TRAFFIC-GENERATED DUST FROM UNPAVED ROADS: AN OVERVIEW OF IMPACTS AND OPTIONS FOR CONTROL

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Abstract

Over 70 per cent of the road network in sub-Saharan Africa remains unpaved. These roads will continue to form the greater part of road networks for the foreseeable future with the adverse impacts from traffic-generated dust being borne disproportionately by the rural and urban poor. The efficacy of dust control products is being studied in developed countries with large lengths of unpaved roads. However, quantitative data on the costs of dust impacts in developing countries and the benefits of longer-term solutions aimed at ameliorating them are scarce. Most trials on dust control in Africa involve the use of commercial products to stabilise gravel roads and control dust but these often fail to provide lasting benefit. This paper provides an overview of the available information on dust from unpaved roads, discusses the impacts of dust and options for its control and postulates the possible long-term consequences for people using and living near unpaved roads.

1. INTRODUCTION

Recognition of the close link between development and transport by development agencies is reflected in the continued support for transport sector projects. Transport services are considered to be essential for the social and economic development of poor rural and urban populations alike. The importance of the provision of transport services is recognised by the World Bank with 23% of its loans allocated to the transport sector. Transport is an intermediate service industry providing added value to investments in other sectors and contributing to economic growth.

Access to essential services by many people in developing countries is severely impeded by poor roads and the consequential poor transport services. It is estimated that some 1.2billion people do not have access to an all-weather road and that 40% - 60% are more than 8kms from a health centre. Transport is also now recognised as an essential ingredient in achieving the Millennium Development Goals (MDG) and is key for inclusive, sustainable globalisation to overcome poverty, promote growth, access challenges in fragile states and for Public Private Partnership. *(Juhel, 2008)*. Furthermore, transport costs are 9% of export values in developing countries compared with 4% in developed countries, which is a further inhibiting factor on economic growth. In Africa, 80% of the continent's goods are transported by road but the transport costs are the highest in the world, which in turn lead to increased costs to the community. All this evidence shows the critical role of roads and transport in development.

Good all-weather roads are an essential component in the provision of the reliable transport services required for safe access to markets, employment opportunities, education facilities, health centres, etc that comprise the components of social and economic development. The most durable roads are those in which the underlying materials are surfaced with wearing course materials bound with bitumen or tar or are surfaced with concrete or stone sets.

However, these roads are also the most expensive to provide in terms of initial costs. Consequently, 70 per cent of the road network in sub-Saharan Africa and most rural roads in other less developed regions of the world remain unpaved. In some countries in Africa, unpaved roads comprise over 90 per cent of the road network. High proportions of road networks in many Asian countries are also unpaved. One common characteristic of all unpaved roads is that they are a source of traffic-generated dust.

Considerable research has been undertaken related in some way to traffic-generated dust. Much of this work has been on the development of models to estimate dust emissions, the development of methods to measure dust and on dust control techniques and products. Most of the work on dust has been carried out in high-income countries such as the USA, Canada, Australia, New Zealand and middle-income countries such as South Africa, all of which have significant lengths of unpaved roads. Some examples for comparison purposes are shown in Table 1.

Table 1. Examples of road network composition (approximate)

Country	Total Road Network (km)	Length Unpaved (km)	Percentage Unpaved (%)
Ethiopia	46 000	39 000	85
Tanzania	87 000	81 000	93
South Africa	900 000	600 000	67
U S A	6 400 000	2 100 000	33

Apart from some areas in South Africa, road users and residents in these countries are generally far less exposed to the effects of fugitive dust than residents in developing countries. Yet it is in these higher income countries that most of the research on dust and dust control has been carried out, although studies have also been done in other countries (e.g. Chile, Mexico)

Many natural and commercial products are available for both the control of dust and for the stabilization of unpaved roads, which also tends to reduce dust emissions. However, the performance of some of the commercial products available often falls short of expectations and questions are often raised about the ways some of these products are marketed, especially in developing countries. In this paper, some of the work that has been carried out on dust and dust control is described with particular reference to developing countries and to the potential impacts of traffic-generated dust on communities living near and using unpaved roads.

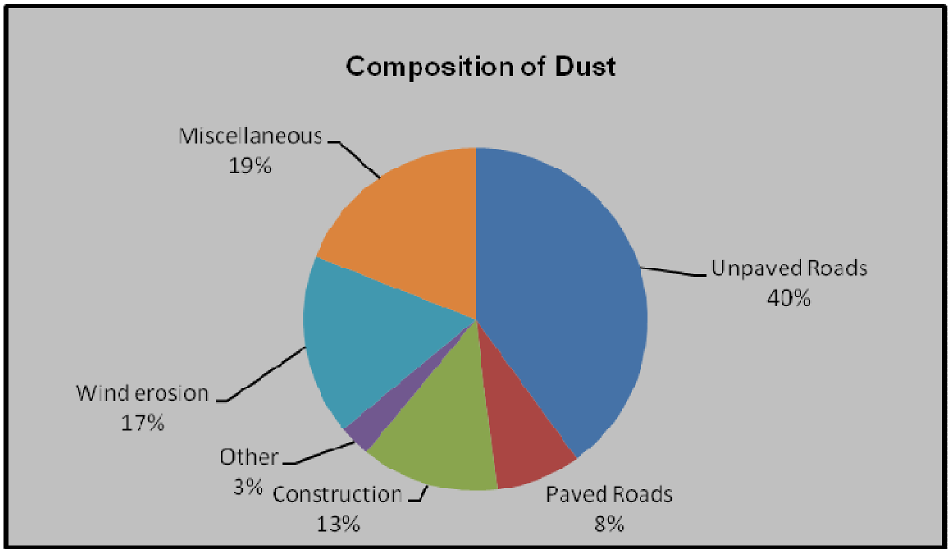
2. TRAFFIC-GENERATED DUST

The problems associated with airborne or fugitive dust are not new and have been studied in the USA since the 1970's. Sources of this dust include construction sites and agricultural land and paved and unpaved roads. Consequently, small amounts of dust are nearly always present in the atmosphere, especially in areas where the climate is dry.

