

Mine Haul Road Fugitive Dust Emission and Exposure Characterisation

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Synopsis

Excessive dust generation from mine haul roads is a problem common to most surface coal mining operations. Optimal wearing course material selection parameters reduce, but do not totally eliminate the potential to produce dust. For existing operations, which may not have optimally designed and maintained roads, the problem of identifying the haul road dust defect, quantifying its impact on both safety and health and assigning priorities within the constraints of limited capital and manpower is problematic. This is reflected in the fact that most surface mine operators agree dust-free roads are desirable, but find it difficult to translate this into cost-effective betterment activities. The aim of this paper is to describe fugitive dust emission and exposure characteristics associated with ultra-heavy mine haul trucks running on unpaved mine haul roads. Models are described which enable mines to assess the likely dustiness of their chosen haul road material as a function of surface loading of fines, traffic types and volume, together with various material parameters. By combining these models with the results of quantitative exposure profiling, a mine can, in conjunction with the assessment, determine the most cost- and safety-effective haul road dust management strategy.

Introduction

Over 70% of copper, 80% of ferrous metals and 95% or 65 million tons of the land's industrial minerals are mined by surface mines and quarries. In the coal mining industry, over 44% of the total coal produced, approximately 100m sales tons or 134m run-of mine tons was produced by opencast methods in 1998 which require, inter alia, the transport of raw coal from the pit to the loading or transfer point. In any surface mining operation, the transport of ore, and to a lesser extent waste, is accomplished by large haul trucks running on haul roads that have, at best, been empirically designed with little or no recognition of the consequences of inadequate design on cost per ton hauled, operational efficiency or safety. From a strip coal mining perspective, in terms of haul truck-based transport, over 800 000 truck trips representing over 7,2m truck kilometres are made per annum. Considering that truck haulage costs can account for up to 50% of the total costs incurred by a surface mine, it is of paramount importance that these costs are minimised. This becomes all the more critical as tonnage increases and larger haul trucks are deployed. Not only do the maintenance costs of existing roads of inadequate design increase, vehicle operating and maintenance costs also increase prohibitively.

The design of mine haul roads encompasses structural, functional and maintenance design aspects as discussed by Thompson & Visser¹. The aim of a structural design is to provide a haul road which can carry the imposed loads over the design life of the road without the need for excessive maintenance, whilst functional design is centred on the selection of wearing course materials where the most suitable choice, application and maintenance strategy is required. Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs. Whilst it is possible to construct a mine haul road that requires no maintenance over its service life, this would be prohibitively expensive, as would the converse but rather in terms of operating and maintenance costs. An optimal functional design will thus include a certain amount and frequency of maintenance (watering, grading etc.) and thus maintenance can be planned, scheduled and optimised within the limits of required road perfor-

mance and minimum vehicle operating and road maintenance costs. By integrating the various road design components, illustrated in Figure 1, particularly wearing course material selection together with a maintenance management system, optimum road performance can be achieved at minimum total road-user costs. These optimal wearing course material selection parameters reduce, but do not totally eliminate the potential to produce dust (Thompson & Visser²) and considerable time and expenditure is nevertheless applied to the reduction of vehicle generated haul road dust.

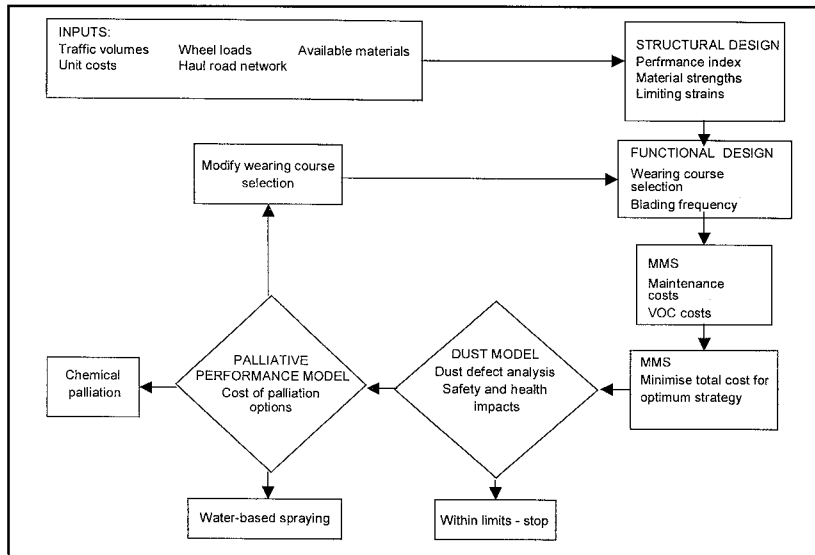


Figure 1 Dust defect analysis in the context of a broader haul road design and management system

For existing operations, which may not have optimally designed and maintained road networks, the problem of identifying existing deficiencies, quantifying their impact and assigning priorities within the constraints imposed by limited capital and manpower is problematic. Assessing the impact of dustiness in order to identify the safety and economic benefits of taking corrective actions such as more frequent watering, regravelling or betterment is hampered by the lack of a

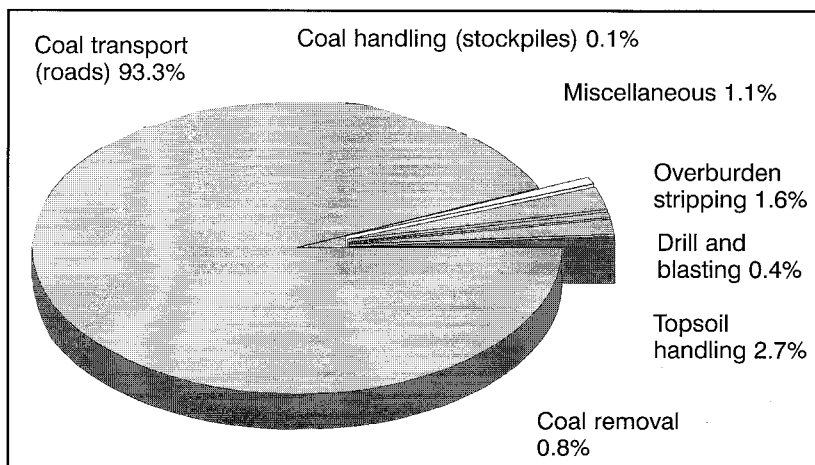


Figure 2 Percentage contributions to total dust emissions from typical South African strip mine (following Amponsah DaCosta³)

problem solving methodology which can address the complex interactions of the various components in a haulage system. This is reflected in the fact that most surface mine operators agree dust-free roads are desirable, but find it difficult to translate this into cost-effective betterment activities.

