

Development of Real-Time Mine Road Maintenance Management System Using Haul Truck and Road Vibration Signature Analysis

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The unpaved road network of 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 (MMSs) work well for predictable traffic volumes, but for complex mine road networks, the MMS becomes onerous and results in suboptimal road maintenance strategies, with the attendant increase in total road-user costs and reduction in service. A real-time MMS was thus sought to overcome the deficiencies of existing systems for mine roads. Because most large mines operate trucks with onboard diagnostic data collation, linked through a centralized communication and Global Positioning System backbone, it was proposed that road condition could be monitored on a real-time basis through onboard vibration signature analysis. A real-time mine haul road MMS was developed. Mine road maintenance practices were reviewed. The real-time system architecture was devised, and a field trial was conducted of onboard vibration signature assessment. Trial results were evaluated in the light of road defect signature recognition, analysis, signature repeatability, and system limitations. This approach is applicable to other situations, such as a network of district roads, subject to an analysis of economic feasibility. The conclusion is reached 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 to road users.

In surface mining operations ultraheavy trucks hauling payloads in excess of 290 ton apply axle loads in excess of 1,900 kN to an unpaved mine haul road. Daily load repetitions are of the order of 200 to 400 trucks; the equivalent in standard U.S. 40-ton trucks is between 950 and 1,900. Figure 1 shows the dimensions of a typical dual rear wheel mine haul truck of 190-ton capacity [(317-ton gross vehicle mass (GVM)]. Typically, these trucks operate on a mine haul road network of 10 to 40 km in length comprising a number of road segments, each with variable traffic volumes and construction and material qualities. Historically, these road networks have been maintained with heavy reliance on local experience. Ever-increasing vehicle sizes have resulted in unpredictable road performance, inadequate road maintenance scheduling, and excessive total road-user costs. Truck haulage costs can account for up to 50% of the total

operating costs incurred by a surface mine, and any savings generated from improved road maintenance benefit the mining company directly as a reduced cost per ton of material hauled.

There is also the need to balance the cost of any asset against its design life. Empirical road maintenance scheduling has the potential for overexpenditure on road maintenance or vehicle operating costs. Typically, premature failure and excessive vehicle operating and road maintenance costs, especially in the case of longer-term-high traffic volume roads, are the result of underexpenditure on design as well as ad hoc maintenance practices. As tonnage increases and larger haul trucks are deployed, the maintenance costs of existing roads increase along with a prohibitive increase in vehicle-operating and maintenance costs.

The design of mine haul roads encompasses structural, functional, and maintenance design aspects as discussed by Thompson and Visser (1–3). Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs. Use of an appropriate road maintenance management strategy has the potential to generate significant vehicle operating cost savings. For a fleet of 91-ton payload, 161-ton GVM rear dump trucks operating on a 3.5-km 7% incline, if road rolling resistance is reduced from 8% to 4%, the capital cost of equipment necessary to move 5 million tons per annum is reduced by 20% and the operating costs is reduced by 14%.

CURRENT STATE OF HAUL ROAD MAINTENANCE MANAGEMENT

The ideal maintenance strategy for mine haul roads should be the one that results in the minimum total cost because, in the case of mine haul roads, the agency maintaining the haul road network is also affected by user operating costs.

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. Selecting the most appropriate maintenance strategy is the key to realizing the economic benefits of reduced transport costs. These strategies are not widely reported in the literature, nor are they tailored to the complex interactions of the various components in a haulage system. In most cases comment is restricted to the functions that make up maintenance, as opposed to the management of maintenance to minimize overall total costs. In addition to the lack of

