Roads, Vehicle Performance and Greenhouse: Costs and Emission Benefits of Smoother Highways

Working Paper

Previous BTCE work (Report 94) has established that reductions in pavement roughness reduce fuel consumption, greenhouse gas emissions (end-use only) and vehicle operating costs. This Paper evaluates the effects on greenhouse gas emissions and vehicle operating costs of reducing the roughness of the National Highway System and the Pacific Highway over the period 1996-2015. The analysis takes account of the emissions involved in the production, transport and application of road rehabilitation materials. Some results of case studies of recently completed highway rehabilitation projects are included in the Paper.

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ROADS, VEHICLE PERFORMANCE AND GREENHOUSE: COSTS AND EMISSION BENEFITS OF SMOOTHER HIGHWAYS

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FOREWORD

Decreasing the roughness of road surfaces by some form of rehabilitation can reduce emissions of greenhouse gases without curtailing travel, because vehicle fuel consumption is related to road roughness.

In November 1996, the Bureau of Transport and Communications Economics issued Report 94, *Transport and Greenhouse: Costs and Options for Reducing Emissions*. Chapter 16 of the Report assessed the potential greenhouse gas reduction benefits from improving the National Highway System by resurfacing.

This Working Paper extends the analysis in Report 94 by including the Pacific Highway, examining in more detail various road rehabilitation measures and their costs, and taking account of the greenhouse gas emissions from the energy expended in producing and applying the materials involved in these rehabilitation measures. A major objective of the paper is to provide road authorities with information that can be used in estimating the changes in greenhouse gas emissions and vehicle operating costs that could be achieved by various road rehabilitation measures. Additionally, the Working Paper reviews and summarises research on a range of issues relating to road construction and maintenance and vehicle performance.

The paper was prepared by Joe Motha and Edwina Heyhoe with some initial research assistance from Robin Clark, and edited by Kate Crowley.

Dr Leo Dobes
Research Manager

Bureau of Transport and Communications Economics
Canberra
May 1997

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ABSTRACT

Previous BTCE work (Report 94) has established that reductions in pavement roughness reduce fuel consumption, greenhouse gas emissions (end-use only) and vehicle operating costs. This paper evaluates the effects on greenhouse gas emissions and vehicle operating costs of reducing the roughness of the National Highway System and the Pacific Highway over the period 1996–2015. The analysis takes account of the emissions involved in the production, transport and application of road rehabilitation materials. Some results of case studies of recently completed highway rehabilitation projects are included in the paper.

An important feature of the paper are tables which may be used as 'ready reckoners' to estimate the reductions in greenhouse gas emissions and vehicle operating costs resulting from different types of road rehabilitation. The paper reviews relationships between pavement surface condition and speed, skid resistance and rolling resistance/fuel consumption, and between speed and fuel consumption. Also discussed are the effects of highway water run-off on the environment, pavement construction and characteristics, and the features of bituminous and concrete pavements.

The results of the analysis indicate that reducing the roughness of highways has the potential to produce modest reductions in cumulative emissions over time, at relatively high marginal costs per tonne.

EXECUTIVE SUMMARY

A measure assessed in BTCE Report 94, *Transport and Greenhouse: Costs and Options for Reducing Emissions*, was reducing the roughness of roads comprising the National Highway System (NHS). The lower the roughness, the lesser the amount of fuel consumed by vehicles and the smaller the quantity of greenhouse gases emitted on an end-use basis.

This paper refines and expands the analysis of highway rehabilitation presented in Report 94. It takes account of the emissions involved in extracting, processing, transporting and applying the materials used in highway rehabilitation. In addition to the NHS, the Pacific Highway has been included in the analysis and several types of rehabilitation have been considered.

A roughness level of 110 NRM (a unit of roughness) or less is generally regarded as acceptable by road agencies. A maximum roughness of 110 NRM has therefore been used as the 'basecase'. The effects of road roughness on fuel consumption have been evaluated using the BTCE's RIAM and HDM-C models.

Marginal costs of emission reduction and cumulative reductions in emissions (CO_2 equivalents) have been estimated for four 'snapshot' years—2000, 2005, 2010 and 2015—at a discount rate of 10 per cent. The results indicate that rehabilitating the NHS and the Pacific Highway to a maximum roughness of 100 NRM would result in a cumulative reduction in emissions by 2015 of about 0.4 million tonnes at a marginal social cost of $252 per tonne. Raising the standard of rehabilitation to a maximum of 90 NRM (a smoother road system) would result in a reduction in emissions of about 0.8 million tonnes by 2015 at a marginal social cost of $701 per tonne. A still further reduction in roughness (80 NRM) would result in about 1 million tonnes of emissions being reduced by 2015 at a marginal social cost of $1530 per tonne.

At the 100 NRM level, rehabilitation costs amount to $304 million, reductions in vehicle operating costs (VOCs) total $253 million, while much smaller values are associated with health benefits ($0.03 million) and fuel producers' costs ($0.65 million). Highway rehabilitation will also result in a loss of Commonwealth tax revenue (sales tax and import duties on vehicles and fuel excise) and State/Territory fuel-based business franchise fees. Rehabilitation to a roughness of 100 NRM would result in an aggregate loss of Commonwealth and State/Territory revenue of $51 million over the period 1996–2015. The loss rises to $100 million at 90 NRM and to $152 million at 80 NRM.

The emission reduction per kilometre of road length over the period 1996–2015 would be 21 tonnes of CO_2 equivalent and would increase to 40 tonnes for 90 NRM and to 56 tonnes for 80 NRM. Over the period 1996–2015, for rehabilitation at 100 NRM, the increase in emissions due to rehabilitation would be 0.1 million tonnes, while the decrease in vehicle emissions would be 0.5 million tonnes. At the 80 NRM level, the figures rise to 0.5 and 1.6 million tonnes respectively.

Case studies of two rehabilitated sections of the Western Highway in Victoria indicate that over a 10-year period, the expected reductions in vehicle emissions are about 14 and 10 tonnes per year. A case study of the effects of the Yass bypass indicates that over a 10-year period following its construction, there would be a reduction in annual vehicle emissions of about 4800 tonnes. Over the same period, however, there would be a net increase in overall emissions of over 10 000 tonnes due to the large quantity of emissions that was produced during the construction of the bypass.

Hypothetical one-kilometre sections of road having an average annual daily traffic level of 1000 were used to assess the effect of highway rehabilitation on VOCs over a roughness range of 30 to 150 NRM. For cars, costs in cents per kilometre were found to increase by about 8 per cent (from 29.0 to 31.2 cents) over the roughness range. The increase was 3 per cent for articulated trucks and 11 per cent for rigid trucks.

Fuel use (measured in litres per 100 kilometres) over the 30 to 150 NRM range is estimated to increase by 3.8 per cent for cars and 4.3 per cent for articulated trucks. The increase for rigid trucks would be significantly higher (6.7 per cent).

Sets of tables detail annual reductions in vehicle emissions and social VOCs that can potentially be achieved by different types of road rehabilitation for one-kilometre sections of road at different traffic levels. These tables may be used as 'ready reckoners' to estimate approximate reductions in emissions and VOCs that may be expected by rehabilitating sections of road of any length.

An appendix reviews relationships between pavement surface condition and speed, skid resistance and rolling resistance/fuel consumption, and between speed and fuel consumption. Other appendixes discuss the effects of highway water run-off on the environment, pavement construction and characteristics, and the features of bituminous and concrete pavements.

CHAPTER 1 INTRODUCTION

THE GREENHOUSE EFFECT AND TRANSPORT

Houghton (1994, pp. 19–27) presents a summary of the scientific debate on the nature of the greenhouse effect and its possible implications. Radiant energy from the sun passes through space and falls on the earth. As this energy passes through the atmosphere, about 6 per cent is scattered back into space by molecules of gases in the atmosphere, about 10 per cent is reflected back to space from the land and ocean, and the remaining 84 per cent is retained to heat the earth's surface. In order to ensure an energy balance, the earth must radiate about the same amount of energy back into space. The amount of radiation emitted by the earth depends on its temperature (the warmer the surface, the greater the amount of energy emitted) and the degree to which the surface absorbs radiation (the higher the degree of absorption, the greater the amount of radiation emitted). Most parts of the earth's surface, including the polar regions, absorb much of the radiant energy they receive.

In order to achieve a balance between the amount of energy received by the earth and emitted from it, it has been estimated that the average temperature of the earth's surface should be about minus 6 degrees Celsius. However, the actual average annual temperature over the earth's surface is about 15 degrees Celsius.

The difference in the temperature balance is explained by the natural greenhouse effect. Nitrogen and oxygen, which comprise 78 and 21 per cent respectively of the atmosphere by volume, do not absorb or emit thermal radiation. The gases present in the atmosphere in smaller proportions, such as water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and ozone (O_3), absorb some of the solar radiation escaping from the earth's surface. These gases act like a blanket for the radiation causing a difference of about 21 degrees Celsius between the actual average temperature of the earth (15 degrees Celsius) and a temperature of minus 6 degrees Celsius for an atmosphere made up only of nitrogen and oxygen. The blanketing effect is known as the 'natural greenhouse effect' because of its similarity to the effect of glass in a greenhouse. The gases causing the effect are known as 'greenhouse gases'.

The 'enhanced greenhouse effect' refers to the additional effect caused by increasing concentrations of greenhouse gases, mainly due to the burning of fossil fuels and deforestation. There is considerable scientific uncertainty about the magnitude and timing of any consequences of the enhanced greenhouse effect. Scientists believe that a doubling of the concentration of carbon dioxide is likely to result in an increase of 2.5 degrees Celsius in average global temperature with concomitant changes in the pattern of precipitation (IPCC 1992). For a more detailed discussion of the issues, see Houghton (1994) and BTCE (1996a).

Due to fossil fuel combustion, transport has global ramifications in terms of its contribution to the enhanced greenhouse effect. In turn, the climatic changes that may be brought about by the enhanced greenhouse effect would have some adverse impacts on the transport sector. Indications of various possible impacts of climate change on the transport sector were provided by R. Basher (pers. comm., 29 January 1997). Changes in agricultural production would change the demand for transport services. Higher temperatures will reduce maximum take-off weights for aircraft, buckle railway lines and melt bituminous material on roads. However, risks due to winter snow and ice on roads would be diminished. Increased rainfall in some areas would cause more landslides, obstructing road and rail routes. Flooding would affect airports, roads, railway tracks and bridges. Increases in the frequency and intensity of storms would adversely affect all transport operations by raising costs, reducing safety, and impacting on tourism and exports. As Australian motorised transport services rely on fossil fuels, economic or regulatory measures to curb fossil fuel use will have restrictive effects on mobility and domestic and international trade.

Australia produces around 1 per cent of the world's greenhouse gas emissions. However, despite its low global ranking, Australia is one of the highest per capita emitters of greenhouse gases (BTCE 1996a, p. 9). Carbon dioxide is the main greenhouse gas emitted by the transport sector. Australia's overall energy emissions and those from the transport sector are above the OECD average.

The Australian transport sector generates both direct (radiatively active) and indirect greenhouse gases. The main direct greenhouse gas emissions apart from water vapour are carbon dioxide, methane, nitrous oxide and CFCs. Indirect greenhouse gases, such as carbon monoxide (CO), oxides of nitrogen other than nitrous oxide (NO_x), and non-methane volatile organic compounds (NMVOCs), do not contribute to a strong radiative effect, but influence atmospheric concentrations of the direct greenhouse gases.

In terms of energy usage, transport contributes about 25 per cent of Australian greenhouse emissions. This figure excludes non-energy sources such as methane emissions from agriculture and coal mines. The transport sector actually contributes only about 12 per cent of Australian greenhouse emissions, and even this figure overstates transport's contribution to nationally attributable emissions, because it includes emissions from ships and aircraft operating outside Australia. Within Australia, transport contributes only about 15 per cent of carbon dioxide emissions.

Road passenger transport accounts for about 60 per cent of total CO_2 equivalent emissions from the Australian transport sector (BTCE 1995a, p. 17). Most of these emissions are from cars, with only 1.8 per cent of transport emissions due to buses and 0.5 per cent to motorcycles.

Trucks carrying freight account for about 28 per cent of CO_2 equivalent emissions in the Australian transport sector (BTCE 1995a, p. 33). This paper presents estimates of greenhouse gas reductions from both rigid and articulated trucks, besides cars, as a result of various highway rehabilitation options.

Animals used for transport in the pre-motorised era produced methane and nitrous oxide—more potent greenhouse gases than carbon dioxide. The motor car has been much maligned as the major contributor to elevated greenhouse gas concentrations in the atmosphere. However, a study by Dobes (1995) concluded that the reliance on fossil fuels by the Australian transport sector is no worse today in terms of greenhouse emissions produced, and is possibly better than in the pre-motorised era, after accounting for growth in population and gross domestic product (GDP).

Apart from its contribution to the global enhanced greenhouse effect, other, more localised, environmental effects of road transport include air and noise pollution, adverse impacts on soil, vegetation and fauna in the vicinity of roads, and underground water contamination due to water run-off from roads and highways. A review of issues relating to highway water run-off and the environment is in appendix I. Vehicle emissions are also responsible for low-level ozone pollution in cities caused by the action of sunlight on oxides of nitrogen and volatile organic compounds (Maddison et al. 1996, p. 15). Oxides of nitrogen also contribute to acid rain, causing acidification of soils and damage to buildings (Maddison et al. 1996, p. 15). An assessment of the social costs (mainly effects on human health) of vehicle emissions is found in BTCE (1996a, appendix X).

RECENT BTCE WORK ON TRANSPORT AND GREENHOUSE

BTCE Report 88, *Greenhouse Gas Emissions from Australian Transport: Long-Term Projections* (1995a) provided estimates of the emissions from cars, trucks, rail, aircraft and ships from 1974 to 2015. BTCE Report 94, *Transport and Greenhouse: Costs and Options for Reducing Emissions* (1996a), examined a range of options to reduce emissions and estimated marginal costs of emission reduction.

It is somewhat counterintuitive to expect that improving roads can result in reduced emissions of greenhouse gases. However, it has been found in a number of studies that road surface roughness is related to vehicle fuel consumption: the lower the roughness, the lesser the amount of fuel consumed.

Decreasing the roughness of roads can therefore reduce greenhouse gas emissions without curtailing travel.

The use of the term 'roughness' to describe the riding qualities of a road surface has become established by common technical usage. However, the term may not be entirely appropriate to describe modern roads, which are relatively smooth and provide good riding qualities. In Europe, the term 'evenness' is used, which is probably more evocative of the surface characteristics of modern roads. John Bethune of the Australian Asphalt Pavement Association prefers the more positive term 'smoothness' (pers. comm., 11 February 1997). However, 'roughness' has been used in this paper to accord with standard technical usage.

Among the options examined in BTCE (1996a) was the resurfacing of the National Highway System (NHS), and chapter 16 of that report sets out results of the analysis. An acceptable level of roughness is defined to be 110 NRM (see chapter 2 of this paper). BTCE (1996a) found that resurfacing the NHS to a roughness of 100 NRM (a smoother road system) would reduce road transport emissions by about 0.7 million tonnes of CO_2 equivalent by 2015 at a marginal social cost of $235 per tonne. Motorists would save about $650 million from fuel and vehicle maintenance, but government expenditure of $699 million would be required and a loss of $107 million in Commonwealth and State/Territory fuel taxes would be incurred. A discount rate of 10 per cent was used in the analysis.

BTCE (1996a) also found that, relative to a basecase of 110 NRM, resurfacing to a roughness of 90 NRM would result in a reduction in CO_2 equivalent emissions of 1.3 million tonnes by 2015 at a marginal social cost of $716 per tonne. Marginal costs were found to rise steeply as roughness was progressively reduced. For example, resurfacing to a roughness of 60 NRM would generate a reduction in emissions of 3.8 million tonnes by 2015 at a marginal social cost of about $9000 per tonne.

This paper expands and refines the analysis in BTCE (1996a, chapter 16) by considering several road rehabilitation options and their costs, and taking account of the greenhouse gases emitted in the production of materials used in rehabilitation and in their transport, heating and application. Savings in vehicle operating costs (VOCs) due to rehabilitation are presented for cars, rigid trucks and articulated trucks. A useful inclusion in this paper are tables which show the potential greenhouse gas reductions and social VOCs relating to various types of rehabilitation for one-kilometre sections of road.

CHAPTER 2 PAVEMENT ROUGHNESS AND ITS IMPLICATIONS

PAVEMENT PERFORMANCE AND ROUGHNESS

There are three generally accepted measures of pavement performance: safety, structural performance and functional performance (Bednar 1989, p. 90). Safety is usually measured by the change in the frictional characteristics between vehicle tyres and the pavement surface over time. A review of pavement characteristics that affect safety is provided in appendix II.

Structural performance relates to a pavement's physical condition in terms of its ability to bear loads or the occurrence of various types of distress such as cracking, ravelling or rutting. Pavement construction and characteristics, including various types of distress, are reviewed in appendix III. Functional performance measures the degree of serviceability of the pavement over time, the usual indicator being ride quality or roughness.

Roughness and other surface irregularities are measured continuously over a specified length of road. The signals generated by the measuring device can be subjected to spectral analysis by which the lengths of the surface irregularities or amplitude of deviations (wavelengths) from a planar surface can be measured. The surface characteristics of pavements have been specified in terms of wavelengths by PIARC (1987, pp. 18–19). The four principal types of surface texture and their associated horizontal and vertical wavelengths are set out in table 2.1. There are two additional surface irregularities: transverse profile (which lies between the wavelengths of megatexture and roughness) and vertical alignment (which includes wavelengths greater than roughness) (PIARC 1991, p. 43).

Microtexture affects skid resistance at all speeds in both wet and dry conditions. Macrotexture affects rolling resistance (and therefore fuel consumption), tyre/pavement noise at medium to high speeds, splash and spray on wet pavements, and light reflection from pavements. Macrotexture also affects skid resistance at medium to high speeds, particularly on wet pavements. The nature of microtexture and macrotexture and their influence on skid resistance is discussed in greater detail in appendix II.

TABLE 2.1 PAVEMENT SURFACE TEXTURES AND WAVELENGTHS

Surface texture	*Horizontal wavelength range*	*Vertical wavelength range*
Microtexture	≤0.5 mm	≤0.2 mm
Macrotexture	0.5–50 mm	0.2–10 mm
Megatexture	50–500 mm	1–50 mm
Roughness		
Short wavelengths	0.5–5 mm	1–20 mm
Medium wavelengths	5–15 m	0.5–5 cm
Long wavelengths	15–50 m	1–20 cm

Source PIARC (1987, pp. 18–19).

