Selection, performance and economic evaluation of dust palliatives on surface mine haul roads

by R.J. Thompson* and A.T. Visser†

Synopsis

Excessive dust generation from unpaved mine haul roads is a problem common to most surface mining operations. While optimal road wearing course material selection parameters reduce the inherent dust generation potential, they do not totally eliminate fugitive dust. Many different classes of suppression or palliative treatments are available for mine haul roads and this paper initially ascertains basic selection guidelines, using a set of ideal dust palliative product, application and performance parameters based on mine road-user requirements.

An evaluation and modelling methodology for truck generated fugitive dust emissions is developed as a basis for the comparative assessment of dust control strategies. For water-based spraying, a watering model was developed to estimate individual mine road watering frequencies for characteristic site parameter combinations during summer and winter operating conditions, for a required level of control or maximum dust defect. This forms the base-case scenario with which to compare the performance of other types of dust palliatives under the same conditions.

Finally, a basic palliative economic evaluation model is introduced with the aim of identifying and costing the establishment, application and maintenance rejuvenation activities associated with the use of chemical palliatives. While palliative cost and performance is generally site specific, it is shown that under certain combinations of conditions, the use of dust palliatives has the potential to deliver cost savings when compared to water-based spraying.

Introduction

In any surface mining operation, the transport of ore, and to a lesser extent waste, is accomplished by large haul trucks running on unpaved or gravel-surfaced haul roads of varying construction and material quality. While rolling resistance is often the primary cost-driver in haulage operations, considerable effort and expense is also incurred in the control of dust generation.

Particles that become suspended for a noticeable length of time are generally <30 μm in diameter and the proportion of material in this range is approximately proportional to the wearing course material's erodibility. In general, the silt and fine sand content of a material (i.e. 2–75 μm) is a good indication of its erodibility. However, this size fraction cannot simply be removed from the wearing course because some fine material is necessary to bind the larger size fractions of the wearing course, without which ravelling, loose material, loose stoniness with the potential for tyre damage and high rolling resistance would result. Erodibility is reduced by cohesion, which increases with clay content and/or the use of additional chemical binders. This forms the basic motivation for the use of some additional agent to reduce a material's inherent erodibility, since the finer fraction, although contributing to cohesiveness, also generates much of the dust, particularly when the material is dry. The presence of larger fractions in the material will help reduce erodibility of the finer fractions, as will the presence of moisture, but only at the interface between the surface and the mechanical eroding action—hence the water-based dust suppression techniques used most commonly on mine haul roads, together with the possible addition of hygroscopic chemical additives to attract more moisture onto the surface of the material.

The nature and particle size distribution of a mine haul road wearing course material has a fundamental influence, not only on the tendency to form dust, but also a number of other critical performance defects. The functional design of a mine road is centred on the selection of wearing course materials; the most suitable choice, application and maintenance strategy is required which minimizes a range of functional defects. Functional design itself is part of a broader,

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

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

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integrated road design strategy (Thompson and Visser, 1999), illustrated in Figure 1. The dust, defect however, is often the most problematic to address, even where the functional design—or wearing course material selection—has been optimized. Established specifications (Thompson and Visser, 2000) for wearing course material selection are illustrated in Figure 2, based on the parameters of shrinkage product (*Sp*) and grading coefficient (*Gc*) defined in Equations [1] and [2].

$$Sp = LS \times P425 \quad [1]$$

$$Gc = \frac{(P265 - P2) \times P475}{100} \quad [2]$$

where:

LS = Bar linear shrinkage (%)

$P425$ = Per cent wearing course sample passing 0.425 mm sieve

$P265$ = Per cent wearing course sample passing 26.5 mm sieve

$P2$ = Per cent wearing course sample passing 2 mm sieve

$P475$ = Per cent wearing course sample passing 4.75 mm sieve

The selection range 1–2 in Figure 2 was derived according to mine road-user requirements to reduce critical safety and operational defects of wet slipperiness, dustiness, tyre

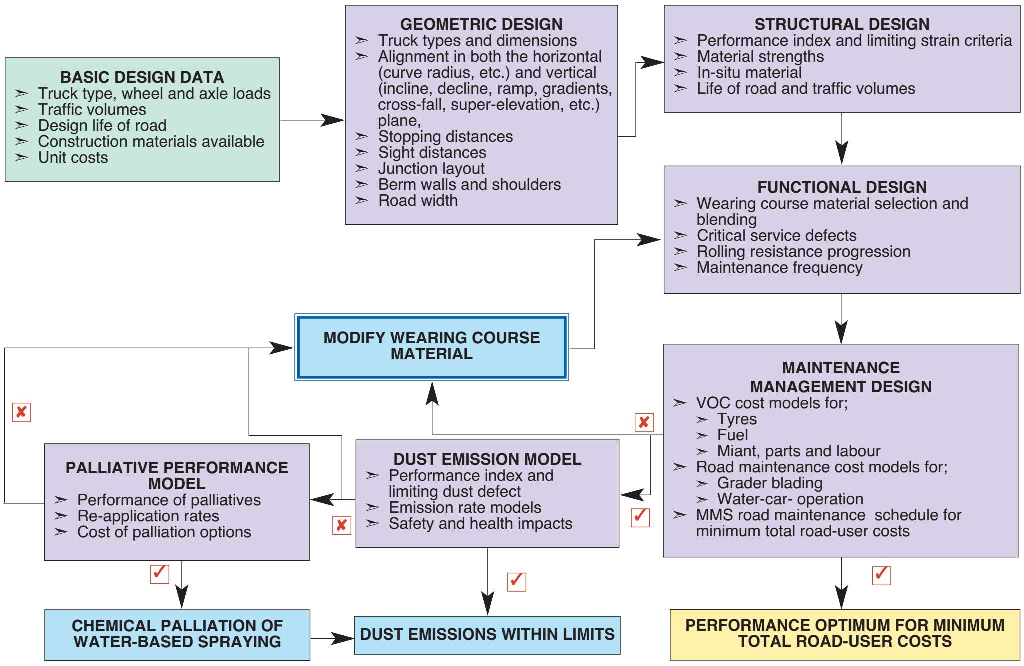

Figure 1—Mine haul road integrated design components

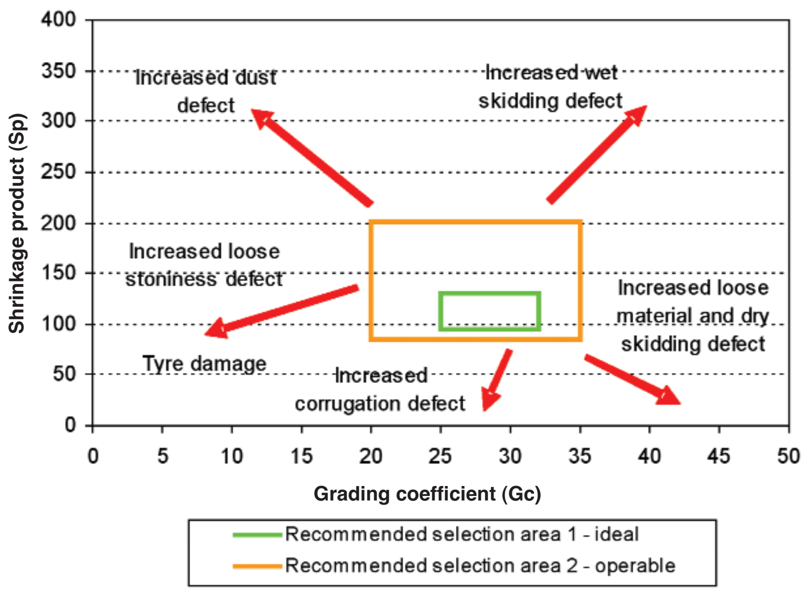

Figure 2—Optimum mine haul road wearing course material selection range and general trends of increasing functional defect scores

damage potential and dry skid resistance, which in turn minimizes (but does not totally eliminate) dust generation. The specification included the parameters of shrinkage product and grading coefficient and limits of 85–200 and 20–35 respectively apply, together with the additional parameters shown in Table I.