2.1 Sources of airborne dust

Drought conditions and poor land-use practices can exacerbate the problem of dust from agricultural sources and in extreme situations can cause 'dust bowl' conditions as evidenced in the USA in the 1930's. Concern over the impacts associated with this event contributed to a major revision in agricultural practices in these areas of the country.

Various figures have been given for the amount of dust generated on gravel roads but the worldwide amount is thought to total over a billion tonnes annually.



Source: Fugitive Dust: Nonpoint sources. University of Missouri Extension

Figure 1. Example of the composition of dust

In South Africa, it has been estimated that dust generated on unpaved roads amounts to 3 to 4 million tonnes per annum. The composition of fugitive dust from various sources depends on a number of factors and will vary significantly between different localities. The *Environmental Protection Agency (EPA)* in the USA estimates dust emissions total 25 million tonnes per year with unpaved roads (approximately 10 million tonnes) as the single largest source of fugitive dust as shown in Figure 1.

Equations such as the one below have been developed to help estimate the volume of dust generated from unpaved roads.

$$E = [2.6\{(s/12)^{0.8}(W/3)^{0.4}\}/\{M/0.2\}^{0.3}] \times 0.2819$$

Where E = emission factor in kg/vehicle km, s = silt content (% surface material < 0.075mm)

W = average vehicle weight in tonnes, M = surface material moisture content (%)

The amount of fugitive dust at any given location is highly variable depending on surface characteristics, meteorological conditions, soil properties and other factors including traffic speed.

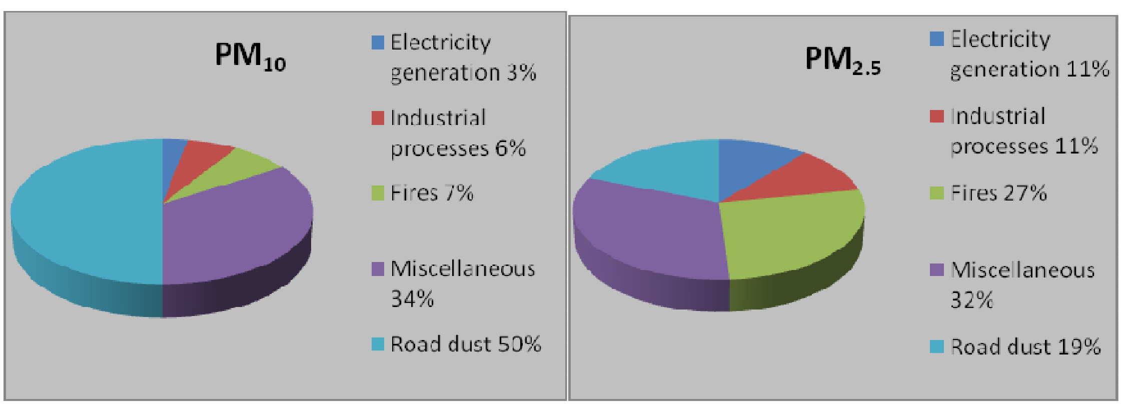
3. DUST AND AIR QUALITY

People worldwide are becoming increasingly aware of the impacts of various forms of pollution on their daily lives, on their livelihoods and on the environment. In most countries worldwide, an Environmental Impact Assessment (EIA) is now an essential requirement in road construction and rehabilitation projects. However, despite expressions of awareness and concern of the potential effects of traffic generated dust expressed by some senior government personnel in developing countries, virtually no studies appear to have been carried out to quantify the impacts of dust on local communities. Most of the available evidence in these countries is anecdotal and is not supported by quantitative data.

In the USA, the allowable amounts of particles in the air are regulated by the *EPA.* Airborne particles such as dust, dirt, soot, smoke and water droplets in the air are referred to as Particulate Matter (PM). Some particles are dark in colour and are sufficiently large to be seen as clouds of smoke or dust. Other particles are so small that they can only be seen with the aid of an electron microscope. Sources of PM include cars, trucks, buses, factories, construction sites, tilled fields, unpaved roads**,** fires, natural windblown dust and desert areas.

The amounts of fugitive dust of most concern that are present in the air are usually classified into two main size fractions, namely PM_{10} and $PM_{2,5}$ with aerodynamic diameters less than 10µm and 2.5 µm respectively. To give a comparative indication of size, the PM_{10} fraction (i.e. from 2.5µm to 10 µm) is about one seventh the diameter of a human hair and is referred to as the coarse fraction. The $PM_{2.5}$ fraction is referred to as the fine fraction. Both the PM_{10} and $PM_{2.5}$ fractions are invisible to the naked eye. The very coarse fractions larger than these are particularly evident in traffic-generated dust. The amount of this dust that is generated and then re-settles on the road surface depends on various factors including traffic speed, vehicle weight, local road conditions and rainfall. The strength and direction of the wind is a highly influential factor on its transportation.

