline information input by the operator and to continuously display recordings of the dust while the road is being monitored. Data can be stored on the hard drive or auxiliary drive of the computer (1).

Output from the Phase III dust monitor is in CSIR dust units. There is no reported practical visibility index measurement for road dust available, most measurements either being recorded in parts per million or grams per cubic metre of dust collected. Since neither of these is considered to be appropriate for rapid road dust measurement, the CSIR dust unit measure was developed. The Phase III instrument measures on a scale of 0 to 100, where 0 indicates no dust and 100 indicates total opacity. The following information is displayed on the screen during operation (1):

- distance travelled in 100 m intervals;
- selected speed;
- receiver reading;
- dust measurement on a scale of 0 to 100, and
- events - these can be entered to remind the operator of particular occurrences while testing and are useful for later information processing.

Information is automatically saved to a data directory on the hard drive of the computer from where it can be retrieved by using the DOS edit screen. Information can also be saved to an auxiliary disc after each test.

**Static Dust Monitor**

The vehicle mounted-dust monitor, although suitable for the general measurement of dust on most unsealed roads, has a number of limitations. These include (1):

- The height of the instrument from the road surface (approximately 60 mm for the Phase II instrument and 120 mm for the Phase III instrument) limits the use of the instrument to roads of a reasonable riding quality. The Phase II dust monitor can not be used on roads with severe ravelling, corrugations, potholing, rutting or stoniness. The geometric design of the section should also enable the vehicle to be driven at a constant speed, preferably 50 km/h or faster.
- A number of time-consuming modifications to the monitoring vehicle are necessary. These modifications are often undesirable for single measurements and are difficult on purpose-built vehicles, such as those used in underground mines.
- The vehicle-mounted instrument is unsuitable for prolonged measurements at a particular point on a road, eg adjacent to a building or to a sensitive piece of equipment.

The static dust monitor was therefore developed to supplement the vehicle-mounted instrument in the areas described above.
Equipment Limitations

Dust is measured by means of an infra-red transmitter and receiver. A number of filters designed to limit interference by the infra-red portion of incident sunlight are included in the electrical configuration of the receiver. However, since not all of the infra-red wavelengths from the sun can be filtered, under certain circumstances this incident sunlight may still affect the instrument. A simple pre-test calibration system was therefore developed to ensure that accuracy and repeatability are maintained.

Testing

All phases of the CSIR dust monitor were comprehensively tested to determine accuracy, durability and repeatability of results. The Phase III dust monitor was tested on twenty five roads and seven different material types. These roads were selected for general testing according to visually determined dustiness. Each road was tested at regular intervals and at different moisture contents to monitor the repeatability of the output (1).

General testing was undertaken using a standard vehicle. However, in order to enable the dust monitor to be used in more distant areas (ie transportable by aircraft) and to eliminate dependence on one specific vehicle, the dust monitor was tested on a number of vehicles with different aerodynamic characteristics. Measurements were made with the monitor being fitted alternately to both the standard vehicle and to the vehicle being tested. Little difference was recorded in the measurements made with different vehicles. The differences can mostly be attributed to the different paths taken by the vehicles, to the dust created by passing traffic and to the natural variability of dustiness along roads. From the results obtained it can be concluded that the aerodynamic characteristics of the vehicles tested do not significantly affect the performance of the dust monitor. This can be attributed to the fact that the dust monitor position is so close to the rear of the vehicle that dust generated by the wheels is recorded before it is influenced by the aerodynamics. For this reason, it was deemed unnecessary to develop a model to convert dust measurements to a standard value. However, the acceptability criteria that have been developed include a tolerance for factors such as passing vehicles and variations in dustiness across the road width. To date, the equipment has not been tested on heavy vehicles (1).

Comparison with the Phase II Dust Monitor

Output from the Phase II dust monitor is on a scale of 0 to 250, with 0 indicating total opacity and 250 indicating no dust. This scale was considered to be impractical for recording, analysis and reporting of dust measurement experiments. The Phase III instrument records on a scale of 0 to 100, with 0 indicating no dust and a reading of 100 indicating total opacity. Comparisons of the readings from the two instruments were therefore necessary to allow the continued use of the acceptability criteria developed with the PhaselII instrument, and to facilitate analysis of results of long term experiments which were started with the PhaselII instrument and which will be completed with the Phase III instrument. The dust monitors were compared on six different roads each of which was constructed with a different material type. Repeat measurements were made to determine the effect of different moisture contents (1).

