



# QUANTIFYING THE IMPACTS OF VEHICLE-GENERATED DUST: A COMPREHENSIVE APPROACH



©2011 The International Bank for Reconstruction and Development / The World Bank  
1818 H Street NW  
Washington DC 20433  
Telephone: 202-473-1000  
Internet: [www.worldbank.org](http://www.worldbank.org)  
E-mail: [feedback@worldbank.org](mailto:feedback@worldbank.org)

All rights reserved

This volume is a product of the staff of the International Bank for Reconstruction and Development / The World Bank. The findings, interpretations, and conclusions expressed in this volume do not necessarily reflect the views of the Executive Directors of The World Bank or the governments they represent.

The World Bank does not guarantee the accuracy of the data included in this work. The boundaries, colors, denominations, and other information shown on any map in this work do not imply any judgment on the part of The World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

#### Rights and Permissions

The material in this publication is copyrighted. Copying and/or transmitting portions or all of this work without permission may be a violation of applicable law. The International Bank for Reconstruction and Development / The World Bank encourages dissemination of its work and will normally grant permission to reproduce portions of the work promptly.

For permission to photocopy or reprint any part of this work, please send a request with complete information to the Copyright Clearance Center Inc., 222 Rosewood Drive, Danvers, MA 01923, USA; telephone: 978-750-8400; fax: 978-750-4470; Internet: [www.copyright.com](http://www.copyright.com).

All other queries on rights and licenses, including subsidiary rights, should be addressed to the Office of the Publisher, The World Bank, 1818 H Street NW, Washington, DC 20433, USA; fax: 202-522-2422; e-mail: [pubrights@worldbank.org](mailto:pubrights@worldbank.org).

Cover picture: Dave Jones

**QUANTIFYING THE IMPACTS OF  
VEHICLE-GENERATED DUST:  
A COMPREHENSIVE APPROACH**



The Transport Research Support program is a joint World Bank/ DFID initiative focusing on emerging issues in the transport sector. Its goal is to generate knowledge in high priority areas of the transport sector and to disseminate to practitioners and decision-makers in developing countries.

# CONTENTS

	<b>CONTENTS .....</b>	<b>V</b>
	<b>ACKNOWLEDGEMENTS .....</b>	<b>VII</b>
	<b>EXECUTIVE SUMMARY .....</b>	<b>VIII</b>
	<b>1 INTRODUCTION .....</b>	<b>1</b>
1.1	BACKGROUND .....	1
1.2	NEED FOR A NEW APPROACH .....	2
1.3	INFORMATION SOURCES .....	3
1.4	DATA AVAILABILITY .....	4
	<b>2 SOURCES OF DUST .....</b>	<b>7</b>
	<b>3 UNPAVED ROADS .....</b>	<b>13</b>
	<b>4 ENGINEERING INFLUENCES ON ROAD DUST .....</b>	<b>15</b>
	<b>5 IMPACTS OF TRAFFIC-GENERATED DUST .....</b>	<b>19</b>
5.1	GENERAL .....	19
5.2	10.2 HEALTH .....	20
5.2.1	<i>Summary of health impacts</i> .....	23
5.3	ROAD SAFETY .....	23
5.3.1	<i>Summary of road safety impacts</i> .....	28
5.4	AGRICULTURE .....	31
5.4.1	<i>Summary of agricultural impacts</i> .....	34
5.5	ENVIRONMENT .....	35
5.6	OTHER IMPACTS .....	36
	<b>6 MEASUREMENT OF DUST EMISSIONS .....</b>	<b>38</b>
	<b>7 DUST CONTROL .....</b>	<b>41</b>
7.1	GENERAL .....	41
7.2	BOUND PAVING .....	42
7.3	WATER .....	43
7.4	MECHANICAL STABILISATION .....	43
7.5	CHEMICAL SUPPRESSANTS .....	43
7.5.1	<i>Hygroscopic salts</i> .....	43
7.5.2	<i>Organic non-bituminous binders</i> .....	44
7.5.3	<i>Petroleum-based binders</i> .....	45
7.5.4	<i>Electro-chemical stabilisers</i> .....	45
7.5.5	<i>Microbiological binders</i> .....	45
7.5.6	<i>Polymers</i> .....	46
7.5.7	<i>Others</i> .....	46
	<b>8 FUTURE TRENDS .....</b>	<b>49</b>
	<b>9 COSTS OF UPGRADING ROADS .....</b>	<b>50</b>
	<b>10 DUST IMPACTS IN INVESTMENT MODELS .....</b>	<b>52</b>

<b>11</b>	<b>OUTCOMES OF DISCUSSIONS WITH SELECTED COUNTRIES.....</b>	<b>53</b>
11.1	GENERAL .....	53
11.2	TANZANIA.....	53
11.3	ETHIOPIA .....	54
11.4	SOUTH AFRICA.....	54
11.5	CAMBODIA .....	54
11.6	LAOS.....	55
11.7	THAILAND .....	55
11.8	CONCLUSIONS FROM COUNTRY DISCUSSIONS.....	55
<b>12</b>	<b>SPOT IMPROVEMENTS.....</b>	<b>57</b>
12.1	CONSTRAINTS ON DATA AVAILABILITY FOR QUANTIFYING AND COSTING IMPACTS .....	58
<b>13</b>	<b>DISCUSSION AND RECOMMENDATIONS .....</b>	<b>60</b>
<b>14</b>	<b>CONCLUSIONS.....</b>	<b>63</b>
14.1	SUMMARY OF CONCLUSIONS.....	64
	<b>REFERENCES .....</b>	<b>66</b>
	<b>LIST OF ABBREVIATIONS.....</b>	<b>70</b>
	<b>LIST OF TABLES</b>	
	Table 1: USA National Ambient Air Quality Standards .....	10
	Table 2: Percentages and number of countries where surfaced roads are below given value of the road network.....	14
	Table 3: Specifications for gravel wearing course .....	15
	Table 4: Global Burden of Disease .....	22
	Table 5: Potential financial losses in the fruit industry in South Africa.....	32
	Table 6: Visual rating for road dust.....	39
	Table 7: Comparison of Phase III device and Static SA Dust Monitor.....	40
	Table 8: Dust Measurements.....	45
	Table 9: Cost of dust suppression by use of various paving treatments .....	48
	<b>LIST OF FIGURES</b>	
	Figure 1: Example of composition of dust .....	7
	Figure 2: Figure 2 PM <sub>10</sub> and PM <sub>2.5</sub> emissions by source .....	9
	Figure 3: Serious traffic accidents in Saudi Arabia caused by reduced visibility from dust .....	12
	Figure 4: Recommended materials specifications for unpaved roads.....	16
	Figure 5: Traffic-generated dust in South East Asia .....	18
	Figure 6: Large commercial vehicles produce the most dust.....	21
	Figure 7: Salt blister damage to a primed surface in Botswana .....	44

# ACKNOWLEDGEMENTS

The study, “Quantifying the Impact of Vehicle Generated Dust: a Comprehensive approach” was prepared for the World Bank Transport Anchor group (TWITR) in Washington which administers and manages the Transport Research Support Program, TRSP, a financing of DFID, the Department for International Development of the United Kingdom Government.

We would like to express our thanks to Tony Greening, who was contracted to provide the framework and the technical content. Peter O’Neill, Infrastructure Advisor, TWITR provided guidance and advice throughout the preparation of the study.

## EXECUTIVE SUMMARY

### 1.1 Main findings

Despite the potentially damaging impacts of the cumulative effects of dust on health (particularly children) and the potentially costly impacts to agricultural production, road safety and the environment, quantitative data on the impacts of dust from unpaved roads is extremely scarce. This is especially so in developing countries where these impacts are likely to be greatest. Therefore, it has been possible only to make some tentative observations from the limited information available during the course of this study.

These are:

- Long-term exposure to traffic-generated dust can reasonably be expected to contribute to the 1.5 to 2 million people (mostly women and children) annually in low-income countries, 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 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 low-income countries.
- 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 certain salts.

- In circumstances where the marketing and use of dust palliative products are properly regulated, then these can provide interim relief from dust impacts at lower initial capital costs than a bituminous seal, although repeated application of such treatment might be necessary. The reliance on manufacturers' representatives for advice on the appropriate use and efficacy of dust control products and lack of regulation on their use 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.

## 1.2 Project Summary

The author was commissioned by the World Bank to undertake a study to attempt to collate information on the identification of the impacts of traffic-generated dust. The ultimate objective (beyond the scope of this project) is to quantify the costs of these impacts and the potential benefits when they are ameliorated when unpaved roads are upgraded to a sealed standard. Quantifying the cost and benefits associated with traffic generated dust will enable them to be included in investment appraisal modelling carried out in connection with Bank loans for projects in the road sector in developing countries.

An extensive literature search, consultation with experts in the sectors in which road dust may have an impact and discussions with representatives of developing countries has indicated that there appears to be universal agreement that dust generated by unpaved roads is a problem. The level of concern in countries like the USA is such that an annual conference to discuss dust control has been initiated.

There is increasing awareness and concern of the potential adverse impacts of dust on health, agriculture, road safety and the environment in high and middle income countries with significant unpaved road networks. Numerous studies on the costs and efficacy of various products aimed at reducing road dust have been undertaken in countries such as the USA, Canada, Australia, New Zealand and South Africa. Far less work appears to have been done in quantifying the cost impacts on people and on their livelihoods.

Few data are available on the cost impacts of dust in general and virtually no quantitative data on the impacts or costs are available for developing countries. This lack of available data has constrained the delivery of some of

the anticipated project outputs. It is clear that a further phase of the work will be necessary in partnership with selected countries and experts from other sectors to collect, collate and analyse the data required to fully meet the required outcomes.

Traffic-generated dust from gravel roads is comprised of various size fractions, the largest of which are re-deposited on the road to be re-entrained and pulverised into smaller fractions by traffic. The smallest particles tend to be suspended for longer, can be transported longer distances from their origin and have potentially damaging health impacts. The larger particles can also cause damage to crops, the environment and cause accidents through reduced visibility.

In developed countries with significant lengths of unpaved roads, pollution by dust from gravel roads is recognised as a contributory factor in the composition of airborne particulates and air quality. In some of these countries, standards have been set for air quality including the  $PM_{10}$  and  $PM_{2.5}$  particulates, which are present in dust generated from gravel roads.

Most developing countries have large unpaved road networks sometimes comprising over 90% of the total road network. Travellers and residents in these countries have greater exposure to traffic-generated dust than those in developed countries and the impacts will be greater.

Awareness of the possible adverse impacts of long-term exposure to dust, especially by children, is increasing in many developing countries. Women and children are reported by the WHO to being exposed to a concentration of airborne particulates that is over 100 times greater than the standards set in the USA, even without the additional impacts of dust.

Dust is rarely included in the list of causes of road accidents on police reports. Consequently data directly relating dust to road accidents are scarce. However, dust is invariably included as having an adverse impact on road safety which clearly implies that drivers and other road users clearly perceive it as being so. Slow-moving road users such as cyclists, ox-drawn carts as well as pedestrians, who are often the main users of rural unpaved roads, are particularly vulnerable when obscured by dust generated by passing motorised traffic.

The effect of dust pollution on crops at a considerable distance from unpaved roads is often evident visually. Some attempts have been made to estimate the probable costs impacts of dust on agricultural products (e.g. New Zealand, South Africa) and these could indicate the approach for future studies, including the impact on subsistence farming.

There is little direct evidence on the costs of the environmental impacts of dust although the consequences for those living near unpaved roads are evident as

is the likely contamination of nearby water sources and water storage facilities.

The need to supply increasing amounts of gravel for the construction and maintenance of gravel roads invariably leads to a need for more quarries to be opened with the inevitable increased environmental impacts from dust on people and on the landscape.

All gravel roads abrade to some extent to produce dust. Roads constructed with good quality materials combined with appropriate design, construction and maintenance tend to reduce dust emissions. Unfortunately, good quality gravels for road building are simply unavailable in parts of some countries and are becoming scarce in many others. Declining availability of this non-renewable resource leads to the use of poorer quality materials, increased frequency and the cost of maintenance and more dust. Various methods of dust measurement are available both for use at the source of dust emissions and in the general environment.

The most effective and conventional long-term method of reducing dust is to seal the road surface with a layer of surface dressing, asphalt or concrete. These measures are the most expensive initially but may also be the most economic in terms of life-cycle costs. Other longer term solutions could include the more unconventional surfacing.

The use of a dust palliative requires lower initial investment but their efficacy is often short-lived, requiring frequent re-application. Some products are water soluble and a number of products need repeated application. These products operate in different ways which can result in an increase in strength as well as in a reduction of dust in some circumstances. Knowledge of the properties of materials being treated and of the road environment in which the chosen product is likely to be used are essential, if application is to be of economic benefit. There is conflicting evidence on the costs effectiveness of these additives. A trial of seven chemical additives in the USA indicated that the construction of a road with a standard bituminous surface was more cost-effective in life cycle terms than any of the chemical additives used in the trial.

Therefore, in countries where their use is regulated and financial sources are unavailable for conventional sealing, dust palliatives can yield an effective, if generally less permanent solution and many publications are available on their costs and effectiveness. However, a serious problem exists in the marketing and use of dust palliatives in many developing countries where their use is unregulated. This situation is open to exploitation by some unscrupulous salespersons and just one of many such experiences is given in this report. Furthermore, funding for repeated application, where this is necessary, might not always be available.

Practitioners in the road sector in a number of developing countries are justifying the upgrading of rural roads at lower traffic levels than hitherto thought possible through the application of the results of research combined with a life-cycle approach to investment. Alternative surfacings such as Otta seals, block paving, fired brick paving, stone setts, unbound macadams, etc are amongst many alternatives which are being considered by engineers.

The HDM<sub>4</sub> model is designed to forecast the costs and benefits from investment in various design and maintenance options for road projects and this has also led to other models such as RED, in which costs and benefits to non-motorised traffic can be included. However, many benefits to poor rural communities from road schemes are non-traffic related and these include benefits from dust reduction. The life-cycle approach to investment is also increasingly being used on roads constructed by labour-based technology. Outline data requirements for incorporation of dust costs and benefits in investment models are included in this report.

