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Haul roads can make money!

by A.T. Visser*

Synopsis

Almost 20 years have passed since the cutting-edge research by Thompson and Visser on the design and management of opencast mine haul roads was conducted in South Africa. This system is based on three principles, namely the structural ability to support the ultra-heavy truck loads, the selection of vehicle and environmentally friendly riding surface, and an appropriate level of maintenance to counteract wear and tear. Obviously, proper layout and geometry are essential.

These principles have been implemented worldwide, and it is useful to review the lessons learned. The objectives of this paper are to present a critical review of the status of mine haul road design and management, and the impact that these principles have made on operations, particularly the cost-effectiveness. The paper briefly reviews the principles of the haul road design and management and the extent to which they are applicable. Case studies of a number of implementations are presented to demonstrate that the principles are sound and have been applied effectively. For example, at an international operation the transport cost of coal was 40% more expensive than anticipated in the feasibility stage, and this made the mining operation uneconomic. Correction of this problem resulted in a viable enterprise. Although designed for opencast operations, the principles are equally valid for underground operations, and initial development work will be discussed.

The main conclusions are that the research approach is valid and its effectiveness has been demonstrated in a number of applications. The anticipated financial benefit has been derived, and has made the mining operations that used the principles more effective. Of major importance is the application of opencast haul road design principles to the future thrust of using driverless vehicles in opencast and underground mining, where the road quality is not negotiable as there is no driver that can avoid obstacles or severe road deterioration.

Keywords
haul roads, structural design, performance, maintenance.

Introduction

Almost 20 years have passed since the cutting-edge research by Thompson and Visser on the design and management of opencast mine haul roads in South Africa (Thompson and Visser, 1996a, 1996b, 1998, 1999, 2000a). This system is based on three principles, namely the structural ability to support the ultra-heavy truck loads, the selection of vehicle and environmentally friendly riding surface, and an appropriate level of maintenance to counteract wear and tear. Obviously, proper layout and geometry are essential.

These principles have been implemented worldwide, and it is useful to review the lessons learned. The objectives of this paper are to present a critical review of the status of mine haul road design and management, and the impact of these principles on operations, particularly the cost-effectiveness. The paper will briefly review the principles of the process and the extent to which they are applicable. Case studies of a number of implementations will be presented to demonstrate that the principles are sound and have been used effectively. Besides the implementation on opencast operations, the principles are equally valid for underground applications, and initial development work will be discussed.

The focus of the proper design of a haul road system is the following:

- ➤ The provision of safe, world-class roads for all road users (safety is non-negotiable)
- ➤ Reduced truck operating costs due to less stress on the drive train, tyres, frame, and suspension, resulting in extended component life
- ➤ Faster cycle times leading to higher productivity and lower cost per ton because of higher asset utilization
- ➤ More effective utilization of road maintenance equipment through a managed approach to routine road maintenance.

Geometric layout

The layout of the haul road network has to be tailored to the mining requirements. This often leads to a conflict in requirements, as the ideal

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layout in terms of vertical gradients and horizontal curvature is not always achievable. The guiding principle should be that the haul road should permit the haul trucks to operate at maximum efficiency. The horizontal curves must be of the largest possible radius to allow the trucks to travel at maximum speed without causing undue damage to the road. A limitation is the curve radius at switchbacks. Invariably there is insufficient space to allow high-radius curves, and the result is severe road damage as the truck wheels scuff around the curve rather than rotate, leaving loose material on the surface which affects traction and increases rolling resistance. A major complication that has been encountered is that switchbacks have a too small a radius when a larger truck fleet is introduced, and there is no space to increase the radius. The result is that the truck has to make a three-point manoeuvre to negotiate the switchback. This is extremely dangerous and affects productivity. At the time of planning the mine layout all switchbacks need to be such that a larger truck, which has a larger turning radius, can be accommodated.