Application

To date, the vehicle mounted and static instruments have been successfully used in a number of projects under various conditions. These projects include (3):

- the determination of acceptability criteria for dust from unsealed roads;
- the determination of the effectiveness of various dust palliatives on municipal, provincial, municipal, farm, forestry, mine and nature conservation roads;
• the determination of a prediction model for dust from typical unsealed road materials;
• the determination of the impact of different unsealed road maintenance strategies on dust generation, and as a means of prioritising upgrading and improving material selection, and
• various ad hoc measurements for specific situations.

ROAD ROUGHNESS MEASURING EQUIPMENT

The longitudinal unevenness of a road's surface, normally termed road roughness, is a good measure of the road condition and an important determinant of vehicle operating costs, vehicle productivity and riding quality. Reliable measurement of road roughness is therefore seen as an important activity in road research and road network management. A variety of vehicle mounted instruments have been developed to make these measurements, and a number of roughness scales have been established.

Literature Review

In South Africa, the measurement of riding quality was initially undertaken by the then National Institute of Transport and Road Research (NITRR) as a service to the various road authorities using the NITRR modified PCA Roadmeter. This instrument, which was fitted into a standard saloon car, operated with a complicated system of electronics which made the instrument expensive to construct and operate. A need for a less expensive, easily maintainable instrument which could be used by the road authorities, consulting engineers and other interested parties was identified and the Linear Displacement Integrator (LDI) was subsequently developed in 1980 to serve this purpose (4).

The Transportation and Road Research Laboratory (TRL) in England identified a need, particularly within developing countries, for a simpler road roughness measuring device. It was required to be inexpensive, easy to calibrate and able to make fairly rapid measurements of reasonable accuracy on one of the standard roughness scales. It was also required to be suitable for calibrating other roughness measuring equipment such as the vehicle mounted bump integrator (a device similar to the Linear Displacement Integrator (LDI). An instrument called the MERLIN (Machine for Evaluating Roughness using Low-cost Instrumentation) was developed by the TRL to fulfill this need (5). The components of the MERLIN are shown in Figure 2.

![Figure 2: The MERLIN roughness measuring instrument (5)](image)

The probe is attached to a moving arm, pivoted close to the probe itself. The arm is weighted so that it moves downward, either until it reaches the road surface or the arm reaches the limit of its traverse. A pointer, which moves over a data chart, is attached to the other end of the arm. The chart consists of a
series of columns where the results are recorded. The position of the parts is such that a 1 mm movement of the probe will result in a 10 mm movement of the pointer. A mark is painted on the rim of the wheel and all measurements are taken with the mark at its closest proximity to the road. At each observation during testing, the machine is rested on the road with the wheel in the marked position and the rear foot, probe and stabiliser all in contact with the road surface. The position of the pointer on the chart is then recorded with a cross in the appropriate column. The handles of the MERLIN are then raised so that only the wheel remains in contact with the road and it is moved forward to the next sample position, where the process is repeated. The spacing between the sample positions is not critical but readings must always be taken with the wheel in the marked position. A spacing of one wheel circumference is thus the most convenient in practice. When the observations have been completed, a series of calculations and measurements on the chart are made before the reading is converted with a predetermined equation to an International Roughness Index (IRI) (5).

Apart from the work that has been undertaken by the TRL, there appears to have been no further developments of low-cost road roughness integrators, and no further published information could be found.

The CSIR Low-cost Road Roughness Integrator (LORRI)

The LDI has been successfully used since its development, to quantify the condition of the country’s sealed and unsealed road network, and in a number of studies to determine the influence of road roughness on vehicle operating costs. However, a number of limitations of the equipment have been identified. These include (6):

• The equipment is relatively expensive (US$10000) and must be installed in a dedicated vehicle with sufficient power to enable a constant monitoring speed of 80 km/h;
• once installed, the equipment cannot be easily transferred between vehicles;
• the LDI requires frequent calibration on prepared sections which must be surveyed on a regular basis;
• the readings are dependant on the number of occupants in the vehicle, load, tyre condition and pressure, and the vehicles suspension, and
• the equipment must be used at a minimum constant speed of 50km/h but preferred speed of 80-km/h. This complicates measurements in urban areas and on short experimental sections.