From the foregoing, it is clear that some conflict of requirements exist for the finer silt and clay fractions in the wearing course and to solve this, recourse is often made to additional wearing course palliative treatments.

Dust generation from mine haul roads

Dust generation from unpaved mine roads is the process by which particulate matter becomes airborne. Such generation is termed a fugitive (or open) dust source. The amount of dust that will be emitted from an unpaved haul road is a function of two basic factors (ARRB, 1996):

- the erodibility of the wearing course
- the erosivity of the actions to which the wearing course is subjected.

The effectiveness of controls applied to reduce dust released from a haul road is thus dependent on changing one or both of these factors.

The potential for an activity to generate dust depends on a number of factors, including:

- the mechanical actions involved
- the amount of energy imparted to the material
- the scale and duration (frequency) of the activity.

Mechanical action involves a combination of reducing particle sizes by impaction and friction, followed by ejection into the air. In the case of mine haul roads, vehicle disturbance can lead to significant wind-related emissions from a surface by:

- physically ejecting particles from the surface by the action of the wheels
- creating local turbulent eddies of high velocity.

Thus the amount of dust generated from a pavement surface can depend on:

- Wind speed at the road surface. Addo and Sanders (1995) report that speed appears to be linearly related to the amount of dust generated (for light passenger vehicles), as does the vehicle aerodynamic shape, especially the wind shear (lower vehicles with many wheels tending to cause an increase in dust)
- The traffic volume, or number of vehicles using the road
- Particle size distribution of the wearing course
- Restraint of fines. This is related to compaction of the road surface, cohesiveness and bonding of the surface material, durability of the material and the amount of imported fines (spillage) on the road
- Climate, particularly humidity, number of days with rain, mean daily evaporation rates and the prevailing wind speed and direction.

In the surface mining environment of southern Africa, many of the above factors combine to create a significant dust problem on unpaved mine roads. The extent of the problem has been noted by various authors (Thompson *et al.*, 1997, Amponsah Dacosta, 1997, Jones, 1996 and Simpson *et al.*, 1996). In general terms these include:

- Loss and degradation of the road pavement material, the finer particles being lost as dust and the coarser aggregates being swept from the surface or generating a dry skid resistance functional defect
- Decreased safety and increased accident potential for road-users, due to reduced or obscured vision and reduced local air quality
- Higher vehicle operating costs, with dust penetrating the engine and other components resulting in increased rates of wear and more frequent maintenance.

Table I

Recommended wearing course material parameter ranges and associated road defects if range limits exceeded

Impact on functionality below recommended range	Material parameter range	Min	Max	Impact on functionality above recommended range
Reduce slipperiness but prone to ravelling and corrugation	Shrinkage product	85	200	Increased dustiness and poor wet skid resistance
Increased loose stones and potential tyre damage from large aggregate	Grading coefficient	20	35	Increased ravelling, poor dry skid resistance, poorly graded aggregate
Reduced dustiness but loose material will ravel	Dust ratio#	0,4	0,6	Increased dust generation
Increased loose stoniness	Liquid limit (%)	17	24	Prone to dustiness, reduced ravelling
Increased loose stoniness	Plastic limit (%)	12	17	Prone to dustiness, reduced ravelling
Increased tendency to ravel, loose stoniness	Plasticity index (%)	4	8	Prone to dustiness and poor wet skid resistance
Poor wet weather trafficability, churning, excessive deformation and cross-erosion. Maintenance intensive	Soaked CBR at 98% Mod AASHTO density	80		Increased resistance to erosion, rutting and improved trafficability
Ease of maintenance, vehicle friendly ride and no tyre damage	Maximum particle size (mm)		40	Poor surface finish following maintenance, potholing and potential tyre damage

Note#

Dust ratio defined as; $\frac{P075}{P425}$

Where; $P425$ = percentage of material passing the 0,425mm sieve

More specifically, the SIMRAC report by Simpson *et al.* (1996) investigating the causes of transport and tramming accidents in South African mines highlighted the fact that 74% of the accidents on surface mines were associated with ore transfer by haul truck and service vehicle operation. Dust generation was identified as a significant contributory factor in a number of these incidents. Further work by Thompson (1996) confirmed these findings for vehicles operating on unpaved mine haul roads.

The broader environmental effects of dust have also been reviewed, from the perspective of both unpaved public and mine haul roads. Of particular importance is the finding of Amponsah-Dacosta who conducted an emission inventory for a South African coal strip mining operation. The emission inventory was based on a characterization of specific dust sources over a specific interval of time, to produce a dispersion model to enable predictions to be made concerning ambient pollution levels and the identification of major control areas. The analysis, conducted according to USEPA (1995) guidelines, found that 93.3% of the total emissions from the mine were attributable to dust generated from the mine haul road (the second highest, at 2.7%, being attributable to top soil removal). Although a high tonnage operation, the extent of the road network on the mine was similar to other such operations and it was concluded that emissions from the road network would be typical of most opencast coal mines, when calculated on a percentage of total emissions basis.

In an attempt to both control and reduce the safety, health and environmental impacts of dust, mines typically re-apply a water spray to the road for palliation purposes. Although water-spraying is the most common means of reducing dustiness, it is not necessarily the most efficient means of dust suppression, especially where high evaporation rates and traffic volumes are found in combination with materials that are inherently dusty.

Current dust suppression practices

To reduce fugitive dust emissions from an unsealed or unpaved mine haul road, the approach would be to initially reduce pick-up from spillage on the road (typically by brooming the road,) together with modification of wearing course erodibilty or the erosivity of the truck-road surface interaction. This can be achieved in part through:

- application of a seal to the road surface
- use of a tightly bound, high strength wearing course material
- armouring the surface (placing a thin layer of higher quality wearing course on the existing material or tyning this into the top 50 mm of material)
- regular light watering of the road
- use of various chemical dust palliatives
- reducing vehicle speed and/or modifying engine/retarder blower configuration to blow over, not under the vehicle.

Of the approaches listed, only regular watering, the application of chemical dust palliatives together with brooming and the optimal selection of wearing course materials, are often the only viable alternatives in controlling mine haul road dust emissions. In terms of the total ton-kilometres hauled on South Africa's surface mine haul road network, minimal dust control is being exercised other than that provided by watering the road, although a significant number of the larger ton-km operations have adopted various chemical dust palliation products with varying degrees of success. Many products are available, which are claimed to reduce both dust and road maintenance requirements for mine roads. Often, however, minimal specifications of their properties and no comprehensive comparable and controlled performance trials have been carried out in recognized, published field trials. Additionally, incorrect application techniques and construction methods often result, which leads to considerable scepticism about such products and their overall cost-effectiveness. In many instances on public unpaved roads, failures that could have been related to incorrect application, inappropriate management or unsuitable wearing course materials were often blamed on the product (Jones, 1999).

From a mining perspective, the following parameters would define an acceptable dust palliative:

- Spray-on application with deep penetration (the ability to penetrate compacted materials), or (less preferable) mix-in applications with minimal site preparation (rip, mix-in and recompact).
- Straightforward applications requiring minimal supervision, not sensitive nor requiring excessive maintenance or closely controlled reapplications.
- The road should be trafficable within a maximum of 24 hours (short product curing period)
- Availability in sufficient quantity at reasonable prices
- Adequate proven or guaranteed durability, efficiency and resistance to deterioration by leaching, evaporation, ultraviolet light and chemical reaction with wearing course or spillage on road
- Effective over both wet and dry seasons
- Evaluated against local and international safety standards and environmentally acceptable.

The broad classes of products available are listed and the general characteristics of each class of product are summarized below, after Jones (1996) and ARRB (1996).

- Water, groundwater containing dissolved salts or wetting agents
- Hygroscopic salts
- Lignosulphonates
- Petroleum (or sulphonated petroleum) resins
- Polymer emulsions
- Tar- and bitumen-emulsion products.

