The development of a real-time mine road maintenance management system using haul truck and road vibration signature analysis

by R.J. Thompson*, A.T. Visser†, R.E. Miller‡, and N.T. Lowe‡

Synopsis

The unpaved road network on a surface mine is extensive, comprising numerous roads of varying construction and material qualities with highly variable traffic volumes. Existing haul road maintenance management systems (MMS) work well for predictable traffic volumes, but for complex mine road networks, the MMS becomes onerous. This results in sub-optimal road maintenance strategies with the attendant increase in total road-user costs and reduction in service.

A real-time maintenance management system was thus sought to overcome the deficiencies of existing MMS for mine roads. Since most large mines operate trucks with on-board diagnostic data collation, linked through a centralized communication and GPS backbone, it was proposed that road condition could be monitored on a real-time basis through on-board vibration signature analysis.

The aim of this paper is to present the development of a real-time mine haul road maintenance management system. Following a review of mine road maintenance practices, the real-time system architecture is introduced and the results of a field trial of on-board vibration signature assessment is presented. The trial results are discussed in the light of road defect signature recognition, analysis, signature repeatability and system limitations.

This approach has applicability to other situations such as a network of district roads, subject to an analysis of the economic feasibility. The paper concludes that modern technology has the potential to apply maintenance as and where needed with possible reductions in authority cost and an improvement in service provided for the road user.

Introduction

The transport of ore and waste in a surface mine is based on a network of unpaved roads, of varying construction and material qualities with highly variable traffic volumes and high vehicle and wheel loadings. Existing haul road maintenance management systems (MMS)[1] work well for predictable traffic volumes, but for complex mine road networks, the MMS becomes onerous. This results in sub-optimal road maintenance strategies with the attendant increase in total road-user costs and reduction in service.

The cost of design and construction (as discussed by Thompson and Visser[2,3]) for the majority of haul roads represent only a small proportion of the total operating and maintenance costs and thus the use of an appropriate road maintenance management strategy has the potential to generate significant vehicle operating cost savings over the life of the road. An optimal road design will include a certain frequency of maintenance (grading, etc.), within the limits of required road performance and minimum vehicle operating and road maintenance costs. The selection of the most appropriate maintenance strategy is the key to realizing the economic benefits of reduced transport costs.

Ad hoc or scheduled blading (as defined by Paterson[4]) are both inefficient means of road maintenance, with the potential to generate excessive costs. The optimized MMS developed for mine haul roads optimizes maintenance scheduling by determining the frequency at which to maintain a road such that vehicle operating and road maintenance costs are minimized over the whole road network. Since the model can accommodate various combinations of traffic volumes and road segments, when used dynamically in conjunction with production planning, it has the potential to generate significant cost benefits[1]. However, whilst the MMS can be applied relatively easily over a road network in which individual segment changes are applied over a period of time (typically, hauling from another ramp, change of tonnage hauled between ramps, etc.), for complex road networks where material is sourced and hauled from a large and highly variable

* *Department of Mining Engineering, University of Pretoria, Pretoria, South Africa.*

† *Department of Civil and Bio-systems Engineering, University of Pretoria, Pretoria, South Africa.*

‡ *National Institute of Occupational Safety and Health, Spokane Research Laboratory, Spokane, Washington, USA.*

 SA ISSN 0038–223X/3.00 + 0.00. Paper received Apr. 2003; revised paper received Apr. 2003

number of loading points, the MMS becomes onerous. In addition to repeated re-modelling of a large number of road segments, many of these segments may be used infrequently and as a result, each reiteration of the MMS program for the altered hauling scenario would have to account for the progressive degeneration of functionality on these infrequently trafficked segments. This would be problematic since in a dynamic mining environment—typically those mines in which production is managed by a centralized truck allocation system—there is no guarantee that the traffic volumes modelled in the MMS would be realized before a change was made to the system. This would result in the likely application of sub-optimal road maintenance strategies with the attendant increase in total road-user costs.