Trucks are happiest when an incline has a constant gradient. Figure 1 shows (red line) a typical gradient out of a pit across the various benches. At every gradient break, which may range from 8% to 13%, the truck has to change gear, and under load this places great strain on the drive train. Every time the torque converter is engaged the wheels spin momentarily and cause damage to the road surface. Since all the truck will change gears in the same area, there is a perpetual maintenance problem that cannot be resolved. The solution is to ensure that the gradient is continuous and uniform, as shown by the green line in Figure 1. This may be readily achieved by overdrilling on the outer part of the bench, so that the correct gradient can be constructed with ease. As an example, considering a 380 t class of rear dump truck, running up the ramp where the grade of the road varies between 8% and 13%, with a 3% rolling resistance. This road 'design' will allow a fleet of seven trucks to transport 340 t per truck-hour. However, by removing the grade-breaks (using a constant 10.3% grade from bottom to top), 470 tons per truck-hour can be transported – an increase of 38% or 500 000 t/a! If an annual excavation target of 10 Mt were set, by using an improved road design and construction guideline, the target could be achieved with five instead of seven trucks.

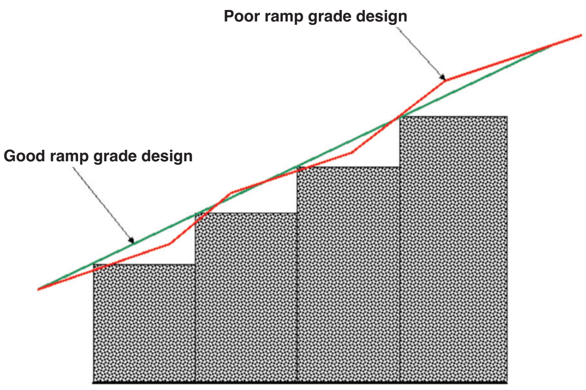

Figure 1—Incorrect (non-uniform) and correct (uniform) gradient

At the mine planning stage a minimum cost approach is often taken. This means that the road layout is designed to a minimum standard, and this includes road width. Due cognisance is not taken of the geotechnical considerations, such as stability of the pit slopes. Serious problems have been encountered when a rockfall or slip has resulted in either a road being closed, or the road is narrowed such that transport operations are impaired. Most opencast operations have at least two haul road exits from the pit due to safety considerations, and a road closure could have serious implications. Where only a half-width of road is open to traffic there is potential conflict and the accident risk is increased, and productivity is affected as trucks have to wait at the narrowing. Road width could also be a factor when a larger truck type is introduced. It is safer to build the roads wider than narrower so that potential complications are minimized.

At a coal operation in South Africa, savings of about 1 million litres of diesel were made in the year following improvement of the non-uniform gradients and curve radii, without any change in the annual volume of material transported. This is a direct saving and does not include improvements in engine and tyre life. Excessive transmission shifting on the laden haul will reduce engine, drive-train, and wheel motor life. On the empty return trip, retarder overheating will occur on the non-uniform gradient with concomitant mechanical wear. These aspects demonstrate the significant savings that can occur by optimizing the haul road geometry.

Road structural considerations

The structural design principles are based on limiting the vertical compressive strains in any layer of the road pavement structure under the highest wheel loads. This is computed using a multilayer linear elastic computer program. The basis for this approach is from structural analysis of public roads (Thompson and Visser, 1996a, 1997). From an investigation of haul road structures, the limiting criteria and the design approach using a dump rock structural layer resulted in the comparison and benefits of the new approach, as shown in Figure 2.

For comparative purposes, two design options were considered; a conventional design based on the CBR cover curve design methodology, and the mechanistically designed optimal equivalent, both using identical *in situ* and road construction material properties. A Euclid R170 (154 t payload, 257 t GVM) rear dump truck was used to assess the response of the structure to applied loads generated by a fully laden rear dual-wheel axle. The assumption, based on multi-depth deflectometer measurements on other roads, was that no load-induced elastic deflections occur below a depth of 3 000 mm. The various design options are summarized in Figure 2.