Dust, created through the mechanical disintegration of particulate matter, is a problem common to most surface mining operations. The broader environmental effects of dust have been reviewed by Amponsah-Dacosta³ who conducted an emission inventory for a South African coal strip mining operation. The emission inventory was based on a characterisation of open 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 USEPA4 guidelines, found that 93,3% of the total emissions from the mine were attributable to dust generated from the mine haul road (the next highest source, at 2,7%, being attributable to top soil handling as illustrated in Figure 2). Although a high tonnage operation, 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.

The SIMRAC report by Simpson et al⁵ 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 Thompson⁶ and Fourie et al⁷ confirmed these findings for vehicles operating on unpaved mine haul roads.

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.

Aim and Scope of Paper

The aim of this paper is to describe fugitive dust emission characteristics associated with ultra-heavy mine haul trucks running on unpaved mine haul roads, developed as part of a Safety in Mines Research Advisory Committee (SIMRAC) research project (Thompson & Visser⁸) to analyse and quantify the safety and health impacts of haul road dust. The development of a qualitative eval-

uation strategy is described, following which models are presented which enables a mine to assess the likely dustiness of their chosen wearing course materials as a function of surface loading of fines, traffic types and volume, together with various material parameters. The results of quantitative air sampling tests are then presented, by means of which the risk associated with truck driver exposure to haul road dust can be evaluated. By combining the results of the exposure profile with that of the water-based palliation models, a mine can, in conjunction with the assessment, determine the most cost- and safety-effective haul road dust management strategy.

CURRENT STATE OF HAUL ROAD DUST SUPPRESSION

Dust generation may be loosely defined as the process by which particulate matter becomes airborne, to be carried downwind from the point of origin or source. Such generation is termed a fugitive (or open) dust source. The amount of dust that will be emitted is a function of two basic factors (ARRB9);

- the erodibility of the material involved
- the erosivity of the actions to which the material is subjected

The erosivity is itself dependent on a number of road- and traffic-related factors;

- Wind speed at the road surface. Addo & Sanders¹⁰ 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.

Dust Suppression Systems

In broad terms, the effectiveness of any dust suppression system is dependant on changing material erodibility or erosivity. The nature and particle size distribution of a mine haul road wearing course material has a fundamental influence on the tendency to form fugitive dust. Particles that become suspended for a noticeable length of time are generally <30µm in diameter.

The amount of material in this range is therefore approximately proportional to a material's erodibility. In general, the silt and fine sand content of a material (ie. 2-75µm) is a good indication of its erodibility.

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. This forms the basis of the water-based dust suppression techniques used most commonly on mine haul roads, together with the addition of hygroscopic chemical additives to attract more moisture onto the surface of the material. Other options available to reduce fugitive dust emissions from a mine haul road include;

- Providing a tightly bound wearing course material or seal.
- Armouring the surface (placing a thin layer of higher quality wearing course on the existing material or tyning this into the top 50mm of material).
- Good maintenance practices
- Use of various chemical dust suppressants (palliatives)
- Reducing vehicle speed and/or modifying engine/retarder blower configuration.

From the foregoing it is clear that in most circumstances regular watering, the application of chemical dust palliatives and/or the optimal selection of wearing course materials are the only viable alternatives in controlling mine haul road dust emissions. Typical wearing course material selection guidelines are described by Thompson & Visser². In terms of the total surface mine haul road network in southern Africa, few mines are fortunate enough to have the ideal wearing course material or mix of materials available locally and as a result, dust control is invariably achieved by regular re-applications of water-based sprays.

FUGITIVE DUST EMISSION MODELLING

Most mine untreated wearing course materials exhibit excessive dust defects and thus there is the need to reduce the dust defect through some form of palliation. Numerous dust palliatives exist, of which water-spraying is the most common solution applied. Unfortunately, most mine haul road dust palliative testing to date has been conducted on an ad-hoc basis with little or no

quantitative data generated and thus no appropriate or cost-effective dust management strategy determined.

Experimental Design

The experimental design adopted for the study entailed the analysis of a number of in-service mine roads which covered the fullest range of factors controlling fugitive dust emission characteristics (Thompson & Visser⁸). Climate as a factor was eliminated from the study since most mines were located in the same physiographical region, as was the road traffic volume factor, primarily since the test site locations did not enable similar materials to be tested under a range of traffic conditions and due to the variable nature of the traffic itself. Traffic volume and road maintenance activities were thus 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. The results of palliative testing presented in this paper are limited to that of water-based spraying. Results for the full range of palliatives evaluated are presented by Thompson & Visser⁸.

Fugitive dust emission rates and particle size distributions are difficult to quantify because of the diffuse and variable nature of such sources and the wide range of particle sizes, including particles which deposit immediately adjacent to the source. Standard source testing methods, which are designed for application to steady-state confined forced-flow conditions, are not suitable for the measurement of fugitive emissions unless the plume can be drawn into a forced-flow system.