Megatexture includes surface irregularities such as ruts, potholes and major cracks. Megatexture causes increased rolling resistance, higher levels of vehicle noise, vibration of buildings along the road, vibration in the walls of tyres, mechanical vibrations in the steering and transmission mechanisms, reduced grip between tyres and pavement, reduced vehicle control and stability, and increased deterioration of tyres and vehicles.

Roughness has an influence on vehicle fuel consumption, tyre/pavement contact, vehicle occupant comfort (due to high frequency vibrations) and noise. Roughness is caused by deterioration of the pavement by environmental or vehicle action originating in any of the pavement layers, including the surface and sub-grade layers. Pavement materials compact and deteriorate under repeated traffic loadings and weathering. Over time, cracks form on the pavement surface.

Increased roughness reduces surface drainage, resulting in water accumulating on the surface and affecting vehicle performance and safety. Roughness also affects vertical movement of the vehicle and can cause passenger discomfort in the form of jolting. Other effects of increased roughness include greater 'wear and tear' on vehicles, higher VOCs and lower travel speeds.

Water commonly affects pavements by a process known as 'pumping'. Pumping results from the ability of water to suspend and dissolve soil particles and mineral matter. Water seeps through surface cracks into the base course of the pavement (see appendix III for a description of pavement courses), forming a suspension of fine particulate matter. The pressure generated by passing traffic pumps the suspension through the cracks to the surface, thereby further weakening the base course. The continuation of this process results in enlargement of the cracks and hastens pavement deterioration.

Water also affects the pavement by virtue of its incompressibility. Water which enters through the surface cracks travels along the interface between the upper pavement layer and the more impermeable base course. Tyre pressure on the surface layer is transmitted under the surface and on to the layer of water below. The water layer, being incompressible, is deformed by the pressure. The pressure transmitted through the water layer then seeks a means of dissipation, and this is accomplished by causing small portions of the surface layer to be dislodged and ejected from the base. The upward pressure of water on the surface layer also results in further cracking. In some instances, the high pressures generated can cause larger sections of the surface to lift away from the base layer, leaving potholes.

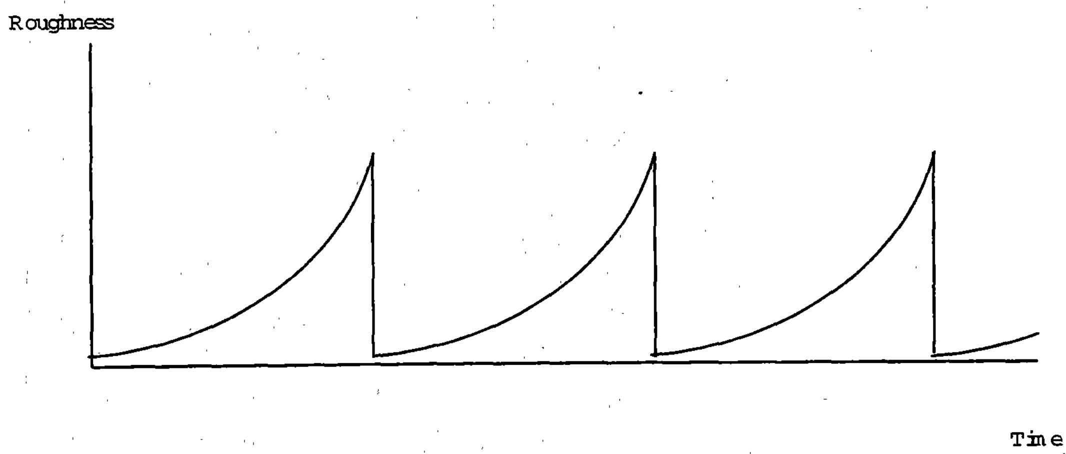
Road condition is a many-faceted concept which includes various types of distress (cracking, potholes, rutting etc.), roughness, structural strength and other factors. However, road roughness is considered the most appropriate means of assessing long-term pavement performance because it is an objective measure, has a low data collection cost, relates directly to road-user costs, and is the most relevant measure of the long-term functional behaviour of pavements (Martin 1996, p. 34). Roughness progression also has the advantage of being a general indicator of both surface distress and pavement/sub-grade stress (Roberts & Martin 1996, p. 2). Although roughness is not the only criterion for assessing the timing and maintenance needs of a pavement, for the purpose of this analysis it has been used as the indicator of the need for rehabilitation.

Paterson (1987, p. 16) cites the following definition of roughness adopted by the American Society for Testing and Materials (ASTM): 'the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage'. Expressed more simply, roughness is the variation in the road's surface profile. The ASTM definition of roughness implies that, on a scale of roughness, the roughness of a true planar surface would be zero.

The life of a highway section comprises a number of cycles. As pavements progressively deteriorate and become too rough, they are rehabilitated (resurfaced or reconstructed). When a pavement is rehabilitated,[1] it commences a new life cycle from which point it begins to deteriorate again. The typical 'sawtooth' cycle of deterioration with increasing roughness and rehabilitation is illustrated in figure 2.1. The application of an overlay will restore the surface condition of the pavement to previous levels, but will have little effect on improving the structural condition of the pavement if it has substantially deteriorated. If deterioration of the base and sub-base layers has occurred, reconstruction of the pavement would be required in order to provide the same level of service and overall structural condition as in the previous cycle.

1. In this paper the term 'rehabilitation' is used in a general sense to describe any process which improves the condition of a pavement, including resurfacing and reconstruction. The terms 'resurfacing' and 'reconstruction' used in the context of this paper refer to specific rehabilitation processes described later in this chapter.

FIGURE 2.1 PAVEMENT LIFE CYCLES



Source BTCE.

Mathematical equations set out in BTCE (1992, p. 12) assume that VOCs are related quadratically to road roughness for cars and linearly for trucks. These relationships suggest that cars are more sensitive to increased road roughness than trucks. However, the model used in the analysis in this paper regards relationships between VOCs and roughness for all vehicles as approximately quadratic.

Direct benefits of highway infrastructure improvements accrue mainly to road users. If highway surfaces deteriorate considerably over time due to neglect, motorists will incur higher VOCs, experience discomfort and increased travel time through reductions in speed, and be exposed to greater crash risk. They may also use alternative routes or transport modes. Road maintenance lowers the costs of vehicle operation and maintenance due to reduced fuel consumption and wear on tyres and suspension components, and extends the service life of vehicles. Timely road maintenance can also considerably reduce overall future maintenance and rehabilitation costs.

Measurement and prediction of roughness

Roughness is readily noticed by road users because of its immediate impact on comfort. It may also be perceived by its influence on vehicle fuel consumption.

The roughness or surface deviations of a road are random in nature, but are characterised by a combination of waveforms of various amplitudes and wavelengths (Paterson 1987, p. 16) which have been specified by PIARC (1987, pp. 18–19). The horizontal wavelengths specified for roughness are: 0.5 to 5 millimetres for short wavelengths, 5 to 15 metres for medium wavelengths and 15 to 50 metres for long wavelengths (table 2.1).

Pavement condition can be expressed in terms of various indexes which are based on the combination of several subjective indicators of pavement distress, including roughness. The various subjective indicators are then also weighted and combined subjectively to produce a single index. Such indexes are not reliable because of their subjectivity, as well as being costly to derive.

Roughness can be objectively measured using mechanical devices mounted on vehicles driven over the road surface, including roadmeters such as the NAASRA Roughness Meter, and laser profilometers. ARRB Transport Research has developed a walking profilometer which is ideally suited for measuring the roughness of new or overlayed sections of road less than 500 metres long (Auff, Tyson & Choummanivong 1995). The unit is about the size of a powered lawn mower and is pushed along slowly by a walking operator.

The international standard used to measure pavement roughness is the International Roughness Index (IRI). The IRI is based on an open-ended scale from zero for a true planar surface, increasing to about 6 for moderately rough paved roads, 12 for extremely rough paved roads with potholing and patching, and up to about 20 for extremely rough unpaved roads (Paterson 1987, p. 29). The units of IRI are dimensionless because it is a slope statistic. (IRI is generally scaled by a factor of 1000, so that it is expressed in units such as metres of roughness per kilometre or millimetres of roughness per metre.)

In Australia, roughness is generally recorded in terms of NAASRA Roughness Meter (NRM) counts. On major Australian roads, a roughness greater than 110 NRM is considered undesirable, and a roughness greater than 140 NRM is considered unacceptable (VicRoads 1992, p. 6). Prem (1989, p. 22) sets out numerical relationships between NRM and IRI.

Either a stochastic or a deterministic approach may be used to predict the future performance of pavements. Stochastic or probabalistic models predict outcomes with a certain probability, whereas deterministic models make an exact prediction. Stochastic approaches use techniques such as probability distributions, Markov chains and survivor curves to estimate the probability distribution of the variable whose progression over time has to be predicted.

In the case of road deterioration, the stochastic approach generally uses various pavement condition indexes, rather than roughness, to predict pavement condition. The approach relies on assumptions about theoretical distributions as well as assumptions about relationships between current and future performance. The stochastic approach also relies on data-intensive empirical models which have to be developed to link the pavement performance indexes with various maintenance measures. An example of a stochastic model is the Financial Planning Network Optimisation System (FNOS) developed and used by the Roads and Traffic Authority (RTA) of New South Wales.

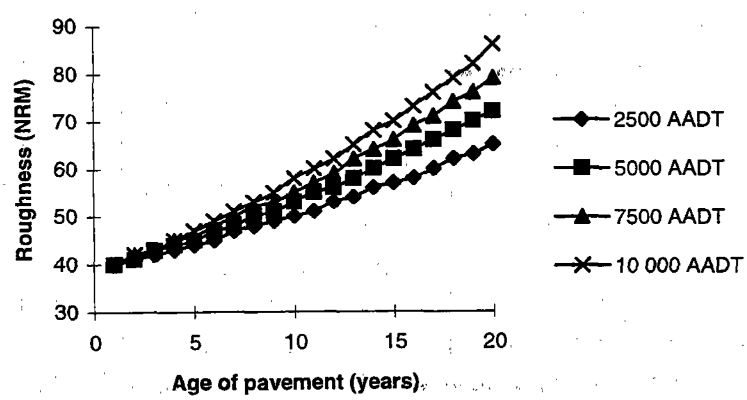
The deterministic approach, used in models such as the World Bank's Highway Design and Maintenance (HDM-III) model, involves determining pavement performance by a function which directly relates pavement condition to variables such as traffic level, measures of pavement strength, pavement age, and environmental factors. The processes postulated in deterministic models are completely determined at any stage by knowing their status at previous stages. Such models therefore require historical data collected over long periods.

Deterministic models calibrated using data from specific locations cannot be used for locations which differ in terms of traffic and environmental conditions. Both stochastic and deterministic models rely on past performance to predict future performance. Therefore, any future changes in variables in the model that have not been reflected in the data used to calibrate the models would result in inaccurate predictions.

Pavement deterioration estimates

The rate of deterioration in pavement roughness determines the timing of rehabilitation and its costs. In this paper, Paterson's algorithm, which is incorporated in the BTCE's Road Infrastructure Assessment Model (RIAM—see appendix IV), has been used to estimate the increase in roughness of a road over time. Figure 2.2 shows the increase in roughness over time of a four-lane road having an initial roughness of 40 NRM using RIAM. Each line in the figure represents the rate of deterioration for a particular level of average annual daily traffic (AADT). Lower traffic volumes result in slower rates of deterioration. In each case considered, the proportion of heavy vehicles (10 per cent rigid trucks and 10 per cent articulated trucks) is assumed to remain constant over time. Total traffic is assumed to grow at a rate of 2 per cent per year.

FIGURE 2.2 CHANGES IN PAVEMENT ROUGHNESS OVER TIME



Note For all traffic levels the road is assumed to have four lanes (two lanes in each direction).

Source BTCE estimates.

Over the 20-year time period considered, roughness increases to 65 NRM with 2500 AADT, but reaches 86 NRM for roads with 10 000 AADT. With a basecase terminal roughness of 110 NRM, roads with 15 000 AADT will be rehabilitated after 17 years, and roads with 40 000 AADT will be rehabilitated after only 11 years. These estimates are derived from RIAM and may not reflect the outcomes of actual road construction strategy, which may involve increasing pavement strength to compensate for traffic volume.

STUDY METHODOLOGY

Pavement rehabilitation

Roughness is only one of several factors, including financial constraints, influencing the timing of road rehabilitation. However, in this study the assumed basecase is that the National Highway System (NHS) and the Pacific Highway are rehabilitated when their 'terminal' or maximum acceptable roughness exceeds 110 NRM.

Terminal roughness is taken as the 'intensity' level of the highway rehabilitation policy instrument for reducing greenhouse gas emissions. The intensity may also be regarded as the threshold level or frequency at which rehabilitation is carried out. Relative to a basecase of 110 NRM, alternative terminal roughness values of 100, 90 and 80 NRM (progressively smoother roads) have been used in the analysis to vary the intensity of rehabilitation. The cumulative reductions in greenhouse gas emissions (in CO_2 equivalents) at progressively lower levels of terminal roughness and corresponding costs have been used to generate marginal cost functions for the years 2000, 2005, 2010 and 2015.

To significantly reduce roughness, substantial rehabilitation must be undertaken in the form of either a reconstruction or overlay. Four types of rehabilitation were evaluated in this study: sprayed seal reconstruction, asphalt reconstruction, asphalt overlay and Novachip[2] overlay (see table 2.2).

Asphalt reconstruction or an asphalt overlay is assumed to be applied to asphalt pavements, while sprayed seal pavements are assumed to undergo a sprayed seal reconstruction. Pavement depth varies significantly with soil conditions and expected traffic volumes, but it was not possible to incorporate this level of detail for the entire NHS and Pacific Highway into the analysis. It was therefore assumed that typical reconstructions were carried out in all

2. Novachip is a proprietary product manufactured in Australia by Boral Asphalt.

locations when roughness levels exceeded the critical value of 110 NRM. The assumed depths are 175 millimetres for a sprayed seal reconstruction, 75 millimetres for an asphalt reconstruction, 50 millimetres for an asphalt overlay, and 17.5 millimetres for a Novachip overlay.

In this study it has been assumed that the cost of minor ongoing maintenance (such as repairing potholes and line marking) is uniform for all types of rehabilitation, and therefore it has not been included in the analysis.

Roughness

RIAM, developed by the BTCE, estimates the deterioration in roughness over the lifespan of a pavement and incorporates the timing and cost of future rehabilitation work. RIAM uses Paterson's algorithm (Paterson 1987, p. 304) to determine annual roughness levels based on pavement age, traffic volume and initial roughness. The model is described in detail in appendix IV.

Post-rehabilitation roughness varies greatly for different types of rehabilitation, and pavements undergoing the same type of rehabilitation may have different post-rehabilitation roughness levels. Information from State authorities suggests that roughness after an asphalt reconstruction may be below 35 NRM, and is typically between 35 and 45 NRM. On the Western Highway in Victoria, VicRoads has achieved post-rehabilitation roughness levels of between 39 and 52 NRM for recent sprayed seal work. The average roughness consequent to each type of rehabilitation was determined after consultation with road agency and industry sources (table 2.2).

TABLE 2.2 EFFECTIVENESS OF DIFFERENT TYPES OF REHABILITATION

Type of rehabilitation	*Typical post-rehabilitation roughness*
Sprayed seal reconstruction[a]	50 NRM
Asphalt reconstruction[b]	40 NRM
Asphalt overlay[c]	35% reduction[e]
Novachip overlay[d]	30% reduction

a. Sprayed seal reconstruction is assumed to involve between 150 and 200 mm of crushed rock and a seal.

b. Asphalt reconstruction is assumed to involve an asphalt layer between 60 and 90 mm thick.

c. Asphalt overlays are assumed to be between 40 and 60 mm thick.

d. Novachip overlays are assumed to be between 15 and 20 mm thick with a seal.

e. For an asphalt overlay, the post-rehabilitation roughness in NRM units is calculated using the formula: new roughness = 0.6 x current roughness + 5 (AAPA, pers. comm., 11 February 1997).

Sources AAPA (pers. comm., 11 February 1997); BTCE estimates.

Emissions

For the purposes of this paper, total emission reductions over a given period resulting from pavement rehabilitation are estimated as the reduction in emissions resulting from reduced fuel consumption of vehicles, minus emissions generated by the production, transport and application of the materials used in the rehabilitation process.

Smoother roads reduce fuel consumption by vehicles. Vehicle fuel consumption has been estimated using the World Bank's HDM-III model as modified by the BTCE. The BTCE's modified version, known as HDM-C ('C' denoting congestion), enables the effects of congestion to be taken into account in estimating VOCs.

The generic HDM model was developed as a result of an international collaborative study initiated by the World Bank which involved data collection and research in several countries. Key physical and economic relationships relating to roads—particularly road deterioration, maintenance effects, and road-user costs—were evaluated and quantified during the study. These empirical relationships were incorporated into the HDM model, making it possible to relate VOCs to road roughness. The BTCE's HDM-C model also incorporates a capacity–congestion module (which includes an hourly vehicle volume profile over an entire year), enabling it to adjust speeds to allow for congestion. HDM-C is described in detail in appendix IV.

In this study, the reductions in fuel consumption of vehicles using smoother roads have been converted into CO_2 equivalent emissions using factors set out in BTCE (1996a, p. 386). Carbon dioxide is the most significant of the greenhouse gases in terms of quantities emitted, but the analysis also includes carbon monoxide, methane and oxides of nitrogen.

All stages of road rehabilitation require energy inputs and therefore generate some greenhouse gas emissions. OECD (1984a, pp. 149–63) provides details of the energy consumed during each component of the road rehabilitation process for different types of pavement. For example, the energy required to process crushed rock is 70 megajoules per tonne, whereas bitumen processing requires 630 megajoules per tonne.

Sixteen measures for reducing greenhouse gas emissions were analysed in BTCE (1996a), including resurfacing national highways. These measures were analysed in terms of end-use emissions only and not total or 'full cycle' emissions, to facilitate comparison between the measures. However, in estimating the total energy needed to rehabilitate each type of pavement considered in this paper, the energy involved in several processes that precede the application of materials to the pavement, such as extracting, transporting, processing and heating the materials, as well as application of the materials, has been taken into account. The results in this working paper will therefore differ from those presented in BTCE (1996a).