In the evaluation of both designs, a mechanistic analysis was performed by assigning effective elastic modulus values to each layer and a limiting vertical strain corresponding to a category II road (2000 microstrain). In the case of the CBR-based design, from Figure 2 it is seen that excessive vertical compressive strains were generated in the top of layers 2 and 3, which are typical gravel layers, whereas the rock layer is buried under the weaker gravel layers. For the optimal

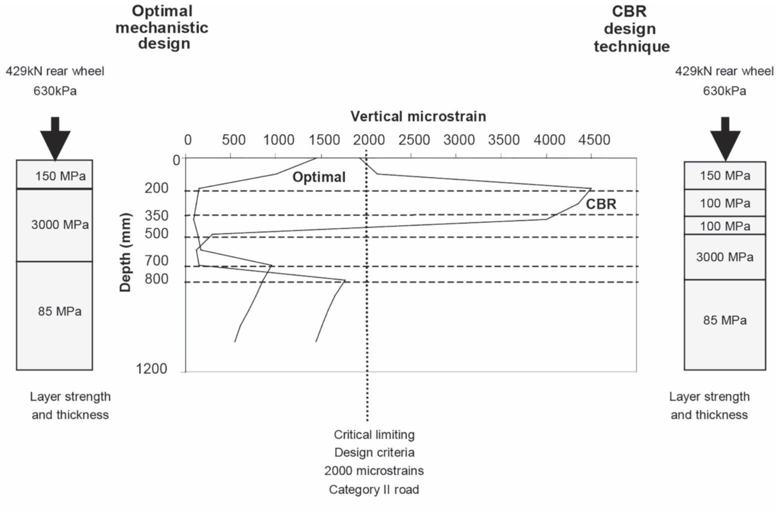

Figure 2—Comparison of new mechanistic design method results with the old CBR method (Thompson and Visser, 2002)

mechanistic structural design, no excessive strains were generated in the structure, due primarily to the support generated by the blasted rock base. Surface deflections were approximately 2 mm compared with 3.65 mm for the CBR-based design which, while not excessive, when accompanied by severe load induced strains would eventually initiate premature structural failure such as rutting and depressions. The proposed optimal design thus provided a better structural response to the applied loads than the thicker CBR-based design and, in addition, did not contravene any of the proposed design criteria.

Originally a single vertical compressive strain criterion was used, but it was realized that, depending on the importance and anticipated life of a road section, the structural design has to be different even though the same traffic volume is carried. The importance of a road section is designated by road category, as shown in Table I, and the structural strength in terms of the vertical compressive strain is related to the road category and expected performance. The daily traffic (kt) is adjusted by multiplying with the performance index, and the permissible vertical strain is shown in Figure 3. For an adjusted traffic volume greater than 240 kt a vertical compressive strain of 900 microstrain should be used. Most South African operations are in the lower range of traffic volume, but many international operations are considerably higher.

These design procedures were developed based on observations of existing haul roads, and monitoring the in-depth deflections. Subsequent to the development of the analysis procedures, at least 10 roads were constructed following the mechanistic design method, and during the extremely wet summers of 1996 and 2000, superior performance and traffic load was reported compared with the

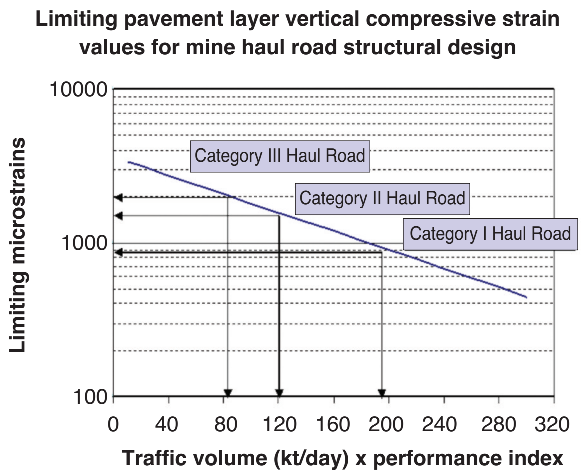

Figure 3—Limiting vertical strain related to road importance and category (Thompson and Visser, 2002)