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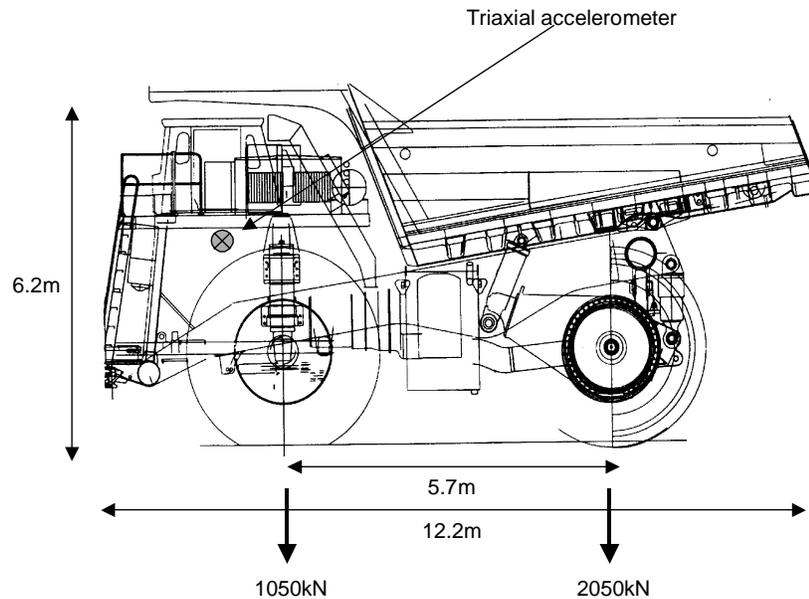


FIGURE 1 Schematic of typical 190-ton capacity (317-ton GVM) mine haul truck used for field trials of road defect vibration signature analysis, showing typical axle loads, dimensions, and triaxial accelerometer location.

unanimous objectives in applying maintenance, the definition of maintenance as applied to mine haul roads varies from mine to mine. Paterson (4) presented a summary of maintenance activities on unpaved public roads; Table 1 summarizes the activities as they would apply to mine haul road maintenance. The routine maintenance category is adopted here to describe the activities envisaged for haul road maintenance; Table 2 summarizes the routine MMSs that mines typically apply.

The most widespread road maintenance activities for mines are either ad hoc or scheduled blading. Both are inefficient means of road maintenance, with the potential to generate excessive costs resulting from over- or undermaintenance of the road. Ideally, an optimized approach is required to minimize total costs. An MMS for mine haul roads has been developed to meet those needs.

MAINTENANCE MANAGEMENT SYSTEM

Optimizing maintenance schedules consists of determining the frequency at which to maintain a road such that vehicle-operating and road maintenance costs are minimized over the whole road network. Mine haul road maintenance intervals are closely associated with traffic volumes and operators electing to forgo maintenance on some sections of a road network in favor of others, which implies a recognition of the need to optimize limited maintenance resources to provide the greatest benefit in relation to total maintenance and vehicle-operating costs. This optimization approach is inherent in the structure of the MMS developed for mine haul roads (3).

Cost savings associated with the adoption of an MMS are dependent on the particular hauling operation, vehicle types, road

TABLE 1 Maintenance Categories and Activities for Mine Haul Roads [Modified After Paterson (4)]

Mode	Activity	Effect
Routine Maintenance	Spot regravelling	Fill potholes and depressions, reduce roughness, exclude water.
	Drainage and verge maintenance	Reduce erosion and material loss, improve roadside drainage.
	Dragging	Redistribute surface gravel.
	Shallow blading	Redistribute surface gravel, fill minor depressions and ruts.
Resurfacing	Dust control/watering	Reduces loss of binder and generation of dust.
	Full regravelling Deep blading	Restore thickness of wearing course. Reprofile road and reduce roughness. Remix wearing course material.
Rehabilitation	Rip, regravell, recompact	Improve, strengthen or salvage deficient pavement.
Betterment	Rehabilitation and geometric improvement	Improve geometric alignment and structural strength.

TABLE 2 Routine Mine Haul Road Maintenance Systems

System	Description
Ad-hoc blading	Reactionary maintenance management in response to poor haul road functionality. Typically managed by daily inspection of the road network and a subjective assessment of road segment functionality and maintenance priorities.
Scheduled blading	Road network is maintained according to a fixed schedule or frequency, irrespective of the actual functionality of the road segment being worked.
Managed maintenance (MMS)	Road network is analyzed to determine rate of functional deterioration of individual segments, based on roughness progression, traffic volumes, etc. and segment blading frequency determined to minimize segment and network total road-user costs.
Real-time road maintenance (RT-MMS)	Instrumented truck fleet to characterize vehicle response to road functionality, both in terms of rolling resistance and individual (isolated) functional defects. Maintenance managed real-time through mine truck location, communication and data management systems.