Rehabilitating a sprayed seal pavement involves transporting, mixing and laying a crushed stone course and spraying a bituminous seal. Reconstructing an asphalt pavement involves processing crushed rock and bitumen and mixing, transporting, heating and laying the asphalt. Constructing concrete roads involves the production of concrete and steel. Table 2.3 is derived from OECD (1984a, annex I) and shows the emissions produced in the rehabilitation of different types of pavement.

TABLE 2.3 EMISSIONS[a] PRODUCED DURING ROAD REHABILITATION

(kilograms of CO_2 per kilometre)

	Pavement type			
Treatment	*2-lane narrow*	*2-lane wide*	*4-lane*	*6-lane*
Sprayed seal	30 955	46 432	103 183	139 297
Asphalt reconstruction	38 159	57 238	127 195	171 714
Asphalt overlay	25 439	38 159	84 797	114 476
Concrete	356 943	535 414	1 189 808	1 606 241
Novachip overlay	7 223	10 835	24 077	32 504

a. Emissions produced include emissions involved in all stages of preparation and application of treatment (including extracting, transporting, mixing, heating and laying).

Sources OECD (1984a, annex I); BTCE estimates.

In this study it has been assumed that all energy produced during road rehabilitation results from diesel combustion, and the factors set out in BTCE (1996a, p. 388) have been used to determine the equivalent quantities of emissions.

Costs and benefits

The change in total social costs due to pavement rehabilitation has been estimated as the sum of changes in health costs, VOCs, fuel producers' costs and rehabilitation costs.

Road rehabilitation costs will vary with terrain, location and predicted traffic volumes. Insufficient data were available for the NHS and the Pacific Highway to determine rehabilitation costs at specific locations. Therefore, as in the cases of initial roughness and pavement depth estimates, an average rehabilitation cost for the whole NHS and the Pacific Highway was used (table 2.4). Appendix V sets out the detailed data obtained from the State and Territory road authorities from which these values were derived.

TABLE 2.4 AVERAGE REHABILITATION COSTS FOR THE NHS AND THE PACIFIC HIGHWAY

(1996 dollars per square metre)

Treatment	*Cost*
Sprayed seal reconstruction	30.00
Asphalt reconstruction	37.50
Asphalt overlay	17.50
Novachip overlay	12.00

Sources Data provided by State and Territory road authorities; AAPA (pers. comm., 11 February 1997); BTCE estimates.

In the analysis in this paper, changes in VOCs due to pavement rehabilitation include changes in fuel, oil, tyre and maintenance costs but exclude time-related costs such as changes in the value of time for vehicle occupants and changes in vehicle depreciation. Any changes in travel time are driven by changes in traffic volume. Because changes in fuel consumption are quite small, it has been assumed that traffic volumes, and therefore also travel times, do not change.

The loss of profits by fuel producers due to reduced fuel sales has been estimated to be equivalent to 2 per cent of the value of the difference in retail fuel revenue (BTCE 1996a, p. 285).

Health costs due to changes in fuel use are likely to be very small, especially in rural areas. Only NO_x and NMVOCs have measurable health costs, estimated at $0.02 per kilogram.

This study does not consider the possible effects of highway rehabilitation on the following:

- *traffic volume*—it is assumed that there would be no induced increase in traffic volume resulting from highway rehabilitation, and therefore no increase in congestion and noise;
- *the 'rebound effect'*—savings in fuel consumed due to highway rehabilitation would effectively result in a decrease in the fuel costs of travel, which would tend to increase the use of motor vehicles (the 'rebound effect'). Using United States car travel data over the period 1966–89, Greene (1992) estimates that the rebound effect has been quite small, amounting to about 5 to 15 per cent or less. Australian highways are used by local and regional traffic as well as by long-distance traffic. However, because of the long distances involved in each corridor, the lack of alternative routes and the mix of traffic, the impact of any rebound effect is not likely to be significant over the entire NHS;
- *driver fatigue and crash risk*—lower pavement roughness reduces driver fatigue, and can therefore contribute to a lowering of crash risk. Ergonomic studies have revealed links between certain vibrations caused by the condition of the highway surface and a number of physiological disturbances such as loss of visual acuity or attention, and changes in breathing and heart activity experienced as 'car sickness' (OECD 1984b, p. 60). High levels of

roughness can also cause water to accumulate on the road surface, resulting in spraying and splashing that can temporarily impair the visibility of drivers;

- *skid resistance*—deteriorating highways increase crash risk, not only by their effects on drivers, but also by reducing vehicles' skid resistance because of the accumulation of water on the surface. While high levels of roughness cause discomfort, lack of adequate microtexture and macrotexture could increase the propensity for skidding. Appendix II contains a review of the effects of road surface condition on safety. Substantial reductions in roughness could also contribute to an increased crash risk by motorists tending to compensate for easier and better driving conditions by behavioural adjustments such as reduced attention to the driving task, greater speeds, shorter stopping distances, and smaller gaps between vehicles (BTCE 1995b, pp. 259–63);
- *damage to goods transported by road;*
- *passenger comfort and smoothness of travel;*
- *vehicle chassis and windscreen damage*—over the longer term, timely maintenance forestalls extensive damage to the road surface, thereby reducing the incidence of vehicle chassis and windscreen damage. However, when road rehabilitation is carried out using bituminous materials, the risk of occurrence of such damage rises markedly just after a road is resurfaced because of the presence of loose debris such as stone chips;
- *the economy*—lower transport costs would have benefits to groups such as the construction, tourism and retail sectors; and
- *greenhouse gas emissions generated in the manufacture of plant and equipment used in road rehabilitation.*

CHAPTER 3 GREENHOUSE IMPLICATIONS OF REHABILITATING THE NATIONAL HIGHWAY SYSTEM AND THE PACIFIC HIGHWAY

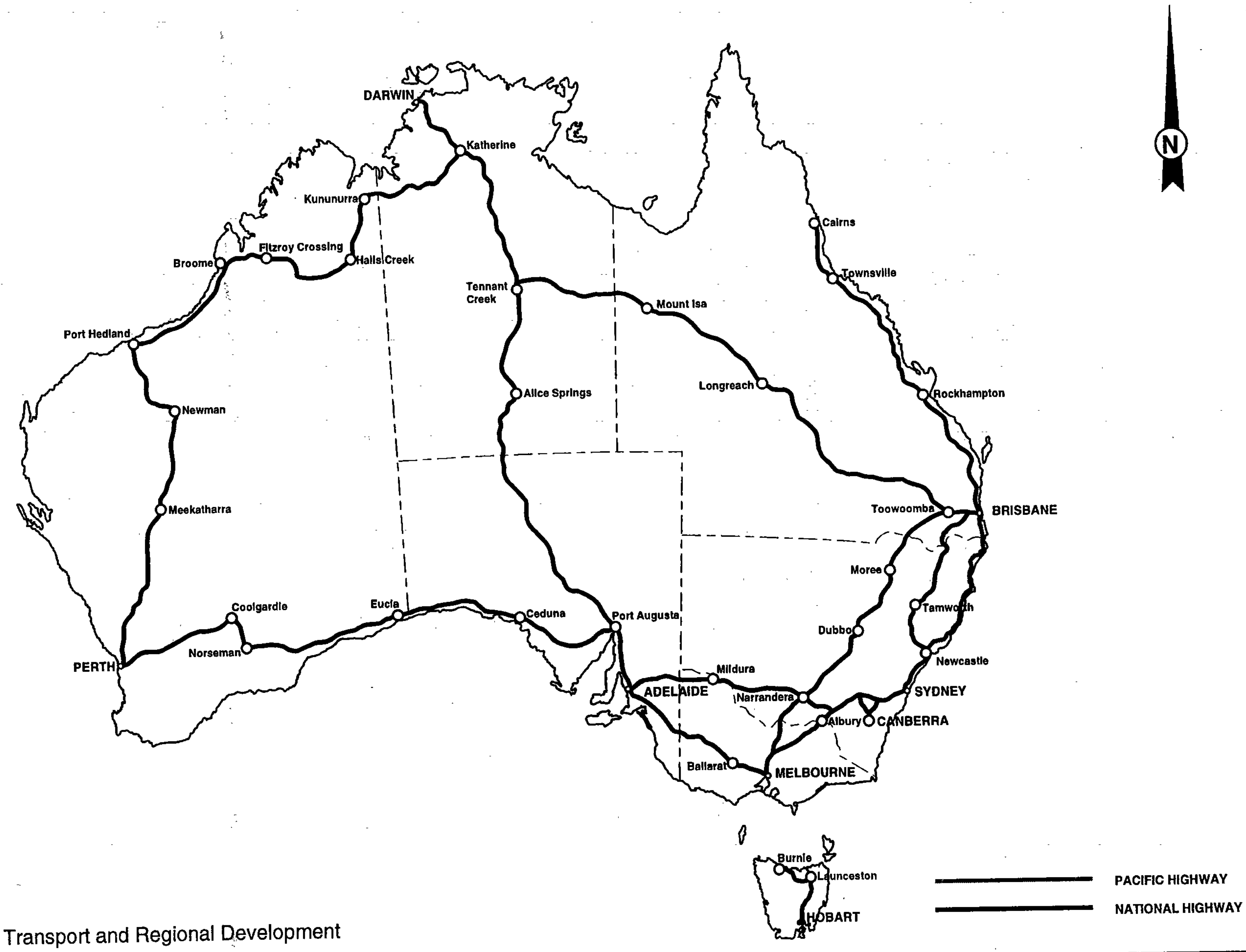
The road network provides vital economic and community links across the vast expanse of the Australian continent. The 810 000 kilometres of roads range from world standard freeways to unsealed outback roads. Ninety per cent of the transport task is carried out on the major routes that comprise 20 per cent of the total road network (Austroads 1997, p. 7).

This analysis focuses on the NHS and the Pacific Highway because of the large volume of long-distance traffic that plies these highways in relatively uncongested conditions.

NATIONAL HIGHWAY SYSTEM

Initially declared by the Commonwealth Government in February 1974, the NHS is a road system that links all the mainland capital cities, as well as Brisbane with Cairns, and Hobart with Burnie. As originally defined, the NHS consisted of 16 000 kilometres of road, which was extended in 1992 to about 18 500 kilometres by the inclusion of two inland freight corridors: Melbourne–Brisbane and Sydney–Adelaide. Since January 1994, links in the form of some urban extensions through Sydney, Melbourne, Brisbane, Adelaide and Perth have been included in the NHS to form a continuous network. The routes comprising the NHS and the Pacific Highway are shown in figure 3.1. Table 3.1 sets out the length of the NHS by State and Territory.

FIGURE 3.1 NATIONAL HIGHWAY SYSTEM AND PACIFIC HIGHWAY, 1997



Source Department of Transport and Regional Development

TABLE 3.1 LENGTH AND TRAVEL DATA FOR THE NHS BY STATE AND TERRITORY

State/Territory	*Length (km)*	*Lane-km[a] (km)*	*Travel (million vehicle-km)*
ACT	15	60	30
NSW	2 900	7 930	8 450
NT	2 677	5 390	290
Qld	3 898	8 170	4 980
SA	2 910	5 820	2 190
Tas.	320	810	640
Vic.	1 031	2 930	2 980
WA	4 640	9 080	1 110
Total	18 400	40 190	20 670

a. Lane-km is the product of road length (along the centre line) and the number of traffic lanes. Increases in road capacity by adding lanes (e.g. duplicating a two-lane road to form a four-lane road) may not increase the overall road length, but would increase the lane-km figure.

Source Austroads (1997, p. 18).

The NHS comprises twelve major routes or corridors, each comprising one or more highways. Table 3.2 sets out the major routes and their highways.

Of the 21 billion vehicle-kilometres travelled on the NHS in 1994, cars accounted for 81 per cent and trucks for 19 per cent (7 per cent rigid trucks and coaches and 12 per cent articulated trucks) (Austroads 1997, p. 33). Figure 3.2 shows usage of the NHS in 1994 in terms of vehicle-kilometres travelled and the contribution to pavement loading by cars, rigid trucks and articulated trucks. Pavement loading in this context refers to the contribution of a class of vehicle (that is, cars, rigid trucks or articulated trucks) to pavement wear. It is the product of vehicle-kilometres travelled and equivalent standard axle load (ESAL)[1] for each vehicle class. Although cars contribute most of the vehicle-kilometres travelled, their share of pavement damage (0.1 per cent) is negligible compared with that of trucks.

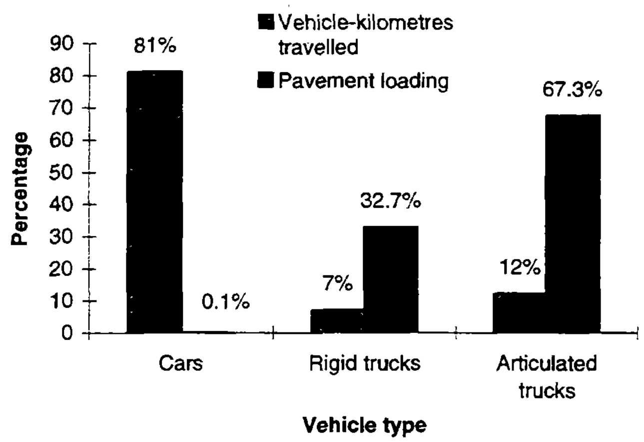
1. The ESAL (sometimes referred to as the equivalent standard axle (ESA)) is defined as the effect on a pavement of a pass by a standard reference axle, which is a dual-tyred axle with a load of 8.2 tonnes.

TABLE 3.2 MAJOR ROUTES AND HIGHWAYS COMPRISING THE NHS

Major routes	*Highways*
Sydney–Melbourne	Hume Highway
Sydney–Brisbane	Sydney–Newcastle Freeway New England Highway Cunningham Highway
Canberra connectors	Federal Highway Barton Highway
Melbourne–Adelaide	Western Highway South-Eastern Highway Dukes Highway
Sydney–Adelaide	Sturt Highway
Melbourne–Brisbane	Goulburn Valley Highway Newell Highway Gore Highway
Brisbane–Cairns	Bruce Highway
Adelaide–Perth	Adelaide–Port Augusta Road Eyre Highway Esperance–Coolgardie Highway Great Eastern Highway
Port Augusta–Darwin	Stuart Highway
Perth–Darwin	Roe Highway Great Northern Highway Victoria Highway
Brisbane–Darwin	Warrego Highway Landsborough Highway Flinders Highway (part) Barkly Highway
Hobart–Burnie	Bass Highway Midland Highway

Source Department of Transport (1995).

FIGURE 3.2 USAGE OF THE NHS IN 1994



Note 1. Pavement loadings are estimated from the product of total vehicle kilometres and ESALs for each vehicle class.

2. Estimates for ESALs are derived from BTCE (1988, table 5.1) and relate to 1986–87.

3. Figures for rigid trucks are for a mixture of two axles and three axles and those for articulated trucks for six axles.

Source Austroads (1997, p. 33).

The total length of the NHS and the Pacific Highway is over 19 000 km. Table 3.3 sets out the length of the NHS and the Pacific Highway by State/Territory and surface type. About 90 per cent of this highway system is constructed with bituminous sprayed seal, about 8.5 per cent is asphalt and less than 2 per cent is concrete (rigid). A discussion of issues relating to the characteristics of bituminous and concrete pavements is in appendix VI.

TABLE 3.3 LENGTH OF THE NHS AND THE PACIFIC HIGHWAY BY STATE/TERRITORY AND SURFACE TYPE

(kilometres)

State/Territory	*Asphalt*	*Concrete*	*Sprayed seal*	*Total*
New South Wales	400	219	3 063	3 682
Northern Territory	10	0	2 661	2 672
Queensland	375	7	3 861	4 243
South Australia	490	0	2 260	2 750
Tasmania	99	2	231	333
Victoria	237	0	752	989
West Australia	16	0	4 643	4 660
Australia	1 628	228	17 473	19 329

Note Data in this table relate to the NHS and Pacific Highway as at 1994.

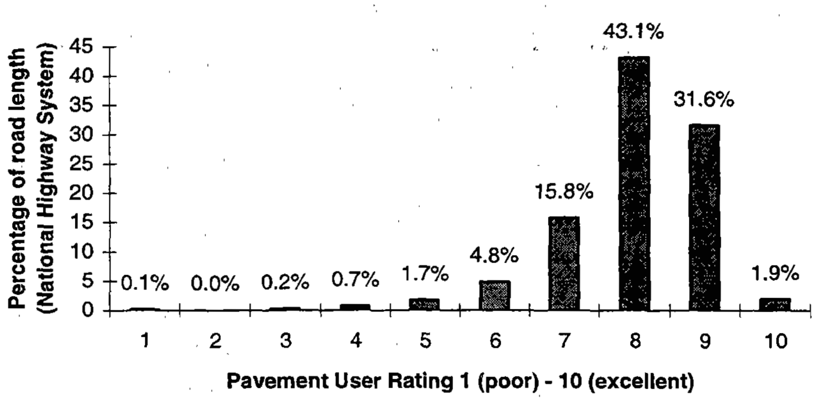
Sources BTCE highways database; Queensland Department of Main Roads (pers. comm., 30 January 1997).

The degree of pavement damage caused by a specific axle (or set of axles) increases very steeply with axle load. The degree of pavement damage has traditionally been considered to be proportional to the fourth power of the ratio of the actual axle load to the 8.2-tonne standard axle (commonly referred to as the 'fourth power law'). However, the fourth power law is considered to hold only approximately, as pavement response to axle loading is complex and depends on factors such as pavement type and thickness, type of pavement distress (for example, roughness, rutting and cracking), severity of distress, and axle configuration (Hajek 1995, p. 68).

The Commonwealth Government funds the construction and maintenance of the NHS, but the road works are managed by State and Territory road authorities. The States and Territories also retain ownership of the roads comprising the NHS. The Commonwealth Government can designate other roads of national significance as Roads of National Importance and fund them out of budgetary allocations for roads or from special appropriations. Total expenditures on the NHS in 1993–94 and 1994–95 were $786.2 million and $816.1 million respectively. In 1994–95, expenditure on the NHS accounted for 14 per cent of total (Commonwealth and State/Territory) expenditure on roads and was a little over half of total Commonwealth expenditure on roads. The NHS comprises 2.3 per cent of the Australian public road network of 810 000 kilometres. The amount of expenditure on the NHS is disproportionate to its length, which reflects its relatively more intensive use than the rest of the network as a whole.

The Pavement User Rating (PUR) is a scale used to assess public perceptions of road roughness and ranges from 1 (poor) to 10 (excellent). Figure 3.3 shows driver perceptions of the NHS based on the PUR. The PUR values indicate that 92 per cent of the NHS has been rated 'good' (approximately 7) or better by drivers.