Table I

Summary of haul road categories (Thompson and Visser, 2002)

Haul road category	Daily traffic volume[1] (kt)	Required performance index[2]	Description
Category I	>25	7–9	Permanent high-volume main roads from ramps to tip. Operating life at least 20 years.
Category II	8–24	5–6	Semi-permanent ramp roads, in-and ex-pit hauling roads on blasted rock on *in situ*, medium traffic volumes. Operating life under 10 years.
Category III	<7	>4	Transient in- and ex-pit roads, low traffic volumes. Operating life under 3 years.

[1] Traffic based on maximum dual rear wheel load of 2-axle 480 t GVM haul truck

[2] Based on acceptable structural performance of roads and maximum deflection under fully laden rear wheel, where 10=excellent performance, 1=unacceptably poor performance, following Thompson and Visser (1996)

previously existing roads. In one particular case, the improved traffic load of the road meant that the planned implementation of trolley-assist could be further delayed by virtue of reduced road construction and improved hauler productivity.

In many cases the improved quality response was anecdotal. As part of the ongoing research, several of the roads that were constructed were monitored and in-depth deflections under haul truck loading were taken at two mines. The latter procedure was fraught with problems since on one mine it was difficult to drill a 40 mm hole through the hard rock layer with many voids. Nevertheless, at the other mine measurements were obtained that confirmed the stiffness of the rockfill layer, but at the lower range of previously determined values. Stress sensitivity was confirmed, which meant that the higher the load the stiffer the pavement structure. This is valuable information when a larger truck fleet is introduced.

On the basis of the research a number of greenfield haul roads were designed and constructed in South Africa as well as in Botswana, Namibia, Brazil, Chile, and Australia. Invariably the contractor will be of the opinion that it is 'a solid road'. As pointed out above, surface deflection of the road under a haul truck is reduced. This means that the deflection bowl in reduced in extent, and this in turn has the result that the tyre does not have to climb out of the bowl, which reduces fuel consumption.

In Thompson and Visser (1996a) it was demonstrated that the design based on the mechanistic procedure was 28.5% cheaper than the old method on an actual tender for variable costs, and 17.4% cheaper on total costs (including preliminary and general costs). At Khomamani iron ore mine in the Northern Cape a significant saving was made on the main haul road construction compared with the budgeted cost. This saving was applied to improve other parts of the road system.

This design procedure has been applied at several mines to investigate whether the haul roads are able to support larger trucks than were then used, and if not, how the deficiencies could be improved. This allowed planning for larger trucks to proceed, without surprises when the trucks arrived. The same procedures have also been successfully applied in designing a route for a dragline to walk from one mine to another. Without the theoretical understanding such major undertakings would not have been possible.

Finally, the concept of a dump rock layer as a strong structural layer (stiffness values were derived) has provided a solution for underground haul roads. Underground tunnels have an uneven footwall as a result of the drilling and blasting technique, and significant quantities of water tend to pond in the low points. This water causes fine material to be pumped out through the concrete slabs under the action of the heavy loads, leading to voids in the layers and faulting, cracking, and potholing of the concrete wearing course. The use of dump rock with minimal fines provides a layer that is strong and water-resistant, and no pumping takes place. Initial experimental sections have shown promise, and further work is being planned.