The need for an alternative and appropriate instrument was therefore identified and the CSIR considered the MERLIN instrument. However, after investigation, a number of limitations associated with this instrument were also identified. These include:

• The use of the instrument and the processing of data is very time consuming;
• the size of the instrument renders it difficult to transport, especially by air, and
• the non-continuous measuring system could render the equipment inaccurate on roads with regularly occurring deformation (e.g. corrugations) or very sporadic deformation (e.g. transverse erosion channels).

General Description

A detailed study on the optimum design of the MERLIN, with special emphasis on determining a base length which would give the most accurate and consistent readings was undertaken by the TRL (5). A study of the findings indicated that the base length selected for the MERLIN would probably also be the most suitable for the CSIR instrument. The disadvantages of the LDI and the MERLIN were taken into consideration in the initial design of the LORRI. The most important issue was that of portability and the need for the instrument to be easily transported in an aeroplane. The design therefore allowed for dismantling, but without compromising on the rigidity of the equipment which has to be maintained to ensure that repeatable measurements are recorded (6). The LORRI is illustrated in Figure 3.
The instrument consists of two 450mm off-road bicycle wheels shod with solid rubber tyres. A rubber scraper clears small loose stones from the road surface ahead of the front wheel. The wheels are connected by a 25mm square tube that has been strengthened at the joins and reinforced with an aluminum plate. The base length of the wheels is 1800mm. A trailing arm with a 150mm inflatable wheel, the centre of which is positioned in the middle of the instrument (ie 900mm from both wheels), pivots on the axle of the front wheel. A linear potentiometer fixed to the frame of the LORRI and connected by a rod to the trailing arm, measures the vertical displacement. A movement limiter between the frame and the trailing arm prevents damage to the potentiometer. A metal detection and sensor system, is mounted on the front wheel for measurement of distance and speed. The linear potentiometer and speed and distance measuring system are connected to a SPORTDAC system, described previously. A 12 volt battery, to power the system, is mounted on the trailing arm of the LORRI. It also serves as a weight to limit bounce of the trailing wheel.

Final processing, display and storage of information is done on a 386 or higher notebook computer. Appropriate software has been written and compiled to accept baseline information input by the operator and to continuously display roughness measurements while the road is being monitored. Information is automatically saved to a data directory on the hard drive of the computer from where it can be retrieved by using the DOS edit screen. Information can also be saved to an auxiliary disc after each test. The output from the LORRI can be changed to suit the requirements of the particular monitoring exercise. The following information is displayed on the screen during operation:

- distance measured in 100m intervals;
- speed in m/second;
- receiver reading;
- roughness measurement in mm/10m or 100m;
- Quarter Car Index (QI)(or alternative) per 10m or 100m (Other options for output display include International Roughness Index (IRI) and Pavement Servicibility Index (PSI)), and
- events.

**Operation**

The LORRI requires minimal pre-test checking and calibration. Checks are limited to ensuring that all fastenings on the frame, wheels and electrical connections are tight. Calibration requires a simple zeroing of the linear potentiometer on a smooth surface. An aluminum straight edge is supplied with the instrument for this purpose. Prior to testing, the operator is guided through the set-up procedure on the computer. Information on the filename, test section name and description and direction is requested. The LORRI is then pushed at normal walking speed (1 m/s, displayed on the computer screen) and the measurement process is then activated at the beginning of the pre-selected section. On completion of the test, the process is deactivated and the data can be immediately viewed, or saved to the hard-drive or auxiliary drive. Each path should be tested at least three times and an average taken of the
measurements. The number of paths selected per road will depend on the variability of roughness across the width of the road. A test in each wheel track will normally suffice (6).