An example of the typical source emissions of the PM_{10} and $PM_{2.5}$ components of fugitive dust is given in Figure 2.



Reproduced from Jones, James and Vitale

Figure 2. PM_{10} and $PM_{2.5}$ emissions by source

Unpaved roads provide an almost inexhaustible supply of dust. The coarser fraction has local road safety, agricultural and environmental impacts on travellers and on residents near unpaved roads. The finer fraction can be transported more widely with potentially highly damaging impacts to health as discussed later in this paper. The visible very coarse fraction that re-settles on the road surface is then also subjected to grinding and re-grinding by traffic to produce the coarse and fine particles as defined above. High volumes of surfacing material are available to be transported into the air as dust clouds and these may also contain other air-borne pollutants. High vehicle speed is an important factor in generating dust due to the increased transfer of energy disturbing the dust from the surface of the road and the greater turbulence which transfers a greater amount of dust into the air. *(Nicholson et al, 2000)*

3.1 Air quality standards

The EPA Office of Air Quality Planning and Standards (OAQPS) has set Air Quality Standards for six principle pollutants identified as 'criteria' pollutants. These are carbon monoxide, lead, nitrogen dioxide, particulate matter (PM_{10}), particulate matter ($PM_{2.5}$), ozone and sulphur dioxide. The standards for particulate matter are given in Table 1. *(USA Environmental Protection Agency, National Air Quality Standards).*

The Primary Standards limits are set to protect public health, including the health of 'sensitive' populations such as asthmatics, children and the elderly. Secondary standards limits are set to protect public welfare, including protection against visibility, damage to animals, crops, vegetation and buildings. The same values have been set for the primary and secondary standards for particulate matter concentrations.

Table 1 USA National Ambient Air Quality Standards

Pollutant	Primary and Secondary Standards	
	Level	Average Time
Particulate Matter PM_{10}	150µg/m^3	24-hour[(a)]
Particulate Matter $PM_{2.5}$	15.0µg/m^3	Annual Arithmetic Average[(b)]
	35µg/m^3	24-hour[(c)]

The annual and 24-hour concentrations of $PM_{2.5}$ particles in the USA decreased by 17 per cent and 19 per cent respectively between 2001 and 2008, which is thought to be directly attributable to the introduction of standards for air quality. *(EPA, 2010)*. Similar standards are in place for countries in the European Community with the aim of reducing the number of premature deaths related to fine particulate matter ($PM_{2.5}$) and ozone from 370 000 a year in 2000 to 230 000 by 2020 with estimated health benefits alone of €42 billion per *year. (Commission of the European Communities, 2005).*

Other countries are also imposing limits on airborne pollutants. It might be some time before developing countries adopt such measures but in many of these countries the impacts are more acute. As awareness of the potentially harmful effects of airborne pollution increases so will the demand for measures to be adopted to counteract them.

4. IMPACTS OF ROAD DUST

4.1 General

Whilst travellers along unpaved roads in high income countries are obviously inconvenienced by dust when they travel on unpaved roads and may also be exposed to health and road safety risks, these impacts tend to be relatively minor compared with the level of risk experienced by residents and regular unpaved road users in developing countries.

The main adverse impacts of traffic-generated dust from gravel roads are:

- Damage to the health of road users and nearby residents
- Reduced production from agriculture
- Increased risk of accidents for road users
- Increase in environmental damage through pollution

- Deterioration in road condition
- Increase in vehicle operating costs

In high income countries, relatively few people live as close to unpaved roads as do residents in developing countries. Road travellers are far less exposed, travelling as most do, in air conditioned vehicles or vehicles in which dust and other airborne agents are filtered out by ventilation systems. However, even in these countries, the problem is of sufficient concern for its impacts to be investigated, although there is also the additional driving factor of the commercial interest of the dust control industry and these two factors combined have resulted in the establishment of an annual conference in the USA on Road Dust Management.

In developing countries, road users in rural areas and poor urban areas predominantly comprise pedestrians, pedal cyclists, motor cyclists, users of motor-cycle-drawn taxis and users of other non-motorised vehicles (e.g. ox and donkey carts, hand-drawn carts, etc). These road users, who regularly walk or travel in open vehicles, will, in general, have a much higher frequency and degree of exposure to dust than users of unpaved roads in developed countries. People travelling in motorised transport in these countries often travel in the open in the back of vehicles such as 'pick-ups' or conventional trucks and are particularly exposed to dust generated both by the vehicle in which they are travelling and by other vehicles.

In rural areas of these countries, few people own their own vehicles so there is a natural tendency to build houses near roads which gives them access to passing trade and shorter journeys to markets and access to transport and other essential services. For much of the year, these dwellings and their occupants are almost constantly exposed to traffic-generated dust.

In urban areas too, it is often the poorest of the poor who are most affected as they tend to dwell in houses close to the road, often in informal settlements, and thus live and travel in areas where dust from unpaved roads and other potentially damaging pollutants are often most prevalent.

4.2 Health

Exposure to dust has, for many years, known to be hazardous to health. People exposed to road dust often complain of a general feeling of sickness. Perhaps this is not surprising given that over 20 different species of allergens have been identified in dust from paved roads together with other substances such as particles from tyres, brake linings etc. Consequently, it is suggested that the impacts from unpaved roads could reasonably be expected to be worse due to the added impacts of dust generated from the gravel road surface combining with these other pollutants. *Miguel and Class, 1999*.