Quantitative data on dust impacts would also help justify strategic targeted interventions (spot improvement) projects such as through villages, near schools and in other situations in which dust impacts are greatest and these interventions also tend to yield high economic benefits.

Discussions with organisations in countries in Africa and Asia to determine the level of interest and concern in the impacts of road dust and to identify possible partners in any follow up phase of the project show considerable interest and willingness to participate and contribute in any research that might be undertaken.

Recommendations have been made for a future phase of this work if attempts are to be made to quantify comprehensively cost the impacts of traffic generated dust in partnership with developing countries. The recommendations include the formal involvement of specialists in the health, agriculture, environment and road safety sectors, the need for committed support from country partners and an approximate estimate of the costs of such an exercise.

# 1 INTRODUCTION

This project can be considered to be an initial process leading to the ultimate objective of identifying and assigning costs associated with the impacts of vehicle-generated dust so that the benefits can be quantified, if these impacts are ameliorated through actions such as the provision of a sealed road surface.

The report outlines the background to the project, the results of the review process, describes the need for a comprehensive approach and identifies and provides some provisional estimates of the possible impacts of traffic-generated dust on road safety, health, agriculture and the environment.

The objectives of the project, the achievements made, the problems encountered and the findings to date are described. The report outlines the overall approach that has been undertaken to achieve the stated aims of the project in relation to the available data. The outcomes from discussions with prospective developing country partners are reported together with the results of correspondence and discussions with other professionals.

Recommendations and conclusions are made on the work undertaken to date.

An outline methodology and Terms of Reference are provided for a follow-up study.

## 1.1 BACKGROUND

The World Bank commissioned this project in recognition of the need to identify the benefits from investments in the improvement of rural road networks, which provide access to transport and other services that are essential to the socio-economic development of poor communities in developing countries. On more highly trafficked roads, the main benefits are economic and arise from a reduction in road user costs (mainly from reduced roughness) whilst social and other non-vehicle-related benefits tend to form the major proportion of the benefits from investments in rural roads. One component of these benefits is a reduction from the various impacts of traffic-generated dust when these roads are sealed.

In order to identify the impacts of traffic-generated dust and the way forward in the context of this study, it has been necessary to undertake a review of the

factors influencing the generation and impacts of dust from unpaved roads. These include:

- Examination of the reasons that traffic-generated dust may be a problem
- A review of how dust can be measured
- Identification of the potential impacts of dust
- Examination of ways in which impacts might be ameliorated
- Determination of the availability of quantitative information on impacts
- Determination of the availability of information on costs and potential benefits
- Reporting discussions with prospective country partners
- Reporting findings and making recommendations for a follow-up phase

## 1.2 NEED FOR A NEW APPROACH

The need for a holistic approach to the problem has been suggested in the past but most publications on traffic-generated dust relate to chemicals that can be used for its suppression rather than on quantifying the impacts.

In India, a large-scale programme initiated by the Prime Minister is underway in which roads connecting 172 000 rural villages are being upgraded, although 80% of roads remain unsurfaced (*Kapaley, 2008*). In the countries of Sub-Saharan Africa, between 70 and 80 per cent of the road network remains unpaved and in many other developing countries around the world, gravel roads will continue to be the chosen method of providing rural access for many decades in the future.

It has been pointed out that many roads in developed countries such as the United States of America (USA) also remain unsealed and an information search shows that considerable work has been carried out in the USA and elsewhere on dust generated by traffic travelling on unpaved roads. Some of these roads are treated periodically with chemical dust suppressants, some generated as bi-products from nearby farm activities or bi-products from the oil and paper industries. In developing countries, products marketed as dust palliatives are mostly imported

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.

There is increasing appreciation in developing countries of the road network as a national asset and of the need to manage the network so that it is in a condition that facilitates the provision of cost-efficient transport services. Models such as the Highway Design and Maintenance Model, (Kerali, Robinson and Paterson, 1996) provide a useful tool in assisting this process. There is also now a greater understanding of the need for a whole-life cost approach even in the provision of rural roads, if investments in roads are to produce sustainable benefits. As gravel resources become depleted, haul distances for road construction and maintenance costs increase and this also helps lower the threshold traffic levels for the economic upgrading, in life-cycle terms, of gravel roads to roads with surfaces that facilitate all-weather access.

If investment models are to be effective, then it is important that all the cost components associated with road provision are identified and quantified and significant progress has been made through research in reducing the cost of sealed road provision. However, the quantification of the social and other non-vehicle related benefits associated with upgrading these roads has proved to be more elusive. To this end, the World Bank and others are attempting to quantify these social and other benefits, such as the impact of traffic-generated dust, in economic terms.

It is evident that gravel roads will form a significant portion of rural road networks for some time to come and the adverse impacts of traffic-generated dust will continue to be disproportionately borne by the rural and peri-urban poor. 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.

Whilst traffic-generated dust is a transport related problem, it is a potentially serious environmental hazard with adverse impacts on health, agriculture and road safety. An assessment of the scale of the problem would provide useful guidance on follow-up actions. Research aimed at quantifying the impacts will need collaboration between experts in environment, transport, health and agriculture.

### 1.3 INFORMATION SOURCES

There are many hundreds of references on dust. *The Air Pollution Engineering Manual* published by John Wiley and Sons in 2000 contains over 140 references in the chapter on Fugitive Dust. Not all references on fugitive dust are relevant to gravel roads, although over 150 publications, articles and presentations have been accessed during the course of this project. Whilst a number of these publications have provided useful information, few give any quantitative data on the impacts of dust. Even fewer refer in any way to the possible impacts on people in developing countries or provide data on the costs of dust impacts on people living in rural and poor urban communities.

An extensive review of the information that is available reveals that there has been considerable research undertaken that is 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.

Although these countries have significant lengths of unpaved road networks, road users and residents in these countries, apart from some rural and poorer urban areas of South Africa, are generally far less exposed to the effects of fugitive dust. Yet it is in these higher income countries that nearly all the work on dust impacts has been carried out.

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 in these countries. Most of the available evidence in these countries is anecdotal and is not supported by quantitative data.

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. An Environmental Impact Assessment (EIA) is now an essential requirement in most road construction and rehabilitation projects, especially those funded by donor agencies. Air quality is already a major concern in some developed countries with standards being set to control emissions. The benefits of such controls on air quality are evident. Dense 'smog', which was composed of water droplets (fog) and particulate matter (mainly smoke from coal fires) used to be a common and life-threatening event in urban areas in the Winter months in Britain but these diminished significantly when smoke-free zones were established and such events are now extremely rare due to regulation governing smoke emissions and the decreased general use of coal fires for home-heating.

Dust in developing countries is accepted by many people as an inevitable nuisance, although awareness is increasing amongst the public and professionals in the relevant sectors alike, of the potentially damaging health and other impacts of traffic-generated dust. This increased awareness together with the expectations of improved conditions by poor communities is likely to lead to a demand for increased information on the effects of dust on residents and travellers and for action to diminish its impacts.

## 1.4 DATA AVAILABILITY

Whilst some of the work that has already been carried out on dust impacts in developed countries might be transferable in part to developing countries, it is



clear that the differences in the scale of the problem, differences between the affected population groups and scarce funding for remedial measures means that there is a need for a comprehensive study on dust impacts to be carried out in partnership with developing countries.

The current project was undertaken to identify possible dust impacts but it was also anticipated that some quantitative evidence would be available in developing countries and that the main need would be for partnership projects to be established to refine, confirm and calibrate existing information. However, it is now evident that little or no data on any of the impacts of traffic-generated dust exists in these countries. There is, therefore, a need to undertake a comprehensive investigation into the impacts of dust on the poor in partnership with selected countries overseas. This will require additional resources to those allocated in the current project. Recommendations for the outline methodology for such a project and a draft 'Terms of Reference' for a possible Phase II are provided in this report.

Traffic-generated dust is primarily a transport and road engineering related problem but the impacts are cross sectoral. Whilst some experts in the relevant sectors have been consulted and have helped in accessing information for the current study, it is clear that should a project be undertaken with developing countries then more formal inputs will be required from experts in these other sectors (e.g. health, agriculture, the environment and road safety) both in the management team and in the partnering countries if the impacts of dust are to be comprehensively addressed and quantified.

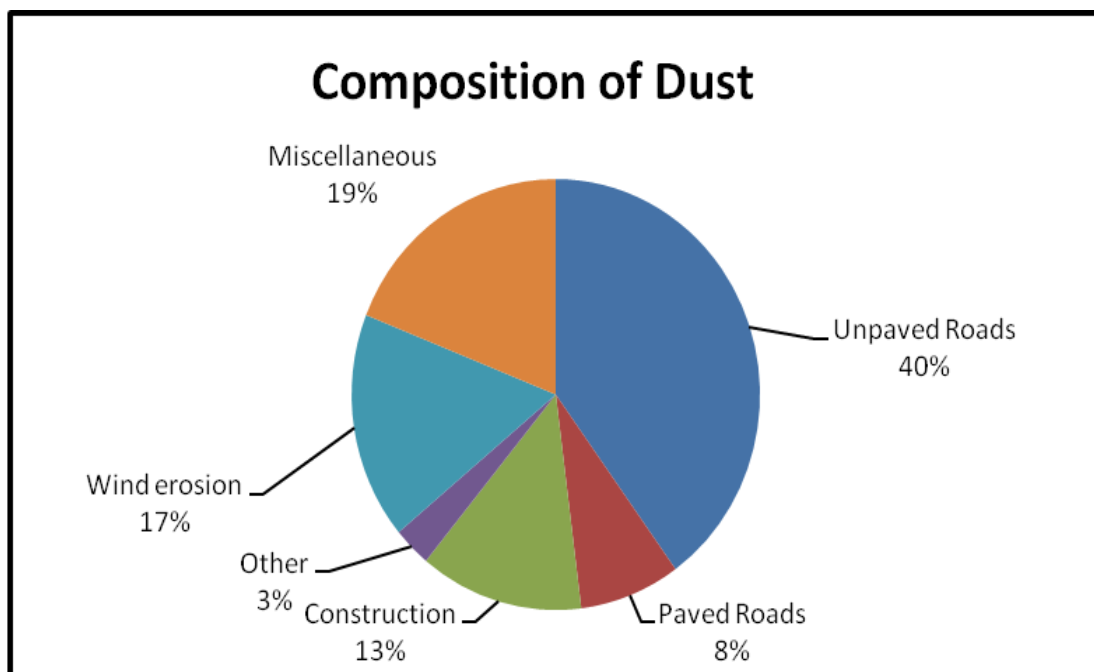


## 2 SOURCES OF DUST

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, which are sometimes also referred to as non-point sources, 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 and vegetation is sparse.

Drought conditions and poor land-use practices in these areas can exacerbate the problem 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.

FIGURE 1: EXAMPLE OF COMPOSITION OF DUST



Source: University of Missouri Extension (based on EPA 1997 estimates)

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.

The mechanisms by which dust is generated, transported and re-deposited have also been the subject of research, particularly in connection with the problems that can arise in arid conditions. (*Veranth et al, 2004*). In the USA, the

*Environmental Protection Agency (EPA)* AP-42 document which included recommendations on dust emissions was first published in 1968 and was revised in 1972 with another major revision in 1985.

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 (%)

There has been some criticism in the literature of its applicability in all circumstances, which is not surprising given the complexity of the mechanisms governing the production of road dust but it is still thought to give a good reflection, empirically, of the factors influencing the production of traffic-generated dust.

Using a version of the EPA formula adapted for South African conditions (*D Jones, 2000*) calculated the dust generated on unpaved roads in South Africa to be about 3 million tonnes per annum. This has since been revised by the Ministry of Transport to 4 million tonnes probably reflecting factors such as higher average vehicle speeds and weight and an increase in the recorded length of unpaved roads. 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.

The amount of fugitive dust at any given location is also highly variable depending on surface characteristics, meteorological conditions, soil properties and other factors including traffic speed, which is a highly relevant factor in the context of this study.

Overall data presented for the amounts and composition of dust emissions generated and present in the atmosphere, therefore also vary significantly. Models have been developed to describe dust generation and transportation but there is considerable disagreement in the literature about the accuracy of these models, which is unsurprising given the influence of local factors.

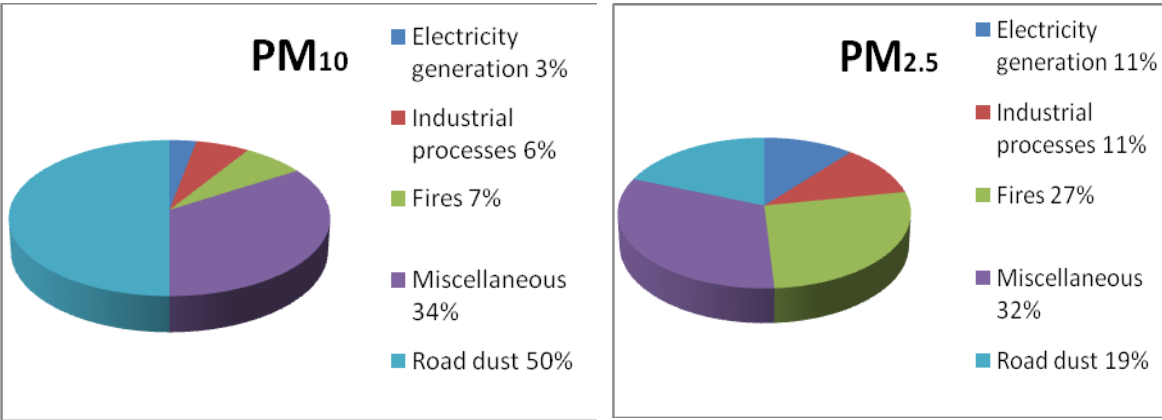
In the USA, the allowable amounts of particles in the air are regulated by the *Environment Protection Agency (EPA)* in the *National Ambient Air Quality Standards* as the amount of Total Suspended Particulates (TSP). Airborne particles such as dust, dirt, soot, smoke and water droplets in the air are 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 present in the air is usually classified in two main size fractions, namely  $PM_{10}$  and  $PM_{2.5}$  with aerodynamic diameters less than  $10\mu m$  and  $2.5\mu m$  respectively. To give a comparative indication of size, the  $PM_{10}$  fraction (i.e. from  $2.5\mu m$  to  $10\mu m$ ) 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.