A further disadvantage of the system for complex networks is the necessity to communicate and regularly update the management strategy to road maintenance resources (grader, water-car, support equipment, etc.) and the difficulty in accommodating rapid localized road deterioration, due to structural failure, poor wearing course performance, effects of rain, spillage, etc. A real-time maintenance management system (RT-MMS) was considered as a solution to overcoming the deficiencies of existing MMS for mine haul roads; the road condition being monitored by on-board analysis of truck-pavement interaction, integrated with the mine's communication and truck location systems.

Aim and scope of paper

The aim of this paper is to present the development of a real-time road maintenance management system. Various types of road maintenance can be carried out on a haul road and following a short review of mine road maintenance practices, the real-time system architecture is introduced and the results of a field trial of on-board vibration signature assessment is presented. The trial results are discussed in the light of road defect signature recognition, analysis, signature repeatability and system limitations. The applicability of the approach to a number of other situations such as a network of district roads where regular users or maintenance personnel vehicles would be instrumented with appropriate sensors to collect similar data, is also considered.

Real-time mine road maintenance management

The most cost effective approach to mine road network maintenance management is based on a real-time system which integrates truck- and pavement-interaction data as a basis for making road management-based decisions. Most large surface mines already utilize various original equipment manufacturers' (OEM) systems of real-time truck vital signs monitoring in conjunction with a spread spectrum radio and high precision GPS communications system backbone. The Caterpillar vital information management system (VIMS) monitors over 300 vehicle operational parameters, as switched, analogue, pulse width modulated, frequency or calculated values, depending on machine type[5]. The most tractable approach to providing the required integrated information and management system would be to use existing hardware and software systems on-board the truck together with the computer-based truck location and communication system hardware.

To develop the management system, a multi-sensor analytical procedure is required in which specific truck vital signs are monitored, filtered, road defect signatures extracted and recognized and trigger levels set to indicate typical pavement defects which impact truck performance. These would form the basis of the key performance indicators used to evaluate and benchmark performance and could encompass, but need not be limited to road rolling resistance/riding quality, strut pressure, tyre type and

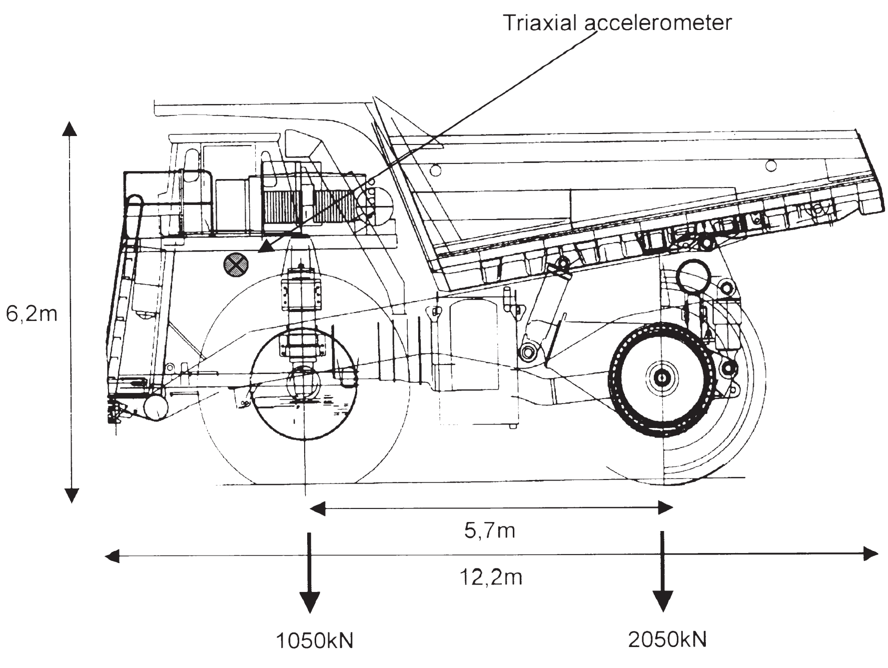

Figure 1—Schematic of typical 190 t capacity (317 t GVM) mine haul truck used for field trials of road defect vibration signature analysis, showing typical axle loads, dimensions and triaxial accelerometer location

pressure and vehicle speed effects on vertical acceleration. Selected VIMS data also forms the basis of a qualitative road analysis control system (RACS) in which strut pressure, speed and mode of operation data are extracted to determine vehicle racking (twisting or pothole effect), pitching (bounce or ditch/hump effect) and load bias (road crown effects)[6]. However, whilst the system provides a qualitative assessment of application severity, it does not have the ability to recognize specific road defects[7].