Functional design

The functional design is related to providing a user-friendly wearing course material. An ideal wearing course for mine haul road construction should meet the following requirements:

- The ability to provide a safe and vehicle-friendly ride without the need for excessive maintenance
- Adequate traffic load under wet and dry conditions
- The ability to shed water without excessive erosion
- Resistance to the abrasive action of traffic
- Freedom from excessive dust in dry weather
- Freedom from excessive slipperiness in wet weather
- Low cost and ease of maintenance.

By examining what wearing course material properties lead to defects, a specification has been developed for wearing course materials selection as shown in Figure 4. The guidelines are based on an assessment of wearing course material shrinkage product (Sp) and grading coefficient (Gc), defined as:

$$Sp = LS \times P425 \quad Gc = \frac{(P265 - P2) \times P475}{100}$$

where

LS = bar linear shrinkage

$P425$ = percentage wearing course sample passing 0.425 mm sieve

$P265$ = percentage wearing course sample passing 26.5 mm sieve

$P2$ = percentage wearing course sample passing 2 mm sieve

$P475$ = percentage wearing course sample passing 4.75mm sieve.

Invariably, mine management wishes to know how to benchmark their haul road network, and the effectiveness of the existing materials. A procedure was developed to relate a range of defects to provide a defect score (Thompson and Visser, 2000a). Defects are evaluated according to the severity of each defect and the areal extent of occurrence to provide a sum of all the defect products as a defect score. The defect score can be related to the need for maintenance, as it was developed in conjunction with mine maintenance teams. Figure 5 shows the influence of daily traffic (in kilotons) and

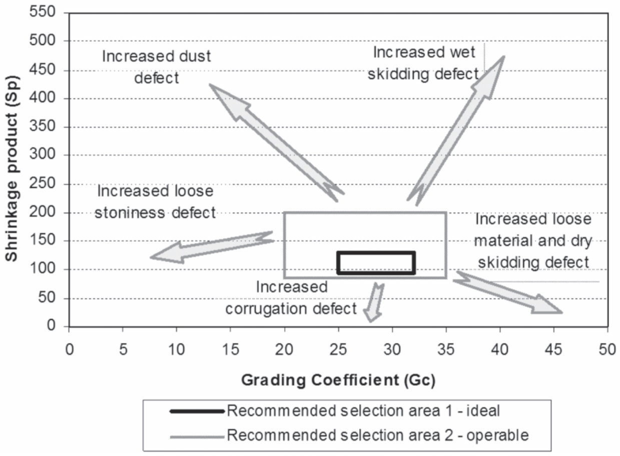

Figure 4—Wearing course selection guidelines (Thompson and Visser, 2000a)

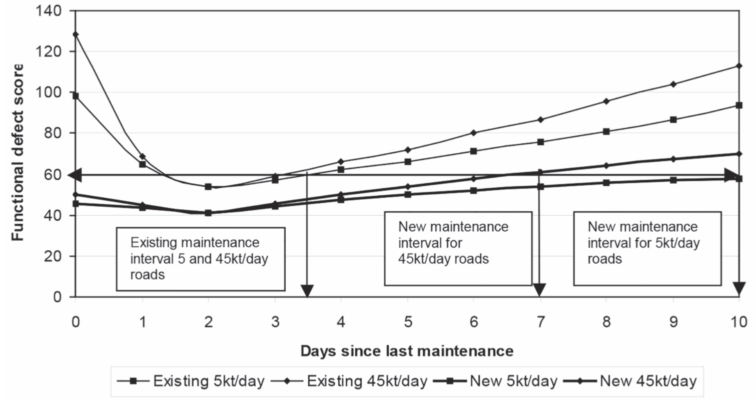

Figure 5—Predicted improvement in functionality for new wearing course material mix at 5 and 45 kt/day traffic volumes (Thompson and Visser, 2002)

the effect of a substandard wearing course material compared with the correct material. The maximum defect score on the mine was 60, which dictated the maintenance frequency. Interestingly, Komatsu adopted this procedure and trained their field staff to provide the mine with recommendations regarding haul road quality and how to improve productivity, reduce costs, and get the best service out of the trucks