Generic dust palliation systems

Water

Water is recognized as the cheapest treatment for temporary dust reduction (ARRB, 1996). However, in the case of mine haul roads in South Africa, the frequent reapplication rates and capital and operating cost of equipment used, together with (in some cases) the scarcity of water, may result in water being the least cost-effective option for mines.

Water acts by surrounding and adhering to adjacent particles, making it more difficult to dislodge them. The period of effectiveness is dependent on weather, wearing course and traffic volumes, and can range from 30 minutes to 3 hours. Regular light watering at approximately 0.3–0.5ℓ/m^2 is more effective than infrequent heavy watering. Heavy watering will generate additional run-off and will produce soft, muddy material in addition to pumping and washing away the finer binding fractions of the wearing course. It will also reduce functionality of the pavement, cause short-term slipperiness and may lead to potholing and rutting. This in turn will require more road maintenance with the potential for greater dust emissions.

Sea or groundwater is thought to be slightly more effective than fresh water due to the presence of small amounts of deliquescent salts. However, high concentrations of salts may lead to efflorescence and the salts may be hygroscopic only at relatively high humidities. In addition, some workers report that the roads treated with water containing salts become excessively slippery when wet. However, such reports often fail to specify the wearing course material to which the water was applied, hence the difficulty in identifying the real causes of such slipperiness.

Surfactants or wetting agents are substances that reduce the surface tension of water to air, thereby allowing water to permeate more easily, wetting a greater number of soil particles and preventing them from becoming dislodged. Common surfactants are in the form of soap and have not been described as a separate group since they are often a component of other chemical suppressants.

Hygroscopic salts

Hygroscopic salts are typically chloride salts and suppress dust by attracting moisture from the air, keeping the road surface moist. They are generally applied as surface sprays or mixed in, followed by a final wash (rates vary according to material type, preparation and traffic). When the atmospheric moisture falls below 70% relative humidity, the hygroscopic chlorides cease to function, whereas the deliquescent chlorides cease to function at about 30–40% relative humidity. The products are thus climate sensitive, and Jones (1998) reports their limitation to a climate region encompassing Gauteng, most of the North West and Free State provinces as well as Mpumulanga (Highveld). Chloride salts are able to have their water-attracting functions recharged with a few hours of adequate moisture and humidity. This can be achieved where low humidity and high temperatures exist through early morning dew recharge. Where applications are required in other climatic conditions, recharge water sprays may be required.

Lignosulphonates

Lignosulphonates are organic binders, generated as waste products of the sulphite pulping industry, their composition being variable depending on the feed and pulping process used. Their action in the road is to adhere to and glue together the wearing course material particles. They also act as a clay dispersant, making the clay more plastic and, after compaction, leading to a denser pavement. Molasses, a residue of the sugar-making process also acts in a similar manner on the wearing course material's finer fraction.

They are more generally applied as a mix-in product (as a solid or liquid), with spray-on maintenance applications thereafter (rates vary according to material type, preparation and traffic). Some are susceptible to leaching from the road and are thus more effective over the dry winter months.

Petroleum (emulsified or sulphonated petroleum) resins

Petroleum (emulsified or sulphonated petroleum) resins are derived as a by-product of the oil refining industry; emulsified petroleum resins are formulated as dust suppressants and stabilizers. Binding agents added to the emulsified petroleum resin (derived from paraffinic crude oil) formulation, which penetrate the wearing course and bind the material, preventing them from becoming airborne. In addition, wetting agents, emulsifiers and dispersants are added to increase the penetration and spreading of the product.

The application methodology is dependent on the wearing course material characteristics, usually an initial mix-in application would be required followed by maintenance spray-on applications.

Polymer emulsions

Polymer dispersions are suspensions of synthetic polymers in which the monomers are polymerized in an aquatic medium. Various formulations are available and the product has been widely used for stabilization, and more recently for dust suppression. Polymer (PVA and PVC) emulsions are used extensively to form thin layers in waterproofing paints for roofs and walls. They no not suffer embrittlement, leaching nor UV degradation and have good adhesive properties, making them potentially successful as dust suppressants by binding wearing course material. Depending on the specific product, they can be mixed in to the upper 100 mm wearing course (rates vary according to product, material type, preparation and traffic). The ARRB (1996) report that the product is very effective on sandy soils in dry climates; however, little published information is available about its use on mine haul roads.

Tar and bitumen emulsion products

Tar-based products are derived from coal tar distillates to which solvents are added to improve penetration. Bituminous based products are based on 80/100 penetration grade bitumens with solvents added. Emulsifiers and wetting agents may be added to enable the product to be mixed with water and applied as a mix-in product, followed by spray-on maintenance applications, at an application frequency and dilution dependent on the product itself, material type, preparation and traffic types and volumes. The palliative works by binding the wearing course material, but performance is sensitive to the quality of the wearing course material.

A summary of the palliative class limitations, together with general observations is presented in Table II, modified for applications to mine haul roads and typical traffic volumes. By combining the observations contained in Table II with the wearing course selection parameters and road-user requirements described earlier, a product selection matrix is proposed, modified after Jones (1999) as shown in Table III. This selection matrix is generalized for mine haul roads and, due to the various types of wearing course materials used, dissimilar truck types and volumes, maintenance regimes and philosophy of provision, Table III should be viewed as a generic guide only.

Selection, performance and economic evaluation of dust palliatives

All the palliative types reviewed will suppress dust for a time, but due to the combined effects of oxidation, leaching or breakdown of the host material exposing fresh untreated surfaces and especially spillage on the road, they will eventually lose effectiveness and require reapplication or rejuvenation. While the selection matrix presented in Table III can be used to identify classes of palliative, which would suit a certain application, the data does not specify the level of performance—or the degree of palliation—that can be achieved as a function of time or traffic volume. An initial indication of the maximum and average degrees of control achievable over a specific time period, together with degeneration rates, is required to establish a basis for performance and economic assessment of the selected palliative.

Dust palliative performance modelling

Several studies have developed an appreciation of the degree of dust palliation achieved by some of the classes of palliatives mentioned previously. In general, these were based on public (unpaved) roads and no indication was given of whether the degree of palliation was maximum, average, nor over what time and traffic volume it applies and the road wearing course or climate conditions. Similarly in South Africa, most mine haul road dust palliative testing to date has been conducted on an ad hoc basis with little or no benchmarkable data generated and thus no comparative palliative-class dust management strategies evaluated.

Experimental design

The experimental design adopted for the study entailed the analysis of a number of mine roads, which covered a range of factors influencing palliative performance, primary amonge these being wearing course type and truck type and speed (Thompson and Visser, 2000a). Climate as a factor was eliminated from the study since most mines were located in the same physiographical region, as defined by Weinert (1988). Weinert's N-value describes the durability of wearing course material, based on the relationship between calculated evaporation rates (for the warmest months of the year) and the average monthly rainfall. Figure 3 illustrates how the Weinert N-value varies over southern Africa and in particular, the typical climatic conditions in the Mpumalanga

Table II

A summary of palliative class climatic, wearing course material and traffic limitations (modified after UMA Engineering, 1987)