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

FIGURE 2: FIGURE 2  $PM_{10}$  AND  $PM_{2.5}$  EMISSIONS BY SOURCE



Reproduced from Jones, James and Vitale

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. 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 report. 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.

Unpaved roads provide an almost inexhaustible supply of dust. The surface of unpaved roads is disturbed regularly so that dust particles are entrained into the air by every passing vehicle. The action of the vehicles wheels also pulverise the road material into ever decreasing particle sizes so that dust of all

sizes is continually being produced, including the potentially dangerous PM<sub>10</sub> and PM<sub>2.5</sub> fractions.

Vehicle movement is one of the main dust-producing activities in the road sector. The shearing action by the tyres on the road surface creates loose material that is then transported into the air by the turbulence caused by the movement of the vehicle. This action is present on both paved and unpaved roads. On paved roads dust, which is often contaminated by fuel products and other pollutants are continually disturbed and made airborne. On unpaved roads, 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)

The EPA has set National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to public health and the environment under the Clean Air Act (as amended in 1990). 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<sub>10</sub>), particulate matter (PM<sub>2.5</sub>), 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 <sub>10</sub>	150µg/m <sup>3</sup>	24-hour <sup>(a)</sup>
Particulate Matter PM <sub>2.5</sub>	15.0µg/m <sup>3</sup>	Annual Arithmetic Average <sup>(b)</sup>
	35µg/m <sup>3</sup>	24-hour <sup>(c)</sup>

Source USA Environmental Protection Agency

(a) Not to be exceeded more than once per year on average over 3 years

(b) 3 year average of the weighted annual mean concentrations not to exceed 15.0µg/m<sup>3</sup>

(c) 3year average of the 98<sup>th</sup> percentile of 24 hour concentrations must not exceed 35µg/m<sup>3</sup>

The annual and 24-hour concentrations of PM<sub>2.5</sub> 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). Although the annual levels of  $P_{2.5}$  have fallen, winter values in the colder states tend to be higher than summer values, which are considered to reflect the impact on air quality from the use of woodstoves. Individual states in the USA also have their own standards which can differ in some respects from National Standards although they are often the same for particulates. (State of Nevada 2010).

There is also concern in Europe about concentrations of airborne particulate matter. In 2001, the EU Community Directive on Cleaner Air for Europe (CAFE) was launched 'to develop a long-term, strategic and integrated policy to protect against significant negative effects of air pollution on health and the environment'. The aim of the strategy is to reduce 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 of €42 billion per year, not including benefits to reduced impacts on eco-systems or the environmental benefits from reduced air pollution.

For particulate matter, the recommendations are for a 20% reduction in  $PM_{2.5}$  concentrations between 2010 and 2020 with a legal reduction requirement governed by a three-year arithmetic average for each member state and on base level recorded in data monitoring between 2008 and 2010. (Commission of the European Communities, 2005).

Other countries are also imposing limits on airborne pollutants but notable for their absence in a list of these would be countries of the developing world where the problems and impacts are often far more acute.

The impact of fugitive dust generated from various different sources depends on factors such as the amount of dust available and weather systems, particularly strong winds, which can transport dust finer dust particles over very large distances indeed. Localised but quite frequent dust storms occur regularly in and near desert areas. When these storms hit built-up areas they can cause severe disruption and reduced visibility. Whilst its origins are clearly different from gravel roads, the photograph in Figure 3 illustrates the road safety implications of a relatively sudden and significant reduction in visibility and the impact on traffic from desert-blown dust resulting in traffic chaos and road accidents.

3: SERIOUS TRAFFIC ACCIDENTS IN SAUDI ARABIA CAUSED BY REDUCED VISIBILITY FROM DUST



Source: Site K9gm.com



### 3 UNPAVED ROADS

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. 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.

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 1.2 billion 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.

Over 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 roads networks in many Asian countries are also unpaved.

An analysis of roads in 38 countries throughout the developing world (*IRF World Road Statistics*) produced the results given in Table 2:

TABLE 2: PERCENTAGES AND NUMBER OF COUNTRIES WHERE SURFACED ROADS ARE BELOW GIVEN VALUE OF THE ROAD NETWORK

Country	40%	20%	10%
Africa (24)	100% (24)	75% (18)	25% (6)
Asia (10)	20% (2)	10% (1)	0
Latin America/Caribbean (11)	100% (11)	64% (7)	30% (4)

Source 'International Road Federation - World Road Statistics'

This list is clearly not exhaustive but for all the African and LAC countries where information was available, the percentage of roads which were surfaced were below the 40% level, whereas in Asian countries 20% were below the 40% surfaced level. Similarly the percentage of countries where surfaced roads were 20% or less of the network was high in African (75%) and LAC countries (64%), but was lower in Asian countries (10%). The analysis also showed that in African and LAC countries, the percentage below 10% surfaced was significant (25% to 30%) whereas no Asian countries were below 10%. A regional report suggested that two Asian countries (Papua New Guinea, Philippines) had in excess of 90% of the network unpaved followed by Vietnam with 81% unpaved.

Developed countries such as Australia (approximately 500,000 km), New Zealand, Canada and middle-income countries such as South Africa (600,000 km) also have lengthy unpaved road networks. In the USA, 1.3 million miles of the total 4 million miles of the road network is classified as unpaved (*Federal Highways Authority Statistics 2009*) and in some parts of the country up to 70% of roads are unpaved.

Further evidence both of the progress made in the provision of improved access and of the clear challenge remaining in developing countries is provided from Ethiopia where the *average* distance to an all-weather road (i.e. paved or gravel) has been reduced from 21km in 1997 to around 12km in 2009. (*Ethiopian Roads Authority, 2009*). This statistic clearly shows that many people in Ethiopia still travel long distances by foot before they even reach a road.

The majority of unpaved roads are in rural areas, although in developing countries, roads in many urban areas, including informal settlements are also of earth or gravel construction and in some of these countries, even parts of the strategic road network remain unpaved.

For residents living near unpaved roads, for the majority of rural road users and for many urban road users in developing countries, traffic-generated dust negatively impacts on their environment, on their health, on their livelihoods and on their safety when travelling.

## 4 ENGINEERING INFLUENCES ON ROAD DUST

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.

Typical of such specifications is the example given in Table 3 (ARRB, 1993) and in a number of similar publications by the above mentioned organisations and others in the road sector. The shaded figures represent the material classified as dust by the ARRB

TABLE 3: SPECIFICATIONS FOR GRAVEL WEARING COURSE

Sieve size (mm)	% Material passing sieve	
	Wearing Course	Sub-base
26.5	100	100 <sup>(1)</sup>
19.0	85 – 100	70 – 100
9.5	65 – 100	50 – 80
4.75	55 – 85	32 – 65
2.36	20 – 60	25 – 50
0.425	25 – 45	15 – 30
0.075	10 – 25	5 – 15

Source Australian Road Research Board

<sup>(1)</sup> Many road authorities accept material up to 40mm for sub-base

The fine clay component (passing the 0.075 mm sieve) which binds gravel wearing courses is comprises much of the component of the materials lost as dust. This changes the engineering properties of the road material and impacts on the performance of the road itself, leading to potholing and high levels of roughness, which in turn leads to high vehicle operating costs.

Over the years, considerable research has been undertaken worldwide 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.

One such equation (Paige–Green, 1989) based on extensive research on roads in South Africa and in other countries by the Council for Scientific and Industrial Research in South Africa is:

$$AGL = \{ADT(0.059 + 0.0027N - 0.0006P_{26}) - 0.367N - 0.0014PF + 0.0474P_{26}\}$$

Where ADT = Average daily traffic

N = Weinert N-Value

$$N = 12 E_j / P_a$$

where  $E_j$  = evaporation in the warmest month

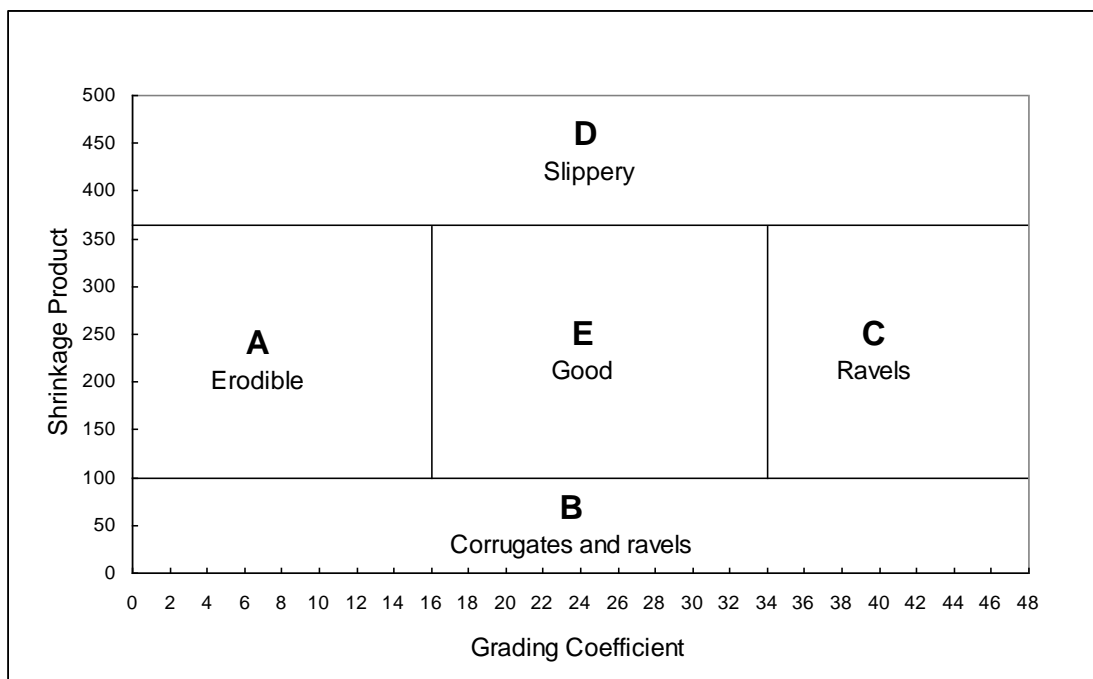
$P_a$  = annual precipitation

$P_{26}$  = Percentage of material passing the 26.5mm sieve

PF = Product of plastic limit and percentage passing the 0.075mm sieve

The consequences of using sub-standard materials are highlighted in the diagram in Figure 4. (Paige Green, 1990).

FIGURE 4: RECOMMENDED MATERIALS SPECIFICATIONS FOR UNPAVED ROADS



Reproduced from Paige-Green PhD thesis

The following conclusions can be drawn about each zone as defined in the figure:

**A** Materials in this area generally perform satisfactorily but are finely graded and particularly prone to erosion: they should be avoided if possible, especially on steep grades and sections with steep cross-falls and super elevations. Most roads constructed from these materials perform satisfactorily but may require periodic labour intensive maintenance over short lengths and have high gravel losses due to erosion.

**B** These materials generally lack cohesion and are highly susceptible to the formation of loose material (ravelling) and corrugations. Regular

maintenance is necessary if these materials are used and the road roughness is to be restricted to reasonable levels.

C Materials in this zone generally comprise fine, gap-graded gravels lacking adequate cohesion, resulting in ravelling and the production of loose material.

D Materials with a shrinkage product in excess of 365 tend to be slippery when wet.

E Materials in this zone perform well in general, provided the oversize material is restricted to the recommended limits.

Although all gravel roads are dusty to some extent, research in South Africa (*TRH 20, 1990*) has also indicated that the probability of the dust level being acceptable is highest when the Shrinkage Product is between 100 and 240.

The depletion of material resources also has an indirect but significant relevance to the dust problem.

As stated above, earth and gravel roads deteriorate through the loss of material, mainly in the form of dust. The poorer the quality of the material the greater is the rate of gravel loss and the sooner the need for costly regravelling. In many countries, 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 and abrade more rapidly leading to increased levels of dust.

FIGURE 5: TRAFFIC-GENERATED DUST IN SOUTH EAST ASIA



Source: Courtesy of Robert Petts

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 are extremely scarce leading to the unavoidable use of sub-standard material and rapid degradation which 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.

The engineering costs of maintaining unpaved roads vary considerably depending on factors such as traffic, terrain, type of material, climate, etc. Loss of the fine material that contains the clay fraction and acts as the prime binding agent is a major cause of deterioration in earth and gravel roads. Typical annual costs of routine and periodic maintenance combined of unpaved roads tend to be in the range of US\$ 5 000 to US\$10 000 per km per year.

## 5 IMPACTS OF TRAFFIC-GENERATED DUST

### 5.1 GENERAL

For people living in developed countries, road dust was primarily considered to be a nuisance. Only relatively recently has it gained greater prominence as a potentially serious polluting agent. However, whilst travellers along unpaved roads in these countries are obviously inconvenienced by dust and may also suffer health and road safety risks, these impacts tend to be relatively minor compared those experienced by residents and travellers in developing countries.

In high income countries, relatively few people live as close to unpaved roads as do residents in developing countries and 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.

Studies by the EPA in the USA have also shown that dust emissions from unpaved roads are significantly reduced by daily rainfall of 0.01inch. Studies in New Zealand in the 1980's (*McCrea, 1984*), also indicated the extent to which road dust was affected by rainfall. However, many tropical countries experience their highest temperatures in the rainy season. In these conditions, road surfaces dry quickly and dust again becomes problem after just a day or so without rainfall.

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. Very few public transport services in developing countries are air-conditioned and ventilation is provided by open windows so that even people travelling in vehicles that may normally be considered to be enclosed are also exposed to dust.

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. In these areas, long-term exposure to the effects of Total Suspended Particulate (TSP) pollution, including road dust, may pose a serious health risk to all inhabitants and particularly to children and the elderly.