Use of the correct wearing course material resulted in a significant improvement in the times between blading, from 3.5 days for the poor-wearing course material to 7 and 10 days for the improved wearing course material on roads carrying 45 and 5 kt respectively. Besides determining the defect score, the visual inspection of defects was also correlated to rolling resistance by considering defects such as potholes, corrugations, rutting, loose material, and stoniness in the surface, which have an influence on rolling resistance. Rolling resistance is an added resistance during motion as a result of energy losses incurred through the wheel/road interaction. A benchmark of 2.0–2.5% is considered as good, and rolling resistance of 6% was encountered on some mines.

If the rolling resistance is higher than that used during mine planning, the trucks are unable to achieve the expected productivity. In one case a diamond mine initiated a pre-feasibility study of block caving, since owing to the excessive rolling resistance the trucks were unable to exit the 450 m deep pit when fully loaded and partial loading had to be resorted to. Replacement of the wearing course material with one that met the functional requirements resulted in the problem being solved, and block caving was postponed for a further 100 m depth. After the successful solution of the problem, the mine manager expressed his unhappiness since a fleet of motor-graders was standing idle. The symptoms of the problem, namely poor road quality and high rolling resistance, were treated by increasing the maintenance activity. By means of the correct design, significant savings in maintenance cost and improved production were achieved, resulting in increased profits.

When a special effort is made to obtain a suitable wearing course material, spillage that can change the material properties needs to be controlled. At one mine it was found that liquid mud was loaded into a dump truck to try and make the loading area operable. As soon as the truck moves onto a gradient, large quantities of mud will be spilt onto the road. This is unsuitable material and generates excessive dust when dry. A further problem is that under normal operations the truck is laden to the limit, again on the level. The material will again spill onto the road. These situations must be avoided. However, a properly loaded fully laden truck may still cause spillage, and consideration should be given to attaching movable flaps at the rear and sides to counter this problem.

Whenever problems are encountered with the wearing course material, one of the first solutions to be considered is a chemical additive, as many marketers claim that the product will improve the road quality. Figure 6 shows the annual costs for the existing inferior wearing course gravel when treated with water and with a chemical additive. Clearly there is a reduction in cost. However, using better quality gravel that meets the requirements results in significant saving compared with the existing gravel treated with the additive. However, a minimal reduction in cost is found when applying the additive to the new wearing course gravel. Chemical additives may be used to minimize road maintenance or even minimize dust, and for managerial reasons such as availability of water, since there are no additional costs. Chemical additives that are mixed into the upper 75 to 100 mm of the wearing course have been found to be the most effective, with rejuvenating sprays applied when necessary. Surface sprays form a thin layer on the surface and tend to wear away rapidly under the abrasive tyre action of dump truck traffic.

When dust control is necessary, the first question to ask is the origin of the dust. Invariably, rejuvenating sprays are applied when dust is visible, assuming that the road generates the dust. If the dust is from spillage, then the spillage should be removed, as further addition of palliative results in a mix of dust and palliative. If the palliative is bituminous, then a layer of bitumen mastic (bitumen and dust) is formed which could become unstable and slippery when hot. The dust should be removed. Sometimes a rotary broom is used, but this has been seen to create large clouds of dust which impair visibility and does not completely remove the dust. A truck-mounted vacuum cleaner, as is used on the diamond mines, is effective in removing the dust rather than displacing it. On a semi-permanent surfacing, which is the case when stabilizers are used on the surfacing,