FIGURE 3.3 DRIVER PERCEPTIONS OF THE ROUGHNESS OF THE NHS



Source Austroads (1994, p. 17).

PACIFIC HIGHWAY

The Pacific Highway runs for 1001 kilometres between Sydney and Brisbane and is the most heavily used interstate road corridor by all vehicle classes. The major part of the highway (896 kilometres) is in New South Wales, running between Hexham and Tweed Heads.

Nehl (1986) considers it a glaring omission that, with the exception of the small stretch of highway between Sydney and Newcastle, no part of the coastal highways between Melbourne and Brisbane is included in the NHS. He notes that this is despite the fact that the majority of Australia's population lives in the south-east part of the country which, along the coast, is serviced by the Pacific and Princes Highways. Nehl observes that the Pacific Highway, both along its route north of Hexham and along its entire length, has a larger population living in local government areas through which the highway passes than populations in areas through which the Hume or New England Highways pass.

Substantial upgrading of the Pacific Highway has been carried out in recent years, but it remains largely a two-lane highway. NRMA (1995, p. ix) reports that the Pacific Highway has had one of the poorest ride qualities of major New South Wales highways for the past 10 years.

The RTA regards a roughness of less than 70 NRM as being very good, 70 to 110 as good, 110 to 150 as fair, and greater than 150 as poor. Based on RTA data, 52 per cent of the Pacific Highway is rated as having a roughness of less than 70 NRM, 38 per cent having a roughness between 70 and 110 NRM, 8 per cent between 110 and 150 NRM, and 2 per cent over 150 NRM (NRMA 1995, p. 22).

The NRMA (1995, p. ix) observes that the Pacific Highway has an average pavement age of 22 years which exceeds its design life of 20 years, making it expensive to maintain in satisfactory condition. Hence, while the costs of rehabilitation used in this analysis may be generally appropriate for the NHS as a whole, they may reflect an underestimation of the costs of effecting similar improvements to the Pacific Highway.

The Commonwealth Government has initiated a 10-year upgrading strategy for the Pacific Highway which includes a funding commitment of $750 million. The funding is contingent on the Queensland and New South Wales Governments matching the Commonwealth contribution on a pro-rata basis, and also maintaining their existing financial commitments to the highway. The initiative will mean that about $3 billion will be spent on improving the Pacific Highway. The improvements are expected to cut travel time between Sydney and Brisbane by at least one hour.

EMISSION REDUCTIONS AND COSTS INVOLVED IN REHABILITATING THE NHS AND THE PACIFIC HIGHWAY

Table 3.4 shows changes in emissions and costs resulting from implementing appropriate rehabilitation at terminal roughness levels of 100, 90, and 80 NRM. Costs are expressed in 1995–96 dollars to facilitate comparison with cost estimates reported in BTCE (1996a). It will be seen from the table that, for the period 1996 to 2000, a terminal roughness of 80 NRM produces lower emission reductions than for terminal roughness levels of either 90 or 100 NRM. This counterintuitive result is because of the substantial amount of rehabilitation required in 1996 to bring the highways up to the required standard (changes in emissions include those produced due to rehabilitation). Over the longer term, the benefits of reduced vehicle emissions overwhelmingly outweigh the emissions produced by rehabilitation in 1996.

TABLE 3.4 REHABILITATION OF THE NHS AND THE PACIFIC HIGHWAY: SOCIAL COSTS[a] OF REDUCTIONS IN EMISSIONS CUMULATED FROM 1996

(1) Terminal roughness[b] (NRM)	*(2)* Cumulative reduction: CO_2 equivalent (million tonnes)	*(3)* Change in cumulative reduction: CO_2 equivalent (million tonnes)	*(4)* Social cost of cumulative reduction ($ million)	*(5)* Change in social cost ($ million)	*(6)* Average social cost[c] ($ per tonne)	*(7)* Marginal social cost[d] ($ per tonne)
1996 to 2000						
100	0.026	0.026	152	152	5 846	5 846
90	0.029	0.003	422	270	14 552	90 000
80	0.017	-0.012[e]	791	369	46 529	f
1996 to 2005						
100	0.105	0.105	157	157	1 495	1 495
90	0.202	0.097	412	255	2 039	2 629
80	0.273	0.071	810	398	2 967	5 606
1996 to 2010						
100	0.247	0.247	122	122	494	494
90	0.463	0.216	373	251	806	1 162
80	0.627	0.164	826	453	1 317	2 762
1996 to 2015						
100	0.409	0.409	103	103	252	252
90	0.764	0.355	352	249	461	701
80	1.077	0.313	847	495	786	1 530

a. All costs are cumulated from 1996 to the year shown, expressed as net present values (1995–96 dollars) using a discount rate of 10 per cent. Costs associated with highway rehabilitation considered in the analysis comprise vehicle operating costs, highway rehabilitation costs, loss of profits by fuel producers due to reduced fuel sales, and externality (health) costs.

b. The roughness at which rehabilitation is undertaken.

c. Average costs are obtained by dividing the figures in column (4) by the corresponding figures in column (2).

d. Marginal costs are obtained by dividing the figures in column (5) by the corresponding figures in column (3).

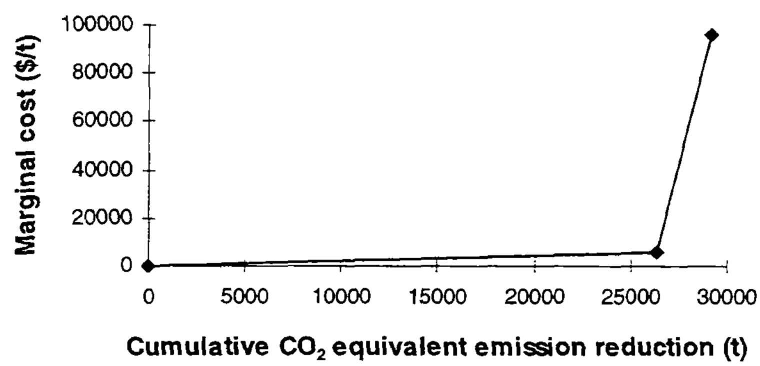
e. The negative sign indicates a decrease in cumulative emission reduction.

f. The marginal cost cannot be calculated because of the decrease in cumulative emissions between terminal roughness of 90 and 80 NRM.

Source BTCE estimates.

The marginal cost data in table 3.4 is presented graphically in figures 3.4 to 3.7, which show the marginal social costs of rehabilitating the NHS and the Pacific Highway for the years 2000, 2005, 2010 and 2015.

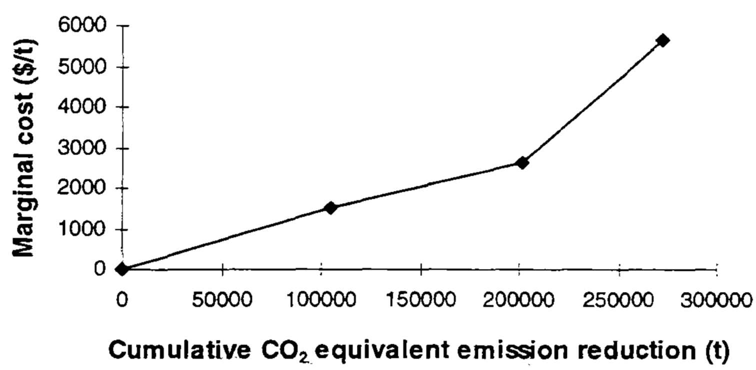
FIGURE 3.4 MARGINAL SOCIAL COSTS OF REHABILITATING THE NHS AND THE PACIFIC HIGHWAY FOR 2000



Note This figure shows marginal social costs for terminal roughness of 100 NRM and 90 NRM only (see note f in table 3.4).

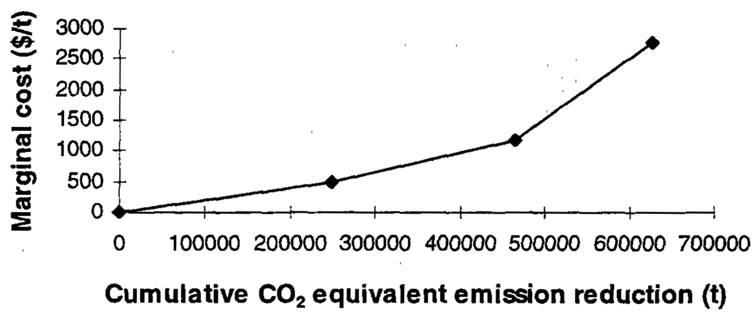
Source BTCE estimates.

FIGURE 3.5 MARGINAL SOCIAL COSTS OF REHABILITATING THE NHS AND THE PACIFIC HIGHWAY FOR 2005



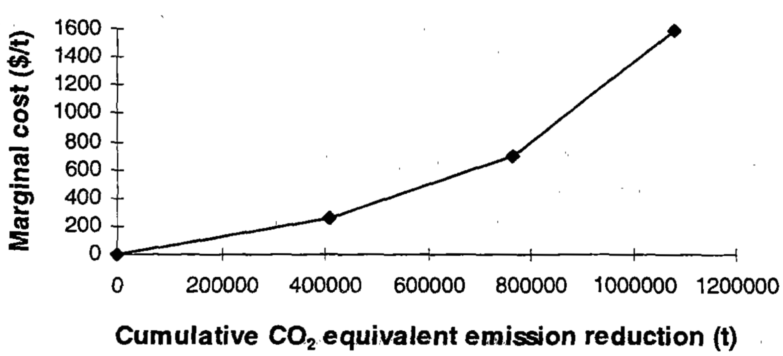
Source BTCE estimates.

FIGURE 3.6 MARGINAL SOCIAL COSTS OF REHABILITATING THE NHS AND THE PACIFIC HIGHWAY FOR 2010



Source BTCE estimates.

FIGURE 3.7 MARGINAL SOCIAL COSTS OF REHABILITATING THE NHS AND THE PACIFIC HIGHWAY FOR 2015



Source BTCE estimates.

As a means of reducing greenhouse gas emissions, highway rehabilitation is evidently quite costly. Overall, vehicle fuel consumption falls by only about 0.5 per cent when rehabilitation is carried out at a terminal roughness of 80 NRM. Restricting the rehabilitation policy to the NHS and the Pacific Highway would also limit its benefits because, although these highways are significant corridors in terms of passenger and long-distance freight movement, they do not represent a large proportion of the Australian road transport task. Data in Austroads (1997, pp. 33, 42) show that, of the 166.5 billion vehicle-kilometres travelled in Australia in 1994, only 21 billion (12.6 per cent) were travelled on the NHS. Around 85 per cent of freight originating in capital cities goes to destinations within the same city, while only a quarter of the freight within a region is likely to be transported outside that region (BTCE 1995c, p. 6).

Over the period 1996 to 2015, the level of total emissions reduced by highway rehabilitation estimated in this study is considerably lower (by almost one million tonnes for a terminal roughness of 80 NRM) than results presented in BTCE (1996a, p. 288). The lower estimates in this paper are due partly to the inclusion of emissions produced by road rehabilitation (these were not included in BTCE 1996a) and partly to differences in the post-rehabilitation roughness estimates of the rehabilitated highway sections. The better rehabilitation cost estimates obtained for this paper are about 50 per cent lower than those used in BTCE (1996a).

Emission reductions per kilometre of road length are very small. Over the period 1996 to 2015, the reductions are 21, 40 and 57 tonnes per kilometre for terminal roughness levels of 100, 90 and 80 NRM respectively.

Table 3.5 shows the costs of rehabilitating the NHS and the Pacific Highway from 1996 to 2015, while table 3.6 details the components of total social costs for 2015. These tables show that costs to government (rehabilitation costs and losses in fuel excise and tax revenue) are the largest component of total costs, whereas changes in VOCs are a substantial benefit (there is no change in time-related costs because speed is assumed to be constant at 100 kilometres per hour). Costs to fuel producers and externality (health) costs (the value of reductions in NO_x and NMVOCs) have virtually no impact on the overall results.

TABLE 3.5 TOTAL COSTS[a] OF REHABILITATING THE NHS AND THE PACIFIC HIGHWAY FROM 1996 TO 2015

Terminal roughness (NRM)	*Rehabilitation cost (1995–96 $ million)*
100	304
90	733
80	1364

a. Costs are discounted at a rate of 10 per cent.

Source BTCE estimates.

TABLE 3.6 COMPONENTS OF TOTAL SOCIAL COSTS[a] OF REHABILITATING THE NHS AND THE PACIFIC HIGHWAY FROM 1996 TO 2015

(1995–96 $ million)

	Terminal roughness		
Cost components	*100 NRM*	*90 NRM*	*80 NRM*
VOCs[b]	-253.00	-486.00	-671.00
Fuel producers[c]	0.65	1.22	1.65
Government[d]	355.00	837.00	1516.00
Externalities[e]	-0.03	-0.04	-0.05

a. Costs are discounted at a rate of 10 per cent. A negative sign indicates a benefit.

b. Savings in VOCs are inclusive of taxes and comprise fuel and lubricant consumption, tyre wear, maintenance labour and parts.

c. Profits forgone by fuel producers due to reduced fuel sales following highway rehabilitation.

d. Costs to government comprise highway rehabilitation costs and losses in fuel excise (Commonwealth and State/Territory), sales taxes, and import duties on vehicles and parts.

e. Estimated externality (health) benefits comprise the value of reductions in NO_x and NMVOCs.

Source BTCE estimates.

Table 3.7 shows the changes in emissions produced by highway rehabilitation and consequent vehicle use. For a terminal roughness of 100 NRM, the increase in rehabilitation emissions is about one-fifth of the reduction in vehicle emissions. For a terminal roughness of 80 NRM, the proportion of rehabilitation emissions increases to about one-third of the reduction in vehicle emissions. As the terminal roughness falls, a greater proportion of the highways is rehabilitated, but with a relatively smaller improvement in roughness and therefore a smaller reduction in vehicle emissions.

TABLE 3.7 CHANGES IN CO_2 EQUIVALENT EMISSIONS FROM 1996 TO 2015 DUE TO HIGHWAY REHABILITATION

(million tonnes)

Terminal roughness (NRM)	*Rehabilitation emissions*	*Vehicle emissions*
100	0.11	-0.52
90	0.28	-1.04
80	0.54	-1.62

Note A negative sign indicates a decrease in emissions.

Source BTCE estimates.

The discount rate used can significantly affect the results of evaluations of long-term projects. If a high discount rate is used in the evaluation, costs and benefits occurring later in the life span of a road would be discounted more heavily relative to those occurring earlier. Table 3.8 shows the total social costs using 5, 10 and 15 per cent discount rates over the period 1996 to 2015. Total social costs are highest when the 5 per cent discount rate is used because the VOC benefits occurring in later years have less impact on the overall results than when discount rates of 10 and 15 per cent are used.

TABLE 3.8 SOCIAL COSTS OF HIGHWAY REHABILITATION FROM 1996 TO 2015 USING DISCOUNT RATES OF 5, 10 AND 15 PER CENT

(1995–96 $ million)

Terminal roughness (NRM)	*5 %*	*10 %*	*15 %*
100	48	103	130
90	297	352	379
80	894	847	821

Source BTCE estimates.

Road rehabilitation costs vary due to a variety of factors including local terrain and distance from sources of raw materials. Appendix V sets out a wide range of estimates for rehabilitation provided by State and Territory road authorities. The maximum and minimum costs in appendix V have been used to test the sensitivity of the results to rehabilitation costs. The cost range for asphalt overlays is between $12 and $20 per square metre. Sprayed seal rehabilitation costs vary between $30 and $58 per square metre. As $30 was the value used for sprayed seal rehabilitation, there is only an upper limit that could be used in the sensitivity analysis. Table 3.9 sets out total social costs for the high- and low-cost scenarios.

TABLE 3.9 SENSITIVITY TESTS FOR HIGHWAY REHABILITATION COSTS

(1995–96 $ million)

Terminal roughness (NRM)	*Low costs*[a]	*High costs*[b]
100	92	359
90	325	967
80	798	1997

a. Low rehabilitation costs are $30 per square metre for sprayed seal reconstruction and $12 per square metre for asphalt overlays.

b. High rehabilitation costs are $58 per square metre for sprayed seal reconstruction and $20 per square metre for asphalt overlays.

Source BTCE estimates based on data from State and Territory road authorities.

Appendix VII contains a set of tables which provide estimates of the potential vehicle emission reductions for different types of pavement rehabilitation and traffic levels for a one-kilometre section of road. These tables may be used as 'ready reckoners' to estimate approximate changes in emissions for any length of road. The differences in emission levels between asphalt reconstruction and asphalt overlay for different traffic levels are also set out in appendix VII.

Equity issues

The four major costs that have been considered in the analysis of highway rehabilitation are costs incurred by road users (VOCs), fuel producers, government, and externality (health) costs (table 3.6).

Highway rehabilitation results in lower fuel consumption and vehicle maintenance costs. Consequently, producers, wholesalers and retailers of fuel would lose revenue. The Commonwealth Government would lose excise, sales tax and import duties and State and Territory Governments would lose fuel-based business franchise fees. It can be inferred from tables 3.5 and 3.6 that rehabilitation at a terminal roughness of 100 NRM would result in an aggregate loss of Commonwealth and State/Territory tax revenue of $51 million over the period 1996 to 2015. The loss would increase to $100 million at a terminal roughness of 90 NRM, and to $152 million at 80 NRM.

The vehicle repair, maintenance and spare parts sectors would also lose revenue. As most travel on the NHS and the Pacific Highway is at or around the legal speed limits, rehabilitation is not likely to generate any significant additional travel time savings.

Highway rehabilitation generally causes some disruption to traffic and inconvenience to motorists (appendix VI). The effects include reduced speed and delays, windscreen and chassis damage, increased crash risk due to altered road and traffic conditions and temporary absence of lane marking, noise, vehicle vibration, and increased stress on motorists. Rehabilitation also increases the risk of injury to road maintenance personnel and can cause temporary inconvenience (including noise, dust and airborne particulate matter) to people living close to highways.

Rehabilitation would reduce the operating costs of interstate bus operators. To the extent that operators' savings are passed on to passengers through the fare structure, less advantaged members of society who are more likely to use bus services would benefit. Tourism, and hence regional economies, would also benefit.

There are many towns, small population centres and farms adjacent or close to national highways and the Pacific Highway. People living close to highways use them to travel to nearby towns for purposes such as obtaining services and provisions. The rehabilitation of highways would have a beneficial effect on regional mobility and welfare.