	Hygroscopic salts	Lignosulphonates	Petroleum-and tar-bitumen based products	Others (sulphonated petroleum, Ionic products, polymers and enzymes)
Climatic limitations	Salts lose effectiveness in continual dry periods with low relative humidity. Selection dependant on relative humidity and potential to water road surface.	Retains effectiveness during long dry periods with low humidity.	Generally effective, regardless of climate but will pothole (small diameter) in wet weather where fines content of wearing course is high.	Generally effective, regardless of climate.
Wearing course material limitations	Recommended for use with moderate surface fines (max 10–20%<0.075 mm). Not suitable for low fines materials or high shrinkage product/PI[1] low CBR[2] or slippery materials.	Recommended for use where high (<30%< 0.075 mm) fines exist in a dense graded gravel with no loose material.	Performs best with low fines content (<10%<0.075 mm). Use low viscosity products on dense fine grained material, more viscous products on looser, open-textured material.	PI range 8–35 Fines limit 15-55% < 0.075 mm. Minimum density ratio 98% MDD (Mod). Performance may be dependant on clay mineralogy (enzymes).
Treatment maintenance and self-repair capability	Reblade under moist conditions. $CaCl_2$ is more amenable to spray-on application. Low shrinkage product materials may shear and corrugate with high speed trucks. Shear can self-repair.	Best applied as an initial mix-in and quality of construction important. Low shrinkage product materials may shear and corrugate with high speed trucks. Tendency to shear or form 'biscuit' layer in dry weather—not self-repairing.	Requires sound base and attention to compaction moisture content. Slow speed, tight radius turning will cause shearing—not self-repairing, but amenable to spot repairs.	Mix-in application—sensitive to construction quality. Difficult to maintain—rework. Generally no problem once cured.
Tendency to leach out or accumulate	Leaches down or out of pavement. Repeated applications accumulate.	Leaches in rain if not sufficiently cured. Gradually oxidize and leach out. Repeated applications accumulate.	Does not leach Repeated applications accumulate.	Efficacy depends on the cation exchange capacity of the host material. Repeated applications accumulate.
Comments	A high fines content may become slippery when wet. Corrosion problems may result.	Generally ineffective if wearing course contains little fine material or there is excessive loose gravel on the road.	Long lasting – more effective in dry climates. May cause layering after several spray-on re-treatments especially where fines content. >15%<0,075mm	Generally ineffective if material is low in fines content or where loose gravel exists on surface. Curing period required.

Notes
1 Plasticity index
2 California bearing ratio (%)

Table III

Palliative product generic selection matrix for mine haul road applications (modified after Jones, 1999)

	High PI (>10)	Medium PI (>10)	Sand	Wet weather trafficability	Ramp roads	Heavy traffic	Short-term	Long-term	Spray-on	Mix-in	Maintainable
Wetting agents		√			√		√		√I/R		√
Hygroscopic salts		√				√	√		√R	√I	√M
Lignosulphonates	√	√	√				√	√		√I/R	√SO
Petroleum emulsions	√	√	√	√	√	√	√		√I	√I	
Polymer emulsions	√	√		√	√	√		√		√I	√SO
Tar/ bitumen emulsions		√		√	√	√		√	√R	√I	√SR

Notes
I—Initial establishment application
R—Follow-on rejuvenation applications
M—Maintain when moist or lightly watered
SO—Maintain with spray-on reapplication
SR—Maintain with spot repairs

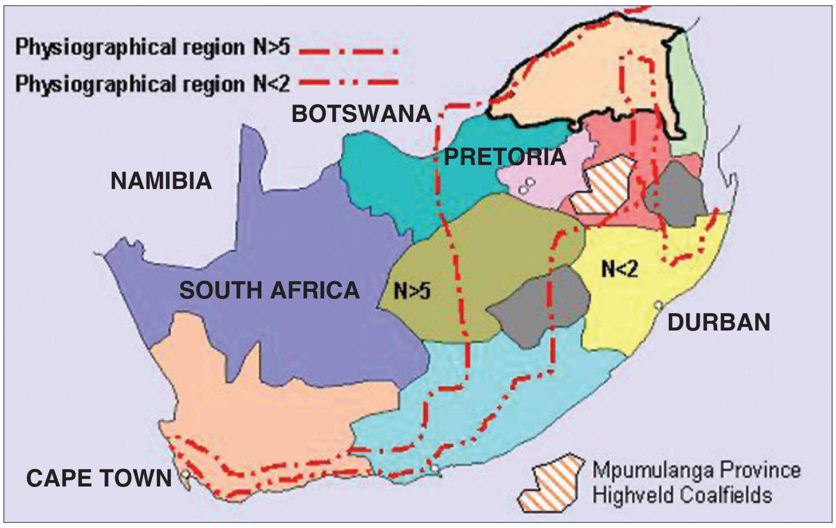

Figure 3—Location of Mpumulanga Highveld coalfields and their associated physiographical region, following Weinert (1988)

Highveld coalfields. Since the majority of South Africa's large strip coal mines are situated in the physiographical region where N=2 to N=5, the work presented in this paper is based on the typical climatic conditions of this region.

The road traffic volume and road maintenance activities were recorded as independent variables for each test site. The class of palliative tested was limited by the selection (previously) made by the particular mine and little control could be exercised over the choice of palliative at each site.

A Hund Tyndalometer (TM digital μP, Hund, 1991) was used to measure the dust generation profiles in 2 dimensions (time and dust reading in mg/m^3 of the minus 10 μm dust fraction) of vehicles passing the measuring point. The instrument operates on the principle of light scattering and is commonly used for routine checking of dust levels associated with mining operations. Details of the measurement system adopted are more fully described by Thompson and Visser (2000a).

As a result of the large number of variables affecting the generation of dust, a visual classification system was developed for the 'degree' of dust defect based on the road user's experience from the point of view of a haul truck travelling at 40 km/h. Table IV gives these descriptions, both as they relate to the Hund Tyndalometer and practically to what the mine would visually experience. In general, the consensus was that a dust defect score of 2 would represent a typical dust defect intervention level (where some dust suppression activity would be initiated). This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impacts.

Water-spray based palliation performance modelling

Judicious watering assists in dust suppression, maintaining compaction and therefore strength of the wearing course, in addition to reducing the potential loss of wearing course material. Although watering itself is often seen as a cheap and simple approach to dust suppression, equipment and operating costs often escalate the cost of suppression. Water retention on mine roads is generally poor, more so during

Table IV

Classification of the degree of haul road dust defect

Typical dust defect photograph showing haul truck travelling past monitor point at 40 km/h descriptions	Dust defect degree and associated Hund peak dust levels (approx. mg/m³ for 10 μm dust per haul truck pass)	Qualitative dust defect degree descriptions
	Degree 1: <3,50	Minimal dustiness
	Degree 2: 3,51 to 23,50	Dust just visible behind vehicle
	Degree 3: 23,51 to 45,00	Dust visible, no oncoming vehicle driver discomfort, good visibility.
	Degree 4: 45,01 to 57,50	Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking hazardous.
	Degree 5: >57,51	Significant amount of dust, window closed in oncoming vehicle, visibility poor and hazardous, overtaking not possible.

adverse conditions where a combination of high temperatures, high wind speeds and low humidity is prevalent. The degree of dust palliation achieved with watering is a function of:

- ➤ The amount of water applied per unit area of road surface
- ➤ The time between reapplications
- ➤ Traffic volumes
- ➤ Prevailing meteorological conditions
- ➤ The wearing course material
- ➤ Extent of water penetration in to the wearing course.

Five test sites were evaluated in terms of the efficiency of the water-spray based dust suppression method. By recording the dust plume generated by a haul truck as it passed at a set distance and speed from the monitor, analysis of the data enabled a first estimate to be made of the time taken for the degree of palliation to decay to zero and the effect of evaporation rate on this time. Figure 4 illustrates a typical dust-time curve from a particular test site, showing how dustiness increases with each vehicle pass from dust defect degree one (immediately following spraying) to degree four 90 minutes after application.