Using a typical mine-wide communication and truck GPS location system as a starting point, the proposed system is illustrated in Figure 2, showing how the existing communication, location and truck monitoring systems are integrated and the information from the system applied in making road maintenance decisions.

Once road defect locations are received by the central communications hub on the mine and the appropriate weights applied (for traffic volumes, defect type and severity, etc.) a transaction is then initiated to automatically inform the grader operator of the defect locations and type. Road rolling resistance can also be monitored on a similar basis, thus areas of high rolling resistance (which may not be associated with a particular road defect, but rather a high density of defects on a given section of road) can also be recognized and repaired on a real-time basis. Other associated benefits derived from this approach are:

- Event map histories which show consistently poor sections of road requiring betterment or rehabilitation
- More effective utilization of existing road maintenance assets: rapid response to identified road defects
- Reduced capital expenditure on road maintenance assets: expanding road network can be effectively maintained with less equipment
- Immediate recognition of haul road conditions—visual inspection for each change of hauler route unnecessary.
- The increased utilization of the existing computer-based mine and transport management system to provide streamlined and integrated data management and information.

Field trial on on-board diagnostic data collation system

To evaluate the feasibility of using on-board truck diagnostic data in conjunction with GPS-based truck location to detect typical road defect vibration signatures, a field trial was undertaken using an instrumented vehicle running on a prepared haul road containing a number of typical road functional defects. The test vehicle was a 190 t capacity (317 t GVM) mine haul truck as illustrated in Figure 1. The truck suspension system was four variable rebound nitrogen-over-oil dampers mounted above each wheel, linked at the rear by a swing axle. Tyres were 37.00-R57 at 650 kPa inflation pressure.

The prepared haul road consisted of 81 typical mine road defects over an area of 24 000m^2, including potholes, fixed stones, washboards, humps and ditches of various 'degrees' of defect (following functionality assessment methodology for mine roads[2]). Figure 3 illustrates the type and location of the various defects, surveyed for the field trial by use of GPS.

The mine truck was instrumented with a triaxial accelerometer mounted in the drivers cab, on the truck frame above the suspension, as illustrated in Figure 1. The accelerometer was a Dallas Instruments, SAVER piezoelectric acceleration recorder which was set up to trigger the GPS when an acceleration trigger occurred with a frequency of