Both the PM_{10} and $PM_{2.5}$ fractions of airborne dust are considered to be hazardous to health through ingestion into the respiratory system because they are sufficiently small to be able to pass through the nose and throat and enter the lungs. Particles larger than 2.5µm but smaller than 10µm (PM_{10}) can lodge in the upper respiratory area where they can be an irritant. The $PM_{2.5}$ component is considered to be the most injurious as these small particles can penetrate deeper into the human respiratory system and into the bloodstream and forms a significant proportion of the estimated 10 million tonnes of particulate matter emissions in the USA each year. Exposure to fine particles is associated with several serious health problems, including premature death, and adverse health effects have been associated with exposure to PM over periods as short as a day. People with various forms of heart or lung disease such as asthma are highly vulnerable, as are the young and the elderly.

In developing countries, these percentages are even higher due to the greater proportion of road networks that remain unpaved. For all rural road users, but particularly children, dust may well present a significant long-term health risk. Many children walk along rural roads each day to travel to and from school, and also live in villages served by unpaved roads. The degree of risk would certainly be assessed if similar circumstances were to prevail in countries of the developed world. Furthermore, some studies have suggested that in areas where these smaller particles are present, indoor levels can be as much as 70% to 80% of outdoor levels (*Chan-Yeung, 2000*).

The *World Health Organisation (WHO)* has published a table of the increased risks to health and on mortality rates from exposure to particulate pollution. Exposure to traffic-generated dust can reasonably be expected to further increase the risk of these individuals developing respiratory diseases, which is ranked as the 3rd highest in the 110 causes of death reported by the WHO.

Particular concerns are stated in *WHO* reports about the effects of long-term exposure, which is highly relevant to the circumstances of many residents in developing countries. The susceptibility of people to effects of air pollution has also been identified in the UK, with special reference made to vulnerable adults and to children. The latter are quoted as being particularly vulnerable as the process of lung growth and development continues until adolescence, and children have incomplete metabolic systems. *(UK Parliamentary Office of Science and Technology, 2006).*

Of further concern is that the effects of fugitive dust are likely to be additive to other particulate exposure such as from fires and other sources. These could be particularly relevant for many residents in developing countries where cooking on open fires is a common household activity. It is estimated that roughly half the World's population living in Asia, Africa and parts of Latin America use solid fuels for cooking. This also contributes to extremely high indoor concentrations of fine particle pollutants. Biomass smoke from cooking appliances in the developing world can result in exposure to concentrations as high as 3000µg per m^3 per day, which are estimated by the *WHO* to cause 1.5 million to 2 million premature deaths each year, predominantly amongst women and children. This is in stark contrast with the general average particulate concentrations in UK cities of between 15µg per m^3 and 35µg per m^3.

It is highly likely that impacts of long-term exposure to dust experienced by children and adults living close to and travelling regularly along unpaved roads will be additive to the high concentration levels from exposure to other sources of particulates (biomass fuels) that cause the 1.5 – 2.0 million premature deaths amongst mostly women and children in developing countries.

4.3 Road safety

The fact that dust is virtually always mentioned as a road safety issue in the context of unpaved roads seems to indicate that it is perceived by road users as a significant cause of road accidents. The contribution of dust as a possible contributory cause of road accidents in Africa was postulated over 30 years ago. *(Jacobs and Hutchinson, 1973).* An examination of police records of accidents taking place on murram roads suggested that poor visibility caused by dust was considered by drivers to be a significant factor. The police were also of the opinion that after staying behind a truck throwing up large volumes of dust for some time, drivers became reckless in attempting to overtake and either met an oncoming vehicle or drove off the highway. Dust from a preceding or passing vehicle can also obscure the view from a following vehicle of defects in the road surface such as corrugations or potholes which if, encountered at speed, can easily cause a loss of traction and control.

Evidence supporting loss of control as the main possible cause of accidents on gravel roads is provided in recent data from New Zealand *(Giummarra, 2009)* in which it was recorded that 65% of accidents were single vehicle, 71% were on curves, 61% of vehicles had run off the road and 40% were roll-overs.

Figure 3 Serious traffic accidents in Saudi Arabia caused by reduced visibility from dust

When dust storms hit built-up areas they can cause severe disruption and reduced visibility. The origins of this dust are clearly different than from gravel roads but the road safety implications of a relatively sudden and significant reduction in visibility on traffic from desert-blown dust can result in traffic chaos and road accidents. Not surprisingly dust storms are common in the Middle East and recent storms in Saudi Arabia involved a 20 vehicle pileup in Jeddah,as shown in Figure 3, killing three people and injuring 20.

Dust is rarely, if ever, included as a causal option on police reporting forms on road accidents, but it is undoubtedly a factor in some accidents on unpaved roads. From the limited data available, it can be conservatively estimated that 5 to 6 million fatalities and casualties annually (about 10% of all) occur on unpaved rural roads in developing countries. Road condition and dust are likely to be contributory causes of these accidents. Road accidents are estimated to cost some developing countries about 2% of GDP. If approximately 10% of these road casualties (fatal and injury) are from accidents on unpaved roads and 10 % of these are due to dust, then the cost of dust-related accidents could be about 0.02% of GDP or a cost to developing countries and emerging nations of around $800 million annually.