If all the other variables affecting dust generation rates are excluded, an initial estimate of the time to zero palliation from when the road was water-sprayed was found, assuming

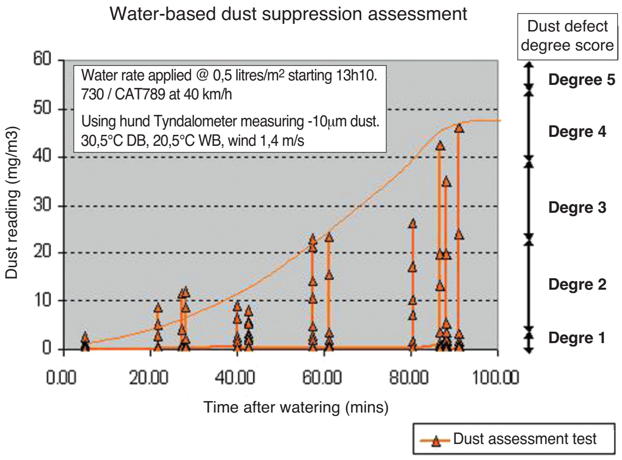

Figure 4—Rate of increase in dustiness following watering on a mine haul road

(initially) that dust generation is independent of vehicle shape and aerodynamics (these effects being analysed in isolation later). Regression of time to zero palliation on monthly evaporation rates for stations in the climatic region N=2 to 5 yielded Equation [3].

$$X_0 = 286.8 - 0.73.E_m \qquad [3]$$

where:

X_0 = Time to zero palliation (mins)

E_m = Average monthly evaporation rate (mm/month) for climatic region N = 2 to 5

If time to zero palliation is considered in terms of the percentage of total dustiness, in typical winter conditions, for an average of 50% palliation, reapplication is required at approximately 3-hourly intervals while in summer, this is reduced to approximately 1½-hourly intervals. These rates are based on an average of 50% palliation, which does not accommodate the road-user preferred dust defect limit of degree 2, corresponding to a maximum dust concentration of 23,5mg/m^3. To determine the reapplication interval required under these circumstances and therefore eventually enable suppression strategies to be compared, consideration needs to be given to the peak and total dustiness of various types of wearing course material and the effect of traffic speed on dustiness.

To provide an initial estimate of the dustiness associated with a particular wearing course material, seven test sites were selected from which data was recorded and analysed to model three parameters:

- Mass of dust as loose material on the road (g/m^2) (model MASS)
- Total dustiness (from consideration of peak and period of plume) (model TOTDST)
- Total dustiness as a function of vehicle speed and mass of loose material on the road (model TOTDST/SPD).

By combining each of the above models, a preliminary estimate of dustiness associated with vehicle type, speed and wearing course was found, from which the required watering frequency (for water-spray based dust suppression) was determined. Table V summarizes the independent variables used in the regression analyses. It should be noted that in applying the model described in Equations [4] to [6], care should be taken when exceeding the range of parameter values used in deriving these models.

For the regression of the independent variables on mass of loose material on the road surface, the following model was selected:

$$MASS = 4202.68 - 630.56.WCP425 + 1548.55. \\ WCP075 + 78.75.WCSP - 392.19.LP425 \qquad [4]$$

The model predicts an increase in the mass of loose material generated on the road when either the wearing course shrinkage product (representing plasticity and fines) or the percentage passing the 0.075mm sieve increase. For the regression of the independent variables on total dustiness, derived from consideration of the peak dustiness (mg/m^3 10 μm dust) recorded per vehicle pass, the following model was selected.

$$TOTDST = 2.92.PKDST + 2260.TYPE \qquad [5]$$

The absence of speed as an independent variable is partly explained by the peak values of dustiness measured increasing with increasing vehicle speed: at the lower test speeds the peak is low, but the period or duration is only slightly longer than at high speeds. This may in part be attributed to a slow vehicle generating dust only from the finer fractions of dust on the road; at higher speeds, the effects of wind shear, etc. entrain both small and large particles, which tend to settle out faster than the smaller diameter particles entrained at low speed.

For the regression of the independent variables on total dustiness, derived from consideration of the mass of loose material on the road, traffic volumes and vehicle parameters, the following model was selected;

$$TOTDST = SPD.(0.04.MASS + \\ 38.33.WSHEAR + 0.12.GVM. \\ WHEELS - 2.44.VOL) + 2260.TYPE \qquad [6]$$

Table V

Independent Variables Used in the Regression Analysis of MASS and TOTDST

Independent variable	Description
WCP425	Percentage of wearing course material passing the 0,425 mm sieve
WCSP	Shrinkage product, defined as; $LS \times WCP\ 425$ where LS= Bar linear shrinkage (%)
WCP075	Percentage of wearing course material passing the 0,075 mm sieve
LP425	Percentage of loose wearing course material passing the 0,425 mm sieve
PKDST	Peak dust reading (x100 mg/m^3) of the minus 10 micron dust fraction, measured by Hund Tyndalometer
TYPE	Indicator for truck type; 0 = Rear dump truck (RD); 1 = Bottom dump truck (BD)
WSHEAR	Wind shear (mm/s.mm) under the truck, defined as; $WSHEAR = \frac{SPD}{3.6 \times 10^{-3}.GRCLEAR}$ where SPD = Vehicle speed (km/h); GRCLEAR = Ground clearance (mm) under lowest part of vehicle
GVM	Gross vehicle mass (t) of fully laden haul truck
WHL	Number of wheels on truck
SPD	Speed of truck over test section (km/h)
VOL	Hourly traffic repetitions on haul road

The model predicts an increase in total dustiness with speed, mass of loose material on the road, wind shear (vehicles closer to the ground, travelling at higher speeds creating a higher wind shear effect), gross vehicle mass and the number of wheels. Traffic volume was negatively correlated with total dustiness, primarily due to the observation that higher traffic volumes led to a more compact wearing course, the removal of most loose material to the sides of the road and entrainment of spillage. This implies that although a high traffic-volume (busy) road may generate more dust per unit time than a low-volume road by virtue of the number of truck repetitions per unit time, the total dust concentration per vehicle pass will be lower.

The number of days since last maintenance was not included as an independent variable in this analysis and steady-state conditions should be assumed when applying these models. A road that has just been bladed, or an excessively ravelled or poorly performing road cannot be reliably modelled using this approach.

Table VI summarizes the application of these models to a typical Highveld surface mine operating rear-dump trucks on a well built and maintained haul road. Using water-based spraying for dust suppression, the rewatering interval required in typical summer conditions is approximately 33 minutes to maintain a dust defect that at no time exceeds a score of two. Under winter conditions, this interval increases to approximately 63 minutes. When using bottom-dump trucks of a similar size and capacity, due to the increase in the number of wheels and the vehicle footprint area, greater concentrations of dust are more rapidly generated after watering and as such watering frequency increases to every 21 minutes in summer and 41 minutes in winter for the same traffic volumes and road wearing course material parameters.

The combinations of models previously described gave an insight into the required watering frequencies for various combinations of vehicle types, speeds, traffic volumes, wearing course material types and evaporation rates. This data can then be used as a base-case scenario with which to compare other types of dust palliatives under the same operating conditions.

Chemical-based palliation performcance modelling

When assessing the performance of chemical-based palliatives, ideally all combinations of wearing course materials, traffic volumes and class of palliative should be assessed. In practice, however, of the various wearing course materials available for road-building, only pedocretes, argillaceous, acid crystalline, carbonates, coal discards and mixtures of materials were analysed. While this appears to limit the applicability of the results, the material types nevertheless form the predominant wearing courses for road construction since the regional distribution of ferricrete (a pedogenic material) is limited by climatic region as defined by Weinert to where $N \leq 5$. The range of palliatives assessed was limited by the particular dust problems encountered and, to a lesser extent, the degree to which the particular product was marketed to the mines. Table VII summarizes the combinations of wearing course materials, specification parameters and palliative products tested.

A number of alternative palliative types and application methodologies (either mine or product manufacturer specifications) were evaluated at ten test sites, to provide an initial indication of the maximum and average degrees of palliation achieved and the time period, together with the degeneration rates, expressed in terms of time from initial establishment and reapplication.

The highest instantaneous control efficiency measured was 92% immediately after application for the tar/bitumen emulsion class of palliative. The highest average efficiencies measured were 75% over 86 days for the same class of palliative and 72% over 118 days for the polymer emulsion class, which was also the longest control period evaluated. Generally, when using spray-on techniques for establishment, the average degree of palliation hovered in the 40% to 60% range for the first two weeks, then decreased rapidly with time, while for mix-in techniques, the average degree of palliation hovered in the 60% to 70% range for the first 7 weeks, then decreased at a slower rate with time. In all cases, a longer analysis period and follow-up reapplications would probably increase the degree of palliation achieved and reduce its degeneration rate, due to build-up of residual product in the road. These results may therefore underestimate the degree of palliation that can be achieved over the long term and therefore overestimate the cost of a long-term chemical dust suppression programme compared to water-spray systems. Table VIII summarizes these results.