For the field measurement of fugitive mass emissions from mechanical entrainment (such as vehicles on a mine haul road), four basic techniques are available (following Cowherd¹¹);

1. The quasi-stack method involves capturing the entire particulate emissions stream with enclosures or hoods and applying conventional source-testing techniques to the flow.
2. Roof monitoring techniques for calculating the mass fluxes entering and leaving an enclosed area, such as a haul truck cab.
3. Upwind and downwind source samplers applied under known meteorological conditions, followed by a calculation of the source strength (mass emission rate) with atmospheric dispersion models.
4. Exposure profiling in which simultaneous multi-point measurements of particulate concentration and wind speed over the effective cross-section of the dust plume are made, followed by a calculation of the net particulate mass flux through integration of the plume profiles.

Because it is impractical to enclose the source or capture entire plume emissions, the most feasible approach generally recognised is that of exposure profiling for fugitive or open dust source monitoring. A USBM study (USBM¹²) adopted a plume profiling approach using an array of dust-fall samplers, profiler heads, RAM-1 monitors and quartz crystal cascade analysers to fully characterise the dust plume created by a haul truck in three dimensions at three test points contiguously, using the total suspended particulate. The testing array incorporated 33 separate instruments and each instrument was read after a certain period or traffic volume.

Such an extensive testing array would be inappropriate for the research considered here. Ideally, a single set-up which provided a qualitative assessment of dustiness at a certain position on the road would fulfil most of the data needs. Since the concept of degree (or percentage) of dust palliation was used, although peak values are liable to misinterpretation (if measured at various positions within a plume), the overall percentage reductions, if the method is repeatable, would nevertheless be valid. With the aim of comparing the performance of different palliatives and conducting a comparative assessment of control strategies, although plume and total suspended particulate matter would provide equally useful data, the extensive instrumentation required would limit its applicability. A direct reading instrument, mounted in a similar position at each test location, together with the recording of dependant and independent variables encountered at each site was therefore selected. This was based on the development of generic dust defect scores, based on typical dust concentrations (mg/m^3 of the minus $10\mu\text{m}$ dust fraction). These dust defect scores enhance the portability of the proposed assessment methodology and obviate the need for expensive equipment and testing schedules when an estimation of comparative dustiness is required.

However, to provide an indication of the actual health risks associated with truck driver exposure to haul road dust emissions and to assess what avoidance and management, as opposed to palliation, strategies may be applicable, a number of quantitative in-cab assessments of truck driver exposures were also undertaken with which to bring the overall results into perspective.

Airborne Particulate Matter Qualitative Dust Sampling Methodology

The Hund Tyndalometer (TM digital μP) was used to measure the dust generation profiles of vehicles passing the selected 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.

The machine is depicted schematically in Figure 3. To measure the dust concentrations, the infra-red beam of a Gas diode source passes through a measuring chamber in which dust particles exist. The consequent scattering of the light is measured at 70° to the primary beam which corresponds to a maximum measured particle size of approximately 8µm. The result of the measurement is the scattered light intensity I_m which is directly proportional to the dust concentration and, depending on the type of dust measured, can be calibrated to an equivalent mg/m³ dust concentration if required. For rock dust this calibration factor is approximately 1,00 (Hund¹³). It is assumed that the dust particle-size profile generated by a vehicle passing the machine remains similar before and after palliation and thus using the 8µm fraction should thus faithfully reflect the change in dust levels recorded. The US Environmental Protection Agency (USEPA) recently updated the national PM-10 (particulate matter no greater than 10 microns in aerodynamic diameter) emission

factors in which it was recognised that the respirable pollutant fraction (PM-10) from both industrial (mine) and public unpaved roads contribute most to the PM-10 emission total and, from a health point of view, the reduction of this respirable fraction is of particular importance (USEPA¹⁴).

The procedure followed in establishing the dust concentration was based on the following methodology:

- (i) Calibration of the instrument prior to sampling.
- (ii) Set machine up centrally within the test section, 1m above road surface and 2m from the inner wheel track of the road test section on both sides of the road (to cater for wind direction effects and to reduce the effect of carry-over dust from the control or buffer sections).
- (iii) Establish with Abbirko Flowmaster anemometer the wind speeds and directions prior to testing and note any significant changes which would affect emission rates. Determine background dust concentration (with no traffic).
- (iv) Each vehicle was instructed to pass 2m from the sampling point along a demarcated track and vehicle speed was recorded. Exceptions were noted.
- (v) The instrument was set to sample at 1 second intervals and the dust concentration readings recorded over a 50s duration (until ambient dust levels were re-established following the vehicle pass).
- (vi) The instrument zero calibration was checked prior to further deployment.

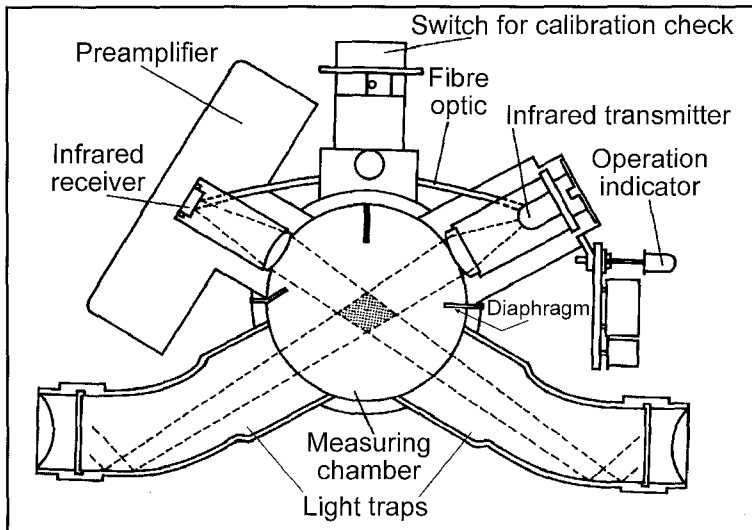


Figure 3 Schematic view of Hund Tyndalometer dust measuring system (After Hund¹³)