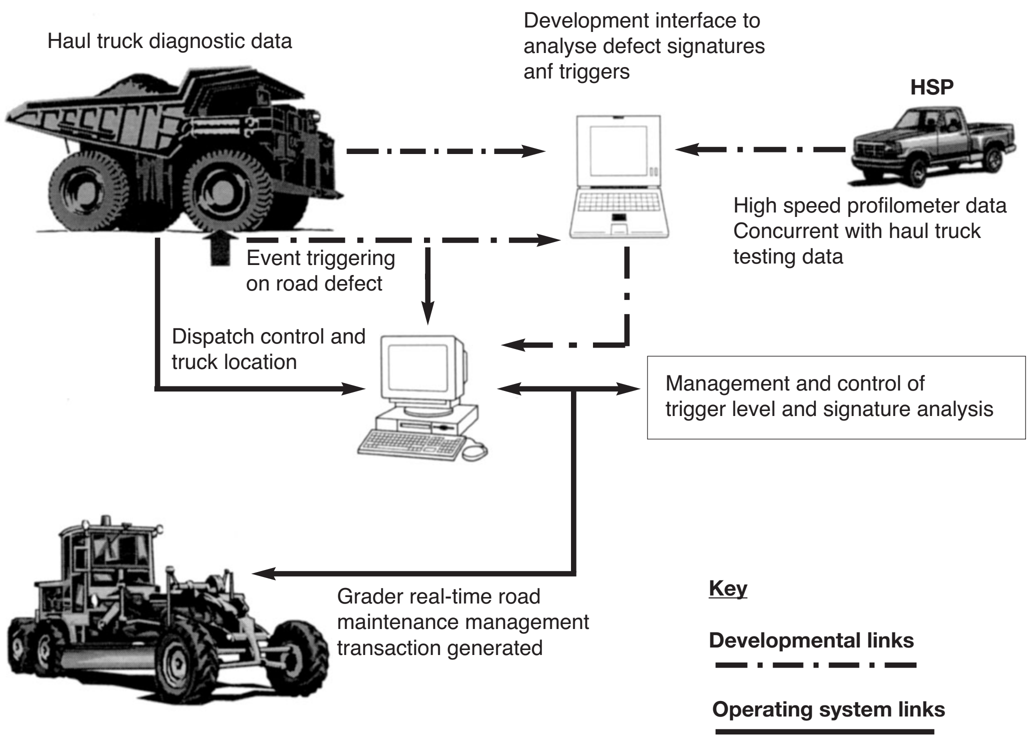

Figure 2—Real-time mine road maintenance system development and integration with existing communication, location and truck monitoring