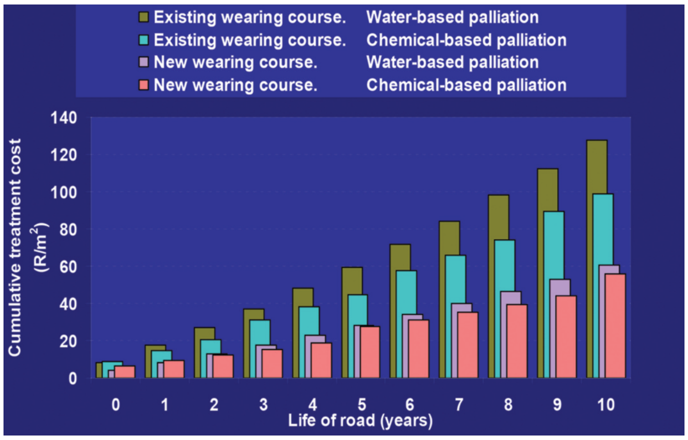

Figure 6—Unit cost assessment of dust palliative options (Thompson and Visser, 2000b)

the maintenance procedures must be adapted, as a motor-grader loosens the surface material which then no longer has a bond and generates loose material and dust.

A major problem on many mines that have a semi-permanent surfacing is that vehicles with tracks are permitted to travel on such haul roads. The tracks loosen the surface material and causes immense damage. The tracks initiate the formation of corrugations, and the only solution is to rip the wearing course and reapply the stabilizer. Tracked vehicles should be moved on a low-bed, or if they need to cross a haul road tyres or old conveyor belting should be used. In some cases a special tracked vehicle haul road is used, but this is often not possible because of restricted space.

Haul roads and loading areas in the pit have been found to be the most problematic in providing a truck-friendly environment. The reason is that drilling takes place at the pleasure of the drilling operator. The depth of a hole is defined from the surface (bonuses are defined by the number of holes), which may be uneven, rather than to a previously defined level. The result is that the floor is uneven, and the problem cannot be resolved by the use of a wearing course material. The solution is to use modern technology such as GPS to guide the drilling operations, to use the electronic systems on dozers to provide an even floor, and to fill in hollows (invariably filled with water) with a rock layer, and to place a 100 mm wearing course layer. Inadequate provision of a suitable riding surface results in excessive truck damage, as shown in Figure 7. The poor road quality resulted in the tie bar being bent, unwarranted repair costs, and the loss of one vehicle in the fleet.

Maintenance management

All types of infrastructure require restoration as a result of wear and tear from use or climate. Haul roads are no different. Typically a motor-grader is used and it starts at one end of the network and completes the network without cognisance of traffic volumes or use. Initially a scheduled system of motor-grader maintenance was proposed, where each road had a frequency of maintenance depending on the type of wearing course, climate, and traffic. Operations at a mine are generally highly dynamic with regular deviations from the planned production schedule because of loader unavailability or other reasons. This means that a planned maintenance regime is not the most effective.

Real-time monitoring of actual vehicle response to road conditions overcomes these limitations (Thompson *et al.*, 2004; Hugo *et al.*, 2007). This is shown schematically in Figure 8. Information on the conditions that a truck