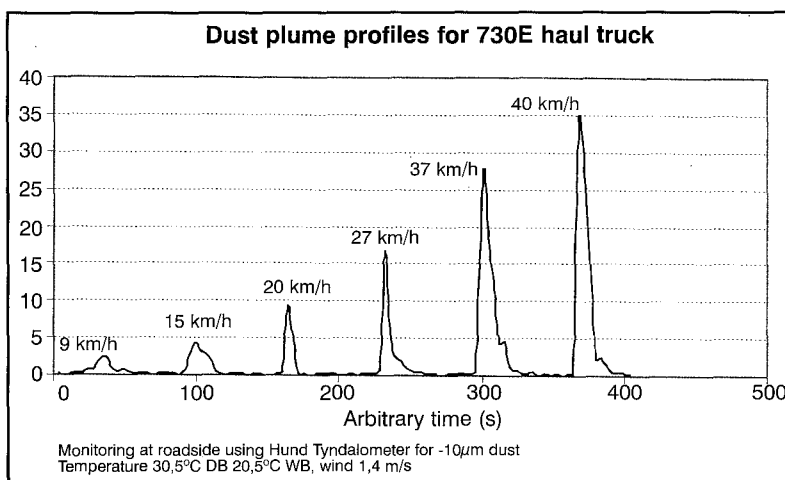


Figure 4 Dust plume profiles for 730E haul truck travelling at various speeds measured using single Hund Tyndalometer at roadside

Results were analysed in terms of the average dust concentrations measured for a number of vehicle passes, or individual passes over time where a degeneration profile was required. Conversion factors are normally required with which to correlate the optically measured results with that of the gravimetric method. The conversion factor was determined by conducting comparative measurements at the same time and same location with gravimetric air sampling equipment. Since the sample mass for one vehicle pass was low, the duration of the pass measurement was only 50 seconds (compared to the required eight hours gravimetric sampling) and the character of the dust between and at each test site may have changed with the application and subsequent degradation of the palliative, no reliable conversion factor was determined. However, it may be assumed that concentrations approximate closely to the control or base case readings taken and the minus 10µm dust fraction. In the analysis, results were reported in terms of a degree of dust palliation, to overcome the necessity to recalibrate for every type of dust

encountered. Figure 4 illustrates the dust generation profiles measured for a Komatsu 730E rear dump truck at various speeds on one particular mine road test section.

In the development of the dust defect scores, mine operating personnel's opinion was used to attach defect scores and descriptions to specific dust readings during the monitoring process. Figure 5 illustrates these defect scores (1-5), superimposed on a degeneration profile for water-based dust suppression. Table 1 summarises the defect score dust concentration ranges and descriptions.

Airborne Particulate Matter Quantitative Dust Sampling Methodology

The health risk associated with exposure to fugitive dust emissions from mine haul roads was assessed through a number of sampling exercises undertaken in mine haul truck cabs, over a

typical operating cycle. The methodology adopted was based on in-cab sampling of the respirable dust fraction concentration ($-10\mu\text{m}$) using the Hund Tyndalometer. Data were recorded for the following general hauling activities;

- Travelling on haul road (unladen)
- Travelling on ramp (unladen)
- Waiting, spotting and loading at loading area
- Travelling on ramp (laden)
- Travelling on haul road (laden)
- Waiting and tipping at dump or tip

Seven test sites were evaluated, covering a range of vehicle and haul road conditions. In each case, the road was evaluated in its dry base-case (unwatered or untreated) condition. In addition to the dust concentration, the following parameters, which could affect air quality in the haul truck, were also recorded;

- Number of vehicle interactions on the road (either following another vehicle or passing another truck in the opposite direction)
- Sealed (air conditioned) cab or open (windows open) cab
- Average time taken to complete each hauling activity.

To determine the typical AQI's that a haul truck driver would be exposed to during a typical cycle, a calculation procedure as specified in the Guidelines for the Gravimetric Sampling of Airborne Particulates for Risk Assessment in Terms of the Occupational Diseases in Mines and Works Act (78/1973) Parent Document¹⁵ was adopted. The sampling methodology did not conform to that outlined in the document since personal gravimetric sampling devices would not allow for intermittent reading and the interrogation of data for each specific activity. The data thus recorded should therefore not be seen as equivalent to that recorded by gravimetric means, primarily because the analysis assumes that the average values obtained over two repeats of the test (of approximately 30-60 minutes duration) and the associated AQI's will apply over a full shift.

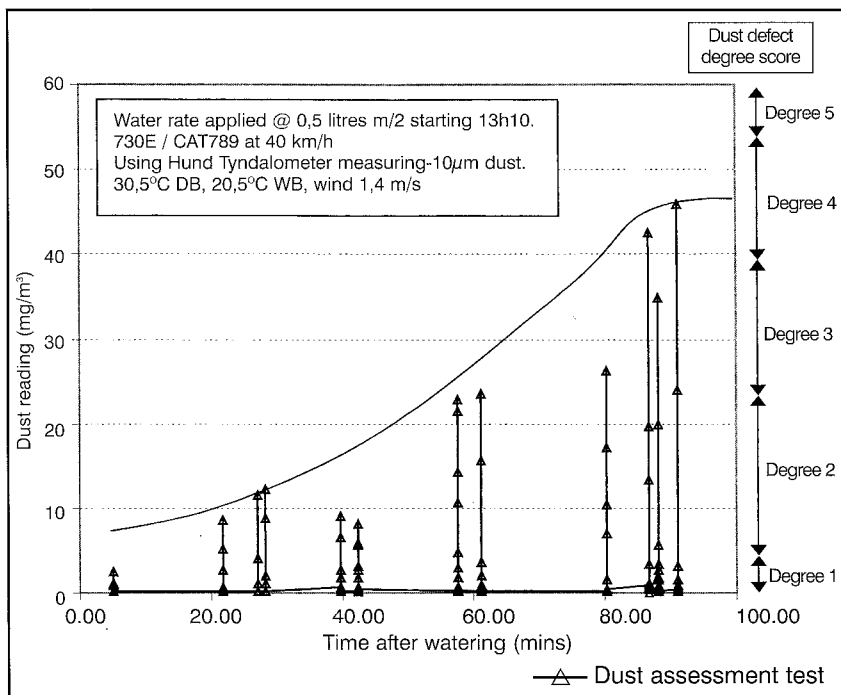


Figure 5 Typical dust increase with time for water-spray based dust suppression system and generic dust defect score ranges