geometry, tonnages hauled, and so forth. Because the model can accommodate various combinations of traffic volumes and road segments, when used dynamically in conjunction with production planning, the model has the potential to generate significant cost benefits (3). However, although 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 in which material is sourced and hauled from a large and highly variable number of loading points, the MMS becomes onerous. In addition to repeated remodeling 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. That would be problematic, because 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 modeled in the MMS would be realized before a change was made to the system. The result would be the likely application of suboptimal 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 that is due to structural failure, poor wearing course performance, effects of rain, spillage, and so on. A real-time MMS (RT-MMS) was considered as a solution to overcoming the deficiencies of existing MMSs for mine haul roads. In this system, the road condition is monitored by onboard analysis of truck-pavement interaction, integrated with the mine's communication and truck location systems.

AIM AND SCOPE

The aim of this paper is to present the development of a real-time road MMS. Various types of road maintenance can be carried out on a haul road. Following a review of mine road maintenance practices, the real-time system architecture is introduced, and results of a field trial of onboard vibration signature assessment are presented. Trial results are discussed in the light of road defect signature recognition,

analysis, signature repeatability, and system limitations. Also considered is the applicability of the approach to other situations, such as a network of district roads on which regular users or maintenance personnel vehicles would be instrumented with appropriate sensors to collect similar data.

REAL-TIME MINE ROAD MAINTENANCE MANAGEMENT

The most cost-effective approach to mine road network maintenance management is based on a real-time system that integrates truck- and pavement interaction data as a basis for making road management-based decisions. Most large surface mines already use original equipment manufacturers' (OEM) systems of real-time truck vital signs monitoring in conjunction with a spread spectrum radio and high-precision Global Positioning System (GPS) communications system backbone. The Caterpillar vital information management system (VIMS) monitors more than 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 computer-based truck location and communication system hardware.

To develop the management system, a multisensor analytical procedure is required in which specific truck vital signs are monitored and filtered, road defect signatures extracted and recognized, and trigger levels set to indicate typical pavement defects that affect 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 and riding quality, strut pressure, tire type and pressure, and vehicle speed effects on vertical acceleration. Selected VIMS data also form the basis of a qualitative road analysis control system in which strut pressure, speed, and mode of operation data are extracted to determine vehicle racking (twisting or pothole effect), pitching (bounce or ditch and hump effect), and load bias (road crown effects) (6). However, although the system provides a qualitative assessment of application severity, it does not have the ability to recognize specific road defects (7).

With a typical minewide communication and truck GPS location system as the starting point, Figure 2 illustrates the proposed system. The figure shows how existing communication, location, and