## 5.2 HEALTH

Exposure to dust has, for many years, known to be hazardous to health. The use of masks to filter out dust and other pollutants potentially damaging to health has become a requirement for many industrial workers but has also become routine in carrying out many day to day DIY tasks in households in developed countries as awareness of the risks has increased. Apart from the specific problems related to health that are discussed in this section, many people exposed to road dust often complain of a general feeling of sickness which also indicates that it is potentially harmful to human health. 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. (*Particulate Matter: Air and Radiation. Environmental Protection Agency. USA*) Particles larger than  $2.5\mu m$  but smaller than  $10\mu m$  ( $PM_{10}$ ) can lodge in the upper respiratory area where they can be an irritant and can be especially problematic to children, the elderly and to those with pre-existing health conditions such as asthma. 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 as well as the



young and the elderly are highly vulnerable. (*Idaho Department of Environmental Quality 2010*).

Some studies in the USA indicate that as much as 50 per cent of  $PM_{10}$  emissions and 19 per cent of  $PM_{2.5}$  emissions are due to road dust. Studies have also reported road dust to be the single largest source of  $PM_{10}$  emissions and 65 per cent of road dust is attributed to unpaved roads. In developing countries, these percentages are even higher due to the greater proportion of road networks that remain unpaved.

When driving along unpaved roads in developing countries during the dry season and even in dry spells in the rainy season, the response to a friendly wave from local children invariably includes the enveloping of these pedestrians and other road users in a cloud of vehicle-generated dust. For all rural road users but particularly children, many of whom walk along these roads each day to travel to and from school and who also live in villages served by unpaved roads; dust may well present a significant long-term health risk. The degree of risk would certainly be assessed if similar circumstances were to prevail in countries of the developed world.

The long-term exposure to high concentrations of dust is evident from its impacts on the health to workers such as coal miners and quarry workers. Whilst road users and residents in developing countries will not normally have such high concentrated exposure, continuous almost daily exposure over many years is, indeed, highly likely to pose a serious health risk. Some studies have also 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*).

FIGURE 6: LARGE COMMERCIAL VEHICLES PRODUCE THE MOST DUST



Courtesy of M O'Connell

The *World Health Organisation (WHO)* has published a table of the increased risks to health and on mortality rates from exposure to particulate pollution. Particular concerns are stated in *WHO* reports about the effects of long-term exposure, which is highly relevant to this study.

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, who are quoted as being particularly vulnerable as the process of lung growth and development continues until adolescence and they 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, which 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<sup>3</sup> per day, which are estimated by the *World Health Organisation (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<sup>3</sup> and 35µg per m<sup>3</sup>.

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 3<sup>rd</sup> highest in the 110 causes of death reported by the WHO. The top 10 causes are shown in Table 4 for comparison.

TABLE 4: GLOBAL BURDEN OF DISEASE

Leading Causes of Death (2008 update) (male, female, all ages)		
Cause	Death (m)	%
Ischemic heart	7.2	12.2
Cerebra-vascular	5.7	9.7
Respiratory infections	4.2	7.1
Diarrhoeal	2.2	3.7
HIV/AIDS	2.0	3.5
Tuberculosis	1.5	2.5
Trachea, bronchus and lung cancers	1.3	2.3
Road Traffic Accidents (RTA)	1.3	2.2
Premature birth	1.2	2.0

Global burden of disease WHO (Revised 2008)

Workers exposed to different types of mineral dust tend to develop different diseases. Therefore, it is also quite likely that the different minerals contained in unpaved road surfaces might also pose different risks due both to the size of the particles in the dust produced and of the actual mineral content of the

material itself. Whilst materials of particularly dangerous minerals, for example aggregates containing asbestos, are much less likely to be used in road construction these days, other minerals can still pose health risks. Of particular concern however, are the potential risks from exposure to all dust sources to the developing respiratory organs of children.

#### 5.2.1 SUMMARY OF HEALTH IMPACTS

In the absence of quantitative information it is only possible to speculate what the impacts of traffic-generated dust on health might be in developing countries. Figures given by the WHO indicate the potentially damaging health effects of exposure to  $PM_{10}$  and  $PM_{2.5}$  particulates in the developing world, especially on women and children. Extrapolation of the results from studies undertaken in developed countries can, to some extent, provide information on some of the probable impacts. Given the number of variables involved, professional research expertise in the health sector will be needed to obtain the data required to enable the impact of traffic-generated dust on health to be quantified.

However, from the available data and the statistics provided by the World Health Organisation, it is possible to speculate on the impacts to some degree.

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.

### 5.3 ROAD SAFETY

The author of this report has direct experience of driving many thousands of kilometres on unpaved roads in Africa. When travelling on a long journey on a gravel or earth road and confronted by a slow-moving bus or truck with the prospect of travelling in its wake of dust for many kilometres, the temptation to overtake is significant even if the forward vision is completely obscured by an opaque dust cloud and even if the road is relatively lightly trafficked. However, such temptation is tempered by having witnessed on a number of occasions, the horrific consequences of such manoeuvres by other motorists. Such manoeuvres can result in loss of control and in head-on collisions, which due to the combined momentum of the vehicles, invariably leads to the death or serious injury of the occupants of both vehicles and sometimes of other road users too. The problem is especially acute when following long multi-axled vehicles with trailers as each wheel of the vehicle generates dust so that vision is obscured both behind and adjacent to the vehicles, which also endangers vehicles passing in the opposite direction. Slow-moving traffic such as tractors, cyclists, ox-drawn carts and pedestrians which are prevalent on rural roads are particularly vulnerable. The contribution of dust as a possible contributory

cause of road accidents in Africa was postulated over 30 years ago. (*Jacobs and Hutchinson, 1973*).

As with most aspects of road safety, engineering is complex. A well engineered road can be very safe, but the level of safety which can be achieved is dependent on the way that the drivers use the road. Road rules and patterns of enforcement will also vary according to road design features.

Many believe that because the main road safety problems are behavioural in nature, they can only be tackled by education and enforcement. This is not the case – safe roads can be designed to be ‘self-explaining’ (having an influence on driver behaviour) and ‘forgiving’ (passively safe). Engineering measures can be used to influence behaviour and can lead to safety improvements in situations where driver behaviour is poor. (*TRL, ODA, 1991*)

Many studies carried out over the years have shown that well engineered roads with inbuilt safety design features are safer than roads with lower geometric design standards. However little work has been done on the safety of unsurfaced roads, how accident rates compare with those of surfaced roads and, most importantly in the context of this study, how accident rates are affected by dust.

That said, the issue is likely to be an important one not least because of the high proportion of roads throughout Africa, Asia and Latin America /Caribbean that are unsurfaced.

One of the earliest recorded studies of road accidents in developing countries was carried out by TRL 1973/74 in Kenya (*Jacobs and Sayer*). In this study, one complete year’s national personal-injury accidents (1972) were collected and analysed in detail. Accidents were analysed by type of road surface, namely those with a bituminous surface, murram (engineered gravel) and earth roads.

It was found that over 75 per cent of all accidents studied occurred on bituminous surfaced roads and 18 per cent on murram roads. At the time of this study, TRL were also carrying out studies of seasonal traffic volumes on different categories of road and thus reasonably accurate traffic flow data were available on roads of different surfaces. This showed that about 5 % of total vehicle kilometres travelled in Kenya took place on murram roads. Thus roads with 5 % of national traffic had on them, 18% of the national personal injury accidents taking place.

This study suggests that accident rates on gravel surfaced roads are over three times greater than on surfaced roads.

The study also showed marked differences in the types of accidents taking place. Thus the percentage of vehicle – vehicle and vehicle – pedestrian accidents on murram roads were half that occurring on surfaced roads.

Conversely the percentage of single vehicle accidents on murram roads was almost three times that occurring on surfaced roads.

Unfortunately, no comprehensive follow up study was ever undertaken to determine the precise reason for this higher accident rate on murram roads in Kenya. However, 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.

In a 1980 study of the optimisation of roadway structural design and maintenance (*Visser and Hudson*), attempts are made to identify at what level of vehicle flow, paving an unpaved road becomes a realistic economic proposition. The paper states that whilst dust and road accidents may be important, they are difficult to quantify in economic terms. The point is made however that in South Africa (unreferenced), accident rates on unpaved roads were lower than on paved roads (which is at odds with results from the Kenya study quoted above). The lower rate on paved roads was thought to be due to greater concentration by drivers on more highly trafficked roads.

There is some suggestion that drivers are slow to accommodate to the changes in road conditions and vehicle behaviour on gravel roads, which is highly probable as these are clearly influencing factors, which differ significantly between paved and unpaved roads. (*Manitoba Public Insurance, date unknown*).

One example of the different conditions that can generally only be found on a gravel road is that of corrugations. These often occur on bends and the reduced contact between the vehicle wheels and the road surface results in a lack of traction not significantly different from that caused by ice. The result of such an encounter at speed is that the vehicle tends to continue moving in a straight line with the steering having little influence on the direction of travel, especially with most modern vehicles having highly geared power steering. (Personal experience in such a situation in Africa has resulted in more than one unexpected visit to the 'bush' but fortunately avoiding the potentially serious consequences if a tree had been in the way). Corrugations are not always easily spotted especially if visibility is obscured by dust from a preceding or passing vehicle.

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.

In a paper by *R. W. Day (Journal of Performance of Constructed Facilities 1992)*, the impact of dust storms on highway accidents in California is investigated. In one particular incident 17 people died and 150 were injured in an accident involving 104 vehicles. The cause of the accident was a dust storm driven by winds gusting at 64 km/h. The incident occurred on a surfaced road and the dust came from adjacent farms which had dry soil due to an ongoing drought. Other contributing factors were the particularly heavy Thanksgiving holiday traffic, excessive traffic speeds and the fact that dust reduced traction between tyres and the road surface.

The five important factors for dust storms were considered by the author to be, in order of decreasing importance, wind, soil type, vegetation, soil moisture and soil density. In countries where dust storms are common, the same factors probably apply. Laboratory tests were developed to study the inter-relationships of these factors, with the behaviour of silt determined at different moisture contents. Below a moisture content of 10%, the silt became easily eroded. The overall safety situation can be improved by the use of advanced warning signs, and improved road surfaces (grooved, possibly), to provide more traction and by the use of barriers such as an elevated kerb to reduce bed-load transport of soil particles across the highway.

Dust storms continue to adversely affect traffic causing delays and road accidents. For example, in December 2009 a dust storm in Arizona, USA caused a chain reaction of car accidents involving up to 40 vehicles, and killing 3 people and injuring 14. The one highway from Tucson to Phoenix is said to be hit by up to 20 dust storms per year, mostly in the summer when roads and farmland are particularly dry. Similarly in Denver, Colorado USA a dust storm involved 14 vehicles and killed 2 people and injuring up to 20 people.

Not surprisingly dust storms are also common in the Middle East and recent storms in Saudi Arabia involved a 20 vehicle pileup in Jeddah, killing 3 people and injuring 20.

The economic disbenefits of dust from unsealed roads were outlined in a paper by the *World Consultancy Service Ltd New Zealand, 1993*). The paper explains that almost half of the New Zealand network of public roads is unsealed and that sealing most unsurfaced roads cannot usually be justified because of the low traffic volumes carried. Nevertheless economic disbenefits from dust emission from unsealed roads impact in numerous ways, including accident potential. The point is made that wind-blown particles is of major concern throughout the developing world and in Nigeria (*Funso 1989*) it has been estimated that 60% of the problems is caused by bush burning and fugitive dust from the road surface. However the US Environmental protection Agency has estimated that 80% of the emission of particulate matter comes from the unsealed roads themselves.

The authors make the point that little data is available on the disbenefits of dust from unsealed roads in developing countries and that disbenefits are generally speculative. Clay is a significant component of the running course of an unsealed road because it is the 'binder' between the aggregate. Loss of fine clay particles as dust or by water scour leads to a loss of cohesion and stability in the running course. As a result, windrows of coarse aggregate develop. These are considered an important cause of accidents on unsealed roads.

Detailed research in Kenya (T E Jones, 1984) showed that the total amount of dust deposited by passing vehicles onto a grid of trays, showed a strong dependence on vehicle speed. Whilst more sophisticated techniques for the measurement of dust are now available, speed has indeed been confirmed as major factor in the amount of dust generated by vehicles.

The paper makes an interesting comparison between fog and dust, making the point that fog is not a suddenly occurring hazard and drivers have time to adjust to the conditions. Poor visibility was thought to be a factor in about 1.7% of all casualties occurring in fog. Similarly, the incidence of accidents due to dust is also considered to be low. As in the above paper, reduced skid resistance was thought to be an important factor. It is thought that one mitigating factor is that drivers may be more vigilant and drive with reduced speeds if driving in dusty conditions on unsealed surfaces. This may well be the case in New Zealand, where driving standards are high but may not be so in countries throughout Africa and Asia.

A comprehensive study in New Zealand (Minchington and Bradshaw 2007) investigated the accident benefits of sealing unsealed roads. The study was conducted in two parts. Firstly a pilot study was undertaken to test whether sufficient data existed to enable accident benefits or disbenefits of sealing a road to be calculated with a desirable level of confidence. This analysis of the entire dates set (all terrains and locations) showed an increase of about 0.1 accidents/year/vehicles km after sealing.

A detailed study of sites by alignment and terrain classification used accident data from the Ministry of Transport Crash System four years before and four years after seal extensions were carried out. Overall, the study concluded that there was no statistically significant benefit or disbenefits in accidents associated with sealing the unsealed roads. The study recommended that further work be undertaken to determine whether a common hazard exists that may be exacerbating the number of accidents following sealing. (In this study, no specific reference is made to the impact of dust). However, it is certainly evident from Figure 5 and Figure 6 that the cyclists shown disappearing into the dust cloud are at risk both from traffic following behind and from any overtaking manoeuvres by oncoming traffic.