Dust defect degree descriptions and associated Hund peak dust levels (approx. mg/m^3 for $-10\mu\text{m}$ dust per haul truck pass at 40 km/h)				
Degree 1 <3,50	Degree 2 3,51 to 23,50	Degree 3 23,51 to 45,00	Degree 4 45,01 to 57,50	Degree 5 >57,51
Minimal dustiness	Dust just visible behind vehicle.	Dust visible, no oncoming vehicle driver discomfort, good visibility.	Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking difficult.	Significant amount of dust, window closed in oncoming vehicle, visibility poor and hazardous, overtaking not possible

Table 1 Classification of the degree of haul road dust defect

Data relating to the specific pollutant threshold limit values was obtained from the Guidelines Document¹⁵ (Supporting Document No.2, 1994) for alpha quartz content data relating to samples, either taken on the mine for the same statistical population of which haul truck drivers are members, or from mine data in which similar wearing courses were used (in terms of weathering product). A threshold limit value time-weighted average concentration of 2,0mg/m³ of the respirable fraction was used where alpha quartz concentrations did not exceed 5%, otherwise a value of 0,1mg/m³ was adopted (for alpha quartz > 5%). AQI was calculated from the time-averaged dust concentration over the complete cycle of activities, using appropriate threshold limit values as outlined above.

The AQI was assessed in terms of the recommended good practice, inspection and cessation of work levels of <0,5, >1,0 and >5,0 respectively, for each of the sealed or open cab tests and for the individual components of the haul cycle, and following the approach outlined in the Draft Guidelines for the Compilation of a Mandatory Code of Practice for an Occupational Hygiene Program (No.1 Personal Exposure to Airborne Pollutants, Department of Minerals and Energy, draft amendment 6 of 1999)¹⁶.

WATER-SPRAY BASED DUST SUPPRESSION MODEL

Judicious watering assists in 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 adverse conditions where a combination of high temperatures, high wind speeds and low humidity are prevalent. These conditions necessitate more frequent watering to maintain dust control. The degree of dust control or palliation achieved with watering was a function of;

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

The management strategy for water-spray based dust suppression was based on user defined levels of dust defect acceptability, both from a health and safety point of view. Previous work by Thompson & Visser² established the functional defect acceptability limits for a number of

functional defects, amongst these dust, in terms of defect degree. 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 40km/h, as given in Table 1. In general, the consensus was that a dust defect score of two would represent a typical dust defect intervention level (the level of dustiness at which some remedial action would be required). This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact.

An approximate appreciation of the role of climatic conditions, expressed as mean monthly evaporation rates, on the time taken for water-spray based suppression to degenerate to zero was determined from a number of test sites over the range of typical summer and winter evaporation rates for stations in the climatic region N=2 to 5 (Weinert¹⁷). The test methodology involved the use of a Hund Tyndalometer to measure 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 role of climate, specifically evaporation rates, on this time. Figure 5 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 (base-case untreated road dustiness level) was found, assuming (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 yielded the formula;

$$X_0 = 286,8 - 0,73.E_m$$

Where;

X_0 = Time to zero palliation (mins)

E_m = Average monthly evaporation rate (mm/month)

This model has an R-squared value of 89%. For the standard error of the model of 27,1, the approximate 95% confidence intervals for a time to zero palliation of 184 minutes lie between 130 and 238 minutes. If time to zero palliation is considered in terms of the degree of palliation as a percentage of total dustiness, in typical winter conditions, for an average degree of palliation of 50%, re-application is required at approximately

3-hourly intervals whilst in summer, this is reduced to approximately 1½-hourly intervals. These rates are based on an average of 50% average degree of palliation which does not accommodate the road-user preferred dust defect limit of two, corresponding to a maximum dust concentration of 23,5mg/m³. To determine the re-application interval required under these circumstances and therefore eventually enable the cost-effectiveness of water-spray based suppression to be compared with other strategies, 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.

MODELLING DUSTINESS AS A FUNCTION OF WEARING COURSE MATERIAL AND VEHICLE SPEED

To provide an initial estimate of the dustiness associated with a particular wearing course mate-

rial, 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/m²) (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 2 summarises the independent variables used in the regression analyses. It should be noted that in applying the models, care should be taken not to exceed the range of parameter values used in deriving these models (Thompson & Visser®).

INDEPENDENT VARIABLE	DESCRIPTION
WCP425	Percentage of wearing course material passing the 0,425mm sieve
WCSP	Shrinkage product, defined as; $LS \times P425$ where LS= Bar linear shrinkage
WCP075	Percentage of wearing course material passing the 0,075mm sieve
LP425	Percentage of loose wearing course material passing the 0,425mm sieve
PKDST	Peak dust reading (x100 mg/m³) 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; $WSHEAR = \frac{SPD}{0,0036.GRCLEAR}$ 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
SPD	Speed of truck over test section (km/h)
VOL	Hourly traffic repetitions on haul road

Table 2 Independent Variables Used in the Regression Analysis of MASS and TOTDST

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

$$MASS = 4202,68 - 630,56.WCP425 + 1548,55.WCP075 + 78,75.WCSP - 392,19.LP425$$

This model has an R-squared value of 98%, F value of 684 which is significant at the 0,001% level for a sample size of 44. For the standard error of the model of 618,2, the approximate 95% confidence intervals for a mass of loose material (g/m² of road surface) of 6751 lie between 5514,6 and 7987,4. 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. The percentage of material passing the 0,425mm sieve is negatively correlated with the mass of loose material, both for wearing course and loose material samples.