4.4 Agriculture

The effect of traffic-generated dust on agriculture might be less obvious to motorists but a walk into fields adjacent to unpaved roads often reveals the extent to which dust has been transported from a nearby unpaved road. Most of the studies of the impacts of dust on agriculture relate to visual evidence or to the measurement by weight of deposited dust. On green crops such as tea, the effects of dust are immediately obvious. The impact of dust on incomes of subsistence farmers with small plots adjacent to unpaved roads could well be significant but needs to be quantified through research.

Anecdotal and qualitative evidence from other projects in South Africa of the impacts of traffic-generated dust have been mentioned *(PhD thesis by D Jones)* which indicated trees in fruit orchards adjacent to unpaved roads were smaller and less productive than those further from these roads and that insecticides were also less effective in these areas. The additional costs of chemical spray were between about $500 and $750 per kilometre (at 1992 exchange rates). Other studies in New Zealand *(McCrae, 1984)* showed that crops were subjected to traffic-generated dust at a distance of between 25m and 250m from the road depending on the nature of the terrain and the direction of the prevailing wind. The main effects reported are:

- Reduced photosynthesis.
- Increased incidence of pests and disease.
- Hindered pollination.
- Reduced effectiveness of sprays.
- Downgrading of products and reduced yield
- Increase in animal health problems.
- Increased economic costs of agricultural production

Some tentative estimates of the potential cost impacts can be derived from the limited studies reported here. One worldwide estimate of the unpaved road network is approximately 13 million kilometres (*nationmaster.com*), Using this figure and a band width of influence of dust of 100m each side of an unpaved roadway, the total area of influence worldwide is then 2.6 million square kilometres. If only 5 percent of this area is under commercial cultivation or used for grazing or for subsistence farming, then the total area of productive land affected by dust is of the order of 13 million hectares. If the average loss to crops and livestock is just $20 per hectare, then the agricultural impacts of traffic-generated dust could amount to $260 million annually.

4.5 Environment

It is estimated that 150 million tonnes of gravel are lost from the 600 000kms of unsurfaced roads in South Africa every year producing some 4 million tonnes of dust in the process. *(Ministry of Transport, 2002).* Water sources located near unpaved roads are considered to be at risk of contamination and the development of algae in some lakes in the USA has been reported to be due, in part, to contamination by dust from nearby unpaved roads.

In many developing countries, roads through villages remain unsealed and vehicle-generated dust is a constant part of the lives of many villagers for much of the year. Dust is one of the main reasons given by rural dwellers for the wanting their roads to be sealed, especially roads through villages. In poor urban settlements served by unpaved roads, dust exacerbates the health and other problems associated with living in a crowded and poorly serviced environment.

Estimates of the gravel lost from unpaved roads and the dust generated in the process vary, but from the South African data the figure for gravel loss is of the order of 25 tonnes per kilometre per year. Of this, over 6 tonnes per kilometre per year is in the form of dust. This figure is in broad agreement with estimates from other countries. Without reliable data, it is difficult to cost the environmental impacts of traffic-generated dust. However, it is clear that there are likely to be significant consequences from the 80 million tonnes of dust generated annually from the estimated 13 million kilometres of unpaved roads worldwide, and potentially severe environmental impacts for people living close to these roads.

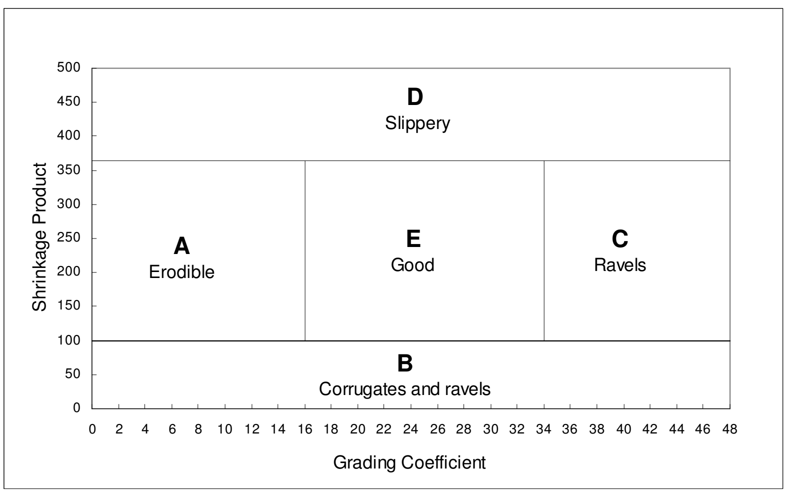
4.6 Vehicle operating costs

The main benefits to vehicles from sealing roads is a reduction in vehicle operating costs, with a large proportion of the benefits arising from a reduction in the consumption of parts and less frequent maintenance. These cost savings arise mainly from less tyre wear, fewer broken springs etc., due to the smoother running surface. However haulage fleet operators have also reported significantly reduced wear on other external moving parts and in vehicle engines as a result of reduced exposure to dust when road surfaces are sealed.

4.7 Road condition

The quality of materials used for the construction and maintenance of unpaved roads is an important factor in road performance and also a factor in the loss of pavement material including dust. Various but similar specifications have been developed for road materials through research by various organisations such as the UK Transport Research Laboratory (TRL Ltd), the Australian Road Research Board (ARRB), the Council for Scientific and Industrial Research (CSIR) in South Africa and various road authorities in the USA.