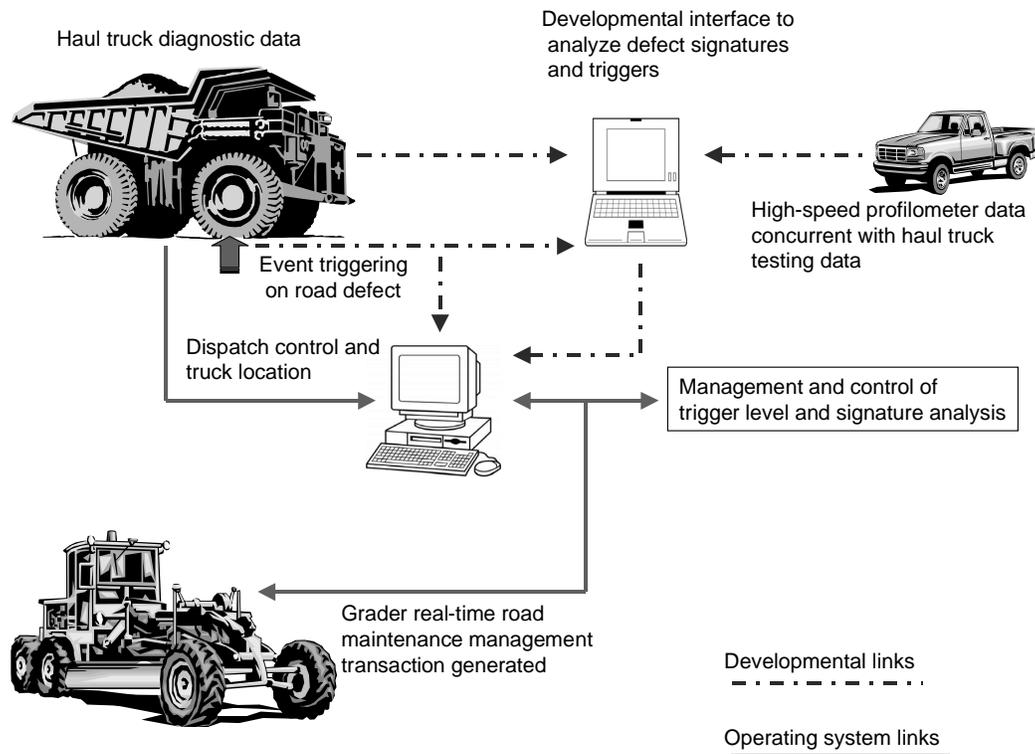


FIGURE 2 Real-time mine road maintenance system development and integration with existing communication, location, and truck monitoring.

truck-monitoring systems are integrated and how the information from the system is 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 initiated to automatically inform the grader operator of the defect locations and type. Road rolling resistance can likewise be monitored; 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 showing consistently poor sections of road that require improvement or rehabilitation;
- More effective utilization of existing road maintenance assets by means of rapid response to identified road defects;
- Reduced capital expenditure on road maintenance assets by effectively maintaining an expanding road network with less equipment;
- Immediate recognition of haul road conditions, which makes visual inspection for each change of hauler route unnecessary; and
- Increased utilization of existing computer-based mine and transport management system to provide streamlined, integrated data management and information.

Field Trial of Onboard Diagnostic Data-Collation System

A field trial was undertaken using an instrumented vehicle running on a prepared haul road containing a number of typical road functional defects. The trial was carried out to evaluate the feasibility of

using onboard truck diagnostic data in conjunction with GPS-based truck location to detect typical road defect vibration signatures. The test vehicle was a 190-ton capacity (317-ton GVM) mine haul truck, as illustrated in Figure 1. The truck suspension system consisted of four variable rebound nitrogen-over-oil dampers mounted above each wheel, linked at the rear by a swing axle. Tires were 37.00-R57 at 650 kPa inflation pressure.

The prepared haul road consisted of 81 typical mine road defects over an area of 24 000 m², 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 types and locations of the defects surveyed for the field trial by use of GPS.

The mine truck was instrumented with a triaxial accelerometer mounted in the driver’s 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 less than 200 Hz and a magnitude of more than 0.6 G positive or negative, and the waveform recording window set at 4 s. A Trimble GPS location beacon was coupled with the accelerometer recording unit to continuously monitor truck location on the course so that event triggers could be located according to time and position. 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 16 truck repetitions over the course. With a selected accelerometer trigger sensitivity of ±0.6 G, 88% of the defects were detected during fast unladen runs, with the number reducing with reduced truck speed and underladen conditions. Figure 5 illustrates the speed and load-based event magnitudes