In a study of crashes on unsealed roads in Australia and New Zealand (*Boschert, Pyta and Turner, 2008*) the authors highlight the importance of unsealed roads which form 60% of the road network in Australia and 36% in New Zealand. Their literature review showed that in three separate studies in Australia, New Zealand and Sweden, crashes per vehicle km travelled on unsealed roads were higher than on sealed roads. The Swedish study, in particular, showed that sealed roads had injury accident rates that were, on average, 40% lower than on unsealed roads, and damage-only accident rates that were about 30% lower on sealed roads. They also make the point that severity levels of crashes were higher on unsealed roads because emergency services take longer to reach crash victims. Poor sight distance and poor surface quality were thought to be factors leading to crashes on unsealed roads as were poor driver behaviour (excessive speed, alcohol and fatigue). Another interesting fact presented was that on unsealed roads, drivers used the 'best part' which means driving in the centre of the road. This can be seen as an additional factor when visibility is poor. Although dust is not mentioned specifically, restricted visibility was identified as a factor on unsealed roads in New Zealand, being present factor in about 10% of all crashes.

#### 5.3.1 SUMMARY OF ROAD SAFETY IMPACTS

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.

In general the amount of information on road accidents on unsealed roads is limited, as are direct comparisons of accident rates on sealed versus unsealed roads. In the majority of cases however the results showed that unsealed roads do have higher accident rates. This may be due to poorer road geometry, especially sight distances, and to road surface condition as well as to visibility and traction problems caused by the lack of a bituminous surface. Accident severity levels are also thought to be higher on unsurfaced roads because of the greater distances that emergency crews have to travel to reach the site of the accident.

Clearly, more information needs to be collected on the impact of dust. Limited information from one or two studies does suggest that dust may have a significant impact on driver visibility and hence on accident rates.

A different type of problem exists in many countries throughout the world where dust storms are common. Recent examples from the USA and Saudi Arabia show that multiple pile collisions caused by the reduced visibility are common with many deaths and injuries taking place.

Although dust rarely, if ever, is a causal option on police reporting forms on road accidents, it is undoubtedly a factor in some accidents on unpaved roads as witnessed by the author of this report and the risks, especially to non-



motorised road users and pedestrians is clear from photographic evidence. Furthermore, on many rural roads no safe haven exists in the form of footpaths or shoulders for vulnerable road users, including schoolchildren.

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. Another way of looking at accidents costs due to dust is to take 1% of the figure of the total cost of road accidents in developing countries (currently estimated at about \$80 billion) which would give a figure for developing countries and emerging nations of approximately \$800 million annually.



## 5.4 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 which appears to indicate that it is the coarser particles that are most problematic in this sector rather than the finer PM<sub>10</sub> and PM<sub>2.5</sub> particles of concern to the health sector.

On green crops such as tea, the effects of dust are immediately obvious and, depending on the direction of the prevailing wind, it can be many metres from the road reserve before the foliage becomes green. It is clear that there is likely to be a cost impact from such contamination even to the owners of large tea plantations. However, the impacts on the incomes of subsistence farmers with small plots adjacent to unpaved roads are likely to be proportionately much greater.

In his thesis (*Dust and Dust Control on unsealed roads*, Jones, 2001) it is stated that there were not, at that time, any direct studies on the effect of dust from unsealed roads on crops and the author of this report has not found any subsequent studies on agricultural impacts on the African continent.

However, anecdotal and qualitative evidence from other projects in South Africa of the impacts of traffic-generated dust are mentioned in the thesis. In one of these studies in a road prioritisation scheme, evidence from infra-red aerial photography showed that trees in fruit orchards adjacent to unpaved roads were smaller and less productive than those further from these roads. In the first three rows from the road, between 80 and 100 percent of trees were smaller than the average for the orchard and it was not until the 8<sup>th</sup> row that trees were unaffected. It is, of course, recognised that without a detailed study, there could also be other factors affecting this trend but the impacts of dust were also supported by the need for additional insecticidal spraying for pest control on trees adjacent to the road. The reasons for this were postulated to be that insects preying on the fruit crop were protected by dust from the full impact of the insecticide whilst parasitic insects were less able to gain access to them because of the layer of dust. The additional costs of chemical spray were between about \$500 and \$750 per kilometre (at 1992 exchange rates) but the reported potential losses in terms of lost income for the industry were substantial as shown in the Table 3.

Studies reportedly undertaken for orchardists in South Africa also indicated that dust was coating fruit typically over a 300m wide corridor centred on unpaved roads. Other studies in New Zealand 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. (McCrae, 1984)

TABLE 5: POTENTIAL FINANCIAL LOSSES IN THE FRUIT INDUSTRY IN SOUTH AFRICA

Damaged Fruit		Loss in foreign earnings (million)		Loss for the producer (million)	
% Damage	Tonnage rejected	Rand	US\$	Rand (1992)	US\$ (1992)
0.5	2687	4.455	1.536	1515	522
1.0	5374	8.910	3.072	3029	1044
2.0	10748	17820	6.145	6059	2089
3.0	16121	26729	9.217	9088	3134
4.0	21496	35640	12.290	12118	4179
5.0	26869	44 549	15361	15147	5223

Based on a table by D Jones, 2001 using an historical average US\$/Rand exchange rate of US\$=R2.9 for 1992

Jones also reported that observations by the National Parks Board in South Africa noted that animals avoided grazing on dusty grass adjacent to roads, preferring grass some distance away. Assuming that this effect was limited only to areas adjacent to unpaved roads, then this would suggest that animals avoid grass contaminated by dust and that it might well, as suggested, have an impact on tourist satisfaction with animals being further away from these roads and thus more difficult to view.

Evidence from the USA (*Vegetable Crops Hotline, 2007*) has reported that dust increases the mite population on watermelon plants nearest gravel roads thus also supporting the notion that one of the impacts of traffic-generated dust is to inhibit the impacts of insecticides.

Road dust also interferes in the efficacy of sprays for weed control. Chemicals used on fields near gravel roads are reported as being rendered ineffective when in contact with dust on leaves. This clearly has implications for product yields as effective weed control is particularly important for many crops.

The study on the agricultural impacts of dust by McCrae was carried out in New Zealand (McCrae, 1984). Although now somewhat dated in some respects, the publication provides an insight into the possible economic consequences of dust on crops in the country.

The study was based for the most part on information published elsewhere. It contains quantitative as well as anecdotal evidence and, although undertaken some 25 years ago it probably remains one of the more complete analyses of the impacts of dust on agriculture.

The main effects reported are:

**Reduced photosynthesis.** This is the process by which energy from sunlight is absorbed through the leaf surfaces of green plants and used to create complex

substances that promote plant growth. Dust coated leaves reduce this process and the reported consequences are a reduction in the buds formed and lower fruit setting; a reduction in fruit size due to inadequate supply of carbohydrates and a lowering of the sugar content.

#### **Increased incidence of pests and disease.**

Studies found that dust accumulation in the nooks and crevices of fruit and plant surfaces aided moisture retention in these areas and provided conditions conducive to the growth of bacteria and fungi.

Other studies found that dust preferentially inhibited the activity of beneficial insects due to differences in the habits and structure of these insects and those which are harmful to plant life.

#### **Hindered pollination.**

Well-pollinated flowers are the basic requirement for the development of large and well-formed fruit and its thought that road dust inhibits pollination with a resulting loss in yield.

#### **Reduced effectiveness of sprays.**

The reduced efficacy of sprays on plant leaves was also reported for both insecticides and herbicides and this effect has been subsequently confirmed in the USA as mentioned previously.

#### **Downgrading of products and reduced yield.**

The most serious consequence of the impacts of dust are in situations in which crops are classified as sub-standard because of size and quality and are unsuitable for export or realise a reduced price in local markets, both of which have economic consequences for producers.

The report concluded that the main agricultural impacts of traffic-generated dust in New Zealand are on horticulture because:

- this land usually returned higher gross revenue per acre
- the industry creates greater use of transport and generates more dust
- products are more vulnerable to dust impacts
- these enterprises are often located close to unpaved roads

#### **Animal health problems.**

The problems relating animal health and dust are largely speculative or anecdotal. Whilst there is little experimental evidence for these impacts, the oral and other evidence presented in the report suggests that there are grounds for a link between road dust and animal health. There is speculation in the report that contamination to animal food crops by road dust could contribute to producing an environment conducive to bacteria development.

Some of this evidence is based on impacts investigated as a consequence of the Mt St Helens volcanic eruption, which although being an extreme case of dust contamination, provided an opportunity to study some of the impacts of dust on crops and animals. It was reported that day-old chicks suffered a 6 per cent growth reduction for each 10 per cent of ash and a 4 per cent reduction for each 10 per cent of sand. Paradoxically, dairy calves exhibited normal growth and mature cows maintained constant levels of milk production at contamination levels of 10 per cent and 6 per cent respectively.

#### **Economic costs of dust on agriculture**

No overall figures for the economic impact of dust on agriculture are given in the McCrae report due to the wide variation in the impacts of the various influencing factors on different crops but examples are given for the dust-related cost impacts on specific agricultural products. Cost impacts appear to vary between approximately 1 percent and 5 percent of total crop values. In his thesis, *D Jones* quotes studies in New Zealand that indicate a one percent decrease in lambing rate for sheep and reduced milk fat rate in cows which are related to depressed pasture yield and a reluctance to graze on dust-contaminated pasture.

The conclusion is made that 'the costs to production have a direct application to cost-benefit studies for the ranking of road projects'. If the various assumptions made in the report are generally applicable, then the results indicate that in some circumstances the benefits from dust reduction alone in terms of Net Present Value would be likely to make a major contribution to the overall benefits of sealing gravel roads.

A further study in New Zealand in 1993 confirmed that very little quantitative information was available on the cost impacts of dust on agriculture although it also concluded that the main disbenefits from dust emissions arose from reduced crop yields and a possible increase in vehicle operating costs.

#### **5.4.1 SUMMARY OF AGRICULTURAL IMPACTS**

It is, therefore, evident that significant areas of commercial farmland worldwide are adversely affected by vehicle-generated dust and that there is an economic consequence of this contamination. It is also very likely that the crops of subsistence farmers are similarly affected and that the relative economic impacts for these producers could be much greater in terms of their livelihoods. In the context of the objectives of the current study, there is very little evidence available to confirm these impacts quantitatively. Further research is required to assess and update previous studies and quantify the adverse economic impacts on agriculture of dust contamination for both subsistence and commercial farmers in relation to road projects and the benefits when road dust is reduced.

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*), although many more kilometres are likely to be missing from the recorded lengths in many countries due to the methods of classification used and the large number of unrecorded roads in rural areas. 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.

## 5.5 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, Road Infrastructure Framework for South Africa, 2002?*)

In South Africa, it has been found that road deterioration is accelerated as a consequence of the reduced binding quality caused by the loss of dust from unpaved roads. Furthermore, not only is dust generated from the road itself a problem but so are the environmental consequences from the additional quarrying activities needed to supply increasing amounts gravel for road maintenance as good quality gravels become scarce.

In New Zealand efforts have been made to estimate the amenity impacts of particulate pollution by 'Willingness to Pay' surveys but these studies have concentrated on impacts in urban areas (*Environet Ltd, 2003*). Other issues raised on impacts of dust in New Zealand are related to changes in land use where farmland is parcelled into smaller plots on which new householders from urban environments are settled in close proximity to gravel roads and complain about dust contamination of clothes, houses, water tanks, etc. (*Smith, 2003*).

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 rural villages worldwide, the provision of clean water remains a challenge. Even when rudimentary measures are available and undertaken to purify water for human consumption, subsequent contamination of stored water remains a problem for many poor rural and urban households with dust being a contributory factor.

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.

Thus, dust impacts in many ways on the environment. Methods developed to quantify environmental impacts of dust in developed countries could help quantify impacts in developing countries.

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 and 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.

## 5.6 OTHER IMPACTS

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.





## 6 MEASUREMENT OF DUST EMISSIONS

It should be noted that there is a significant difference between the measurement of road dust at source as described below 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. The results from the Kenya measurements indicated a loss due to dust of some 25 tonnes per km per year for a road carrying 100 vehicles per day travelling at average speed of 75km/hour. Other studies have indicated losses due to dust as high as 300 tonnes per km per year and this range of values indicate the variations that can be expected on different roads in differing environments.

On a road maintenance contract in Botswana in the 1980's, deterioration on one section of road carrying approximately 100 vehicles a day was sufficiently high to warrant regravelling after less than one year following the previous regravelling contract. Whilst this rate of deterioration is exceptional, it is indicative of the high attrition rates that can be expected when weak fine-grained materials are used for gravel wearing courses with much of the material being lost as dust. Such events are likely to escalate as sources of good gravels become depleted and the use of weaker materials increases.

The Kenya study also demonstrated the influence of speed on the generation of dust but one of the surprising results from the study, was the conclusion that nearly all the dust fell within 7 metres of the road edge. Even given the more sophisticated dust measurement methods available now, this result is in stark contrast with other observations which indicate a much wider area of influence of dust generated on gravel roads. It is also at odds with other measurements around the same period in the USA. (*Handy et al, 1975 and Hoover, 1981*), which indicated a corridor of influence at a distance of about 50m from the centre of the road and a figure of 300m quoted for some orchards in South Africa.

Many so-called 'dust measurements' have been carried out by visual estimation by the driver of a vehicle or a roadside observer ranking dust according to a given scale. One such scale, presumably suited for driver observations, is shown in Table 6, which is clearly subjective and operator dependent.

There are many problems with observational methods of this type, including the large variations in the assessment of dust clouds in relation to the position of the observer with respect to the position of the sun, the strength and direction of the wind and other factors. (*D Jones, 2001*)

There was substantial agreement at the severest levels of dust (a value of 5 in the scale given in Table 6) but there tended to be large variations between observers at lower dust levels. More sophisticated methods have been developed in recent years. These are based in sedimentation, filtration, photometric and infra-red technology.