CASE STUDIES

The analysis of the effects on vehicle emissions of hypothetical rehabilitation of the NHS and the Pacific Highway provides useful estimates of the greenhouse gas mitigation potential and associated costs of such rehabilitation. However, an analysis of specific road sections that have been rehabilitated can provide useful detailed information that a more general hypothetical analysis may not be able to offer. Two case studies involving the Yass bypass in New South Wales and sections of the Western Highway in Victoria provide estimates of actual emission changes due to rehabilitation and the costs incurred. These case studies also provide insights into the factors that have the most influence on emission reductions.

Western Highway

The Western Highway is the Victorian section of the main road linking Melbourne and Adelaide. In this case study, the BTCE evaluated two small sections of road that were rehabilitated in western Victoria—a 1.1-kilometre section east of Lilimur and 416 kilometres from Melbourne, and a 1.78-kilometre section near Ararat, 196 kilometres from Melbourne. These projects were part of ongoing rehabilitation along the Western Highway. The Ballarat office of VicRoads provided detailed information on the costs and effectiveness of the rehabilitation in terms of reductions in roughness. Table 3.10 sets out details of the two projects.

TABLE 3.10 DETAILS OF WESTERN HIGHWAY PROJECTS

	Lilimur	*Ararat*
Rehabilitation		
Length	1.1 km	1.78 km
Distance from Melbourne	416.2 km	196.46 km
Width	11 m	11 m
Seal	12 100 m^2	19 580 m^2
Base	250 mm	200 mm
Sub-base	150 mm	150 mm
Crushed rock and sandstone	9529 t	28 636 t
Roughness before rehabilitation	95 NRM	68 NRM
Roughness after rehabilitation	44 NRM	52 NRM
Emissions from rehabilitation	143 t	410 t
Traffic		
AADT	2200	3500
Per cent commercial vehicles	24.3%	20%
Traffic growth rate	2.5%	2.5%
Annual reduction in vehicle emissions (CO_2 equivalent)	14.2 t	9.7 t

Sources VicRoads (pers. comm., 13 January 1997); BTCE estimates.

The Lilimur road has two lanes and partially sealed shoulders having a sealed surface of 11 metres and an unsealed surface of 1 metre. The new pavement consists of a primer sealed layer, a base of class 2 crushed rock, and a sub-base with a 50/50 mix of class 3 crushed rock and sandstone.

Total energy consumed during road rehabilitation depends on the volume of raw materials used. Energy estimates used in this analysis are from OECD (1984a). In this case, the total volume of crushed rock and sandstone used was 4235 cubic metres. Assuming an average density of 2.25 tonnes per cubic metre, the weight of the rock and sandstone is 9529 tonnes. The energy required to extract, transport, mix and lay this raw material is assumed to be 165 megajoules per tonne. Therefore, the total energy expended to create the crushed rock course is 1.57 million megajoules. Primer seal is a process of applying bitumen to the road surface topped with a layer of crushed rock and requires 713.2 megajoules per square metre. Total energy expended to produce the primer seal is therefore 0.2 megajoule.

Although the overall amount of energy estimated for the Lilimur project includes the energy expended in many of the processes involved in road rehabilitation, it is an incomplete estimate. Drainage and landscaping are essential elements of road rehabilitation, but the energy expended in these activities has not been taken into account in the analysis. The total quantity of emissions produced during rehabilitation of the Lilimur section is estimated at 143 tonnes of CO_2 equivalent.

To estimate the reduction in vehicle emissions due to rehabilitation, the average difference (over 10 years) between the expected emissions resulting from the new road and the expected emissions had rehabilitation not occurred was estimated. Beyond 10 years the results are less reliable because the roughness of the unimproved road is likely to become very high and is unlikely to be acceptable to road users. The estimated average reduction in vehicle emissions is 14.2 tonnes of CO_2 equivalent emissions per year.

The same method of estimation was used for the Ararat section of road, for which rehabilitation produced 410 tonnes of CO_2 equivalent emissions. The decrease in roughness for the Ararat section of road was small (68 NRM to 52 NRM), resulting in a correspondingly small reduction in vehicle emissions of 9.7 tonnes of CO_2 equivalent emissions per year.

Yass bypass

The results of the Yass bypass case study are not directly comparable with other results in this paper because the construction of the bypass, besides decreasing road roughness, also significantly altered traffic flows. Therefore, this case study should be regarded as a study of the greenhouse implications of bypass construction, rather than road rehabilitation. As in the case study of the Western Highway projects, the analysis of the Yass bypass project involves a basecase (a hypothetical situation which assumes that the bypass had not been built) and the current situation with the bypass. The change in emissions estimated in this analysis is the difference between the emissions in the two cases.

The Yass bypass consists of two parts: the 18.5-kilometre bypass and a 7.3-kilometre Barton Highway connector. Before the bypass was built, all Hume Highway traffic, including vehicles travelling between Melbourne and Canberra, had to travel through Yass. Since the completion of the bypass and the Barton Highway connector, the only traffic that uses the previous Hume Highway section is local Yass area traffic. All through vehicles have access to the higher quality bypass. In effect, this means that changes in overall greenhouse gas emissions and VOCs will result from a combination of the increase in traffic due to the improved road, the reduction in congestion experienced by motorists, the slight change in journey length, the reduced roughness of the new road, and the process of road construction.

Construction of the entire project took place in two stages. The bypass itself was opened in July 1994 and the Barton Highway connector was opened in May 1995. For both stages, the combined cost of road works, earth works, drainage and concrete pavement amounted to $97 million of the total cost of $150 million. The cost per kilometre for the entire project was $5.7 million. This figure is significantly higher than estimates derived from appendix V. A factor which contributed to higher costs was the bridgeworks, which represented about 14 per cent of total construction costs. If the cost of the bridgeworks is excluded, the cost per kilometre of the project falls to $4.9 million. Details of construction costs for the Yass bypass are set out in table 3.11.

TABLE 3.11 YASS BYPASS CONSTRUCTION COSTS

($ million)

	Yass bypass	*Barton Highway connector*	*Total*
Pre-construction	8.41	5.72	14.12
Earth works/drainage	44.46	9.89	54.35
Concrete pavement	29.44	13.14	42.58
Bridge works	12.76	8.51	21.27
Landscaping	2.12	1.12	3.24
Administration	10.23	4.39	14.62
Total	107.41	42.77	150.17

Source RTA (pers. comm., 15 November 1996).

The calculation of changes in VOCs and greenhouse gas emissions in this case study is different from the general approach used in the rest of this working paper. Firstly, as the volume of traffic in the current case is greater than in the basecase, VOCs will increase simply because of the increased traffic. Secondly, changes in road capacity, road geometry and traffic volume will result in changes in congestion, causing changes in time-related costs such as travel time costs for occupants of cars, and crew and capital costs for heavy vehicles. Thirdly, the Hume Highway section through Yass has a speed limit of

60 kilometres per hour, which would lower fuel consumption relative to the bypass (which has a speed limit of 110 kilometres per hour).

Traffic estimates for the Yass bypass were obtained from the RTA and from the highways database maintained by the BTCE. The total volume of traffic through the bypass and the former highway section through Yass is estimated to have risen slightly due to the bypass. As expected, the volume of traffic passing through Yass township has fallen substantially. Before the bypass was constructed, articulated trucks accounted for about 20 per cent of total traffic. It has been assumed in this analysis that the proportion of articulated vehicles through Yass has fallen to 2 per cent of total traffic through Yass. The volume of traffic on the new divided bypass is lower than the original volume of traffic passing through Yass (because of the elimination of local Yass traffic), but the proportion of articulated trucks using the bypass has increased to over 27 per cent of bypass traffic.

The RTA measured roughness levels shortly after the opening of the bypass. The new concrete roads had very low roughness ranging from 32 NRM at the southern end of the bypass to 44 NRM for the Barton Highway connector. Data on roughness deterioration of concrete roads are sparse. However, available United States evidence (Bednar, 1989) suggests that the roughness of concrete pavements deteriorates at about half the rate of asphalt pavements.

Table 3.12 sets out the changes in emissions and costs for the Yass bypass project.

TABLE 3.12 ESTIMATED CHANGES IN EMISSIONS AND COSTS FOR THE YASS BYPASS PROJECT OVER A 10-YEAR PERIOD

	Emissions (tonnes CO_2 equivalent)	*Costs ($ million)*
Construction	58 406	150.17
Vehicles (for 10-year period)	-47 739	-10.04
Total over 10 years	10 667	140.13

Note A negative number indicates a decrease.

Source BTCE estimates.

The results indicate a net rise in emissions of 10 667 tonnes, but a fall in annual average vehicle emissions of 4774 tonnes (largely caused by the shorter distance vehicles using the bypass now need to travel). The gains in terms of VOCs barely impact on the total cost of the project. Vehicle costs and emissions were only projected 10 years into the future because, beyond this period, rehabilitation of the Hume Highway is likely to significantly affect the results.

CHAPTER 4 EFFECTS OF HIGHWAY REHABILITATION ON VEHICLE OPERATING COSTS

Pavement roughness is a key parameter in estimating VOCs. The HDM-C model (described in appendix IV) has been used to estimate the expected operating costs associated with a wide range of roughness levels. The results presented in this chapter relate to a hypothetical one-kilometre section of a wide two-lane road carrying a relatively small volume of traffic per day (1000 AADT). VOCs were estimated for flat, undulating and mountainous terrain for this one-kilometre section of road. Roughness ranged from 30 NRM (a very smooth road) to 150 NRM (a very rough road). Table 4.1 details traffic and construction characteristics of this hypothetical road.

TABLE 4.1 ROAD AND TRAFFIC CHARACTERISTICS

Characteristic	*Description*
Traffic	1000 AADT: 10% rigid trucks and 10% articulated trucks
Roughness	30 to 150 NRM in increments of 5 NRM
Terrain	flat
Lanes	2 lanes each of 3.7 m width
Shoulders	2-m sealed shoulders

Source BTCE estimates.

CHANGES IN VEHICLE OPERATING COSTS WITH ROUGHNESS

As roughness increases, VOCs also increase. Table 4.2 shows costs for cars and rigid and articulated trucks separately. For cars, costs increase by about 8 per cent (from 29.0 to 31.2 cents per kilometre) over the range of roughness. The increase for articulated trucks is about 3 per cent. Roughness has a relatively greater influence on the operating costs of rigid trucks, increasing costs by 11 per cent over the roughness range.

TABLE 4.2 CHANGES IN VOCs[a] RELATIVE TO PAVEMENT ROUGHNESS

(cents per kilometre)

Roughness (NRM)	*Cars*	*Rigid trucks*	*Articulated trucks*
30	29.0	105.1	110.6
50	29.1	105.6	111.1
70	29.3	106.1	111.6
90	29.6	107.8	112.1
110	30.1	110.8	112.6
130	30.6	113.8	113.2
150	31.2	116.8	113.7

a. VOCs comprise fuel, oil, tyres, maintenance (parts and labour) and time-related costs.

Source BTCE estimates.

Roughness directly affects fuel and oil consumption, tyre wear, and expenditure on vehicle maintenance (parts and labour). Table 4.3 shows the percentage increases in elements of VOCs for roughness levels of between 30 and 150 NRM. Results from the HDM-C model indicate that time-related costs are about 50 per cent of total passenger car operating costs on roads with low congestion. But because roughness does not affect travel time, it does not affect time-related costs. For heavy vehicles, time-related costs include capital costs and crew costs.

TABLE 4.3 PERCENTAGE INCREASE IN VOCs CORRESPONDING TO AN INCREASE IN ROUGHNESS FROM 30 TO 150 NRM

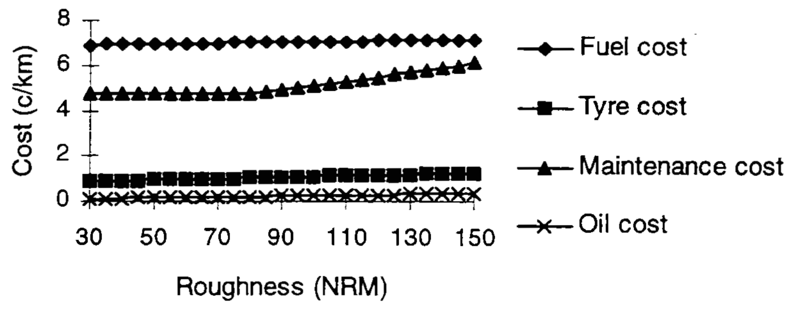
(per cent)

Cost	*Cars*	*Rigid Trucks*	*Articulated trucks*
Fuel	3.7	6.6	4.3
Tyres	42.5	13.0	13.6
Maintenance	27.8	54.3	0
Oil	250.5	54.8	38.9
Total	7.6	11.1	2.8

Source BTCE estimates.

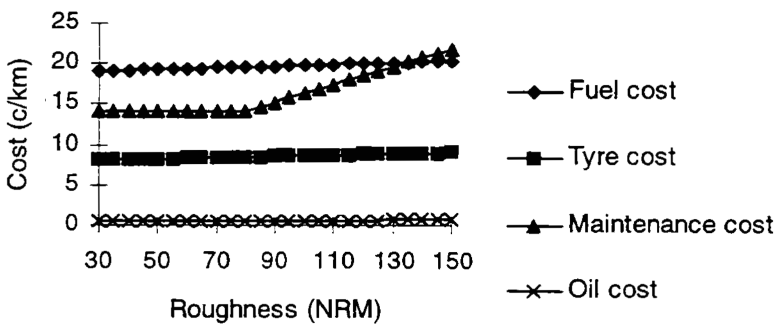
Figures 4.1 to 4.3 show changes in some components of VOCs as road roughness increases. The costs of fuel, oil and tyres increase linearly with roughness. Maintenance costs remain constant until roughness reaches about 80 NRM and then increase rapidly for cars and rigid trucks. For articulated vehicles there is no change in maintenance costs when roughness levels are in the range of 30 to 150 NRM. Roughness only affects the maintenance costs of articulated trucks when its value exceeds 300 NRM. Articulated trucks may be less sensitive to changes in roughness because of their large size.

FIGURE 4.1 FUEL, TYRE, OIL AND MAINTENANCE COSTS PER KILOMETRE FOR CARS



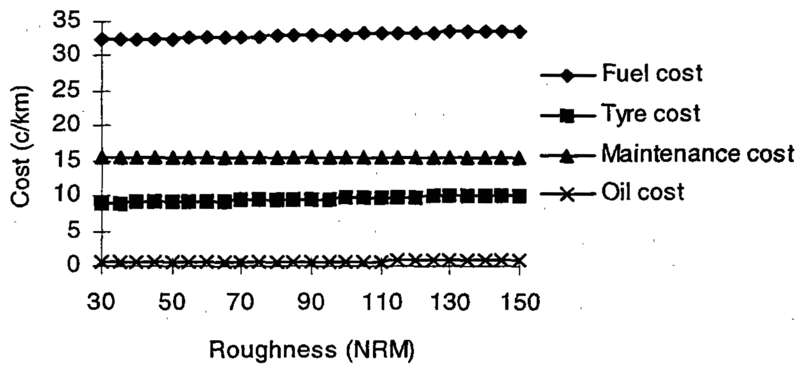
Source BTCE estimates.

FIGURE 4.2 FUEL, TYRE, OIL AND MAINTENANCE COSTS PER KILOMETRE FOR RIGID TRUCKS



Source BTCE estimates.

FIGURE 4.3 FUEL, TYRE, OIL AND MAINTENANCE COSTS PER KILOMETRE FOR ARTICULATED TRUCKS



Source BTCE estimates.

Appendix VII contains a set of tables that provide estimates of reductions in social VOCs due to different types of pavement rehabilitation and traffic levels for a one-kilometre section of road. These tables may be used as 'ready reckoners' to estimate approximate changes in VOCs for any length of road.

FUEL INTENSITY

Fuel intensity (the intensity of fuel use) is typically measured in litres per 100 kilometres. Estimates of vehicle fuel intensity were derived from estimates of vehicle fuel consumption obtained from the application of the HDM-C model and are shown in table 4.4. Over the roughness range of 30 to 150 NRM, the fuel intensity of cars and articulated trucks increases by 3.8 and 4.3 per cent respectively. Over the same range of roughness the fuel intensity of rigid trucks increases by 6.7 per cent, indicating that rigid trucks are relatively more sensitive to roughness in terms of fuel use than cars or articulated trucks.

TABLE 4.4 INCREASE IN FUEL INTENSITY WITH ROUGHNESS

(litres per 100 kilometres)

Vehicle type	*30 NRM*	*150 NRM*
Cars	9.3	9.7
Rigid trucks	27.2	29.0
Articulated trucks	48.2	50.3

Source BTCE estimates.

APPENDIX I HIGHWAY WATER RUN-OFF AND THE ENVIRONMENT

Highway construction, maintenance and use have implications for highway water run-off and its environmental effects in both urban and rural areas. Exhaust emissions that affect run-off, such as uncombusted and partially combusted hydrocarbons, nitrous oxide and other oxides of nitrogen, and heavy metals (notably lead), are generally lower in relatively unimpeded highway traffic than in congested urban conditions.

The rehabilitation of existing highways can cause changes in natural run-off patterns which can significantly change flow rates and run-off water quality. Kerri, Racin and Howell (1985) have developed regression equations for estimating pollutant loads in highway run-off water.

SOURCES AND EFFECTS OF POLLUTANTS

Pollutants in highway water run-off originate from a number of sources besides road maintenance operations and exhaust emissions. These sources include fuel and oil leaks, pavement abrasion and weathering, deterioration of paint used in road markings, tyre wear, vehicle wear and corrosion, litter, spillage of hazardous materials, atmospheric deposition such as acid rain, and the use of herbicides to eliminate intruding vegetation during road maintenance. In addition to rubber, polymers, and other organic compounds, tyres also contain zinc and traces of other heavy metals. The process of road deterioration known as 'pumping' (chapter 2) can result in various pollutants, including heavy metals such as iron from slag, rising to the pavement surface and contaminating run-off water. The type, quantity, and effects of pollutants in highway water run-off vary over time depending on the volume and type of traffic, road surface characteristics, type and frequency of road maintenance, and drainage and catchment facilities. Highway water run-off filters into the ground or is carried away into above- or below-ground watercourses by gutters, drains, ditches and the like.

The degree of penetration and toxicity of the pollutants in the areas surrounding highways depends on the physical and chemical properties of soils such as structure and texture, pH (percentage hydrogen) level (the solubility of heavy metals tends to increase with increasing soil acidity), and the presence of substances that can react with the pollutants. Different pollutants have different effects when dispersed in soil due to their degrees of solubility and mobility, but pollutant concentrations generally decrease with increasing sub-surface depth.