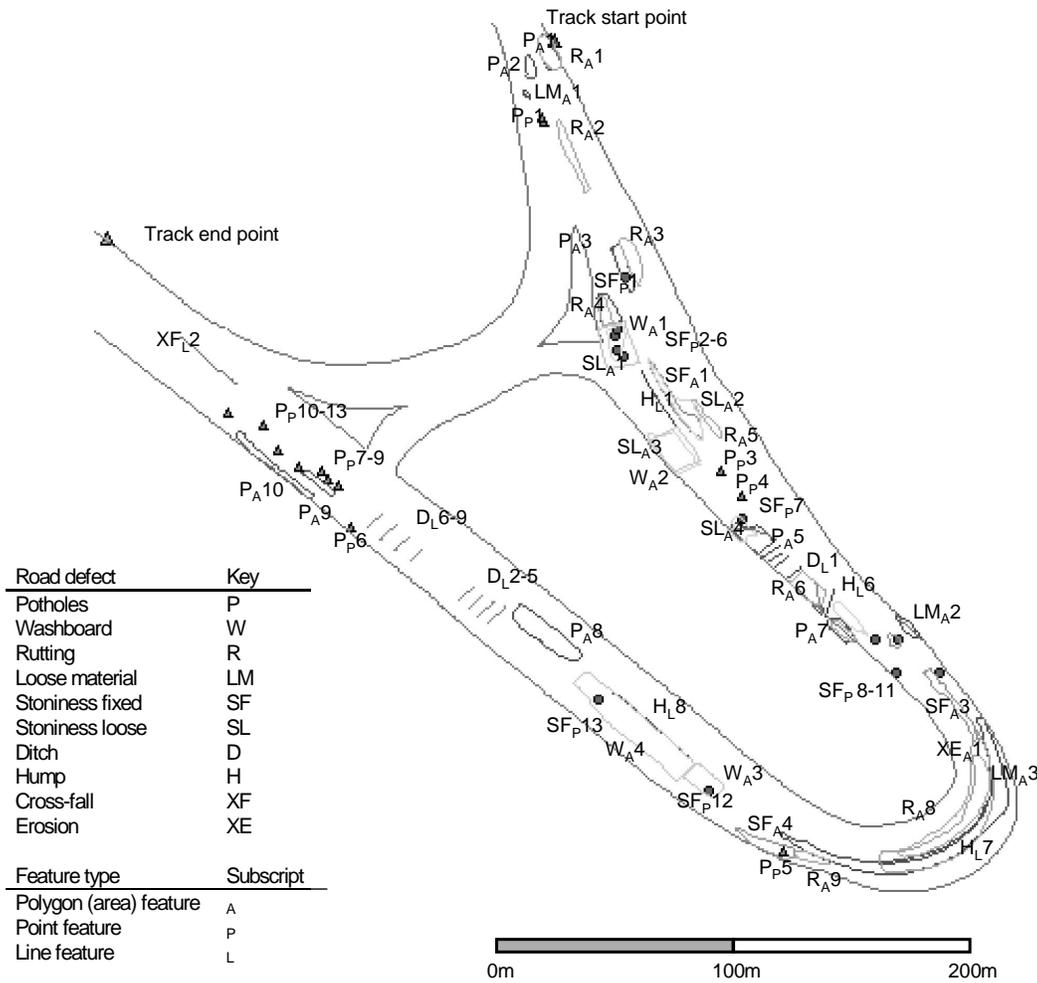


FIGURE 3 Field trial road defect type and location.

compiled by dividing the test track into 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 km/h) test runs (LF and ULF in Figure 5), emerged. For the medium (16–32 km/h) and slow (8–15 km/h) runs, event magnitude was not significantly different for load condition, being only speed-related.

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

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 onboard 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 in relation to magnitude of the accelerations. Superimposed on Fig-

ure 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.

Repeatability of the vibration signatures was associated with truck speed; at lower speeds less variation was evident. This result is ascribed to the tendency of a mine truck to run in a well-defined wheelpath 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 an RT-MMS based on truck-pavement vibration signatures, a critical requirement would be the ability to analyze, recognize, and interpret various forms of the same defect signature, depending on how the truck both encountered and responded to the particular defect. 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

Although the qualitative vibration signature analysis enabled system architecture to be confirmed, for the further development of the