The fine clay component, which binds the materials in unpaved roads forms much of the component of the materials lost as dust. This changes the engineering properties of the road material and impacts on its performance, leading to potholing and high levels of roughness, which in turn leads to high vehicle operating costs. Considerable research has been undertaken on the performance of gravel roads and this has resulted in the recommended material specifications shown above and relationships developed that relate material properties to gravel loss. The consequences of using sub-standard materials are highlighted in the diagram in Figure 4. (*Paige Green, 1990).*



Reproduced from Paige-Green PhD thesis

Figure 4. Recommended materials specifications for unpaved roads

The depletion of material resources also has an indirect but significant relevance to the dust problem. The poorer the quality of the material the greater is the rate of gravel loss and the sooner the need for costly regravelling. Sources of good quality gravels for the construction and maintenance of gravel roads are becoming depleted. Haul distances to sources of good quality material increases costs and poorer quality gravels available locally are often the preferred option leading to an increased frequency in the cycle of deterioration and repair. Poorer quality materials also often tend to be weaker, abrade more rapidly and increase levels of dust.

In low-lying areas of some countries such as in the Mekong delta region of South East Asia, good gravel material suitable for road construction is extremely scarce leading to the unavoidable use of sub-standard material and rapid degradation. This results in roads which are virtually impassable in the wet season and extremely dusty in the dry season as shown in Figure 5. In these circumstances, the costs of maintaining roads to a reasonable standard can be expected to be high and there is often a strong economic case, based on life-cycle costs, for upgrading such roads to a bituminous standard.

Figure 5: Traffic-generated dust in South East Asia

5. MEASUREMENT OF DUST EMISSIONS

There is a significant difference between the measurement of road dust emissions at source and the measurement of general airborne particulate matter in relation to air quality standards, for which filtration methods are usually adopted. Various publications are available on measurement of airborne particulates of which road dust is a component. *(World Health Organisation/European Commission, 2004).*

The earliest measurements of dust were by gravimetric methods, usually derived from the weight of dust deposited in trays near roads in Kenya *(T E Jones, 1984)* or deposited in collection equipment in vehicle-drawn trailers. Studies have indicated losses due to dust as high as 300 tonnes per km per year. The Kenya study also demonstrated the influence of speed on the generation of dust. Measurements in the USA, (*Handy et al, 1975 and Hoover, 1981)*, indicated a corridor of influence at a distance of about 50m from the centre of the road but a figure of 300m has been quoted for some orchards adjoining unpaved roads in South Africa.

Some dust 'measurements' are carried out by visual estimation by the driver of a vehicle or a roadside observer ranking dust according to a given scale although such subjective approaches are less reliable than physical measurements. More sophisticated methods have been developed in recent years. These are based in sedimentation, filtration, photometric and infra-red technology. In his thesis *(D Jones, 2001)* a review is made of the advantages and disadvantages of the various measurement techniques.

6. DUST CONTROL

6.1 General

The use of products for dust control is problematic for the road engineer because of the large range of products available, the variability of the natural materials used in gravel road wearing courses, and the uncertainty of the durability and life-time benefits. Each product and material combination needs to be tested individually. This can require the use of non-standard engineering tests or, if these are unavailable, on information supplied by the supplier. This is clearly not a satisfactory situation for a number of reasons. An additional problem in developing countries, where product use tends to be unregulated, is that practitioners may find themselves under political pressure to use products which turn out to be of no engineering or economic benefit.

It should be noted that all roads are subject to wear by abrasion to some extent. It should also be recognised that dust palliative measures might reduce the rate of wear and dust emissions, but the impact of such measures are inherently transient with relatively frequent repeated applications required with some products. Thus whilst dust reduction is not in itself the main reason for sealing a road, sealing is generally recognised as a more permanent or long-term solution to solving the problem of dust than the use of palliatives, and it also has other long-term benefits.

The USA is probably at the forefront of work on dust although considerable work has also been done in other countries, including South Africa (*D Jones, P Paige-Green),* where extensive research on dust control and dust palliative products has been carried out. A number of publications *(e.g. Foley et al 1996, Addo, Sanders et al, 2004) also* give an overview of the options for dust control and comment on the effectiveness of various products in varying circumstances. A brief indication of some types of dust palliative products available is given here, but many publications are available on the beneficial results of the application of specific products. Perhaps, not surprisingly, very few reports tend to be published, where the result of their use has been less than effective. When failures are reported to suppliers, blame is usually based on incorrect application methods by local practitioners in the road industry rather than on the efficacy of the products themselves, or on their compatibility with the available road materials or with the local road environment.

Even in the 1980's many products claiming to have dust palliative credentials were available on the market. The report by the Australian Road Research Board provided the names of over 30 proprietary chemical dust palliatives available at that time. The descriptions given here on the types of additives available have been extracted from the Australian publication *(Foley et al, 1996)*, from South Africa work *(D Jones 2001)* and others *(e.g. Canadian Municipalities, 2005)* in order to provide a brief overview of the different mechanisms of the actions of dust reducing agents. The list is not exhaustive as new products with dust palliative properties are continually arriving on the market.