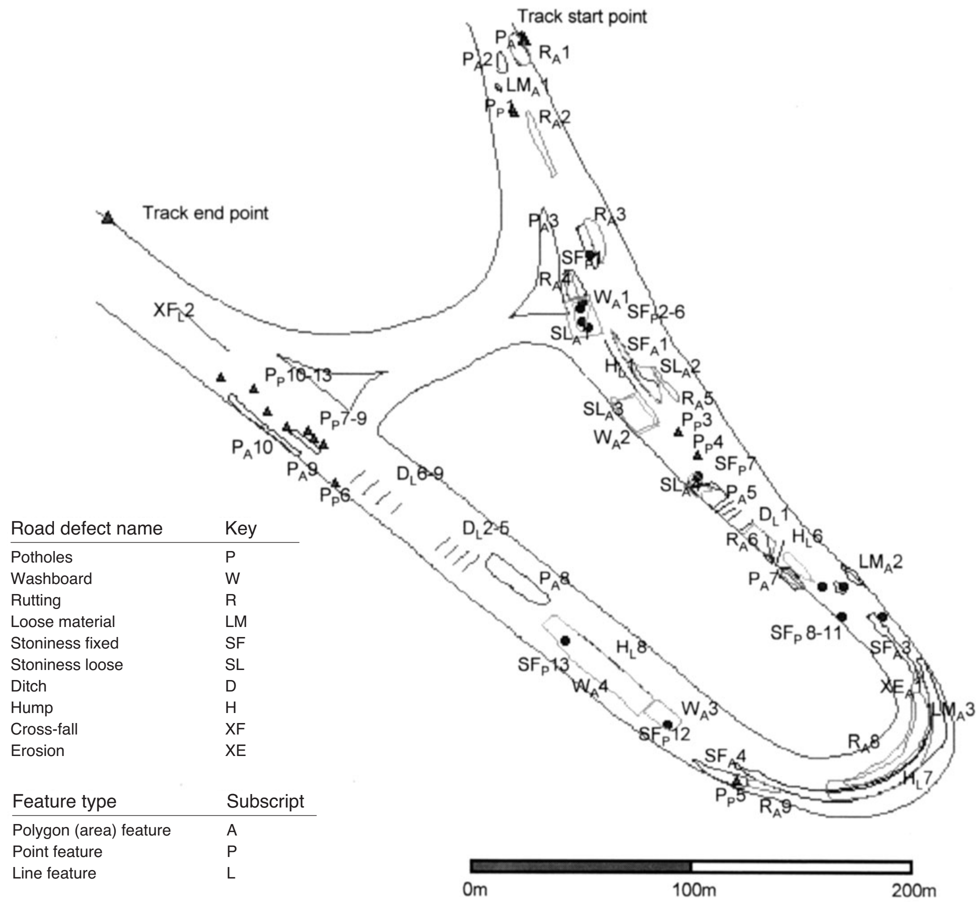

Figure 3—Field trial road defect type and location

less than 200 Hz and a magnitude of more than 0,6 G's positive or negative and the waveform recording window set at 4 seconds. A Trimble GPS location beacon was coupled with the accelerometer recording unit to continuously monitor truck location on the course, to enable event triggers to be located time- and position-wise. Figure 4 shows the haul truck track through the course and the road defect and trigger event locations recorded for a laden high speed run.

A total of 189 triggers were recorded for sixteen truck repetitions over the course. Using the selected accelerometer trigger sensitivity of ±0.6G, 88% of the defects were detected during fast unladen runs, the number reducing with reduced truck speed and under laden conditions. Figure 5 illustrates the speed and load-based event magnitudes, compiled by dividing the test track into a number of segments and determining the power spectral density associated with triggers recorded for these segments at various load and speed conditions. Some evidence of vehicle speed and load effects on event magnitudes, mostly during higher speed (>33 kph) test runs (LF and ULF in Figure 5) was evident. For the medium (16–32 kph) and slow (8–15 kph) runs, event magnitude was not significantly different for load condition, only being speed related.

For all the runs combined, 7% other extraneous triggers were recorded. By combining on-board truck diagnostic information with this data, it is possible to determine the source of these additional defect-unrelated triggers. In the majority of cases, these were ascribed to harsh braking, gear change (torque converter lock-up to first gear) or centrifugal effects during sharp high speed manoeuvres.

Road defect vibration signatures

A preliminary assessment of the road defect vibration signatures was undertaken, initially using vertical acceleration uniaxial waveforms only. From these waveforms, in conjunction with truck on-board and location data, it was possible to differentiate between most road defect signatures qualitatively. Truck speed and laden condition generated significant variations in the waveforms recorded, especially with regard to magnitude of the accelerations. Superimposed on Figure 3, Figure 4 shows the location of the specific defect triggers and typical vibration signatures recorded for a number of triggered defects during a high-speed laden run.

The repeatability of the vibration signatures was associated with truck speed; at lower speeds less variation was evident. This is ascribed to the tendency of a mine truck to run in a well-defined wheel path during each run. At higher vehicle speed, more vehicle wander occurred across the pavement and some defects triggered only on the front or rear wheel, resulting in slightly different signatures. In the development of a RT-MMS based on truck-pavement vibration signatures, a critical requirement would be the ability to analyse, recognize and interpret various forms of the same defect signature, depending on how the truck both encountered and responded to the particular defect.