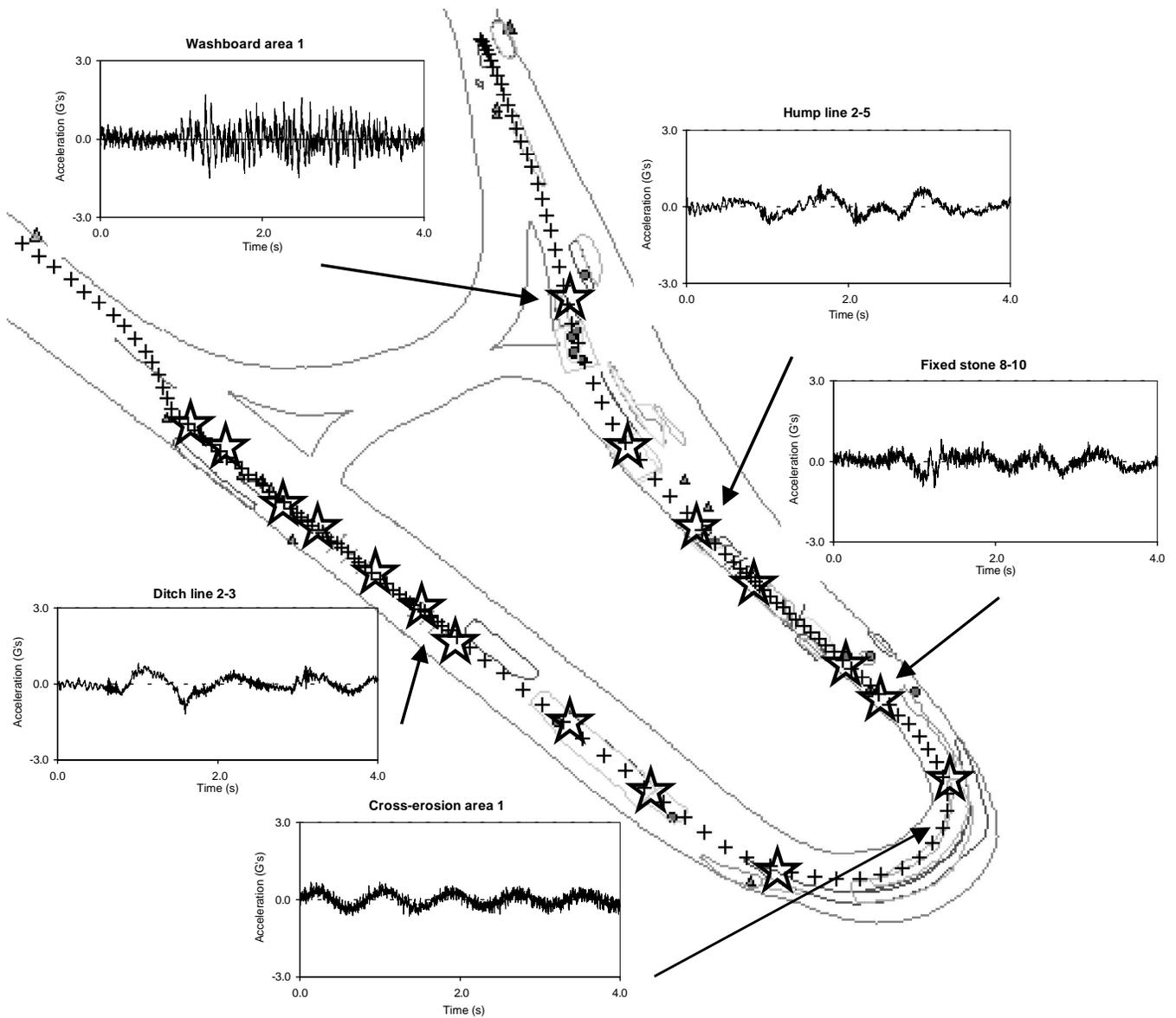


FIGURE 4 Truck position over field trial course, showing location of defect triggers and typical vibration signatures for selected defects.

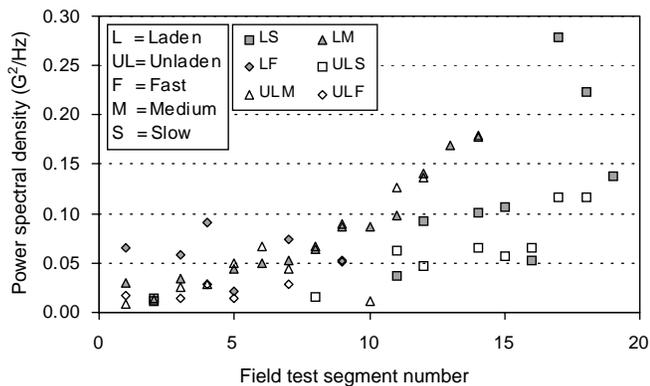


FIGURE 5 Summary of truck speed and loading effects on combined road segment event magnitudes.

system, a more rigorous analytical methodology is required, one that can accommodate a number of system variables previously ignored during the field trial and can integrate multisensor information to eventually isolate and recognize a road defect vibration signature from combined data sources.