12.2 Bound paving

Research carried out by the Norwegian Road Research Laboratory has resulted in practitioners in Africa using Otta seals for rural roads. *(Norwegian Public Roads Administration, 1999).* The costs of this seal are similar to those of a surface dressing with the added advantage of the ability to utilise weaker aggregates. The Otta seal produces a highly durable layer similar to a thin premix so that aggregates in the surfacing are protected from point loading by traffic and a reduction in the exposed surface area of bitumen. This also reduces the susceptibility to oxidation and embrittlement of the binder.

The ability to use (weaker) locally-available material screened for use as surfacing aggregate in Otta seals makes this type of surfacing ideally suitable for sealing roads using labour-based technology.

12.3 Water

Spaying with water, if available, is a cheap but effective technique for suppressing dust. Unfortunately, the benefits are short-lived and frequent, almost daily, applications are required in the hot and very dry conditions typical of many areas where gravel roads are most prevalent.

Sea water or borehole water containing salts are considered to be more effective than salt-free water due to the hygroscopic and deliquescent properties of some salts.

12.4 Mechanical stabilisation

The blending of different materials is one option for producing a material with the desired properties. This operation adds to the costs. Material with similar properties will need to be available for maintenance purposes and the process is only feasible if materials suitable for blending are readily available.

12.5 Chemical suppressants

Hygroscopic salts

Many reports are available describing the actions of salts such as the chlorides of sodium, calcium and magnesium as dust palliatives. These salts are often available as industrial bi-products. Both hygroscopic and deliquescent materials are less effective at the low levels of humidity typical of many plateau regions of Africa and in many other places in the dry season, although some salts are reportedly ‘recharged’ if moisture becomes available, even in some cases just by heavy dew.

Research into the use of calcium chloride in South Africa indicated a significant reduction in gravel loss to between approximately 10% and 20% that of untreated sections, a significant reduction in blading frequency and a reduction in road roughness over a 12 month period. *(D Jones, 2001)*. A table containing a ‘product selection matrix’ is also given in the report.

If salts or salt-bearing water is used on a road as a temporary dust reduction measure before applying a bituminous seal, then this should be discontinued long before the seal is applied. Otherwise the migration to the surface of salts in solution is likely to result in damage to the primed surface *(Obika et al, 1995)*.

There are also some reports of gravel roads treated with salts becoming slippery when wet and some salts also tend to be corrosive.

Organic non-bituminous binders

These products include lignin sulphonates, which are mainly bi-products of the pulping industry and on which many reports are available. Other similar products also include molasses and pine tar. The action of these products is to glue together soil particles which leads to higher densities achieved by compaction.

(Addo, Sanders and Chenard, 2004) reported on the performance of trial sections using magnesium chloride and lignin and a combination of both on two different gravel wearing course materials. Interestingly, although the results showed some variability, the initial reductions in dust levels on the treated sections appear to be reversed significantly after a period of just over one year. The study concluded that the $MgCl_2$ sections in particular require two applications a year to be effective because these materials tend to be soluble, with their effectiveness being reduced due to leaching after heavy rain.

Petroleum-based binders

These comprise recycled waste oils, bituminous emulsions and tar.

Although longer-lasting than some other products, they often need ‘blinding’ with dust to avoid pick-up by vehicle tyres so that their application becomes relatively more difficult and costly.

Electro-chemical stabilisers

These include sulphonated petroleum products and various enzymes and are ionic stabilisers. Their action is relatively slow, often taking 20 days to achieve full impact from expelled adsorbed water that result in higher levels of compaction. Effectiveness is dependent on the type of clay present in the materials being processed and is also very construction as well as material dependent.

Microbiological binders

With these products, microbes act on the clay particles, whereby a polymeric residue is produced that acts as a binder. A high clay content is required for these products to be effective.

Polymers

Little information is available in the Australian report but these products are reported elsewhere as suppressing dust by cementation of the soil particles and may also provide control against moisture changes.

Overall conclusions on palliatives

The overall impacts of these products as dust suppressants can perhaps be summarized in three statements.

1. Water is the cheapest dust palliative when adequate supplies are readily available, but is the least effective over time with repeated frequent application required almost daily in some circumstances.

2. Sealing with a bituminous/aggregate surface dressing, is more expensive initially but is a longer lasting solution, can provide additional benefits to road users and may also be the most cost-effective in terms of life-cycle costs.

3. Chemical palliatives fall somewhere in between these extremes both in cost and in effectiveness, depending on the local circumstances (topography, climate, material properties, etc) and the product selected.

One of the problems with many of the proprietary products is that manufacturers are understandably reluctant to reveal their chemical composition. In countries such as the USA and South Africa, research has been undertaken that has resulted in increased knowledge on the composition of dust palliatives and about the way in which various products act on different road materials and in different environments. This knowledge, combined with greater awareness of any potential environmental damage they may cause, now means that the use of products with dust palliative credentials is controlled by guidelines and legislation in many states in the USA, and in some other countries with large unpaved road networks.

No such control exists in most developing countries.

Many chemicals do indeed exhibit properties that can help reduce dust as shown in the examples quoted previously. However, products sold in developing countries are often marketed by salespersons as cure-all solutions and they also tend to target hi-level politicians at ministerial or permanent secretary level. As a result of these experiences, the general impression of additives used as palliatives for dust control or for stabilisation purposes in many developing countries is that:

(a) They are expensive
(b) Their use may have environmental impacts
(c) Lasting improvement in road performance are rarely observed
(d) Any benefits are of short duration or are not readily apparent
(e) Their use is not cost-effective in life-cycle terms

It must also be stated that these impressions are not universal. In countries with better knowledge of the properties of proprietary products and of the circumstances in which they can be used effectively, their use has been found to be beneficial in reducing dust. However, although not primarily a dust control study, the results of a trial of seven products for stabilising a gravel road in Virginia *(Bushman, Freeman and Hoppe, 2006)* reported that 'the life cycle cost analysis indicates that constructing a standard bituminous treated roadway and maintaining it as such is much more cost-effective than using any of the products in the trial'.