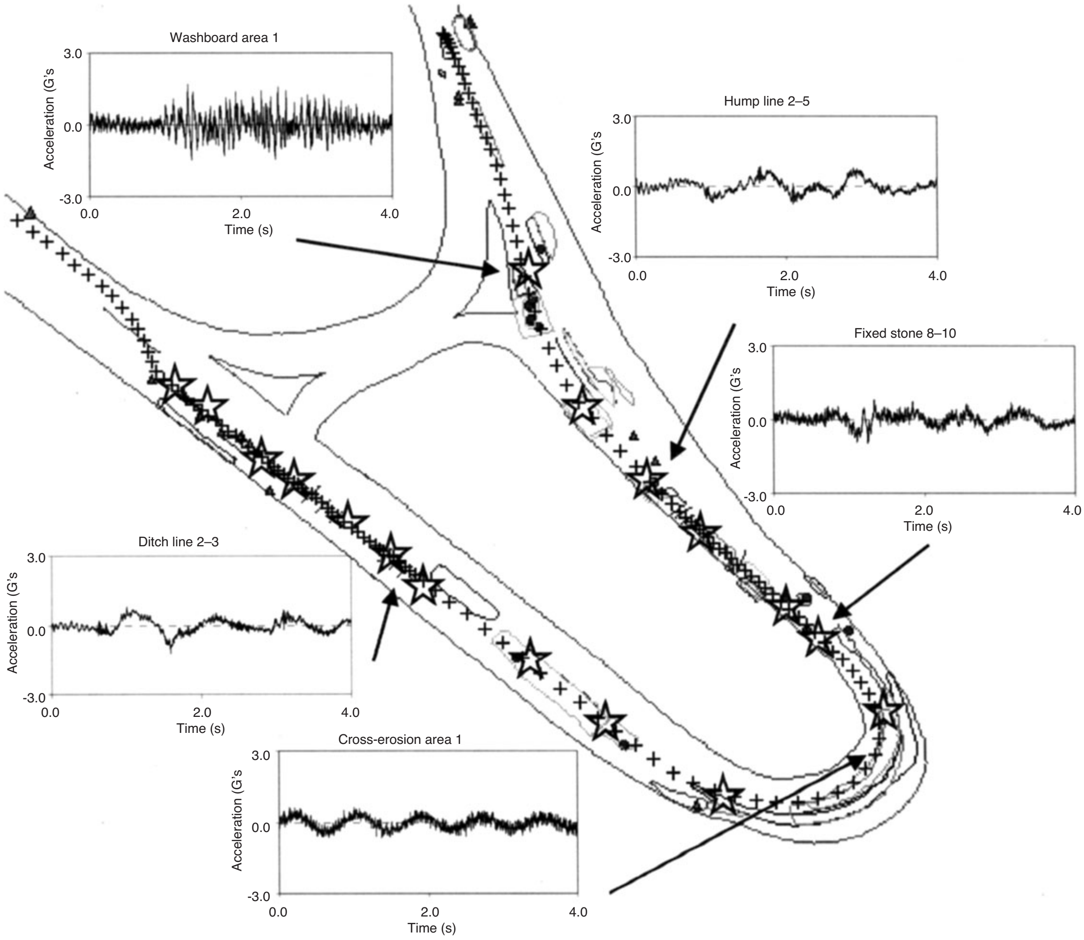

Figure 4—Truck position over field trial course showing location of defect triggers and typical vibration signatures for selected defects