Figure 6 illustrates the analytical model, which integrates onboard data acquisition from OEM vehicle vital signs and tire-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. That 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, tire failure or low inflation pressures, suspension defects, and so on. In its simplest form, the algorithm would validate triggers only when the truck

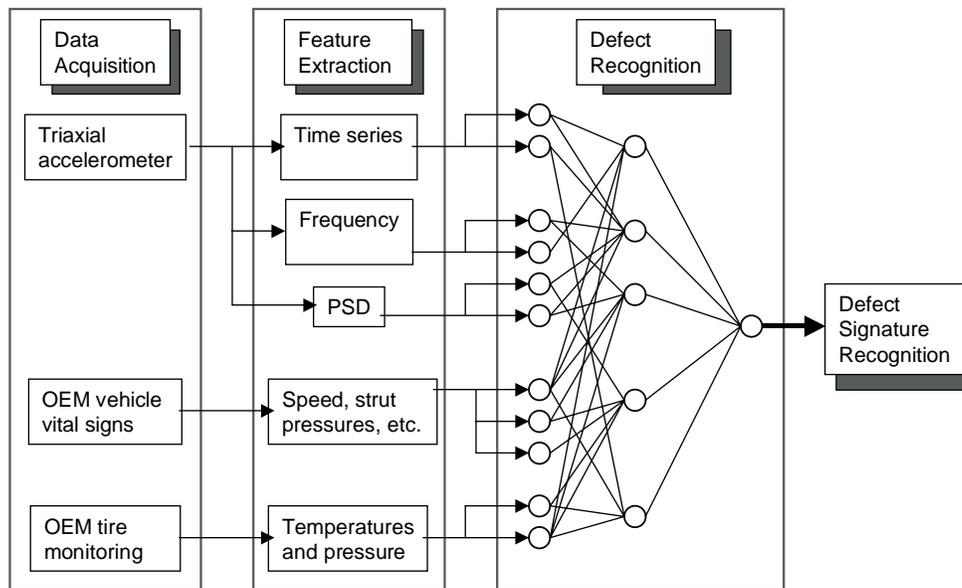


FIGURE 6 Analytical model integrating onboard data acquisition and accelerometer array data with neural-based signature-recognition algorithm to recognize specific road defects.

was operating in a predefined envelope of parameters. For mine haul road applications that approach is possible because 10 to 20 truck repetitions per hour could be expected on the same road segment.

An RT-MMS for mine haul roads is relatively easy to apply, by virtue of the onboard and data communications backbone that already exists in the mine and trucks. In addition, traffic is limited to a relatively short network of road segments on 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 is indicative of the economics of heavy hauling operations. The approach could also be adopted for a number of other situations, for instance, a network of district roads on which 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 and relayed to a central maintenance dispatch system. In these cases, the economics are different; the agency maintaining the road is not affected by user operating costs. An analysis of the economics of each proposed application would be required to determine whether 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 onboard 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 onboard systems can either be real-time or near real-time, the latter using onboard 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 not monitored during a defined period. When this approach is used, 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 MMSs are problematic when applied to complex mine road networks. The result is the application of 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 those deficiencies; it is based on truck onboard diagnostic data collation, linked through a centralized communication and GPS backbone, to monitor road conditions on a real-time basis through onboard vibration signature analysis.

A field trial was conducted to evaluate the feasibility of using onboard 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 onboard 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 in relation 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 that integrates onboard data acquisition from OEM vehicle vital signs and tire-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 validate triggers only when the truck was operating in a predefined 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 whether investing in instrumented low-volume road vehicles would result in a positive return on the investment. When this approach is used, 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.

ACKNOWLEDGMENTS

The authors acknowledge the Fulbright Commission for the award of a Fulbright Scholarship, under which aspects of the real-time maintenance initiatives are being developed, as well as National Institute of Occupational Safety and Health 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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