All palliatives (with infrequent reapplication rates) shared one common failing as compared with frequent water-spray systems. Material spillage on roadways was extremely common at all sites and spilled material was subject to re-entrainment. With frequent watering, the spilled material is moistened at approximately hourly intervals, while with hygroscopic products, if spillage is not too excessive, some

Table VI

Model data and results for typical haul road watering frequency simulation

Truck type	Rear dump 6-wheel		Bottom dump 10-wheel	
Season and monthly evaporation rate (mm/mth)	Summer (260)	Winter (140)	Summer (260)	Winter (140)
Time to zero palliation (mins)	96.3	184.2	96.3	184.2
Per cent palliation required[1]	65	77	65	77
Reapplication interval[2] (mins)	33	63	21	41

Notes
1.Average percent reduction in dustiness (compared with base-case untreated conditions) to maintain a dust defect score that at no time exceeds 23.5mg/m^3 -10 μm dust (equivalent to degree 2 defect score).
2.For a single application of 0.5 litres/m^2 water.

Table VII

Summary of chemical palliative test site wearing course material parameters

Wearing course			Coal discards	Coal discards	Ferricrete	Ferricrete	Ferricrete	Ferricrete	Sand and calcrete	Dolomite discard	Dolomite	Discards, ash, clay and shale	Weathered granite
Material parameter specification range	**Min**	**Max**											
Shrinkage product	85	200	55	67	30	157	164	82	1	117	93	162	13
Grading coefficient	20	35	16	31	21	13	28	30	1	26	17	25	30
Dust ratio	0.4	0.6	0.6	0.4	0.4	0.5	0.5	0.4	0.2	0.6	0.5	0.6	0.3
Liquid limit (%)	17	24	22	18	-	18	23	21	np	35	21	27	sp
Plastic limit (%)	12	17	18	13	SP	13	16	17	-	20	12	18	-
CBR at 98% Mod AASHTO	80		76	88	64	73	41	116	13	-	81	78	46
Maximum particle size (mm)		40	150	38	13	13	19	13	5	63	38	53	38
Class of palliative tested			W TBE	W TBE	W LS	W LS	W	W	W TBE	PR PR	W HS LS	W PE	W

Notes
Class of palliative tested
W—Water, groundwater containing dissolved salts or wetting agents
HS—Hygroscopic salts
LS—Lignosulphonates
PR—Petroleum (or sulphonated petroleum) resins
PE—Polymer emulsions
TBE—Tar- and bitumen-emulsion products

Table VIII

Summary of palliative test section analysis

Palliative	Application technique			Degree of palliation (%)	
	Application	**Mix-in rate (ℓ/m^2)**	**Spray-on (ℓ/m^2)**	**Maximum**	**Average (%) and period (days)**
Hygroscopic salts	Establishment	-	2.0	90	45% over 14 days
	Reapplication	-	0.5		
Lignosulphonates	Establishment	?	?	88	66% over 23 days
	Reapplication	-	0.2		
	Establishment	?	?	82	70% over 23 days
	Reapplication	-	0.2		
	Establishment	-	1.0	88	47% over 18 days
	Reapplication	-	0.5		
Petroleum resins	Establishment	-	0.7	64	52% over 16 days
	Reapplication	-	-		
	Establishment	-	1.2	82	62% over 20 days
	Reapplication	-	0.11		
Polymer emulsions	Establishment	0.95	-	82	70% over 58 days
	Reapplication	-	0.3		
Tar/bitumen emulsions	Establishment	3	-	88	75% over 86 days
	Reapplication	-	3		
	Establishment	3	-	78	72% over 69 days
	Reapplication	-	3		
	Establishment	3	-	92	70% over 20 days
	Reapplication	-	1.5		

Notes
Refer to individual site analyses for full data (Thompson and Visser, 2000a). Summary data not necessarily comparable between sites since traffic types and volumes, wearing course material types and climatic conditions prevailing at time of test are dissimilar. Application technique refers to test site only and may differ between applications. Applications noted (?)—no data available with which to qualify establishment treatments.

sympathetic transfer of moisture may take place between treated road and the spillage, reducing dustiness. In the case of once-only applications, or those products requiring reapplication only over longer intervals, spillage would go untreated for 2–7 weeks and as such generate most of the fugitive dust emissions from the road. Blading the spillage from the road is problematic in that it creates new untreated surfaces (especially in the case of spray-on applications) and, for mix-in applications, may damage the treated layer. Use of a tractor-towed rotating brush would be a more appropriate solution for spillage removal on treated roads.

In locations where trackout from an untreated onto a treated road is a problem (ramps to main haul road and tipping point to main haul road especially), watering these untreated sections aggravates the problem with moisture and mud. The use of a palliative in these areas is problematic since it was seen at a number of sites that the palliative, whether mix-in or spray-on high, could not withstand the high lateral shear forces generated by slow speed, tight radius manoeuvering. In permanent tip areas, the solution may lie in the provision of either a cement-stabilized wearing course or concrete cast *in situ* pavement, which can be swept clean.

From the analyses undertaken, it is clear that a poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative. The haul road wearing course material should ideally meet the minimum specifications presented in Table I. If not, the inherent functional deficiencies of the material will negate any benefit gained from using dust palliatives. In road surfaces with too much gravel, dust palliatives do not appear to work effectively, more especially where a spray-on technique is used as opposed to a mix-in. The palliatives do not aid compaction of the surface because of the poor size gradation, nor form a new stable surface. New surface area is created from exposed untreated material while, with a mix-in application, poor compaction leads to damage and ravelling of the wearing course, traffic inducing breakdown of the material and eventual dust generation. With regard to water-soluble palliatives, rapid leaching may be problematic.

In compact sandy soils, tar and bituminous-based emulsion products appear effective where leaching of water-soluble products may be problematic. However, in loose medium and fine sands, bearing capacity will not be adequate for the tar/bitumen products to maintain a new surface and degeneration was seen to occur rapidly. In road surfaces with too much silt, it is unlikely that a dust suppression programme will be effective. Excessive silt or sand fractions may lead to a slippery road while poor bearing capacity leads to rutting and the need for road rehabilitation or maintenance, which destroys most products. Small-scale potholing was observed on a number of pavements following spray-on application or reapplication, as a result of trafficking lifting fine cohesive material from the road. Again, where no depth of treatment has built up, this will lead to the creation of new untreated surface areas.

In general, spray-on applications do not appear appropriate for establishment of dust treatments, especially for depth of treatment required. A spray-on reapplication or rejuvenation may be more appropriate, but only if penetration of the product into the road can be assured, otherwise it will serve only to treat loose material or spillage build-up, which will rapidly breakdown and create new untreated surfaces. A spray-on treatment is, however, useful to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically being uncompacted, would provide some depth of penetration and a reduction in dust emissions from truck-induced turbulence.

For chemical-based dust suppressants, the average degree of dust palliation and the period over which it applied was considerably better than that achievable by water-based spraying alone. However, in terms of cost-effectiveness, an evaluation model is required with which to determine the extent of the cost benefits attributable to chemical-based dust suppression, together with an indication of those factors likely to alter the trade-off between water- and chemical-based dust palliation.

Modelling palliative cost-effectiveness

The development and evaluation of dust control strategies requires an analysis of the relative costs of alternative palliation options, such that the most cost-efficient option can be determined, together with an indication of the sensitivity of the selection in terms of the primary modelling parameters. A prerequisite of any cost evaluation is a model that provides a rapid means of making a consistent comparison of the real costs of alternative control measures. Changes in cost of dust control resulting from the introduction of alternative strategies are utilized to evaluate dust control options. This allows the economic implications of the introduction of alternative strategies to be expressed in terms of a base-case cost, in this case water-based spraying.