TABLE 6: VISUAL RATING FOR ROAD DUST

Rating	Rating Descriptor
1	No visible dust behind the vehicle
2	Dust just visible through the rear window
3	Dust easily visible but not enough to cause driver discomfort
4	Very dusty causing major discomfort when passing approaching vehicles but not causing dangerous loss of visibility
5	Extremely dusty, the surroundings being obscured to a dangerous level and the impact on drive/passenger comfort and safety aspects being totally unacceptable

Reproduced from D Jones PhD Thesis

In his thesis (*D Jones, 2001*) a review is made of the advantages and disadvantages of the various measurement techniques. The original vehicle mounted technology was based on earlier equipment developed in the USA (*Taylor, 1987*). However, various problems relating to vehicle dynamics resulted in the design of a refined dust monitoring vehicle-mounted device that was developed at CSIR over a 5-year period. A static device based on infra-red technology has also developed. The outputs from these devices are in dust units (du), on a scale of 1 to 100 where 1 represents transparency and 100 represents complete opacity.

Both devices have been used to measure dust levels on various roads in South Africa including the effectiveness of dust palliatives and in the development of a dust prediction model. Drivers of various vehicles were interviewed to develop a rating scale in terms of dust units and acceptability. In the context this report, the static device may be of particular significance because of its portability and it could therefore be transported and used in other countries in Africa and elsewhere. It has the attraction of being independent of observer bias and local environmental influences whilst benefiting from extensive calibration. (Table 7)

TABLE 7: COMPARISON OF PHASE III DEVICE AND STATIC SA DUST MONITOR

Road	Average dust level (du)		
	Phase III	Static	Difference
1	10	10	0
2	10	10	0
3	26	25	-1
4	14	14	0
5	57	59	+2
6	17	17	0
7	74	73	-1
8	41	42	+1
9	33	32	-1
10	65	68	+3

Reproduced from D Jones PhD Thesis

The main drawback would seem to be in the capability to make comparisons with other measurements of dust which are reported in different units. (i.e. usually in tonnes per m<sup>3</sup> or in tonnes per kilometre). Site tests indicated a close agreement between the two devices as shown in above Table 7.

For this reason, there may well also be merit in developing countries for using one of a number of the other reported methods that measure the emissions of traffic-generated dust directly by gravimetric methods.

## 7 DUST CONTROL

### 7.1 GENERAL

It should be noted that all roads are subject to wear by abrasion to some extent. Even roads sealed with a bituminous or concrete wearing course produce some dust, although in much reduced quantities than unpaved roads. 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 application often 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 chemical palliatives.

In situations where neither of the above options are possible, then the use of good quality gravel, and high standards of road design, construction and maintenance will reduce traffic-generated dust emissions. It has also been suggested that dust control should be included as part of an asset management strategy for gravel roads (*Jones, Sadzik and Wollmarans, 2001*). However it should also be recognised that compliance with these recommended measures are sometimes difficult, especially if good quality road building materials are unavailable and haul distances are limited as is the case when labour-based technology is used for road construction. It could, of course, also be argued that it is precisely in such circumstances that chemical dust suppressants might be most effective as a maintenance reduction measure and their report concluded that significant economic benefits could accrue from the use of calcium chloride on roads in South Africa.

There are probably more publications on the control of dust than on any other aspect of the problem. This is due in part to the concern of air quality standards in places like the USA and the need to comply the subsequent air quality standards and complaints about dust by road users and residents alike. It is also, to a significant extent, probably due to the plethora of dust control products available on the market and to strong lobbying supporting their use by suppliers.

Considerable research on dust control has been undertaken in most of the of the high income countries with significant lengths of unpaved roads (USA, Canada, Australia and New Zealand) and in some middle income countries such as South Africa. The USA is probably at the forefront of this work although considerable work has also been done in other countries. The Australian Road Research Board has published a document, which gives an

overview of the problem and describes experience with the use of dust palliative products in Australia (*Foley, Cropley and Giummarra, 1996*).

Extensive research on dust control and dust palliative products has also been carried out in South Africa (*Phil Paige-Green and D Jones*). A number of publications (*e.g. Addo, Sanders and Chenard, 2004*), give an overview of the options for dust control and comment on the effectiveness of various products in varying circumstances. Some products have been around for many years while new products (and sometimes similar products under different names) are continually arriving on the market.

A selection of the types of dust palliative products available is given here but many publications are also available in which 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 mid 1990'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, another from South Africa (*Jones, 2000*) 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 probably not exhaustive as new products with dust palliative properties are continually arriving on the market.

## 7.2 BOUND PAVING

As stated above, a bound pavement of concrete, asphalt or surface dressing is reported as the most effective method of reducing dust. Material in the surface of the base is protected from rapid abrasion of traffic by this layer. The cheapest of these options is surface dressing which was often considered the most appropriate seal for upgrading rural roads carrying relatively low levels of traffic.

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 the bituminous layer which also reduces 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.

## 7.3 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.

## 7.4 MECHANICAL STABILISATION

As stated earlier, the performance of a gravel road wearing course is critically dependent on the properties of the material used for its construction. For example, oversize material will result in a loss of compaction and early potholing and finely graded weak or non-plastic material will lead to erosion or ravelling. The presence of some clayey material is essential for binding purposes whilst too much clay will cause slipperiness in wet weather. Roads constructed with poor quality materials tend to be dustier.

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

## 7.5 CHEMICAL SUPPRESSANTS

### 7.5.1 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*) as shown in Figure 7.

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

FIGURE 7: SALT BLISTER DAMAGE TO A PRIMED SURFACE IN BOTSWANA



Reproduced from the SADC Guideline for low-volume sealed roads

### 7.5.2 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 on their performance. 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. The results are reproduced in Table 8.



TABLE 8: DUST MEASUREMENTS

Sampling Date	Strang Test Sections				Horton Test Sections			
	Untreated	MgCl <sub>2</sub>	Lignin	MgCl <sub>2</sub> Lignin	Untreated	MgCl <sub>2</sub>	Lignin	MgCl <sub>2</sub> Lignin
6/8/2000	3.12	1.16	0.90	0.70	5.96	1.20	0.61	1.07
7/3/2000	2.58	2.13	1.75	0.64	4.19	4.04	5.24	4.17
7/13/2000	4.46	1.49	1.01	1.13	4.69	1.47	2.13	3.41
7/27/2000	5.29	1.00	0.53	0.49	6.04	1.76	1.25	1.30
8/8/2000	4.38	1.23	0.53	0.64	5.77	1.03	1.89	2.30
8/21/2000	2.47	2.58	1.85	1.23	3.50	1.36	1.33	1.29
9/16/2000	4.40	1.42	1.45	1.82	4.78	2.32	3.41	4.31
10/8/2000	3.11	2.43	1.24	0.64	3.77	1.75	1.98	2.13
5/17/2000	2.60	1.64	0.98	0.75	4.45	1.22	1.98	1.49
5/31/2000	2.63	3.16	1.17	1.50	2.93	1.01	1.82	2.33
6/21/2000	2.83	2.72	1.11	1.69	5.33	1.90	3.05	3.87
6/28/2000	1.26	2.02	1.55	0.61	3.25	2.51	2.83	2.47
7/18/2000	2.70	2.62	1.17	1.17	6.07	3.04	4.14	4.17

Reproduced from Addo, Sanders and Chenard

Interestingly, although the results show 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<sub>2</sub> 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. Another problem is that the surfaces of lignin and salt treated roads often give the appearance of slipperiness and can indeed become slippery in some circumstances.

### 7.5.3 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 they are application becomes relatively more difficult and costly.

### 7.5.4 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.

### 7.5.5 MICROBIOLOGICAL BINDERS

These act by microbes acting on 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.

### 7.5.6 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.

### 7.5.7 OTHERS

Various other products are described in the Australian and other reports, including bentonite which is a product that acts by ionic exchange on the clay particles and was considered to be specific to limestone. Other products are now available which claim to act in a similar way on the clays contained in other minerals.

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 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 user 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 are 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. Glossy photographs are often displayed showing how roads have, apparently, been improved and few senior politicians have the technical knowledge to ask the discerning questions needed to establish the precise

circumstances and length of time over which products are claimed to have been effective.

The author of this report has had experience in Zimbabwe where a product was used under circumstances in which it was clearly unlikely to be beneficial and the treated section of the road deteriorated rapidly to a worse condition than it was in prior to treatment and to a far worse condition than a short adjoining section that was left untreated for comparison purposes. The local egg producer who had paid for the product and for its application under the supervision of a representative from the supplier had no recourse for compensation from the company which was based in South Africa. Similar experiences are not uncommon on the African continent and elsewhere where the use of dust palliatives is unregulated.

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:

1. They are expensive
2. Their use may have environmental impacts
3. Lasting improvement in road performance are rarely observed
4. Any benefits are of short duration or are not readily apparent
5. 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, of the circumstances in which they can where their use has been found to be beneficial including a reduction in dust. However, it should also be stated that is often unclear whether these benefits are long-lasting or cost –effective in life-cycle terms because long-term comparative trials with more conventional non-palliative sealing measures are rarely carried out.

Publications are available which give guidelines on the use of palliatives so that practitioners using them can comply with prevailing legislation aimed at preventing or limiting environmental impacts.

The ARRB report (Foley, Cropley and Graham) reports a study in the USA that gives suggested agency costs (i.e. construction and maintenance costs) of four options for dust suppression as shown in Table 9.

TABLE 9: COST OF DUST SUPPRESSION BY USE OF VARIOUS PAVING TREATMENTS

Treatment to unpaved street	PM <sub>10</sub> reductions (per mile/ton/yr)	Cost to reduce each ton of PM <sub>10</sub> dust (US\$/yr)
50mm of asphalt paving	50.7	500
Two-coat sprayed seal	50.7	389
Oiling (emulsified bitumen)	20.5	229
Calcium chloride	20.5	140

Source: Foley, Copley and Graham - Australian Road Research Board

However, whilst not primarily a dust control study, it should also be stated that 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'.

The use of products for dust control is problematic for the road engineer because of the large permutation of options given the range of products available, the variability of the natural materials used in gravel road wearing courses, the uncertainty of their durability and life-time benefit. These factors are exacerbated by a lack of knowledge by many practitioners of the composition of many of the products being marketed and of the processes by which they are effective. 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 which is clearly not a satisfactory situation for a number of reasons. An additional problem in developing countries, where their use tends to be unregulated, is that practitioners frequently find themselves under political pressure to use products which turn out to be of no engineering or economic benefit.

## 8 FUTURE TRENDS

With increased access to global information, rural populations in developing countries are becoming increasingly aware of how their livelihoods compare with others. Expectations are rapidly increasing for year-round access to essential services such as health centres, schools, markets and reliable transport which provide access to employment opportunities as well as for improvements to their environment such as reducing dust impacts. Politicians and practitioners are aware of these expectations and of the associated pressure by poor communities for the delivery of measures that will help improve their livelihoods.

Gravel roads comprise such a large proportion of the total road network in many developing countries that the resources required to upgrade them by conventional methods are unlikely to be available in the foreseeable future. More energy-efficient methods of producing bitumen products are being developed which might reduce production costs but the current forecast is that the cost of products based on oil derivatives such as bitumen are likely to increase in real terms as demand increases.

Efforts are being made through research to improve the cost-effective delivery of more durable all-weather surfaced roads through the development of innovative designs and new (and greener) technologies. Despite these advances, gravel roads are likely to remain a significant part of road networks in developing countries for many years to come.

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 in specific problem areas where the impacts of dust are deemed to particularly hazardous. Measures (including 'green' technology) applied to reduce dust impacts to the health of those most at risk (e.g. near schools, clinics and hospitals, through villages, markets) 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. Road improvement schemes would then be more easily justified and be more likely to attract by investment by government, donor agencies and the private sector.

## 9 COSTS OF UPGRADING ROADS

Considerable research has been undertaken in recent years to develop new construction techniques, to evaluate and exploit the properties of locally available material resources and to motivate a culture of innovation amongst engineers, all of which has been aimed at the provision of all-weather, durable and sustainable roads for poor rural communities.

For many years, investments in rural roads in developing countries were treated differently from roads carrying higher traffic levels. Investments in roads carrying much lower levels of traffic were often based on construction costs alone and this particularly applied to roads constructed by labour-based methods. Different investment models are often used for different types of roads in developed countries but decisions to invest in rural roads in these countries is usually based on some version of cost-benefit analysis carried out over a defined investment period.

Models such as HDM were developed to assist the estimation of costs and benefits of various design and maintenance options for a road project over a user-defined investment period. However, the main benefits from improvements on more heavily trafficked roads are derived from reduced vehicle operating costs, mainly in the form of lower vehicle maintenance costs when road roughness is reduced. At the time of the development of HDM, agencies such as the World Bank had fixed norms of traffic before roads could be considered for upgrading (e.g. a lower limit of 200 vehicles per day was usually quoted for sub-Saharan Africa).

Subsequently, greater appreciation of the asset value of networks as a whole, including the unpaved component, resulted in a whole-life or life-cycle approach to investments in rural roads carrying lower levels of traffic. Results from research also demonstrated the cost reduction options available from increased knowledge of the behaviour of local materials previously thought to be unsuitable for use in road pavements and from experiences with alternative sealing techniques such as the Otta seal which enable weaker locally available aggregates to be used for surfacing.

This life-cycle approach to investments in low-volume roads combined with the outcomes of research in Africa and elsewhere showed that the economic upgrading of rural roads could be effected at much lower levels of traffic in some circumstances than was hitherto considered possible. (*SADC Guideline for sealed roads, 2003*). The technical and other innovations described in the Guideline significantly lower the traffic threshold for upgrading unpaved roads to a sealed standard.

HDM-4 has been enhanced to include benefits from non-motorised traffic in the investment appraisal of road projects and these are also included in other simplified road investment tools such as RED (*Archondo-Callao, 1999*). The evaluation of non-vehicle related benefits in economic terms remains more elusive although awareness of the potential importance of these benefits to rural communities is increasing, including the impacts of dust. Studies are being undertaken by various organisations to evaluate many of these, primarily social, benefits.

Despite these efforts, which have reduced investment costs and increased the pace of provision of sealed roads, earth and gravel roads will continue to be a significant proportion of rural road networks for many years to come as, unfortunately, will the impacts of traffic-generated dust.