The effects of waterborne pollutants, unlike those of airborne pollutants, are generally felt in an area relatively close to the highway. Near highways, soil and plant matter generally contain relatively high concentrations of heavy metals such as iron, copper, zinc, nickel, chromium, cadmium and lead. The effects of pollutants on soils close to highways are not conducive to healthy plant growth. Animals that inhabit the environments close to highways are also subject to absorption of pollutants. The seepage of pollutants into rivers and streams can harm fish and other aquatic life. Particulate matter in water causes turbidity, which can retard photosynthesis and cause blockages in the gills of fish. The consumption of fish from polluted waterways by humans can lead to various health problems. The discharge of pollutants from highway use can, in sufficient concentration, also cause contamination of ground water.

Maestri, Dorman and Hartigan (1988) reviewed several studies on the effects of highway water run-off and concluded that run-off has the potential to adversely affect the water quality and aquatic biota of receiving waters. The significance of these adverse effects was found to be event-specific, depending on the highway, receiving water and run-off event. Maestri, Dorman and Hartigan also found that run-off from urban highways with high average daily traffic (ADT) volumes may have a relatively greater potential to cause adverse effects, whereas the potential for adverse effects of rural highway run-off with low ADT volumes was relatively small.

Folkeson (1994) has reviewed 156 studies on the environmental effects of highway water run-off. He notes that elevated pollutant levels in water, plants and sediments in waters that receive highway water run-off are well documented, and that reduced species diversity and unstable species composition of vegetation and fauna have also been demonstrated. Folkeson also notes that laboratory experiments using different plants, animals and bacteria have often produced contradictory results. The lack of consistency in results is attributed to the influence of several factors including precipitation regime, run-off chemistry, pollutant speciation, hydrology of the receiving water, and other local conditions. Another key finding is that biological effects in waters receiving highway run-off are highly dependent on the sensitive equilibrium between nutrients and toxic substances: biological growth may be inhibited if the concentration of heavy metals becomes excessive.

In some northern hemisphere countries, the use of salt (sodium chloride) as a de-icing agent in winter and the accumulation of pollutants in snow causes further stress on highway ecosystems.

EFFECTS OF HIGHWAY WATER RUN-OFF ON A LAKE

Nordic Road and Transport Research (1994) reports on a study of the effects of water pollution from highways on a small lake. During 1980–83, the Norwegian Road Research Laboratory (NRRL) engaged the Norwegian Institute for Water Research (NIVA) to undertake an investigation of the effects of run-off water and dust deposition from the heavily-trafficked E18 highway near Oslo on the water quality of Lake Padderudvann, which is close to the highway. The investigation showed that both run-off water and dust deposition from the highway were heavily polluted by polycyclic aromatic hydrocarbons, heavy metals and particulate matter. However, the pollutants quickly settled on the sediments, and the outlet water from the lake was therefore largely unaffected by the pollutants.

In 1992, NRRL re-engaged NIVA to study the long-term effects of the highway pollutants on the biological system of Lake Padderudvann. Lake Semsvann, situated 4 kilometres north-east of Lake Padderudvann and having very low traffic density in its vicinity, was selected as the reference lake.

Lake Padderudvann had been receiving pollution from the highway since it opened for traffic in 1969. Run-off water from the highway in 1982 and 1992 contained considerable quantities of heavy metals such as cadmium, copper, zinc, iron, nickel, vanadium and lead. The run-off water also had high concentrations of calcium from highway surface wear and chlorides from de-icing salt.

Vegetation on the roadside by the lake had become almost extinct, probably because of the steep stone bank formed during road construction. Vegetation had disappeared at the site close to the main drainage pipe from the highway, probably because of traffic pollution. The community of benthic invertebrates was studied at different sites in the lake. The community close to the main drainage pipe from the highway was affected by pollution, as evidenced by reduced diversity and the disappearance of freshwater shrimp and most snail species. Some plant species and a species of perch were used to study accumulation of heavy metals in biological tissues. The accumulation was generally found to be low. However, high levels of cadmium and zinc were found in a plant species and high levels of cadmium and lead were found in the liver of the perch.

The study concluded that pollution from road traffic had negatively affected the aquatic ecosystems and changed the properties and useability of the water of Lake Padderudvann. The lake is regarded as having been moderately affected by traffic pollution. The threat to the lake from pollutants, in the future is expected to be essentially of the same nature as in previous years.

TREATMENT OF HIGHWAY WATER RUN-OFF

Quantifying the impact of highways on water pollution is a formidable task. It is difficult to determine the extent to which highways contribute to water pollution because the effects have to be isolated from aggregate effects that occur over time. Valuation of water quality and impacts on vegetation and animals also present considerable problems. Available economic valuation techniques such as contingent valuation are beset by various methodological problems. An alternative approach is to estimate the (control) cost of avoiding any damage from pollutants in run-off water by means such as purifying the water before it is allowed to infiltrate soil.

Purification by sedimentation may be achieved by a variety of techniques, including channelling the water through relatively long ditches or by collecting the water in sedimentation ponds. More costly options involve the use of water treatment plants using sophisticated techniques such as air flotation and micro-straining. Sometimes, special retention ponds or basins may be provided beside highways to remove pollutants from water by settlement.

A study by Colwill, Peters and Perry (1985) assessed the effect of different drainage systems in removing pollutants from motorway run-off at an experimental catchment on the M12 motorway near Toddington, Bedfordshire, in the United Kingdom. The drainage systems assessed were a concrete sedimentation tank, a shallow lagoon lined at the bottom with a polyvinyl chloride (PVC) membrane and a French drain. The French drain consisted of a 50-metre long vitrified clay pipe, 150 millimetres in diameter with 6.25-millimetre perforations along two longitudinal rows. The pipe was placed in a drain and covered with granular material.

The study found a considerable improvement in the water quality of motorway run-off brought about by the use of the three drainage systems. The discharges from these systems contained consistently lower levels of suspended solids and contaminants than untreated run-off. The lagoon was found to be the most efficient system for the removal of contaminants, followed by the French drain and the sedimentation tank.

Maestri, Dorman and Hartigan (1988) reviewed several methods of managing highway run-off water and rated them on the basis of effectiveness and cost. They identified vegetative controls (such as grassed channels which provide filtration, sedimentation and infiltration); wet detention basins (especially for 'first flush' run-off, when a large proportion of the total pollution load is produced by a relatively small proportion of run-off volume during the initial stages of run-off); infiltration systems (such as open basins, infiltration trenches and wells, where run-off is temporarily stored and allowed to infiltrate the ground); and wetlands (an area of land where the ground water table is at or near the surface). They recommend the combination of two or more management measures for highway water run-off.

ROADS AND ECOLOGICALLY SUSTAINABLE DEVELOPMENT (ESD)

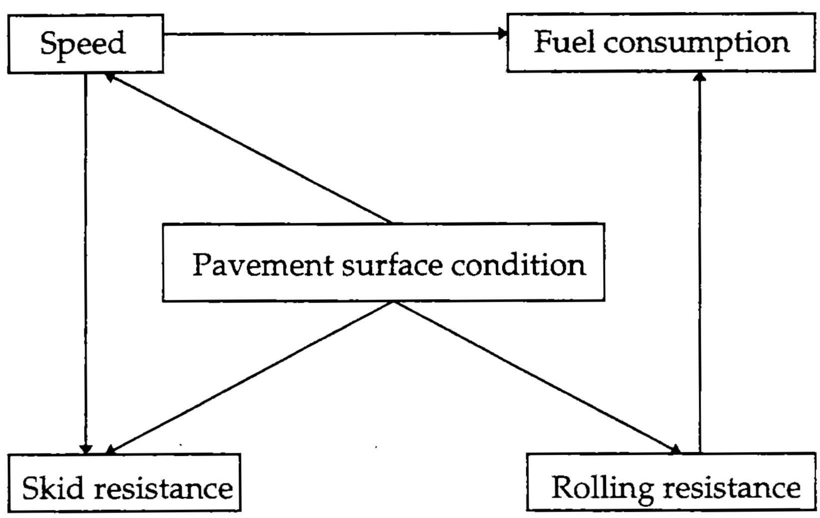
Farmar-Bowers (1994, 1995) has been developing applications of ecologically sustainable development (ESD) analysis to roads. A large but unknown proportion of Australia's biodiversity is represented on transport corridors, which may be regarded as Australia's most diverse, but least protected, biodiversity reserve. A cooperative management system called the National Protocol System (NPS) has been initiated under the auspices of two Austroads strategies: an environmental strategy and an ESD strategy.

The NPS aims to bring all stakeholders into a single agreement called the 'protocol core' and seeks their commitment to this agreement through documents called 'protocol chapters'. Stakeholders are agencies, companies and individuals who use any resources on transport corridors. The commitment of stakeholders to biodiversity conservation is achieved through the efficient and effective use of management arrangements. Stakeholders would work out what they should do to achieve the objectives in the protocol core and commit their program of action to paper (the protocol chapter). There would be no central administration of the NPS—it is intended to be run, monitored, developed and reformed by the stakeholders themselves.

APPENDIX II RELATIONSHIPS BETWEEN PAVEMENT SURFACE CONDITION AND VEHICLE PERFORMANCE

Pavement surface condition affects vehicle fuel consumption through rolling resistance. Surface condition also affects skid resistance and vehicle speed, and speed in turn affects fuel consumption. These relationships are shown schematically in figure II.1.

FIGURE II.1 RELATIONSHIPS BETWEEN PAVEMENT SURFACE CONDITION AND VEHICLE PERFORMANCE



Source BTCE.

EFFECT OF PAVEMENT SURFACE CONDITION ON ROLLING RESISTANCE AND FUEL CONSUMPTION

Fuel consumption can account for more than 50 per cent of total VOCs (PIARC 1991, p. 35) but typically accounts for 20 to 40 per cent of VOCs (Gu, 1989, p. 1). Fuel consumption is influenced by a range of factors including vehicle mass and shape, road geometry, road surface characteristics, vehicle characteristics, traffic conditions, speed, wind resistance, and driver behaviour.

Rolling resistance refers to the resistance generated by a vehicle's pneumatic tyres, and is a measure of the energy dissipated per unit distance rolled by the tyre. Rolling resistance may also be regarded as the aggregate force, with the exception of aerodynamic drag, acting on a free-wheeling vehicle (with clutch disengaged). The coefficient of rolling resistance is calculated by dividing the rolling resistance by the load. A typical value for car tyres is about 1 per cent (PIARC 1983, p. 20). The main source of rolling resistance is the deformation of the tyre as it moves over the road surface. Vehicle fuel consumption is related to road roughness through rolling resistance.

The coefficient of rolling resistance can be determined by mathematical relationships which link the mass and acceleration of a vehicle to parameters which include the driving power, vertical gradient, coefficient of rolling resistance, mass density of air, and drag coefficient of the vehicle. Data for determining the coefficient of rolling resistance can be obtained by conducting a 'coast-down' experiment in which the drive force of the vehicle is zero.

A coast-down experiment involves allowing a vehicle to coast down from a high speed on a section of road whose conditions are known. Speed, time, distance and deceleration are measured, and the rolling resistance coefficient is estimated using a relationship such as the physical force balance equation (Watanatada et al. 1987). The results of such an experiment showed that the rolling resistance of a vehicle increased with road roughness and that the rolling resistance for heavy vehicles was lower than for light vehicles (Watanatada et al. 1987).

Four sets of factors affecting rolling resistance can be identified in the literature: wheel characteristics (including number and size of wheels), tyre construction (cross-ply, radial etc.), tread pattern and depth; environmental conditions (temperature, water, ice); operating conditions (speed, load, inflation pressure, camber angle, slip angle); and road surface characteristics (microtexture and macrotexture).

Rolling resistance has components that are dependent on mass (proportional to mass) and independent of mass. The component of rolling resistance that is independent of mass comprises roughly a quarter of the rolling resistance of an unladen truck and increases with vehicle size (Biggs 1988, p. 3). The mass-dependent component has been found to closely match the tyre rolling resistance measured in a laboratory for both car and truck tyres (Biggs 1987) and is inversely proportional to tyre diameter (Biggs 1988, p. 3).

The greater sensitivity of rolling resistance to road surface conditions with increasing tyre diameter is because higher tyre inflation pressures and harder rubber tyres used in commercial vehicles result in a smaller hysteresis loss (Cenek 1996, p. 8). Hysteresis is a property of rubber and certain other materials that enables them to dissipate internal energy under cyclic deformation. Hysteresis losses occur when the tyre rubber in contact with the road surface becomes compressed or distorted as it passes over the projections and asperities in the road surface.

The mass-independent component of rolling resistance is related to the number and size of the wheels and may be interpreted as the part of rolling resistance attributable to the frictional resistance of all moving parts in the car (Biggs 1988, p. 3).

Higher vehicle speeds result in greater rolling resistance because increasing speed causes greater tyre flexing and vibration. Biggs (1988, p. 3) cites Smith, Tracy and Potter (1978) as postulating that a component of rolling resistance is proportional to the square of the speed and inversely proportional to the square of the tyre diameter. However, Descornet (1990, p. 408) found that the coefficient of rolling resistance increased linearly with speed. Biggs (1987) found that the speed-dependent component of rolling resistance was significant for light vehicles but insignificant for articulated trucks, and did not appear to be related to mass.

The degree of rigidity of the tyre and pavement surface determines the degree of tyre penetration, surface compression and tyre deformation. Consequently, hard, smooth and dry pavement surfaces provide relatively low rolling resistance.

High tyre pressures on hard surfaces decrease rolling resistance because of reduced friction, but increase rolling resistance on soft surfaces due to greater surface penetration. A high tyre temperature causes greater tyre flexibility and results in less resistance during tyre deformation. The following exponential formula describes the relationship between the coefficient of rolling resistance and temperature (Descornet 1990, p. 407):

$$C_R(T) = C_R(T_0)\exp\{(T-T_0)/T_1\}$$

Where C_R is the coefficient of rolling resistance which varies with temperature T, T_0 is a reference temperature, and T_1 is a temperature constant which depends on the tyre and rim assembly.

Mannering and Kilareski (1990, p. 19) estimate the contribution of various factors to total rolling resistance. The work needed to overcome tyre deformation accounts for about 90 per cent of total rolling resistance. Tyre penetration and compression at the pavement interface typically accounts for about 4 per cent of total rolling resistance. Frictional motion due to tyre slippage on the pavement surface, and to a lesser extent the 'fanning effect' (air circulation around the wheel and tyre), account for about 6 per cent of total rolling resistance.

Early studies in the United States on the relationship between vehicle fuel consumption and road characteristics include those by Claffey (1971) and

Zaniewski et al. (1979), who found that pavement roughness influenced fuel consumption to the extent of 30 per cent and 10 per cent respectively. However, a later study by Zaniewski (1983) produced contrary results. Zaniewski (1983) tested eight vehicles of different sizes (four cars and four trucks) on asphalt, concrete, surface-treated and gravel surfaces. Zaniewski found that there were no statistically significant differences at the 95 per cent confidence level between the fuel consumption on the paved sections. Fuel consumption on the unpaved (gravel) section was found to be slightly higher than consumption on paved sections. Zaniewski concluded that pavement condition did not affect fuel economy over the range of conditions normally encountered in the United States.

However, Claffey (1983) takes issue with the findings of Zaniewski's (1983) study. Claffey points out that large-scale studies of the effects of road surface condition on fuel consumption of all vehicle types show that fuel economy drops sharply for operation on road surfaces that:

- allow wheel slippage (due to loose surface material);
- force tyre indentations (due to exposed embedded stones and/or a spalled surface condition; and
- provide a coarse-sandpaper type of surface (due to certain stone surface treatments).

Claffey further notes that the test road sections used in Zaniewski's study were not representative of all United States roads, and argues that surface characteristics do have a significant influence on fuel consumption.

Bester (1984) determined the effect of rolling resistance by measuring the speed, at regular intervals, of a coasting vehicle (a vehicle running freely with the engine disengaged) on sections of road with constant gradient and roughness. The road sections used for the tests were asphalt, concrete, several different types of surface treatments, and an unpaved surface. Both the constant and speed-related rolling resistance coefficients for cars were found to be affected by roughness, whereas for trucks only the constant rolling resistance coefficient was found to be affected by roughness. The roughness of paved roads had a small effect on the rolling resistance, and therefore on the fuel consumption of cars. Unpaved roads were found to have a much greater effect. At 80 kilometres per hour a car can use 29 per cent more fuel, and a truck 18 per cent more fuel, on a gravel road than on a paved road in good condition.

Descornet (1990, p. 410) used a 'quarter car' trailer designed and built at the Belgian Road Research Centre for measuring the rolling resistance of a tyre on different types of road surfaces. He found that the worst road surface tested had a rolling resistance 47 per cent greater than the best surface. This difference in rolling resistance translates into a 9 per cent difference in fuel consumption. The main factor in the extra rolling resistance was identified as megatexture (surface irregularities with wavelengths (λ) between 50 millimetres and 500 millimetres.

Delanne (1994) also used an experimental approach to determine the relationship between pavement characteristics and fuel consumption. He found that short wavelength roughness ($0.7 < \lambda < 2.8$ metres) can influence fuel consumption by up to 6 per cent and that macrotexture ($0.5 < \lambda < 50$ millimetres) can influence fuel consumption by up to 5 per cent. Although macrotexture is required for skid resistance at high speeds, it is responsible for extra fuel consumption and low frequency noise.

Cenek (1996) reports the results of a research program conducted between 1988 and 1995 to quantify the influence of pavement textures of New Zealand roads on tyre rolling resistance. A Nissan Pulsar car specially instrumented to measure tyre rolling resistance was driven over 12 different road surfaces whose roughness ranged from 37 to 57 NRM. The difference in rolling resistance between the most extreme surfaces tested was 55 per cent. Cenek notes that it is generally accepted that, for a light car, a 20 per cent reduction in tyre rolling resistance will reduce fuel consumption by about 4 per cent for both urban and rural driving. On this basis, he concludes that fuel consumption can be expected to vary over a range of 11 per cent for the surfaces investigated.

Cenek (1996) found that the same decrease in fuel consumption can be achieved by reducing surface texture depth from 2.2 millimetres to 1.4 millimetres as can be achieved by reducing road roughness from 150 to 70 NRM. He concludes that pavement macrotexture is as important as pavement roughness in influencing the fuel consumption of cars, and that both factors should be taken into account in pavement design.

Cenek (1996, p. 8) observes that the greatest potential for reducing fuel consumption through road design is in reducing short wave roughness (0.6- to 3.2-millimetre wavelengths) and megatexture (60- to 500-millimetre wavelengths). He also notes that the control of macrotexture is important, especially in the speed range of 60 to 70 kilometres per hour.