The development of the model consisted of identification of the key components that affect the overall cost of dust control and their interrelationship and effect on the total cost of road treatment (R/m^2). The major cost elements considered in dust control include:

- capital equipment
- equipment operating costs
- road maintenance frequency
- material cost (palliative cost)
- activity-related costs and efficiencies, such as surface preparation, dust palliative application, grading, watering and finishing, for either a mix-in or spray-on establishment or rejuvenation reapplications.

These parameters are, in turn, influenced by the selected palliative, application methodology and frequency for the specified level of control, as shown schematically in Figure 5.

The benefits derived from the application of any palliative must be completely characterized to fully determine the value of dust suppressants. The primary benefit—that of improved air quality and road—and driver-safety is problematic to assess. It has been established that a truck driver's exposure to the dust produced, and for how long, is not critical in terms of AQI for the characteristic dust involved, except where a combination of open cabs and short hauls or high traffic volumes are found (Thompson and Visser, 2003). The safety benefit is more tangible—the current practice of applying water at 60–90 minute intervals is incorrect in view of the much reduced levels of dustiness and visibility required to be maintained on a mine haul road. This would imply that by reducing the frequency of watering, through the use of palliatives, this may offset the additional costs of material and construction required for their effective application. Table IX summarizes the primary data classes recognized in the cost analysis in terms of cost or benefit, highlighting those used in developing the cost model.

The palliative performance is assessed following data presented in Table X, in terms of the product's establishment application rate (ℓ/m^2), establishment method (spray-on or mix-in) and reapplication rate (ℓ/m^2 spray-on only) and frequency, to achieve a comparable average degree of dust palliation as to that achieved by water under the same conditions. Use of this data implies that the palliative establishment and rejuvenation rates and methods (Table X) are tailored to the individual wearing course characteristics of the road (refer Table VIII), which, where conditions differ from those specified, may not be the case. The performance

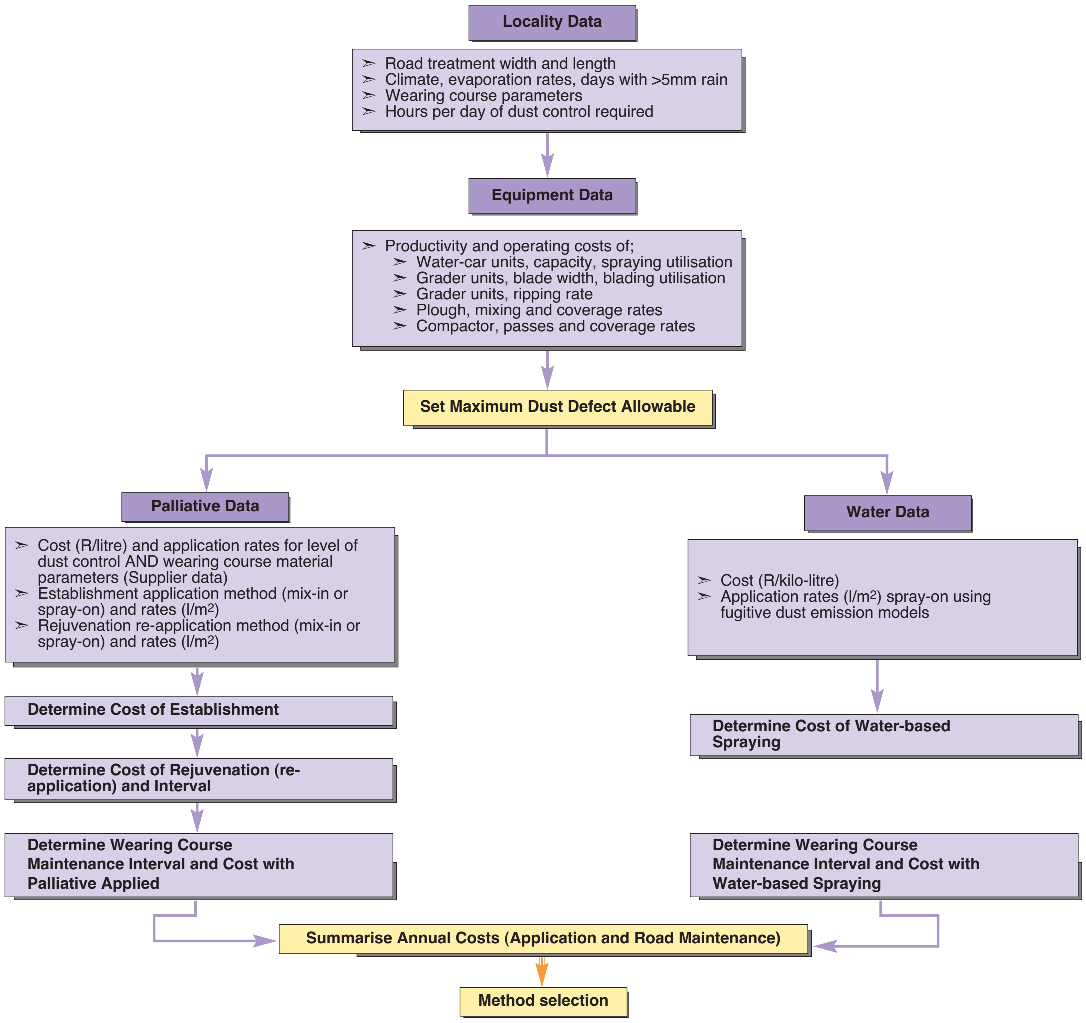

Figure 5—Schematic model of dust palliative cost evaluation

Table IX

Summary of cost/benefit analysis for cost model development

Benefit	Included in model	Cost	Included in model
Improved safety	X1	Surface preparation, palliative establishment application and finishing costs (equipment and material)	√
Improved health	X1	Palliative reapplication (equipment and material)	√
Reduction in grading cost	√	Remaining grading costs	√
Reduction in grading frequency or gravel loss	√	Remaining watering costs	√
Reduction in watering cost	√2	Reduced safety (cost of accidents)	X1
Reduction in vehicle down-time and maintenance	X	Reduced health (cost of exposure to low AQI)	X1
Improved hauler cycle times	X3	Reduced water-car fleet utilization	X2

Note
1Not analysed, but if model comparison is based on the cost to achieve a specified level of control efficiency, many of the costs become equal or do not apply. For example, the comparative safety and health benefits from reduced dustiness would become equal, irrespective of control methodology applied (water-spray base-case or palliative).
2Reduced utilization of water-car or road maintenance fleet would not necessarily generate savings, except for reduced maintenance, parts and fuel, since vehicle and driver would still be required. However, where the fleet consists of more than 1 vehicle in use, the reduction in numbers may generate savings.
3Improved hauler cycle times are significantly effected by rolling resistance. Even relatively small reductions in rolling resistance on a laden haul can be beneficial to cycle time and tons/hour. These savings have been discussed elsewhere (Thompson and Visser, 2006).

results incorporated into the model may therefore not represent the optimal performance of the palliative selected. Care should be taken when specifying the modelled or alternate establishment and rejuvenation strategies—it is important that the data used closely reflect the anticipated palliative performance under the (often unique) conditions of its application.