## 10 DUST IMPACTS IN INVESTMENT MODELS

Developing countries are likely to be the main beneficiaries of the quantification of non-vehicular benefits from upgrading roads, given the proportion of the road networks that remain unpaved and the potential benefits from a reduction in the adverse impacts of traffic-generated dust. The large number of publications on dust accessed in undertaking this project would appear to indicate that there are increasing concerns about the impacts of dust. However, the relatively few studies that have attempted to apply actual costs to these impacts is perhaps indicative of the difficulty of this task.

In this section of the report some indication is given of the type of data required if the results are to be included in investment appraisal models such as HDM-4.

The HDM-4 analytical framework is 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 impacts of road condition and road design standards on road users are measured in terms of road user costs and other social and environmental effects.

Road user costs in HDM-4 comprise vehicle operating costs (fuel, oil, tyres, spare parts, vehicle depreciation, etc), costs of travel time and costs of accidents. Road user costs can be derived for both motorised transport (motorcycles, cars, trucks, buses, etc) and non-motorised transport (bicycles, human powered tricycles, animal-pulled carts, etc)

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.

Economic benefits from road investment are determined by comparing the total cost streams for various road works and construction alternatives against a base case alternative, usually representing a minimum standard of routine maintenance.

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.



## 11 OUTCOMES OF DISCUSSIONS WITH SELECTED COUNTRIES

### 11.1 GENERAL

Attendance at technical conferences in Africa and Asia provided an opportunity to meet and discuss issues relating to dust impacts with local practitioners and other professionals undertaking research in the transport sector.

From these discussions it is clear that there is growing awareness of the potential harmful effects of dust by professionals in the transport sector. This was considered to be due in part to the relatively high profile given to dust control in the countries like the USA, increasing local awareness of environmental issues, presentations related to dust and dust control given at conferences and to increased access to related publications on the internet. Increased expectations for more reliable access by rural communities and for roads that reduce adverse impacts on their daily lives by poor rural and urban communities alike that are often served by unpaved roads was also mentioned as a factor that has resulted in greater awareness of dust impacts.

It is also clear from these discussions and other meetings with country representatives and various organisations that very little, if any, work was being done on dust impacts in any of the developing countries represented at these conferences. The main reasons given were a shortage of funding and lack of local expertise to carry out the required research. From the discussions and meeting undertaken during the project, the following countries have emerged as possible partners should the project be taken to a further stage.

### 11.2 TANZANIA

In Africa, the Technology Transfer Centre at Dar es Salaam, which is one of the more active T<sup>2</sup> centres on the continent, the staff stated that they were unaware of any publications on studies of dust in any African country apart from the work done in South Africa and no further information has become available since the meeting. Support, in principle, for a project on dust was expressed by the head of the road agency (Tanroads) in Tanzania and a willingness to participate in a project to research the impacts of dust was also expressed by the Engineering Faculty of University of Dar es Salaam. Tanzania is one of the African countries with less than 10 percent of its road network paved.

### 11.3 ETHIOPIA

Ethiopia is a country with one of the lowest density of roads per population in the world and here too, less than 10 percent of its roads are sealed. Interest in participating in a project on dust has also been expressed by representatives of the Ethiopia Roads Authority. The University of Addis Ababa has a reputation for undertaking research and could be expected to be an active partner in a project on dust. The UK Department for International Development (DFID) is currently collaborating with a number of countries in Africa, including Ethiopia, in a programme of research and implementation (*AFCAP*) for the application of low-cost surfacing improvements to rural roads. It is also reported that the World Bank is intending to support the establishment of a centre for research for the road sector in the country. These initiatives could provide opportunities for research into dust impacts.

### 11.4 SOUTH AFRICA

South Africa is not a developing country in the context of this study. However, many of its rural areas and poorer urban areas are served by the 600,000 kilometres of unpaved roads in the country. In this respect, South Africa is not sufficiently different from many other African countries.

Considerable research on deriving standards for unpaved roads, on the efficacy of dust control products and on the development of dust measuring techniques as mentioned earlier in the report has been carried out in South Africa. Much of this work has been undertaken at the Council for Scientific and Industrial Research (CSIR) but various universities have also been involved in research on unpaved roads. A meeting was held with Dr Phillip Paige-Green at the CSIR to discuss the work on dust in relation to the current project.

Although the research on dust at CSIR did not have a primary focus on the cost impacts of dust on communities, the work that has been conducted there has provided background information for this study. Given the previous work on dust, consideration could also be given to South Africa as a possible partner if a follow-up project is undertaken in Africa.

### 11.5 CAMBODIA

In South East Asia, the deputy head in the Ministry of Rural Development in Cambodia expressed particular concern about the health of children, particularly the very young, exposed to traffic-generated dust.

Concern about the impacts of dust has led to consideration by the Ministry for the introduction of measures such as the planting of small trees between the edge of the road verge and adjacent footpaths to help shield pedestrians and nearby dwellings from traffic-generated dust. Interest in participation in a study on dust was also expressed by the Cambodia Institute of Technology.

Dust control may also be linked to the 'Green Corridor' approach and the 'Climate Change Impact' programme being undertaken by the Research Centre of the Ministry of Public Works and Transport.

## 11.6 LAOS

In Laos, it was reported that the governor of one province had referred to people travelling in 'a sea of dust' which is evidence of recognition of the problem at a senior political level in the country. It was also stated that the scale of the problem and the context of its impacts in Laos is significantly different from that in developed countries. As in many countries in South East Asia good quality roadbuilding materials are scarce in many areas, leading to land slips in mountainous regions in the wet season and very dusty roads in dry conditions. The head of the National Road Safety Committee confirmed that dust was a road safety issue in Laos but have no relevant data. The Public Works and Transport Institute carries out research on behalf of the Ministry of Public Works and Transport were keen to be involved in a dust research project which would need a formal approach to be made through the Ministry.

## 11.7 THAILAND

Thailand has a strong research capability based at the various universities and could provide a strong partnerships into traffic generated dust. Some research has been carried out on the impacts of dust and road safety but the evidence available in the literature suggests that this has mainly been on the impacts of road dust and debris on paved roads.

## 11.8 CONCLUSIONS FROM COUNTRY DISCUSSIONS

In Africa, the UK Department for International development (DfID) is sponsoring the African Community Access Programme (AFCAP), (*Greening and O'Neill, 2009*) which is aimed at providing opportunities for local practitioners to apply evidence-based innovative approaches derived from research to sealing rural roads and to carry out research aimed at solving specific local problems. The countries involved in the programme to date are Ethiopia, Kenya, Malawi, Mozambique and Tanzania. The demonstration and research projects in the programme could provide opportunities to include projects aimed at collecting quantitative information on the costs and benefits related to traffic generated dust.

The above programme follows a similar DFID-sponsored programme in South East Asia (SEACAP) which was undertaken in partnership with Cambodia, Laos and Vietnam. In this programme, research was carried out on alternative and innovative approaches to the design, construction, surfacing and maintenance as well as evaluating options for upgrading rural roads in terms of life-cycle costs and the use locally available (non-standard) materials. Although this programme has been completed, many of the outcomes from the research carried out during the programme are being implemented. Given the interest

expressed by local practitioners and researchers in measures aimed at reducing dust impacts, Cambodia and Laos could provide opportunities for partnership projects. Vietnam has also continued to undertake research themselves as a result of the SEACAP initiative and it has been reported that there is also considerable interest in the country on implementation of dust-reduction measures.

If a follow-phase of the project is approved, then more detailed discussion will be required with the countries identified and selected as prospective partners.

## 12 SPOT IMPROVEMENTS

One of the more cost-effective ways of improving roads when funding is scarce is to adopt a strategy of 'spot improvement' or 'targeted intervention'.

Although it is not unusual in developing countries for long sections of road to become impassable at certain times of the year, on many roads it is often only short sections that regularly cause problems of accessibility. The spot improvement approach is often targeted at these areas such as river crossings or short sections of roads with soft clay or on steep hills. It is often on these locations that roads deteriorate to a standard in which transport services are disrupted and access by rural communities to essential services is impeded in the wet season.

Other candidate sections are sections of roads through villages or on strategic links such as those from village to schools, clinics, local markets and other services considered as being essential to the livelihoods of people living in poor rural communities. The benefit-cost ratios from such targeted interventions tend to be high and costs savings of 50% to 90% are reported as having been achieved by this approach. (*Lebo and Schelling, 2001*).

A similar approach would appear to be highly beneficial in the context of situations where traffic-generated dust impacts are likely to be most acute. It is clear that measures such as the provision of a bituminised road surface designed to improve wet-season access could also be highly beneficial to dust reduction in the dry season and between rainfall events in the wet season.

In the context of a spot improvement approach but in situations where the capital or mobilisations costs of a sealing option is considered too expensive, then other dust control measures such as the use of palliatives would seem to be potentially appropriate, even if the benefits are more transient. However, the problems discussed earlier in the report in relation to the lack of control in the use of palliatives and the somewhat unprofessional marketing techniques by some salespersons in the industry in developing countries has clearly lead to local practitioners being extremely reticent about their use. There is also the problem of the availability of funding for the more frequent repeat applications required to maintain a relatively dust-free environment, It is, therefore, not surprising that practitioners prefer to press for more proven, longer term solutions such as a surface dressing or an Otta seal in these situations.

## 12.1 CONSTRAINTS ON DATA AVAILABILITY FOR QUANTIFYING AND COSTING IMPACTS

Quantifying and costing the impacts of traffic-generated dust will be a challenge. However, various techniques have been developed to measure most of the particulate component in dust clouds. Although the finest and most dangerous particles in terms of health impacts might require more sophisticated methods of measurement, the major components of road dust generated on gravel roads are generally in the fraction  $P_{10}$  or greater, which whilst still having adverse impacts on health, are also more easily measured.

One of the possible reasons that there appears to be such sparse quantitative data available on the costs of traffic-generated dust impacts from unpaved roads may be due to the difficulty of assessing the evidence with a degree of statistical significance that render the results reliable. Researchers would need to determine ways of eliminating possible other impacts which might be dust related but may not necessarily be caused by dust generated from traffic on these roads.

The collection of reliable data could be quite difficult in relation to impacts on the health of rural populations in developing countries, where other potential impacts of air borne PM such as from cooking on open fires, bush fires or other pollution may be equally damaging. Specialists in health research would be capable of providing advice on population sampling methods to help isolate the impacts of traffic generated dust on vulnerable groups including schoolchildren, which many people consider are particularly at risk. Another major problem is that impacts on health may not immediately be apparent but develop over time and this might also present problems although health experts could probably also devise sampling techniques to address this issue.

These problems might be less acute in measuring the impacts on agriculture. Clearly, there are many impacts that affect crop growth and quality apart from dust but it might be easier to isolate the dust impacts and to repeat trials over a number of growing seasons to increase confidence in the results. The basic work done on agricultural impacts in New Zealand and South Africa would provide a starting point but agricultural research experts should be able to advise on the development of an appropriate research matrix to measure these impacts.

Measurement of the environmental impacts of dust should also be possible. Some of the work referenced in this report show that relatively high levels of dust have been measured inside buildings near places where dust is being generated. In developing countries where daytime temperatures can be high, houses are often built in close proximity to unpaved roads and are designed to provide maximum ventilation. Such dwellings are particularly susceptible to

the intrusion of dust. Measurement of these environmental impacts and others, such as the potential pollution of water sources, should easily be possible using the one of the methods developed for measuring dust.

Road safety is nearly always mentioned when discussing the impacts of dust. As mentioned earlier in the report, the author has experienced first-hand the potential safety problems related to roads in Africa and the horrendous consequences of dust-related accidents. Many road accidents in rural areas of developing countries are unreported, especially those that do not cause death or serious injury and it is highly likely that dust will be a factor in at least some of these. Poor visibility of any description inevitably leads to an increase in road accidents. However, data on road accidents directly related to dust will only become available if dust is included on police accident reporting forms as a category in the list of contributory causes when road accidents are recorded. Such a measure is clearly possible if data on the road safety impacts of dust are considered to be sufficiently important.

## 13 DISCUSSION AND RECOMMENDATIONS

Results of studies in developed countries have clearly showed the potential adverse impacts of dust and this has resulted in restrictions being put in place in these countries to limit the damaging effects of dust. There is clear agreement that people are adversely affected by dust in general and that dust from unpaved roads is a major contributor component to airborne or fugitive dust. This is reflected by the level of concern in developed countries, where standards have been set for air quality and where there is a need for compliance with limits set for airborne particulates. It is also clear that the long-term remedy for controlling dust on roads (e.g. surfacing the road with a bituminous or concrete seal) requires relatively large up-front investment that is often unavailable to the local authorities responsible for many of these roads even if the life-cycle benefits justify investment in longer-term solutions.

Consequently, much of the effort in addressing the dust problem in high and middle income countries with large unpaved road networks tends to be concentrated on less costly shorter-term measures. Considerable efforts have been made to develop methods for the measurement of dust emissions and measurement of air quality, the development of models that help predict the likely emission and transfer of dust. Many studies have been conducted into the use and efficacy of various dust palliatives.

From the evidence available, most of the studies that include costs seem to be related to cost comparisons of these shorter-term measures and often involve the use of proprietary products. Few studies seem to have been undertaken to compare the performance of these measures of dust control with longer-term conventional approaches. In the SEACAP and AFCAP programmes various traditional and innovative options for sealing road surfaces such as Otta seals, stone setts, block paving, fired bricks, dry-bound macadam, etc are being considered depending on local circumstances. Some of these approaches are particularly suited to a targeted intervention approach and could be adopted for short road sections, where road dust is a particularly severe problem.

Despite awareness and increasing concern of the possible adverse impacts of dust described in this report, little quantitative evidence is available on the cost implications from the impacts of dust on people or on their livelihoods. Even recognising the difficulties of quantifying and costing these impacts in monetary terms, it is surprising that more research has not been done in an attempt to do so, given the level of concern about dust and the potential harm it can cause.



In developing countries, the situation is significantly different from high-income countries. Parts of the trunk road network remain unpaved in many countries together with strategic roads serving rural communities and roads in poorer urban settlements. As stated earlier in this report, the impacts on people are greater too, with far higher exposure to dust by travellers and residents alike.