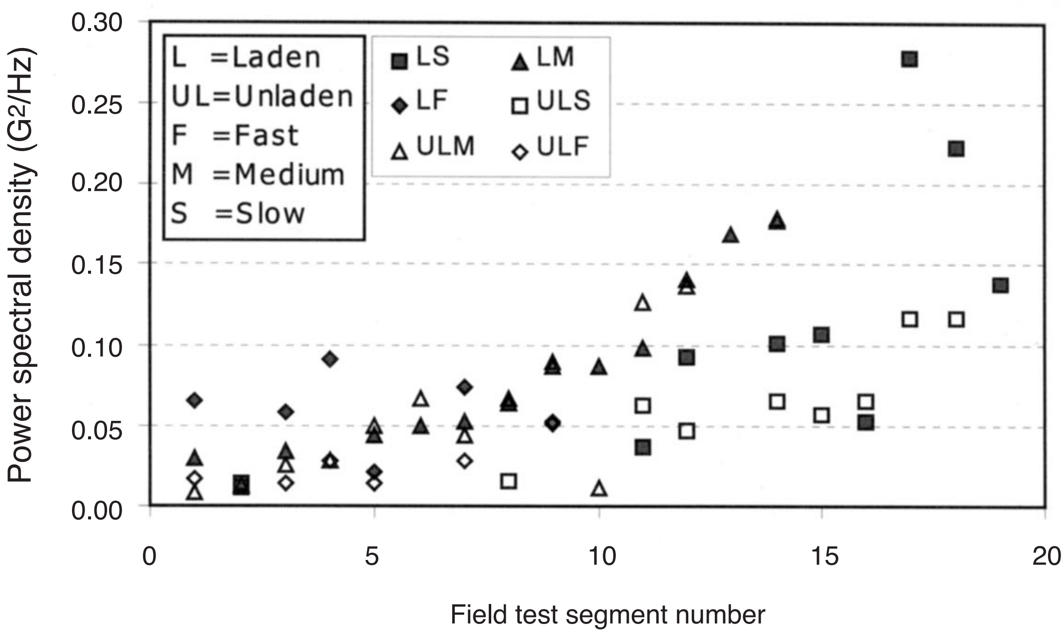

Figure 5—Summary of truck speed and loading effects on combined road segment event magnitudes

Depending on the rate of wearing course material deterioration and the quality of road maintenance applied, the threshold trigger level could be progressively reduced to detect less significant features, as riding quality improves.

Analysis of signatures and system development issues

Whilst the qualitative vibration signature analysis enabled system architecture to be confirmed, for the further development of the system, a more rigorous analytical methodology is required which can accommodate a number of system variables previously ignored during the field trial, and integrate multi-sensor information to eventually isolate and recognize a road defect vibration signature from combined data sources.

Figure 6 illustrates the analytical model, which integrates on-board data acquisition from OEM vehicle vital signs and tyre monitoring systems and the accelerometer array. Feature extraction for individual sensors can then be integrated with a neural-based signature recognition algorithm using normalized data for speed, load and suspension characteristics. This will generate information regarding specific defect and defect severity. Feature extraction and signal recognition must also be able to accommodate data variations arising from uneven load distribution, tyre failure or low inflation pressures, suspension defects, etc. In its simplest form, the algorithm would only validate triggers when the truck was operating within a predefined envelope of parameters. For mine haul road applications this approach is possible since 10–20 truck repetitions per hour could be expected on the same road segment.

Application of real-time monitoring to public road networks

A RT-MMS for mine haul roads is relatively easy to apply, by virtue of the on-board and data communications backbone that already exists on the mine and trucks. In addition, traffic is limited to a relatively short network of road segments within the mine property and traffic volumes are determined as part of the truck allocation system. The fact that these systems are used in large mining operations are indicative of the economics of heavy hauling operations. The approach could also be adopted for a number of other situations such as a network of district roads where regular users, such as a daily delivery service, public transport or road maintenance vehicles would be instrumented with appropriate sensors and information related to position detected by a GPS relayed to a central maintenance dispatch system. In these cases, the economics are different; the agency maintaining the road are not effected by user operating costs. An analysis of the economics of each proposed application would be required to determine if investing in instrumented low volume road vehicles would result in a positive return on the investment.

The real-time approach would require the development of on-board data acquisition systems for these vehicles and their calibration to road conditions. In contrast to unpaved mine roads, public roads will exhibit much reduced deterioration rates over a much wider network of roads and thus the on-board systems can either be real-time or near real-time, the latter using on-board data storage and daily downloads. In addition, records need to be kept of the roads evaluated so that supervisory staff can schedule field visits to those roads