For the regression of the independent variables on total dustiness, derived from consideration of the peak dustiness (mg/m³ -10µm dust) recorded per vehicle pass, the following model was selected;

$$TOTDST = 2,92.PKDST + 2260.TYPE$$

This model has an R-squared value of 95%, F value of 757,3 which is significant at the 0,001% level for a sample size of 73. For the standard error of the model of 2455,1, the approximate 95% confidence intervals for the total dustiness of 12 400 lie between 7489,8 and 17310,2. 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 similar or 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 larger 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;

$$TOTDST = SPD.(0,04.MASS + 38,33.WSHEAR + 0,12.GVM.WHEELS - 2.44.VOL)$$

This model has an R-squared value of 88%, F value of 70,7 which is significant at the 0,01% level for a sample size of 44. For the standard error of the model of 221,9, the approximate 95% confidence intervals for the total dustiness of 12 400 lie between 11 956,2 and 12 843,8.

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 and the removal of most loose material to the sides of the road. 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 individual 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.

When applying these models to a southern African strip coal mine operating a large fleet of rear-dump trucks running on a well built and maintained haul road and using water-based spraying for dust palliation, re-watering in typical summer conditions is required at approximately 30 minute intervals to maintain a dust defect that at no time exceeds a score of two. Under winter conditions, the re-application interval extends to approximately 50 minutes.

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 conditions. This aspect of the work is more fully developed by Thompson & Visser¹⁸.

EVALUATION OF HAUL TRUCK DRIVER EXPOSURE TO HAUL ROAD RESPIRABLE DUST

The health risk associated with exposure to fugitive dust emissions from mine haul roads was assessed through a number of sampling exercises undertaken in mine haul truck cabs, over a typical operating cycle. Seven test sites were evaluated in terms of the typical air quality indices (AQI's) that a truck driver would be exposed to during a normal working day, linking sources of dust to overall AQI contribution during the haul cycle. Using the previously established intervention level and re-application frequencies to generate an average degree of dust palliation, the impact of this reduced dustiness can be assessed in the light of expected improvements in the overall AQI.

Figure 6 summarises the results of the respirable dust assessments for a selection of seven test sites evaluated, following the experimental methodology and sampling procedures described earlier. The percentage contribution is shown for each cycle activity, calculated from the time-weighted average concentrations of respirable dust recorded. The percentage source contribution is shown, for both open and closed (sealed) cab conditions. When the specific road-related activities of travelling on the haul road and ramps, in both laden and unladen conditions is considered, it is seen that 48% of the total respirable dust emissions are generated from these sources for closed cab trucks. When the cab is open, this figure increases to 54%. Although closed cab conditions result in only a small percentage reduction over the open-cab conditions when analysed on a per source contribution basis, the reductions as a percentage of total respirable dust recorded are significant for the closed cab for a number of activity cycle components.

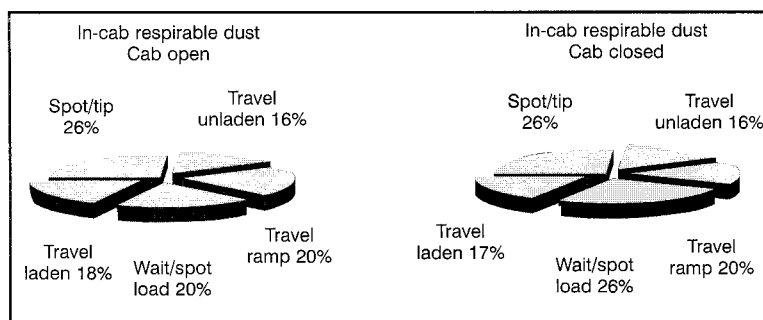


Figure 6 Source contribution of respirable dust concentrations measured in open and closed haul truck cab during typical hauling cycles

The data in Figure 6 was compiled from the time-weighted exposure averages of all test site activities combined and as such includes considerable variation from dusty wearing course materials and/or specific vehicle types. The exposure time in each assessment is also important since lower tonnage operations, employing shorter roads should report lower road-related exposure levels than would a high tonnage operation and longer haul roads. The number of vehicle interactions is an important factor in the analysis since the majority of dust exposure is generated from dust plumes created by other vehicles (except on the slower ascending or descending ramps areas where the truck is typically engulfed in its own plume). Figures 7 and 8 illustrate a typical dust test data set which shows the open-cab conditions recorded for loading, travelling, truck interactions and dumping (Figure 7) and the closed-cab conditions for a similar haul, also including two interactions (Figure 8). Only the loading, top of ramp (where the haul truck slowed and was engulfed in its own dust plume) and the dump points are comparable in terms of dust exposure

for the open and closed cab conditions.

The tendency of the wearing course itself to generate excessive dust was also a significant factor in the total dust exposure. With reference to two test sites A (high tonnage, large truck and long haul distance) and F (low tonnage, small truck, short haul distance), with a cycle time of 32 minutes, site A drivers were subjected to an AQI of between 1,5 and 3,7 at dump and load points whilst the corresponding AQI's at site F were 5,5 to 5,7. For the road component, site A AQI's lay between 0,1 and 0,7 whilst those of site F were between 2,6 and 3,3. It was anticipated that the effects of haul road length and fleet size (an indirect measure of tonnage hauled) would cancel out in the analysis, since low tonnage operations operating shorter roads with fewer vehicles would generate a similar number of interactions as a high tonnage operation with longer roads and more vehicles. This was confirmed from the testing, as only 2 to 3 oncoming vehicle interactions were observed in each test. However, to more reliably interpret the results, a more rigorous experimental design would be required in which the dependant variables are analysed at different levels. In each assessment at each site, readings were discarded when the recording vehicle either approached a vehicle ahead, or was overtaken by another vehicle. The decision to discard these readings was taken on the basis of observations of normal operating practice; haul truck drivers tended to space themselves on the road to avoid the worst part of the preceding vehicle's dust plume.