**Testing**

Prior to the start of testing with the LORRI, an experimental matrix was defined to ensure that a wide range of road conditions was tested with the instrument. The condition of the roads selected varied from very smooth to very rough, with QI's of between 40 and 400 and 20 and 120 being recorded with the LDI on the unsealed and sealed sections respectively. Typical defects included stoniness, corrugations and potholes on unsealed sections and stoniness, unevenness, potholes and patching on sealed sections. Measurements were taken in the inner and outer wheel tracks of each section with two runs, in the direction of normal traffic, being made in each wheel track. The displacements for the four runs were totalled and the mean calculated. The mean was then used as a value for comparison with the LDI measurements. A number of recording configurations were experimented with. The best correlation with the LDI was achieved with a combination of 18 measurements per revolution of the wheel and all displacements of less than 3mm being discarded (6).

The type of deformation affecting riding quality differs between sealed and unsealed roads, and hence could influence the correlations of the data. For this reason, each set of data was divided into three categories for analysis namely, unsealed roads, sealed roads and all roads. A regression analyses were carried out for each set of data (Table 1 and Figure 4) (6).

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>REGRESSION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unsealed</td>
</tr>
<tr>
<td>18 spoke/&gt;3mm</td>
<td>0.969</td>
</tr>
</tbody>
</table>
Figure 4: Regression of LORRI and LDI

The following conclusions were drawn on completion of the analysis (6):

- the best results are obtained using an 18 spoke/> 3mm configuration (the new distance and speed recording system has been installed for this configuration);
- the instrument should be calibrated according to the type of surface that is going to be tested (sealed or unsealed);
- the type of deformation affecting riding quality differs between sealed and unsealed roads and will therefore influence any correlation with LDI measurements if all the readings are used together, and
- longwave deformation on roads (wavelength >3600mm), usually resulting from expansive clay activity in the subgrade, is not detected by the LORRI, but is detected by the LDI.

It should be noted that the LORRI is still considered to be in the developmental phase and that other limitations may be identified during ongoing testing programmes.

Application

A number of different applications for the LORRI have been identified. These include (6):

- monitoring of experimental and identified sections where the cost of the LDI will prohibit roughness measurements being taken (eg neighbouring countries) or where the required higher
speed of the LDI or High Speed Profileometer (HSP) prevents their use (eg in developed and developing urban communities and on roads with poor geometry such as those found on forest plantations);

- monitoring of road roughness in underground mines;
- quality control of labour intensive and community based construction and maintenance, and
- calibration of LDI equipment.

**CONCLUSION**

The CSIR identified the need for simple quantitative measures of road dustiness and road roughness in order to provide more reliable and repeatable methods for monitoring the performance of unsealed roads for research and management purposes.

The dust monitor has been developed in three phases to address this need. The Phase I instrument, based on an American design, proved to be unsuitable for local conditions. The Phase II instrument was then developed and successfully used in a variety of projects over a period of four years. The Phase III instrument was developed to overcome a number of limitations identified with the Phase II dust monitor. These improvements include the re-design of the equipment to allow a higher ground clearance, the installation of a separate transmitter and receiver on opposite sides of the instrument to improve the accuracy of the readings and eliminate static build-up on the reflectors, and the development of computer software to allow the processing and display of the data on a notebook computer. This equipment has been used effectively for the determination of acceptability criteria for dust from unsealed roads, the development of a dust prediction model, the measurement of dust levels in sensitive areas, the monitoring of the effectiveness of various dust palliatives and in the development of road management systems.

The road roughness integrator (LORRI) was developed from similar equipment produced elsewhere in the world. The LORRI incorporates a frame with front and rear wheels. A trailing arm with a measuring wheel is attached to the front wheel. A linear potentiometer connected between the frame and the trailing arm measures vertical movement and hence the road roughness. Speed and distance travelled is determined with a metal detection/sensor measuring system. Information is displayed and stored on a notebook computer. Repeatability tests and a comparison with a linear displacement integrator (LDI) were carried out on unsealed and sealed road surfaces of varying roughness. The repeatability of the measurements were considered acceptable and correlations with measurements from the LDI of 0.969 for unsealed roads and 0.956 for paved roads were obtained. Applications for the LORRI include testing of sections where the use of traditional equipment is not feasible or cost-effective, quality control of labour intensive and community based construction and maintenance, and calibration of LDI equipment.

**ACKNOWLEDGEMENT**

The work described in this paper was conducted as part of the programme of ongoing research by the Division of Roads and Transport Technology, CSIR, and is published by permission of the Division Director.
REFERENCES