Despite the obvious need for this information, it has not yet been possible in this study to identify any projects that have attempted to quantify or to cost traffic-generated dust impacts from unpaved roads in developing countries. The main objective of identifying the main impacts of dust has been addressed in this project and has also confirmed the need to quantify the associated costs and benefits in the context of upgrading roads in developing countries.

Quantitative information on the cost implications of dust and of the potential benefits from its reduction would help justify the upgrading of some of these roads and the implementation of targeted interventions in situations where the impacts and benefits are likely to be greatest.

Consultations with professionals working in the sectors on which dust has potential adverse impacts support the need for quantitative data. There is also increasing awareness and concern about these impacts by practitioners in the transport sector in developing countries. The adverse effects of road dust in combination with other particulates on residents, travellers, crops and the environment, including the possible damaging effect on the health of schoolchildren in these countries is frequently raised in these discussions.

There is a clear need for better information on dust impacts and this demand is likely to increase as awareness of the potential adverse consequences of dust increases and the expectations for improved livelihoods by the poor in developing countries, who are the group most affected by dust, also increase.

Attempts have been made in this report to estimate some of the potential impacts of traffic-generated dust although it should be stated that these are somewhat speculative given the sparse quantitative information available. However, it is clear that the quantitative impacts of dust tentatively identified would, if properly costed, be likely to produce sufficient benefits, when these impacts are ameliorated, to help justify investments (in life cycle terms) in longer term measures such as upgrading to a sealed standard.

As a result of the work and consultations undertaken in this study, a strong recommendation is made for a follow-up study to be undertaken in partnership with developing countries (possibly one in Africa and one in South East Asia selected from those where support for such a project has already been expressed) to provide quantitative data on dust impacts. Any future work should involve experts in the various sectors. Such an endeavour will need considerable financial resources but could also be phased to reduce costs. An

approximate estimate of costs is included in the methodology and TOR for Phase II given in Appendix 2.

## 14 CONCLUSIONS

The engineering costs of maintaining unpaved roads vary considerably depending on factors such as traffic, terrain, type of material, climate, etc. Loss of the fine material that contains the clay fraction and acts as the prime binding agent is a major cause of deterioration in earth and gravel roads. Typical annual costs of routine and periodic maintenance combined of unpaved roads tend to be in the range of US\$ 5 000 to US\$10 000 per km per year.

In the absence of quantitative information it is only possible to speculate what the impacts of traffic-generated dust on health might be in developing countries. Figures given by the WHO indicate the potentially damaging health effects of exposure to PM<sub>10</sub> and PM<sub>2.5</sub> particulates in the developing world, especially on women and children. Extrapolation of the results from studies undertaken in developed countries can, to some extent, provide information on some of the probable impacts. Given the number of variables involved, professional research expertise in the health sector will be needed to obtain the data required to enable the impact of traffic-generated dust on health to be quantified. However, from the available data and the statistics provided by the World Health Organisation, it is possible to speculate on the impacts to some degree. 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.

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. Another way of looking at accidents costs due to dust is to take 1% of the figure of the total cost of road accidents in developing countries (currently estimated at about \$80 billion) which would give a figure for developing countries and emerging nations of approximately \$800 million annually.

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*), although many more kilometres are likely to be missing from the recorded lengths in many countries due to the methods of classification used and the large number of unrecorded roads in rural areas. 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.

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 and 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.

The use of products for dust control is problematic for the road engineer because of the large permutation of options given the range of products available, the variability of the natural materials used in gravel road wearing courses, the uncertainty of their durability and life-time benefit. These factors are exacerbated by a lack of knowledge by many practitioners of the composition of many of the products being marketed and of the processes by which they are effective. 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 which is clearly not a satisfactory situation for a number of reasons. An additional problem in developing countries, where their use tends to be unregulated, is that practitioners frequently find themselves under political pressure to use products which turn out to be of no engineering or economic benefit.

## 14.1 SUMMARY OF CONCLUSIONS

- Long-term exposure to 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 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 certain salts.
- In circumstances where the marketing and use of dust palliative products are properly regulated, then these can provide interim relief from dust impacts at lower initial capital costs than a bituminous seal, although repeated application of such treatment might be necessary. The reliance on manufacturers for advice on the appropriate use and likely efficacy 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.

## REFERENCES (in the order than they are first mentioned in the text)

- Kapaley, *Prime Minister's Rural Road Programme* Presentation to ADB/gTKP Transport Forum, Asia on the Move: Energy efficient and inclusive transport, Philippines, Sept 2008.
- Kerali, Robinson and Paterson. *The new highway design and management tools (HDM-4)*. 75<sup>th</sup> TRB Conference. Washington DC. 1996
- The Air Pollution Engineering Manual published by John Wiley and Sons in 2000
- Fugitive Dust: Nonpoint sources*. University of Missouri Extension, 1999
- Veranth, PardyJak, Sheshadri, Kaser and Yin, *Measurement of Fugitive dust, suspension and re-deposition under Dona County, New Mexico conditions*, University of Utah, 2004.
- Environmental Protection Agency, USA, 1972, (1985)
- D Jones, *Road dust – Just a nuisance or a significant road management issue*. Council for Scientific and Industrial Research, South African Transport Conference. Action in Transport for the new millennium, July 2000.
- D Jones, James and Vitale, *Road dust management: State of the practice*. 1<sup>st</sup> Road Dust Management conference, San Antonio, Texas, November 2008.
- Nicholson et al, 2<sup>nd</sup> Edition of Air Pollution Engineering Manual Ch 4, John Wiley and Sons, 2000.
- National Air Quality Standards (NAAQS), Air and Radiation*, USA Environmental Protection Agency, USA, 2009
- USA Environmental Protection Agency - 2010 *Our Nation's Air: Status and Trends through 2008, USA, 2010*.
- Ambient Air Quality Planning – Pollutants of Concern*, Bureau of Air Quality Planning, State of Nevada, 2010).
- Staff Working Paper*, Commission of the European Communities, 2005
- Marc Juhel, *Safe clean and affordable transport for development, World Bank business strategy*, Presentation to the Asia on the Move transport forum, Manila, Philippines, Sept 2008.
- World Road Statistics*, International Road Federation,

*Federal Highway Authority Statistics*, October, 2009

Ethiopian Roads Authority, *Road Sector Development Programme performance: twelve years later*. Ministry of Works and Urban Development, The Federal Republic of Ethiopia, Nov 2009.

*Unsealed roads Manual. Guidelines to good practice*, Australian Road Research Board, 1993.

P Paige-Green, *The influence of geotechnical properties on the performance of gravel wearing course materials*. PhD Thesis. University of Pretoria. 1989.

*The structural design, construction and maintenance of unpaved roads*. Technical Recommendations for highways. TRH20, Department of Transport, South Africa. 1990.

McCrae, *An assessment of the effects of road dust on agricultural production systems*. Research Report No 156, Agricultural Economics Research Unit, Lincoln College, New Zealand, 1984.

A Miguel and G Class. *Allergens in paved road dust and airborne particulates*. Environmental Engineering and Science Department. California Institute of Technology, 1999

*Economic disbenefits of dust from unsealed roads*, Transit New Zealand Research Report, Wellington. 1993

*Particulate Matter: Air and Radiation*. Environmental Protection Agency. USA  
???

*Air Quality: Health and Air Pollution*. Idaho Department of Environmental Quality 2010.

Chan-Yeung, Hong Kong Medical Journal, Vol 6 No.4 Dec 2000.

*Global Burden of Disease*. (2008 update). World Health Organisation (WHO)

*Ambient Air Quality*. Postnote No 272, Parliamentary Office of Science and Technology. November 2006.

G D Jacobs and Hutchinson. *A study of accident rates in developing countries*. TRRL Report 546, Crowthorne, 1973

*Towards Safer Roads in Developing Countries*. TRL/Overseas Development Administration, London 1991

G D Jacobs and I Sayer. *An analysis of road accidents in Kenya 1972*. TRRL Report LR775. Crowthorne. 1977

A Visser and R Hudson. *Optimization of roadway structural design and maintenance strategies with special reference to developing countries*.

- Department of Agriculture, Berkeley. CA. Transportation Research Record 875. Jan 1980
- Road Safety, Gravel Roads*, Manitoba Public Insurance, USA.
- Giummarra. Crash Results for New Zealand, Unsealed Roads Manual, Australian Road Research Board, 2009
- R. W. Day. *Accidents on interstate highways caused by blowing dust*. Journal of Performance of Constructed Facilities Vol 7 No 2 May 1993
- World Consultancy Service Ltd. Transit New Zealand Research Report No 16, Wellington, New Zealand, 1993.
- T E Jones, *Dust emission from unpaved roads in Kenya*, TRRL Report 1110, Transport Research Laboratory, Department of Transport, Department of the Environment, London United Kingdom, 1984.
- Minchington and Bradshaw, *Accident benefits of sealing unsealed roads*. Land Transport New Zealand RR314, Feb 2007.
- Boschert, Pyta and Turner, *Crashes on unsealed roads*. Australian Road Research Board, ARRB Australia 2008.
- D Jones. *Dust and dust control on unsealed roads*. PhD Thesis, Faculty of Engineering, University of Witswatersrand, South Africa, 2001.
- C Gunter, Vegetable Crops Hotline, No 481, Purdue University Cooperative Extension Service, July, Indiana, USA, 2007.
- Road Infrastructure Framework for South Africa*, Ministry of Transport, South Africa 2002?
- Facts and Figures- Transportation*. Nationmaster.com
- Amenity effects of PM<sub>10</sub> and TSP concentrations in New Zealand*, Environet Limited for the Ministry of the Environment, New Zealand, August 2003.
- Heather Smith, *Dust options and the triple bottom line*. Rodney District Works Infrastructure Ltd, New Zealand, 2003.
- Review of methods for monitoring PM<sub>2.5</sub> and PM<sub>10</sub>*, World Health Organisation/European Commission, Berlin, Germany October 2004.
- Handy, Hoover, Bergeson and Fox *Unpaved roads as sources for fugitive dust* Transportation Research News No 60 Washington DC. National Research Council, Transportation Research Board. 1975
- Hoover, Pitt, Lustif and Fox. *Mission oriented dust control and surface improvement processes for unpaved roads*. Iowa State University. 1981



- Taylor, Irwin and Aneshansley *A device to measure road dustiness on aggregate surface roads*. United States department of Agriculture Forest Service, (Report 7170-8). 1987.
- D Jones, Sadzik and Wollmarans, *The incorporation of dust palliatives as a maintenance option in unsealed road management systems*. 20<sup>th</sup> ARRB Conference 2001.
- Foley, Cropley and Giummarra. *Road Dust Control Techniques, Evaluation of chemical dust suppressants performance*. Australian Road Research Board, Special Report 54, Oct 1996.
- Addo, Sanders and Chenard. *Road dust suppression: Effect on maintenance stability, safety and the environment. Phase 1 -3*. Mountain Plains Consortium. Universities Transportation Centre Programme USA May 2004.
- Dust control for unpaved roads, roads and sidewalks*. Infraguide. National Research Council and Federation of Canadian Municipalities. Canada. 2005
- A guide to the use of Otta seals*, Norwegian Public Roads Administration. Road Technology Department. Publication No 93. Oslo Norway, 1999.
- Obika, Freer-Hewish, Woodbridge and Newill. *Prevention of salt damage to thin bituminous surfacing: Design Guidelines*. Proceedings of the 6<sup>th</sup> International Conference on Low-volume Roads, Minneapolis, Minnesota, June 1995.
- Bushman, Freeman and Hoppe, *Stabilization techniques for unpaved roads* Transportation Research Record Vol 1936 / 2005.
- Guideline: Low volume sealed roads*. Southern African Development Community. Gaborone, Botswana. 2003 (Revised 2007).
- Archondo-Callao. *Roads Economic Decision Model (RED) for the economic evaluation of low-volume roads*. Sub-Saharan Transport Policy Programme Technical Note No 18. World Bank Africa Regional Office, Washington DC. 1999
- Greening and O'Neill. *SEACAP and AFCAP: Programmes to stimulate innovation through research in the provision of rural access*. International Conference on Engineering Education and Research (ICEE), Seoul Korea. August 2009
- J Lebo and D Schelling. *Design of rural transport infrastructure*. Rural Transport knowledge base. Rural Travel and Transport Programme, World Bank. 2001

## LIST OF ABBREVIATIONS

ADT	Average Daily Traffic
AFCAP	African Community Access Programme
AGL	Annual Gravel Loss
ARRB	Australian Road Research Board
CAFE	Cleaner Air for Europe
CSIR	Council for Scientific and Industrial Research
DFID	Department for Overseas Development
ED	Economic Downturn
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
ERR	Economic Internal Rate of Return
GDP	Gross Domestic Product
HDM	Highway Design and Maintenance model
HDM-4	Highway Development and Management Model
HDM-4	High way Design and management Tools
IRF	International Road Federation
MDG	Millennium Development Goals
NAAQS	National Ambient Air Quality Standards
NPV	Net Present Value
NPV/km	NPV divided by the length of the road section
OAQPS	Office of Air Quality Planning and Standards
ODA	Overseas Development Administration
OPRC	Output and Performance Based Road

	Contracting
Pa	Annual Precipitation
PAD	World Bank Project Appraisal Document, its draft or the like
PAF	Price Adjustment Factor
PM	Particulate Matter
PM <sub>10</sub>	Particles with aerodynamic diameters between 2.5 and 10 micrometres
PM <sub>2.5</sub>	Particles with aerodynamic diameters less than 2.5 micrometres
RED	Roads Economic Decision model
SEACAP	South East Asia Community Access Programme
TAF	Traffic Adjustment Factor
TRL	Transport Research Laboratory
TSP	Total Suspended Particulates
VPA	Variance of Price Adjustment Factors
WEO	World Economic Outlook April 2010, IMF
WHO	World Health Organisation



Transport Division

Transport, Water and  
Information and Communication  
Technology Department

The World Bank

1818 H Street NW

Washington DC 20433

USA

[www.worldbank.org/Transport](http://www.worldbank.org/Transport)

**DFID** Department for  
International  
Development