Figure 9 shows the variation in percentage source contribution for the open and closed cab measurements. From this Figure it was evident that the majority of exposure was attributable to loading and dumping activities with the haul roads and ramps themselves accounting for between 10%-15% each of the total exposure (open cab) and 5-10% each (closed cab). A 30%-55% reduction in dust concentrations measured in a sealed cab as compared to an open cab was realised for the haul road related activity cycles, only the wait/spot and load cycle activity demonstrating a smaller percentage reduction, primarily as a result of the operators opening the cab windows to improve rear vision when reversing towards the loader or dump point. These results, although in contrast to Amponsah Dacosta's³ work which established that haul road generated dust was the single most significant source of dust on a typical surface strip coal mine, are only related to a specific population's exposure to haul road generated dust and not the total dust generated (haul truck drivers only being exposed to their own vehicle's dust on ramp sections or when wind direction is coincident with, and exceeding the speed of, the truck).

Figure 10 summarises the data in terms of the

overall AQI for each test site evaluated. In general, haul truck drivers in open cabs were exposed to poorer quality air than their equivalents in sealed or closed cabs. For open cabs, the average AQI over a typical operating cycle was approximately 3,0 which exceeded the correction intervention level of 1,0. For sealed cabs, the average cycle AQI was generally less than 1 but not less than the established good practice level of 0,5. A combination of high traffic volumes, a wearing course material prone to dustiness, infrequent re-spraying of the road, high alpha-quartz respirable fraction content and dry loading or dumping conditions resulted in sealed cab AQI's exceeding 1,0.

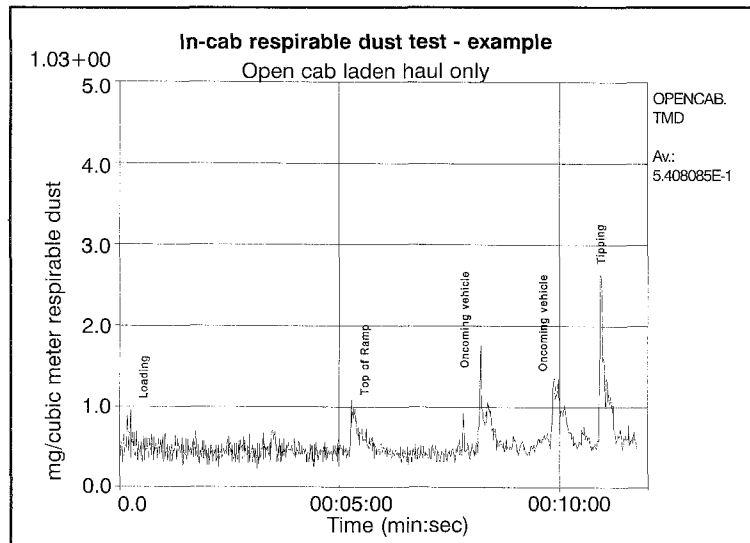


Figure 7 Laden haul respirable dust recording profile – typical readings from load to dump point for open cab conditions

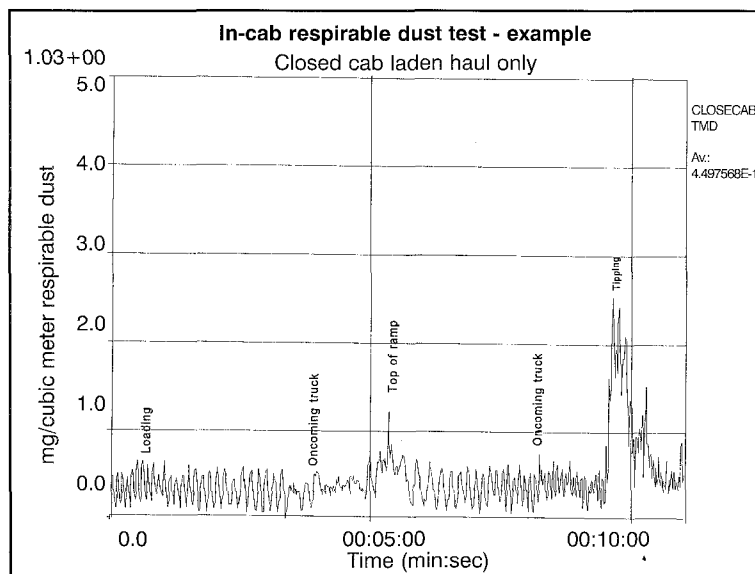


Figure 8 Laden haul respirable dust recording profile – typical readings from load to dump point for closed cab conditions

In summarising the evaluation of haul truck driver exposure to haul road respirable dust it was clear that, despite the limited data, basic experimental design and numerous assumptions implicit in the analysis of the data, it is unlikely that haul road generated respirable dust poses a significant threat to average air quality in the driver's cab, especially where sealed cabs are

used. In most large mine haul trucks, a sealed and air conditioned cab is a standard feature. The greatest contribution to dust generation was derived from loading and dumping points, combined with the fact that drivers tended to open cab windows to improve visibility whilst reversing. Further benefit could be gained from the use of wet scrubbers in the air conditioning system where ambient dust levels warrant concern, or where the dust, once inside the sealed cab, needs to be removed quickly.