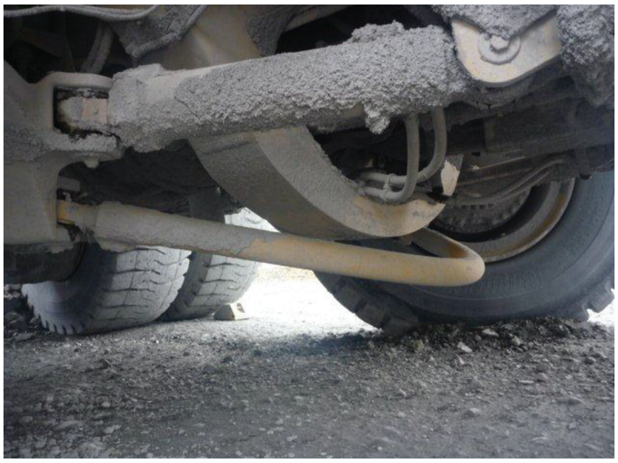

Figure 7—Bent tie bar as a result of poor road quality

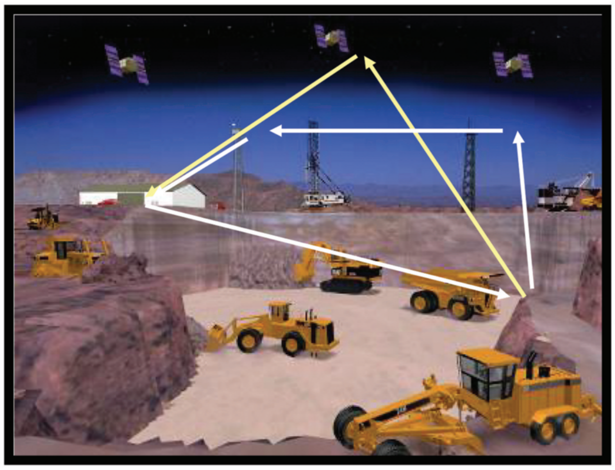

Figure 8—Real-time mine road maintenance system development and integration with existing mine-wide communication, location, and truck monitoring systems (Thompson *et al.*, 2003)

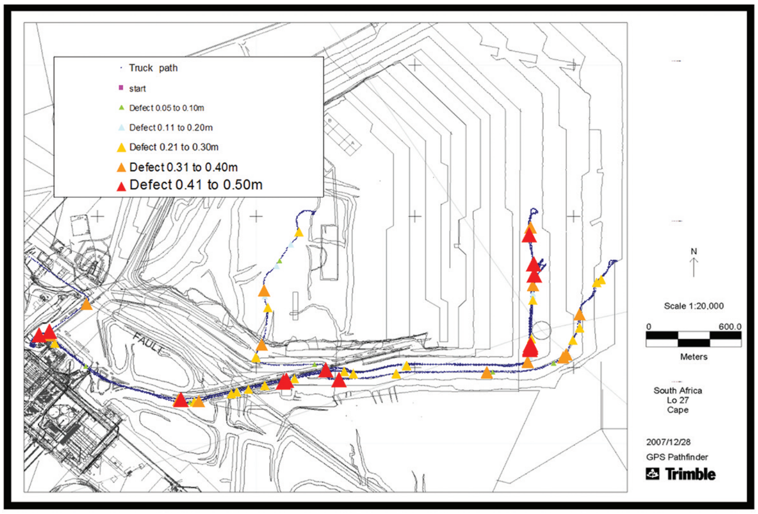

Figure 9—Road defect density map for field trials at Grootegeluk Mine. Symbols represent defect magnitude (depth or height) (Marais *et al.*, 2008)

experiences is relayed to dispatch, where the type of result shown in Figure 9 is provided. It is immediately clear which sections of the haul road network are being used and where the most severe conditions are found, and these should be targeted for maintenance. If the defects are such that a motor-grader is able to rectify the situation this would be used, otherwise a load of suitable material or other techniques are applied.

Technology has advanced significantly since the original work was performed. Electronic interfaces to a computer had to be built to capture the required information, but nowadays there are special plugs that allow extraction of the information from the onboard computer directly into a computer, and data is processed using standard software. This approach is being applied in further studies in Chile, and holds promise for focused maintenance interventions.

Conclusions and recommendations

The cutting-edge research that was conducted in the 1990s is valid and its effectiveness has been demonstrated in a number of applications. Focus on appropriate layout and geometry, structural capacity, a user-friendly wearing course material, and where necessary a semi-permanent riding surface through the use of chemical additives, and a real-time indication of road quality as sensed by the haul trucks has generated the anticipated financial benefits. Mining operations that use the principles have benefited by being more effective. Of major importance is the application of opencast haul road design principles to the future technology of using driverless vehicles in opencast and underground mining, where the road quality is not negotiable as there is no driver that can avoid obstacles or severe road deterioration.

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