Gu (1989, 1990) reviewed several studies on the relationship between road roughness and fuel consumption. He concludes that although the studies have generally shown that fuel consumption increases with road roughness, there is considerable uncertainty about whether the effect is significant. The studies reviewed by Gu indicated that between 'smooth' and 'rough' pavements the change in fuel consumption varied between a nil effect and a 56 per cent increase. However, the results of these studies are difficult to compare because of differences in a range of factors that affect the results, including road and vehicle characteristics, vehicle speeds and methods of roughness measurement.

The HDM-III model estimates fuel consumption as a function of average speed, gradient, vehicle mass and roughness. There are several fuel consumption models incorporated in HDM-III that are based on calibrations using data from the Caribbean, Kenya, Brazil and India.

Gu (1990) conducted sensitivity tests on the fuel consumption models in HDM-III. He found that fuel consumption is an increasing function of roughness when speed is kept constant. He also found that the relationship between speed and fuel consumption is a U-shaped curve: fuel consumption reaches a minimum value at a certain speed.

Based on results using HDM-III, Gu also found that fuel consumption was the major component of VOCs, accounting for between 19 and 56 per cent of VOCs. Gu's sensitivity tests indicated that, for small passenger cars, an increase in roughness from 25 to 150 QI[1] results in an increase in VOCs of 44 per cent for the Caribbean model and 31 per cent for the Kenyan model. The Indian and Brazilian models predicted an increase in fuel consumption of 51 and 33 per cent (with increases of 51 and 33 per cent in VOCs) over a roughness range of 25 to 150 QI, with varying speed induced by road conditions. Holding speed constant, Gu found that roughness had a substantial impact on fuel consumption (with the exception of the Caribbean model).

Gu also attempted to validate the HDM-III model for Australian conditions. He found that the effect of roughness was overwhelmed by the effects of other variables such as gradient, wind velocity and vehicle speed. Gu concluded, by isolating the gradient effect, that the effect of roughness on fuel consumption under Australian conditions was significant, particularly at high speeds.

The HDM-C model used in the analysis in this paper is a modified version of the World Bank's HDM-III model that has been calibrated for Australian road conditions by the ARRB, but retains the fuel consumption algorithms of HDM-III. However, the subsequent version of the World Bank model (HDM-4) incorporates revised fuel consumption algorithms which model fuel consumption more accurately. The fuel consumption algorithms in HDM-III are believed to generate excessive fuel consumption values for most vehicle types, particularly at low vehicle speeds, because engine speed is assumed to be constant (Cox & Arup Transportation Planning 1996, p. 21). However, the implications of this overestimation would not be significant in the analysis in this paper because speed is assumed to be constant at a highway speed limit of 100 kilometres per hour.

Rolling resistance in relation to bituminous and concrete pavements is discussed further in appendix VI.

PAVEMENT SURFACE CONDITION AND VEHICLE SPEED

Vehicle speed can be affected by a number of factors including vehicle type and shape, pavement type, road geometry, gradient, speed limits, traffic

1. Quarter-car Index. The International Roughness Index (IRI) is based on a mathematical model, called the 'quarter-car' model, of the dynamic response of a real vehicle to the longitudinal road profile (Prem 1989, p. 10).

composition and density, weather conditions, time of day, driving habits and behaviour, fuel cost, and road surface condition. Motorists may tend to drive more slowly on roads whose surfaces are rougher, or which exhibit substantial surface deterioration, relative to roads having more even surfaces. If motorists do increase speed on more even roads, a possible consequence is an increase in the frequency and severity of crashes.

Cooper, Jordan and Young (1980) measured speed distributions on three major roads in the United Kingdom before and after resurfacing to determine whether surface deterioration significantly affects traffic speeds. The study was designed to eliminate, as far as possible, all factors which influence speed other than road surface condition. It was considered that driver reaction to a visibly short length of uneven surface might be more variable than to lengths where the total length of the surface condition could not be seen. A length of 500 metres was considered to be the minimum that would provide clear evidence of any adjustment in speed by drivers. The selected test sites were 1.2, 3.3 and 1.7 kilometres in length.

On all test sites, traffic speeds were sampled over three one-hour periods of a particular day, both before and after resurfacing. Resurfacing of two of the three sites did not produce a statistically significant change in mean traffic speed levels. However, the third site, which had a greater unevenness before resurfacing and a greater improvement following resurfacing than the other two sites, showed statistically significant increases in mean traffic speed after resurfacing.

In the case of this third site, the study found that increases in daily mean speed averaged over four monitor points after resurfacing were 2 kilometres per hour for private cars (after applying a correction of –2 kilometres per hour because of relaxation of speed restrictions and an increase in fuel prices during the period of the study), 2.3 kilometres per hour for light goods vehicles, 2 kilometres per hour for medium goods vehicles, and 2.6 kilometres per hour for heavy goods vehicles. Before resurfacing, the site was considered to be representative of the worst state of surface irregularity likely to be found on major roads in the United Kingdom. The study therefore concluded that the level of increase in mean speed was unlikely to be exceeded for the resurfacing of any other major road in the United Kingdom, all other factors remaining constant.

At one of the sites at which no statistically significant speed changes occurred, the surface unevenness showed little change before and after resurfacing, but the texture depth was substantially improved. It was therefore concluded that changes in texture depths of flexible roads, within the depth range examined on major flexible roads, do not significantly influence traffic speeds.

A study carried out in Sweden by Linderoth (1981) and reported by Wretling (1996) investigated the relationship between road surface and travel speed in Sweden using a sample of resurfaced roads and a control group of roads that were not resurfaced. The study concluded that there was no evidence of reduced speed due to roughness.

Wretling (1996) also describes another Swedish study by Anund (1992) that investigated the relationship between surface quality (rut depth and roughness measured in IRI) and speed for cars, trucks and trucks with trailers. The results showed that there was a statistically significant speed reduction of 1.6 kilometres per hour for passenger cars between 3.00 p.m. and 9.00 a.m. if the rut depth increased by 10 millimetres, and a reduction of 2.2 kilometres per hour if the IRI increased by 1 millimetre per metre. The corresponding figures during 9.00 a.m. and 3.00 p.m. were 1.9 kilometres per hour and 3.0 kilometres per hour. For trucks with and without trailers, no significant speed reduction with increased roughness or rut depth was found.

The results of the aforementioned studies seem to support the intuitive notion that vehicle speed will be significantly affected only when road condition deteriorates beyond some critical level. PIARC (1987, p. 84) makes the following conclusions about the effect of pavement surface condition on speed:

- An increase in microtexture probably has no effect on chosen speed in normal straight-ahead driving. It appears that it may have an effect on increasing cornering speed.
- An increase in macrotexture and the lower orders of megatexture generally induces the driver to reduce speed. The effects of speed and rolling resistance are therefore opposed and the net fuel consumption will rise or fall depending on the relative magnitude of the two effects.
- Increases in megatexture and greater roughness, or the incidence of loose gravel or deep snow or mud, frequently have the effect of inducing the driver to reduce speed to below 50 kilometres per hour. In this case, lower speeds result in an increase in fuel consumption with both rolling resistance and speed effects acting in the same direction.

It appears from the range of research reviewed above that, all other factors influencing speed remaining constant, the average range of surface condition of modern roads does not appear to have an unduly retarding effect on vehicle speeds. Considerable surface deterioration would have to occur before average traffic speeds are markedly reduced.

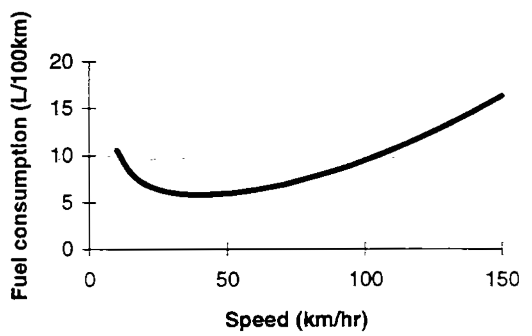
VEHICLE SPEED AND FUEL CONSUMPTION

Vehicle engines convert only a part of the energy produced by internal fuel combustion into useable mechanical energy. The amount of energy available from internal combustion is reduced by internal engine friction and drive train losses. Energy is also required to overcome tractive forces such as inertia and air, rolling, gravitational, grade and cornering resistance. Additional energy is required to power vehicle accessories such as air conditioning, radio and cassette equipment, power steering, water pump, cooling fan and alternator. In order to overcome tractive forces, sufficient power generated by the engine has to be transmitted to the wheels. The transmission of power occurs through the gear box and differential, which also dissipate some of the power input. Automatic vehicles lose even more power in the torque converter and transmission oil pump.

It has been traditionally believed that high vehicle speeds considerably increase fuel consumption. One reason for this is that the power required to overcome rolling resistance and aerodynamic drag increases as speed increases. Another reason is that vehicle engines become less efficient as the number of revolutions increase. The speed at which optimum fuel efficiency is achieved therefore involves a trade-off between the low rolling resistance and aerodynamic drag at low speeds and the most efficient rate of engine revolutions per minute. Graphs of fuel consumption as a function of speed have traditionally been U-shaped, with optimum speeds being in the moderate range of 60 to 80 kilometres per hour.

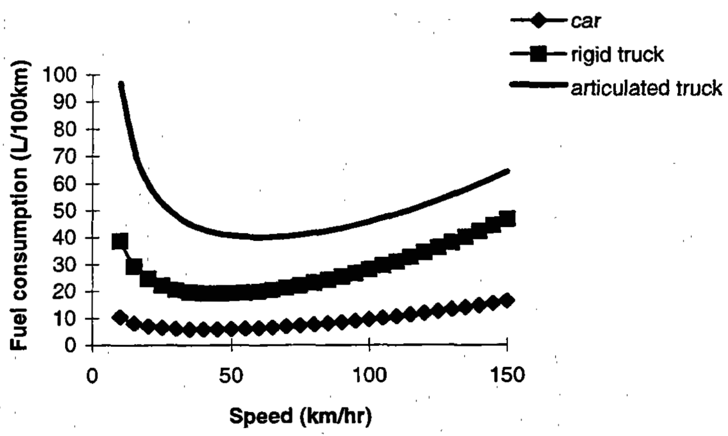
The HDM-III model is believed to give excessive fuel consumption values for most vehicle types, particularly at low vehicle speeds, because engine speed is assumed to be constant (Cox & Arup Transportation Planning 1996, p. 21). Figure II.2 shows a typical fuel consumption curve for cars generated by the BTCE's HDM-C model (which has the same fuel consumption algorithms as HDM-III). Figure II.3 shows the same curve for cars compared with the curves for rigid and articulated trucks.

FIGURE II.2 RELATIONSHIP BETWEEN FUEL CONSUMPTION AND SPEED FOR CARS GENERATED BY HDM-C



Source BTCE estimates using HDM-C.

FIGURE II.3 RELATIONSHIP BETWEEN FUEL CONSUMPTION AND SPEED FOR CARS AND TRUCKS GENERATED BY HDM-C

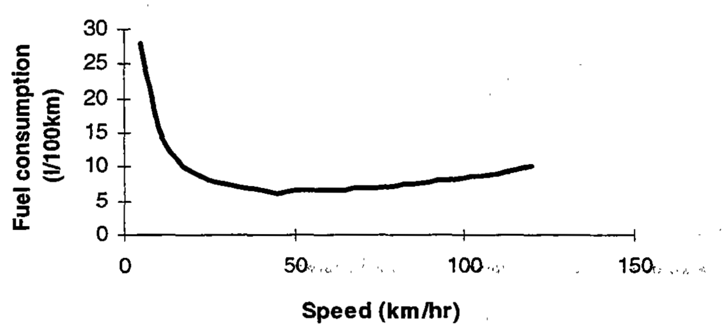


Source BTCE estimates using HDM-C.

In developing HDM-4, the World Bank has replaced the fuel consumption algorithms in HDM-III by fuel consumption models derived from ARFCOM (the ARRB Road Fuel Consumption Model). ARFCOM uses a mechanistic approach which takes account of tractive forces, vehicle accessories, internal engine friction, and drive train inefficiencies to estimate total power requirements of vehicles. Additionally, the incorporation of an engine fuel efficiency factor enables the model to estimate fuel consumption.

The variation in fuel consumption with speed predicted by the mechanistic HDM-4 model is not the traditional U-shaped curve (as seen in figures II.2 and II.3), but is more in the nature of a 'ski-slope' shape (figure II.4).

FIGURE II.4 RELATIONSHIP BETWEEN FUEL CONSUMPTION AND SPEED FOR CARS GENERATED BY HDM-4



Source BTCE estimates adapted from Archondo-Callao and Faiz (1994).

The Royal Automobile Club of Victoria (RACV) regularly carries out travel time surveys of various roads in Melbourne using a 1991 automatic Mitsubishi Magna TR and also records fuel consumption values. Cox and Arup Transportation Planning (1996) used this data to analyse major arterial and freeway routes in the morning and evening peaks and off-peak. It was found that, although a similar ski slope shape to that in figure II.4 was obtained for the relationship between fuel consumption and speed, there was no significant difference between the results for morning peak, evening peak and off-peak, periods for both freeways and arterials. Most roads were associated with a fuel consumption of about 20 litres per 100 kilometres at 10 kilometres per hour, decreasing asymptotically to just under 10 litres per 100 kilometres at about 80 kilometres per hour.

The change in the fuel consumption–speed relationship from the traditional U-shape to the more recent ski slope shape is attributable to the combined effect of several technological improvements in vehicles. These improvements include reduced drag due to better aerodynamic design, electronic fuel injection, improved engine performance, overdrives, and radial tyres which generate lower rolling resistance at high speeds than cross-ply tyres.

PAVEMENT SURFACE CONDITION AND SKID RESISTANCE

The condition of a road surface not only determines VOCs in terms of fuel consumption and vehicle wear, but also has a bearing on safety. However, road crashes are multi-causal events, and it is difficult to attribute, with any precision, particular numbers of crashes on a road solely to the skid resistance characteristics of the road.

Pak-Poy and Kneebone (1988, p. 44) reviewed several studies on the relationship between road surface condition and crashes and report that many of these studies identify low frictional characteristics of worn or poorly constructed surfaces as a significant contributor to crashes. For example, they cite a study by Giles and Sabey (1959) who found that, in Great Britain, 8 per cent of crashes in dry conditions and 27 per cent of wet-weather crashes involved skidding.

Kumar and Holtrop (1991, p. 1) report that their international literature search indicates that 10 to 30 per cent of total crashes occur in wet weather and that these crashes could be reduced by up to 70 per cent by skid resistance surface restoration, which is considered to be a cost-effective treatment.

The skid resistance of a site depends on several factors including texture of the surface, site geometry, weather conditions, vehicle speeds, the number and type of vehicles using the site, and tyre characteristics. Sites such as intersections, roundabouts and bends are subject to relatively greater braking and turning which cause polishing of surface aggregates, lowering their frictional resistance. Surface texture is an important determinant of skid resistance, especially in wet weather. Of the different types of surface texture (see chapter 2), macrotexture and microtexture are most relevant to skid resistance.

Macrotexture refers to the overall or large-scale surface profile of the road surface visible to the naked eye and is the texture that can be felt when the hand is drawn across the road surface. On an asphalt surface, macrotexture is provided by exposed aggregates such as stone or stone chippings. Macrotexture in a concrete pavement is provided by transverse grooves produced by sawing after the concrete sets, or by brushing the surface with hessian before the concrete sets. Macrotexture is gradually eroded by the action of traffic.

Macrotexture contributes to noise mitigation and skid resistance. An open-textured or porous surface such as open-graded asphalt provides good noise attenuation and skid resistance because of the coarse macrotexture which absorbs noise and increases frictional resistance. A key factor in reducing skid resistance at high speeds on wet surfaces is the ability of open-textured surfaces to rapidly disperse water from under the tyres of vehicles, which also contributes to better visibility by reducing splashing and spraying in wet weather. Macrotexture also provides the projections or asperities which contribute to hysteresis losses in tyres, which is an important factor in the braking process (Roe, Webster & West 1991, pp. 13–15).

Microtexture refers to the detailed or fine-scale surface characteristics of the aggregate and binder. It is the texture of individual pieces of aggregate and can be felt by rubbing a finger on pieces of aggregate. In an asphalt surface, microtexture is provided by the particles of aggregate (stone) as well as by the tiny particles, including embedded sand. Microtexture is provided on good concrete pavements by the sand in the mortar, whereas on worn pavements it is provided by the surfaces of the coarse stone aggregate. Microtexture is subject to continual change, especially in temperate climates. During warm and dry weather, traffic polishes the stone aggregates resulting in a loss of microtexture. However, during cold and wet periods, abrasive action by frost, ice, de-icing salt and fine particulate matter tends to restore the microtexture.

Like macrotexture, microtexture also contributes to skid resistance, but is more important at relatively low speeds. Traffic tends to affect microtexture by a polishing action which reduces the roughness and renders the surface more susceptible to skidding.

In wet weather, most of the water at the interface between the tyre and the road is dispersed by the tread of the tyre and, more importantly, by the coarse macrotexture. The role of the microtexture is to further disperse the thin film of water which remains between the tyre and the road, producing virtually a dry area of contact. On roads where low vehicle speeds are common, such as in the vicinity of intersections and on circular roads, roundabouts and loops, a relatively rough microtexture is required. On roads where higher speeds are the norm, such as exits from high speed freeways and near traffic signals on major arterials, a relatively rough macrotexture is required.

Resistance to polishing and abrasion are important characteristics of skid-resistant surfaces. If there is inadequate resistance to polishing, the road surface will become increasingly smooth due to action by tyres. Inadequate abrasion resistance would mean that aggregate will tend to be dislodged or wear off from the road surface. The action of water, tyre rubber and grime on such degraded surfaces will exacerbate the tendency for skidding to occur, especially at high vehicle speeds.

Resurfacing would generally result in an improved (coarser) microtexture or macrotexture which resists skidding. While resurfacing, it is also possible to rectify worn or improperly aligned cross-falls, often at no extra cost. An adequate cross-fall facilitates drainage away from the pavement surface and reduces the risk of aquaplaning[2] in wet weather.

However, resurfacing, by also reducing roughness and providing a smoother ride, could induce drivers to increase speeds, thereby limiting the full benefit of improved skid resistance. This phenomenon, known as 'risk compensation' (BTCE 1995b, pp. 259–63), could cause motorists to drive more cautiously on roads with a poor surface condition but drive at higher speeds after resurfacing, thereby increasing the risk of crashes. Also, speeding is likely to increase crash rates if the road surface is improved without improving road geometry, especially for roads with poor horizontal and vertical alignment (Craus, Livneh & Ishai 1991, pp. 53–4).