Whilst the data would motivate against the use of dust palliatives purely on the grounds of improvements to air quality, the results should be viewed holistically with regard to the overall mine dust palliation strategy, more particularly, the control of the various dust sources and the safety aspects associated with reduced visibility on the road. Where low capacity open cab trucks are used, typically in low tonnage operations with short haul distances, in conjunction with inherently dusty wearing course materials (especially with high (>5%) respirable alpha-quartz fractions – typically fly-ash or high quartz sand content wearing course materials), palliation may significantly improve AQI's, especially if the benefits of palliation were extended to better dust control at the loading point, since on short haul trips, the time spent loading represents a greater proportion of the overall cycle time. The frequency of re-application of water-based palliation as discussed earlier entails considerable capital and operating expenditure. Coupled with the need to reduce dust from a safety perspective, the use of palliatives can still be motivated where water-spray tankers are re-deployed to reduce dust emissions, especially at the loading area. Excessive water in the loading area is problematic since it may lead to tyre damage where slow speed manoeuvring is required, but a fine mist applied to the loading face as it is exposed would obviate the need for short-term, high volume applications which lead to excessive run-off. Due to the dynamic nature of the loading face, effective suppression can only be realistically achieved by either the use of a dedicated water-car or releasing the water-car from haul-road dust suppression duties. The basis for such a re-deployment can now be determined from the combined dust emission and watering frequency models presented here, in combination with the identification of safety and health critical activities associated with truck-based transport on mines.

CONCLUSIONS

In any surface mining operation, the transport of ore, and to a lesser extent waste, is accomplished by large haul trucks running on haul roads that have, at best, been empirically designed with little or no recognition of the consequences of inadequate design on cost per ton

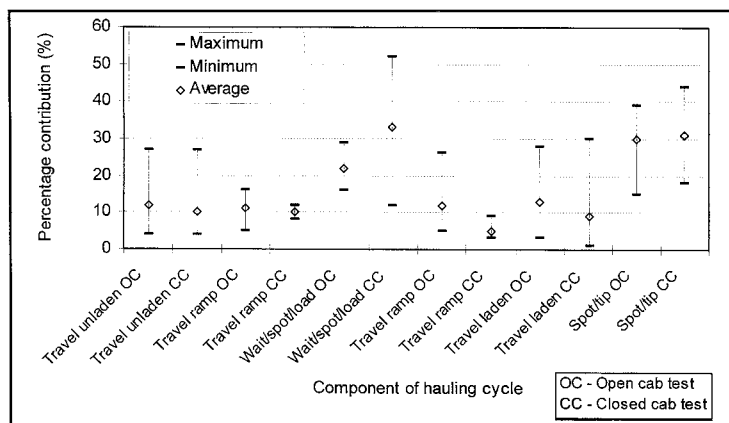


Figure 9 Variation in percentage source contribution to time-weighted in-cab (open and closed) respirable dust concentrations

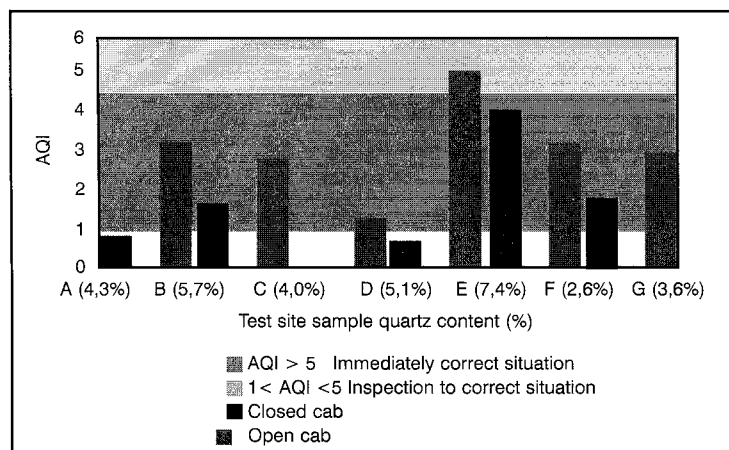


Figure 10 Summary of average cycle-time weighted AQI's for each test site and the associated alpha-quartz concentrations of the respirable sample

hailed, operational efficiency or safety. For existing operations, which may not have optimally designed and maintained roads, the problem of identifying a haul road dust defect, quantifying its impact and assigning priorities within the constraints of limited capital and manpower is problematic. This is reflected in the fact that most surface mine operators agree dust-free roads are desirable, but find it difficult to translate this into cost-effective betterment activities.

The development of an integrated evaluation methodology for truck generated fugitive dust emissions fulfilled the need for a structured approach to dust palliative performance assessment. The approach adopted in characterising and modelling airborne particulate matter generated from haul road 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 40km/h. The dust defect score approach enhanced the portability of the proposed assessment methodology and, with the objective of providing easily realisable 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, both from a health and safety point of view. 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 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 conditions.

The health risk associated with exposure to fugitive dust emissions from mine haul roads was assessed through a number of sampling exercises undertaken in mine haul truck cabs, over a typical operating cycle. The tendency of the wearing course itself to generate excessive dust was a significant factor in the total dust exposure. It was established that the effects of haul-road length and fleet size cancelled out in the analysis, since low tonnage operations operating shorter roads with fewer vehicles generated a similar number of interactions as a high tonnage operation with longer roads and more vehicles. However, to more reliably interpret the results, a more rigorous experimental design was recommended.

The majority of truck driver exposure was attributable to loading and dumping activities with the haul roads and ramps themselves accounting for between 10%-15% each of the total exposure (open cab) and 5-10% each (closed cab). A 30%-55% reduction in dust concentrations measured in a sealed cab as compared to an open cab were realised for the haul road related activity cycles, only the wait/spot and load cycle activity demonstrating a smaller percentage reduction, primarily as a result of the operators opening the cab windows to improve rear vision when reversing towards the loader or dump point.

It was clear that, despite the limited data, basic experimental design and assumptions implicit in the analysis of the data, it is unlikely that haul road

generated respirable dust poses a significant threat to average air quality in the driver's cab, especially where sealed cabs are used. However, whilst the data would motivate against the use of dust palliatives purely on the grounds of improvements to air quality, the results should be viewed holistically with regard to the overall mine dust palliation strategy, more particularly, the control of the various dust sources and the safety aspects associated with reduced visibility on the road. The basis for managing and reducing haul road dust emissions can now be determined from the combined dust emission and watering frequency models presented here, in combination with the identification of safety and health critical activities associated with truck-based transport on mines.

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