There is, therefore, a need to identify and measure the impacts of the dust generated on gravel roads so that the benefits when these are ameliorated can be quantified in monetary terms and used to help justify upgrading these roads. This information would also help smaller scale targeted interventions (spot improvements) in specific problem areas where the impacts of dust are deemed to particularly hazardous. These could include sections of roads near schools, clinics and hospitals, through villages, etc or on sections of road near susceptible crops, or where dust is a road safety hazard, or where materials are particularly poor or where there is likely to be high environmental impact.

Advice to the engineer on the suitability of a palliative for dust control is sometimes biased. There are instances of products being recommended by suppliers even when they are clearly unlikely to be effective. Furthermore, the initial contacts by people marketing these products are often made at highly influential but non-technical levels of government with resultant considerable pressure being applied to engineers to use them. In many developing countries, this situation is exacerbated by the lack of regulation governing both the marketing and use of dust palliatives and on the possible environmental impacts from their use.

7. DUST IMPACTS IN INVESTMENT MODELS

It is evident that little or no quantitative data on any of the impacts of traffic-generated dust exists in most developing countries. However, the relatively few studies worldwide that have attempted to apply costs to these impacts is perhaps indicative of the difficulty of this task.

Some evidence from work in high income countries can be utilised in other countries but there are also significant differences between the impacts on residents and road users in developed and less developed countries. Relatively few pedestrians use unpaved roads in developed countries and vehicle occupants often travel in a closed or an air-conditioned environment protected from the worst effects of dust. The largest numbers of road users in the rural areas of less developed countries are pedestrians, motor cyclists and users of non-motorised transport such as bicycles, who are fully exposed to the effects of traffic-generated dust.

Models such as the HDM-4 analytical framework (Kerali et al.1996) are based on the concept of pavement life cycle analysis which predicts road deterioration, road works effects, road user effects and socio-economic and environmental effects. The social and environmental effects currently comprise vehicle emissions and energy consumption. These are often difficult to quantify in monetary terms, but they can be incorporated within the HDM-4 economic analysis if quantified exogenously. The effects of dust reduction could be included in the social and environmental effects. However, as with the existing components of vehicle emissions and energy, the difficulty is quantifying the effects of dust in monetary terms. For example, sealing an unpaved road will reduce the levels of dust from a presumably known level to almost zero. Quantifying the effects of this reduction say on health, agriculture, education, etc in monetary terms is the challenge. If investment models are to be effective, then it is important that all the cost components associated with road provision are identified and quantified. Therefore, it is important that the costs of the impacts of vehicle-generated dust, and the benefits when these effects are ameliorated, are quantified so that they can be included in road investment evaluation.

8. CONCLUSIONS

Quantification of the impacts of traffic-generated dust and the likely benefits when these are ameliorated is extremely difficult due to the absence of data, but even more so in developing countries. Therefore, pending further research on the subject, it is possible only to deduce what the impacts might be based on the limited evidence available. These are given below.

- Long-term exposure to dust has been shown to be hazardous to health. The young (including schoolchildren), the elderly and those suffering from heart or lung disease are particularly at risk.
- Traffic-generated dust can reasonably be expected to contribute to the 1.5 to 2 million people annually in low-income countries (mostly women and children), who die prematurely from the effects of exposure to high concentrations of airborne particulates.
- Impacts of dust from the estimated 13 million kilometres of unpaved roads worldwide can conservatively be expected to adversely affect some 26 million hectares of productive land (crops and grazing) worldwide.
- Reduced annual revenue to agriculture from the impacts of dust from unpaved roads could be of the order of $260 million. A significant proportion of these losses will be borne by subsistence farmers.
- In the absence of definitive data, it is conservatively estimated that 5 to 6 million (about 10%) of all road casualties (death and injury) occur on unpaved rural roads in developing countries and that road condition and dust are the two most likely causes of these road accidents.
- If dust is the cause of 10% of these accidents then the cost could amount to as much as 0.02% of GDP in some developing countries and total about $800 million annually.
- It has not been possible to determine the extent or cost of environmental impacts during the course of this project but these impacts are significant and will be additional to those described above.
- The available evidence suggests that the most cost-effective and durable form of dust control in life-cycle terms is a bitumen-based seal such as a surface dressing, Cape seal or Otta seal. Treatment with bitumen emulsion alone is less effective and is also prone to surface damage if the compaction water or gravel contains high levels of some salts.
- In circumstances where the marketing and use of dust palliative products is properly regulated, then these can provide interim relief from dust, although repeated application of such treatment might be necessary. The reliance on manufacturers for impartial advice on the suitability of dust control products remains a cause for concern in many developing countries.

- Although detailed information is scarce, it is clear that if the costs associated with the impacts of road dust and the benefits when they are ameliorated are properly costed and included in investment models, then it is likely that the sealing of many more unpaved roads could well become economically justified in life-cycle terms.

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