Figure 6 summarizes a site-specific analysis for the palliatives listed in Table X, using a maximum allowable dust defect score of two, equivalent to an average degree of dust palliation of 65% and watering every 33 minutes. Details of the palliative cost, establishment and reapplication rates and methodologies, together with the average degree of palliative performance achieved for the particular combination of haul

Table X

Typical palliative application and performance modelling data

Palliative	**Application methodology (ℓ/m^2 @ interval) (S = spray-on M = mix-in) for specified dust defect score**			
			Dust defect score 2	**Dust defect score 4**
Water	Spray @ 0.5ℓ/m^2	S	Every 33 mins	Every 68 mins
Hygroscopic salts	Establishment	S	2ℓ/m^2	2ℓ/m^2
	Reapplication	S	0.5ℓ/m^2 every 10 days	0.25ℓ/m^2 every 12 days
Lignosulphonates	Establishment	M	1l/m^2 ?	1ℓ/m^2 ?
	Reapplication	S	0.2ℓ/m^2 every 10 days	0.1ℓ/m^2 every 14 days
Petroleum resins	Establishment	M	1.2l/m^2	Unknown
	Reapplication	S	0.11ℓ/m^2 every 20 days	Unknown
Polymer emulsions	Establishment	M	0.95l/m^2	0.95ℓ/m^2
	Reapplication	SS	0.05ℓ/m^2 every 15 days	0.025ℓ/m^2 every 20 days
Tar/bitumen emulsions	Establishment	M	3ℓ/m^2	3l/m^2
	Reapplication	S	0.125ℓ/m^2 over 15 days	0.063ℓ/m^2 over 15 days

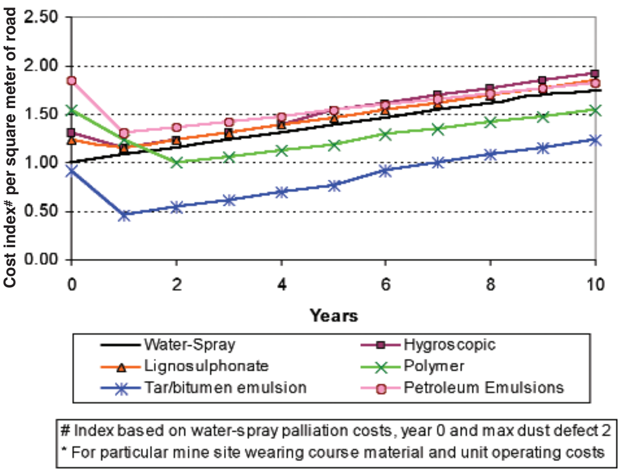

Figure 6—Economic evaluation of dust palliatives where a dust defect score of no more than 2 must be maintained

road, wearing course and traffic volumes used in this example are presented in more detail by Thompson and Visser (2000a). In this particular case, polymer and tar/bitumen emulsion products show a cost benefit over water-based spraying, the polymer emulsion only following establishment after year one (initial costs being higher due to higher activity and product-related establishment costs), while the tar/bitumen-emulsion class of product is cheaper throughout the life of the road, by virtue of lower establishment and reapplication quantities and costs. In this example, there is no cost associated with the water consumed, only the operational (spraying) costs are included. If a cost for water consumed, of 0.1c/kl and 1c/kl is included in the example above, the water-spray cost index increases to 1.46 and 5.66 respectively. This would therefore significantly enhance the cost-effectiveness of using dust palliatives at both the control levels specified.

When the maximum allowable dust defect score is increased to three, watering frequencies reduce to 48 minutes and only the polymer and tar/bitumen products show any cost benefit over water-based spraying, and only after initially higher establishment costs in the first year. When the allowable dust defect score is increased to four, watering becomes the cheapest dust palliation option, as shown in Figure 7. Current mine operating practice is typically represented by a dust defect value of between three and four, which would indicate that in some circumstances, watering is the cheapest form of dust palliation. However, it was established earlier that a maximum dust defect score of two was desirable from mine operators' point of view and therefore, some form of chemical palliation would be most likely to be beneficial in the long-term, subject to cost and wearing course material constraints remaining valid.

The economic evaluation can be extended to explore the most cost-effective option in the case of roads where the existing wearing course does not meet the minimum specifications introduced earlier. In this case, four options typically exist, namely water-based spraying or chemical palliation, both in conjunction with or without improvement to the existing wearing course material. The cost-effectiveness of the various management strategies for either water-based

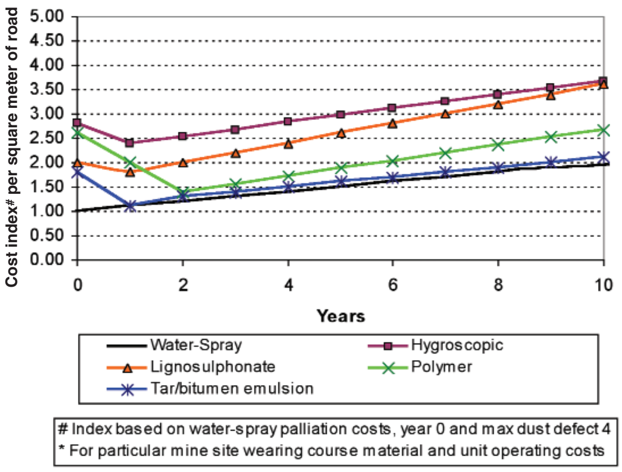

Figure 7—Economic evaluation of dust palliatives where a dust defect score of no more than 4 must be maintained

spraying, the application of a chemical palliative, or improvement of the wearing course material, can be analysed. This is achieved through consideration of the establishment and reapplication costs associated with each type of wearing course and palliative combination, in comparison to the additional costs associated with the placement of the improved wearing course. In this latter case, the activity cost of wearing course improvement is inclusive of palliative establishment, thus reducing costs of establishment while leveraging the benefits of an improved wearing course, in terms of reduced palliative application frequencies and rejuvenation rates.

Conclusions

Excessive dust generation from unpaved mine haul roads is a problem common to most surface mining operations. Optimal road wearing course material selection parameters reduce, but do not totally eliminate the potential of a wearing course to produce dust under the action of mine haul trucks. The development of selection guidelines, performance and economic evaluation models for dust palliative treatment options fulfils the need for a structured approach to dust palliative performance assessment and costing. Initially, a set of ideal dust palliative product, application and performance parameters were identified, based on mine user requirements. encompassing application, management and performance factors.

The development of an evaluation and modelling methodology for truck generated fugitive dust emissions was based primarily on a qualitative methodology, enabling a rapid comparative assessment of control strategies to be made. The development of generic dust defect scores was based on typical dust concentrations associated with a haul truck running at 40 km/h. The dust defect score approach enhanced the portability of the assessment methodology and, with the objective of providing easily realizable technology transfer, obviated the need for expensive equipment and testing schedules when a rapid estimation of comparative dustiness is required by the mine.

The management strategy for water-spray based dust suppression was based on user defined levels of dust defect acceptability. In general, the consensus was that a dust defect score of two would represent a typical dust defect intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact. A watering model was developed to determine individual mine road watering frequencies for characteristic site parameter combinations during summer and winter operating conditions, for a required level of control or maximum dust defect. To provide an initial estimate of the dustiness associated with a particular wearing course material, three models were derived based on mass of dust as loose material on the road, total dustiness and total dustiness as a function of vehicle speed and mass of loose material on the road. The combinations of these models gave an insight into the required watering frequencies for various combinations of vehicle types, speeds, traffic volumes, wearing course material types and climate. This data can then be used as a base-case scenario with which to compare the performance of other types of dust palliatives under the same conditions.

A basic palliative economic evaluation model was determined with the aim of identifying and costing the establishment, application and maintenance rejuvenation aspects associated with the use of chemical palliatives, compared to that of water-based suppression alone. Palliative establishment and rejuvenation rates can be determined for various levels of maximum dust defect, but these must be tailored to the individual wearing course characteristics of the road itself, and should not be generalized. However, a mix-in establishment was generally recommended for mine haul roads, irrespective of palliative type, followed by spray-on maintenance reapplications. It is clear that a poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative; the inherent functional deficiencies of the material will negate any financial benefit gained from using dust palliatives. Ideally, the wearing course should be rehabilitated to specification and a dust palliative applied at the same time, thus minimizing the establishment costs and allowing the return on expenditures to be realized sooner. When a wearing course material is close to specification, the use of dust palliatives has the potential to deliver cost savings compared to water-based spraying, although not necessarily initially, but more certainly in the longer-term and especially where a cost is applied to the quantity of water used for dust suppression.

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