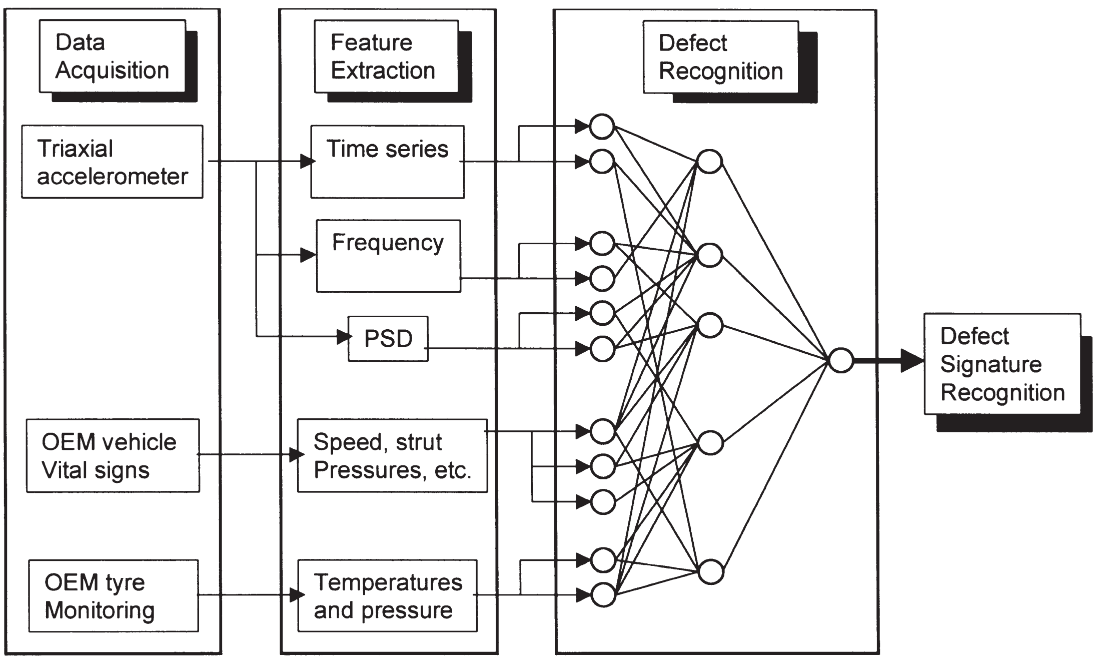

Figure 6. Analytical model, integrating on-board data acquisition and accelerometer array data with a neural-based signature recognition algorithm to recognize specific road defects

not monitored during a defined period. Using this approach, the real-time system has the potential to manage maintenance as and where needed and, depending on the economics of the application, reduce authority cost and improve service for the road user.

Conclusions

Existing mine haul road MMS are problematic when applied to complex mine road networks. This results in the application sub-optimal road maintenance strategies with the attendant increase in total road-user costs and reduction in service. The RT-MMS was thus proposed to overcome these deficiencies, based on truck on-board diagnostic data collation, linked through a centralized communication and GPS backbone, to monitor road condition on a real-time basis through on-board vibration signature analysis.

A field trial was conducted to evaluate the feasibility of using on-board truck diagnostic data in conjunction with GPS-based truck location to detect typical road defect vibration signatures. A preliminary assessment of the road defect vibration signatures was undertaken, initially using vertical acceleration uniaxial waveforms only. From these waveforms, in conjunction with truck on-board and location data, it was possible to differentiate between most road defect signatures qualitatively. It was found that truck speed and laden condition generated significant variations in the waveforms recorded, especially with regard to magnitude of the accelerations.

From the field trial it was found that distinct signatures were generated for each road functional defect and that these could be recognized qualitatively. Therefore, an analytical model was proposed which integrates on-board data acquisition from OEM vehicle vital signs and tyre monitoring systems and the accelerometer array. Feature extraction for individual sensors can then be integrated with a neural-based signature recognition algorithm using normalized data for speed, load and suspension characteristics.

Of the vibration signatures triggered and recorded, 7% were not associated with a particular road defect, but rather with vehicle operation. Therefore, feature extraction and signal recognition must also be able to accommodate data variations and, in its simplest form, the algorithm would only validate triggers when the truck was operating within a pre-defined envelope of parameters.

The real-time approach could also be adopted for a number of other situations such as a network of district roads. In these cases, the economics of the application differ from that of mine roads and an analysis of the economics would be required to determine if investing in instrumented low volume road vehicles would result in a positive return on the investment. Using this approach, the real-time system has the potential to manage maintenance as and where needed and, depending on the economics of the application, reduce authority cost and improve service for the road user.

Acknowledgements

Acknowledgement is given to the Fulbright Commission for the award of a Fulbright South African Researcher Scholarship under which aspects of the real-time maintenance initiatives are being developed, together with NIOSH Spokane Research Laboratory researchers Rusty Miller and Ted Lowe for assistance with field test data collation, analysis and GPS survey work.

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