McCullough and Hankins (1966) analysed skid resistance and crash data for 517 rural sections of randomly selected Texas highways. The study indicated that increasing the coefficient of friction of highway sections from 0.275 to between 0.359 and 0.467 resulted in decreases in crashes by between 33.4 and 42.5 per cent. The study recommended that coefficients of 0.4 at 20 miles per hour and 0.3 at 50 miles per hour should be used as minimum standards, and that surface upgrading should be undertaken when skid resistance falls below these values.

Wretling (1996) has reviewed research, mainly in Nordic countries, on the relationship between the properties of road surfaces and safety. He reports that three studies in Sweden (Schandersson 1981; Bjorketun 1982, 1984) have shown that roads with a surface treatment have had lower crash rates than untreated asphalt roads. The study by Bjorketun (1984) included the total number of crashes on the Swedish paved national road network between 1977 and 1980. The study showed that roads which had a surface treatment in the southern and

2. 'Aquaplaning' or 'hydroplaning' refers to skidding of vehicles under wet conditions. Aquaplaning occurs when a vehicle's tyres lose contact with a pavement surface due to the presence of a water layer, resulting in the vehicle riding on the water layer.

central parts of Sweden had crash rates that were about 10 per cent lower than the rates for untreated asphalt roads. However, no differences were found in northern Sweden.

Wretling (1996) also reports the results of a joint Nordic research project in Denmark, Finland, Norway and Sweden by Hemdorff et al. (1989) in which traffic safety was investigated on roads with different pavement surfaces and surface wear. It was found that crash rates increased with ageing pavements on days with more than 10 millimetres of precipitation. The crash rates were about 7 per cent lower on inferior pavements than on good pavements (due to the lower rates during days without precipitation). However, on very rainy days (with more than 10 millimetres of precipitation) crash rates were higher on inferior road surfaces than on good surfaces. One of the conclusions of this study was that resurfacing is not necessarily a safety measure: the effects depend on the climatic conditions, especially the frequency and duration of rain.

Pak-Poy and Kneebone (1988) cite a study by the NSW Department of Main Roads (1986) relating to the Pacific Highway which indicates that resealing sections with high wet-weather crash rates could reduce the total crash rate by 11.7 per cent. Another study by the Road Traffic Authority (1986) in Victoria estimates potential crash rate reductions of at least 6 per cent due to resealing. Pak-Poy and Kneebone estimate that pavement resurfacing of rural roads in Australia has a benefit–cost ratio of 9.0 and is therefore a highly effective measure. Nevertheless, they expect benefits of resurfacing in Australia to be lower compared to countries such as the United States, the United Kingdom and Germany (which have crash reductions between 25 and 75 per cent) because of generally lower traffic levels and less frequent incidence of wet weather.

Papaleontiou, Meyer and Fowler (1991) conducted a comprehensive study to identify and evaluate the variables in the vehicle–driver–road–weather system that contribute to crashes, with particular emphasis on the friction number. The friction number (or coefficient of friction) is the ratio of the frictional force causing the vehicle to move along a surface to the force normal to the surface.

This study used crash information and skid data for 94 000 crashes that occurred in Tarrant County, Texas, between 1982 and 1987. A stepwise regression model was used to analyse the contribution of a range of crash causal factors as well as their pair-wise effects. The results revealed no specific relationship or trend between crashes and friction. The researchers note, however, that because of various uncertainties in the analysed data, this finding does not necessarily mean that a relationship does not exist.

There is some evidence that trucks may be particularly sensitive to pavement roughness. Jackson (1986, p. 141) cites two examples of truck crashes that may have been related to roughness. The trucks overturned, possibly due to failure of critical truck components, as they travelled over rough sections of the pavement. Jackson also cites a report (TRB 1984) which suggests that trucks may be sensitive to certain wavelengths of road roughness. The report notes that there is anecdotal evidence from truck drivers relating to control problems experienced when travelling over some road sections characterised by certain long-wave undulations as typified by pavement settlements in bridge approach areas. Because the driver is located near the extremity of the vehicle, and far from its centre of gravity, large vertical and horizontal vibrations can be imposed on the driver, complicating the task of maintaining control.

TRB (1987, pp. 96–7) reviewed research available at the time on the safety effects of resurfacing, and reported the following tentative conclusions:

- Routine resurfacing of rural roads generally increases dry-weather crash rates by an initial amount of about 10 per cent, probably because of increased speeds. Dry-weather skid resistance and stopping are unaffected by resurfacing unless the original pavement is so rough that tyres do not maintain contact with the paved surface.
- Routine resurfacing of rural roads generally reduces wet-weather crash rates by an initial amount of about 15 per cent. Apparently, this follows from improvements in wet-weather stopping distances and vehicle controllability that more than compensate for any effects of somewhat higher speeds following resurfacing.
- For most rural roads, the net effect of resurfacing on crash rates is small and gradually diminishes with time. Initially, the total crash rate typically increases following resurfacing, by an amount likely to be less than 5 per cent. When averaged over project life, the effect of resurfacing is much less.
- Resurfacing improves the safety performance of roads that experience an abnormally high frequency of crashes in wet weather.

Roe, Webster and West (1991) measured the macrotexture of about 2000 kilometres of roads in three different areas of England over a three-year period, and compared the measurements with data on over 4000 crashes that occurred on the same roads. The measurements were made using the laser-based High Speed Texture Meter (HSTM). These measurements were used to calculate the sensor-measured texture depth (SMTD)—the average texture depth for each 10-metre length of road. Skid resistance measurements were also made to eliminate the effect of microtexture on the results. The results of the study showed that the numbers of both skidding and non-skidding crashes, in both wet and dry conditions, were lower at higher macrotextures than at low values.

The study also found that the risk of crashes begins to rise for roads with an average SMTD below about 0.70 millimetres, indicating that higher texture depths would reduce the number of crashes. This finding suggested that higher texture depth was in some way providing drivers with additional control and manoeuvrability in all driving conditions. Roe, Webster and West (1991) attribute this effect to tyre rubber hysteresis, which is a secondary means of reducing a vehicle's kinetic energy during braking (the primary means is the conversion of the kinetic energy into heat in the braking system while the wheels are rotating).

The contribution of tyre hysteresis to skid resistance occurs under both wet and dry conditions. When the macrotexture is coarse, hysteresis will result in the dissipation of energy before skidding can occur, thereby enabling drivers to reduce speed and avoid crashes.

Craus, Livneh and Ishai (1991) investigated the effect of pavement surface condition on crashes as part of a survey of the feasibility of investing in the maintenance of the inter-urban road network in Israel. The analysis for the whole network attempted to correlate the state of the pavement surface with conditions of safety. The study found that pavement condition did not influence the crash rate in the case of the whole network. However, a similar analysis which concentrated on specific road sections indicated that an improvement in the pavement surface might improve or worsen traffic safety, depending on the geometric or traffic characteristics of the section under investigation.

The Land Transport Safety Authority in New Zealand has developed a crash investigation monitoring system that contains data on sites at which engineering works have been implemented. The results of resealing 50 routes and 26 bends in both urban (less than 70 kilometres per hour) and open road (greater than 70 kilometres per hour) speed-limited areas have been recently analysed (Land Transport Safety Authority 1996). No distinction was made in the analysis for the type of surfacing used, which included chip seal, friction course and slurry seal.

It was found that there was an overall crash reduction of 39 per cent. Crashes in wet conditions reduced by 49 per cent, whereas crashes on dry pavement reduced by 30 per cent. Loss-of-control crashes reduced by 32 per cent on open road straight sections, but increased by 9 per cent on straight sections in urban areas. Loss-of-control crashes on bends in urban areas reduced by 10 per cent, and on open roads by 42 per cent. Head-on crashes reduced by 58 per cent on straight sections, and by 75 per cent on bends.

The research on the relationship between pavement surface condition and safety reviewed above suggests that the evidence is somewhat mixed. However, on balance, it appears that rehabilitation of the road surface often has a positive effect on safety, especially when investigated on a case-by-case basis as opposed to a network basis. However, rehabilitation can also result in a decline in safety in some instances by inducing an increase in speed.

APPENDIX III PAVEMENT CONSTRUCTION AND CHARACTERISTICS

Pavement construction and maintenance involves a range of materials and methods. Pavements have several desirable characteristics and are subject to various defects and surface texture deficiencies over their lifetimes.

BITUMEN AND ASPHALT

The terms 'asphalt' and 'bitumen' are sometimes used interchangeably, implying that they refer to the same substance. However, asphalt is a mixture of bitumen, sand and aggregate (stones). Natural asphalt is a naturally occurring mixture of bitumen, minerals such as limestone, and organic matter. Naturally occurring asphalt is common in the Middle East.

Natural bitumen is considered to be the oldest petroleum product used by human beings. Bitumen was used by the ancient Egyptians for embalming mummies and in jewellery making. Such bitumen was obtained from natural seepage from the ground. Naturally occurring bitumens now account for less than 0.5 per cent of total bitumen consumption.

Asphalt was used as a water seal in the brick walls of a reservoir in the Indus Valley city of Mohenjodaro (in modern Pakistan) in about 3000 BC. The oldest known road in which bituminous material was used was constructed around 700 BC at an Assyrian temple. However, modern bitumen usage has been confined to a period of about 100 years. Bitumen is used in road construction and maintenance as a binder or glue to hold the surface aggregate together and provides a waterproof seal which protects the lower layers of the pavement. In road construction, the main alternative to bitumen is cement.

Bitumens are produced from crude petroleum oils by fractional distillation. Crude oils used in bitumen production are of the naphthenic or aromatic variety (Australian crude oils are too light and waxy for bitumen production). In Australia, bitumen is obtained as a by-product from the refining of crude oils from the Middle East, which are mainly used to produce fuels including petrol and diesel. Australian annual bitumen consumption is currently around 750 000 tonnes.

Bitumens exhibit visco-elastic rheological properties (*Highways* 1997, p. 17). This means that when temperatures are very low or loading times are very short, bitumens behave like elastic solids. Conversely, at very high temperatures or very long loading times, bitumens behave like viscous fluids. Therefore, the visco-elastic properties of bitumen are a combination of the viscous characteristics of fluids and the elastic characteristics of solids. Under intermediate conditions such as those encountered in normal traffic flow, bitumens exhibit a combination of elastic and viscous properties. When used in asphalt mixes, these properties, to a lesser degree, are transferred to the asphalt.

Viscosity or flow resistance is therefore a critical property of bitumen. The higher the viscosity (measured in pascal seconds (Pa.s)), the stiffer the bitumen. As viscosity depends on temperature, bitumens are classified on the basis of viscosity at 60 degrees Celsius. The degree of adhesion to granular aggregates, fuming during application, and pavement ageing is related to the viscosity of bitumen.

Bitumen classes 50, 170, 320 and 600 are used in Australia, the viscosity increasing with class number. Class 170 (the class most commonly used in Australia) is used for spray sealing on roads with light to medium traffic. Class 320 is used in asphalt mixtures suitable for roads with medium to heavy traffic.

Bitumen is mainly composed of hydrocarbons, an important component being asphaltenes, which are hydrocarbons having high molecular weights. An increase in the proportion of asphaltene in bitumen causes increasing hardness and brittleness. The viscosity and plasticity of bitumen is due to a resinous hydrocarbon oil in which the asphaltenes are in colloidal suspension.

Bitumen is subject to oxidation in the presence of air. Light, and elevated temperatures, hasten the oxidation process. Oxidation results in hydrogen in the bitumen combining with atmospheric oxygen to form water molecules. The removal of hydrogen from the bitumen results in an increasing proportion of carbon, causing the bitumen to become hard and brittle.

Bitumen has certain characteristics which make it highly suitable for road construction. These characteristics include strong adhesiveness, water resistance, flexibility, ductility, resistance to weathering, and non-toxicity. In response to increasingly demanding road and traffic conditions, special modified bitumens continue to be developed for use in 'designed' asphalt mixes. Bitumens are modified by various additives in order to change their natural rheological properties. In particular, viscous strain on the bitumen can be reduced without adversely affecting the flexibility or workability of the asphalt mixture.

Bitumen properties can be enhanced by additives such as adhesion agents to improve the adhesion of bitumen to aggregates, asphaltene to increase viscosity, oxidation inhibitors to reduce hardening, and polymers (plastomeric binders) and rubbers (elastomeric binders) to improve the mechanical properties of bitumen. Rubber and polymer-modified binders (PMBs) are used in spray sealing, as well as in heavy duty asphalt mixtures, to improve the performance of bituminous binders by increasing the cohesion of granular aggregates and reducing reflection cracking.

High proportions of rubber (15 to 25 per cent) may be used in bitumen to produce a flexible membrane to reduce strain and cracking in the lower pavement layers that is reflected in the surface. A strain alleviating membrane (SAM) comprises a PMB covered with a layer of aggregate and may be applied in single or multiple layers. A strain alleviating membrane inter-layer (SAMI) is an interlay of PMB covered with aggregate which is applied before an asphalt overlay. SAMIs absorb strains in lower pavement layers and reduce cracking in the surface layer. They are usually applied in a single layer. SAMs and SAMIs are used for waterproofing pavements and to reduce reflection cracking.

Hot mix asphalt is prepared by heating and drying aggregate and then mixing it with hot bitumen in a pugmill or drum mixer. The temperature during mixing has to be carefully controlled. A temperature that is too high will result in oxidation which would cause excessive hardening of the bitumen. A temperature that is too low will not permit the asphalt to be properly spread and compacted at the site.

Cold mix asphalt is mainly used for filling potholes in roads. It is prepared by mixing bitumen emulsion or fluxed or cutback bitumen (to soften the mixture or lower its viscosity) with aggregate in a pugmill. Cold mix can usually be stored for a limited period before the cutback bitumen or bitumen emulsion hardens.

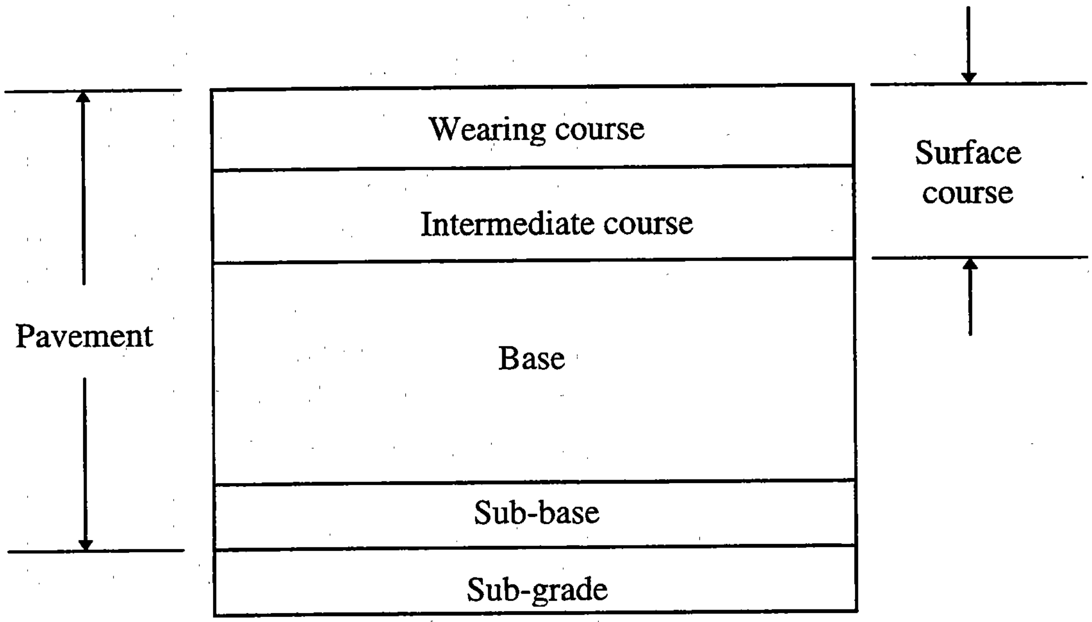
PAVEMENT TYPES AND WEARING SURFACES

There are two main types of pavement: flexible and rigid.

A flexible pavement is designed to deflect under traffic load and is usually built up from layers of gravel and/or crushed rock and covered with a bituminous surface layer. A rigid pavement is constructed with concrete or a material with a high cement content and does not deflect appreciably under traffic flow. The two types of pavement may occur together in the form of a composite pavement, as, for example, in the use of an asphalt base and wearing course over a concrete sub-base.

A flexible pavement usually consists of a surface course (which sometimes consists of an upper wearing course which is in direct contact with traffic and a layer below it called an intermediate course), a base course, sub-base course and sub-grade (figure III.1). The surface course must resist traffic wear and water penetration, and in paved roads consists of one or more layers of bituminous material such as asphalt or sprayed seal.

FIGURE III.1 COMPONENTS OF A FLEXIBLE PAVEMENT



Source AAPA (n.d.).

The base course mainly supports traffic load and is made up of one or more layers of asphalt or granular aggregate such as crushed rock. The sub-base course prevents the sub-grade from penetrating into the base course, provides additional pavement thickness, and may also serve the purpose of providing a stronger layer over a relatively weak sub-grade. The sub-base course is made up of one or more layers of material such as stone, gravel or asphalt.

As vehicle wheel pressure is transmitted through the layers of a pavement, it fans out over a wider area. The load is therefore more widely distributed over lower pavement courses than it is at the surface course. The material used in the sub-base course may therefore be inferior to the material used in the base course. The sub-grade is the foundation of the pavement and generally consists of in situ earth or compacted fill material.

There are three main types of flexible wearing surface used in road construction in Australia: asphalt (or asphaltic concrete), sprayed seal and bituminous slurry surfacing. Increased use is being made of ultra-thin asphalt products. For example, a proprietary product called Novachip being increasingly used in

Australia involves a hybrid application process with features of both sprayed seal and asphalt.

Sprayed seal is the most common type of wearing surface used on the NHS and rural roads in Australia because it performs well and is relatively inexpensive. Asphalt and concrete pavements are mainly used in heavy traffic situations, particularly on urban roads. Asphalt has been used on some sections of the NHS, particularly in South Australia, New South Wales and Queensland. Concrete has been used to construct several sections of the F3 (Sydney to Newcastle Freeway) and sections of the Hume and Federal Highways in southern New South Wales. Bituminous slurry is generally used for maintenance of urban roads.

Characteristics and types of asphalt

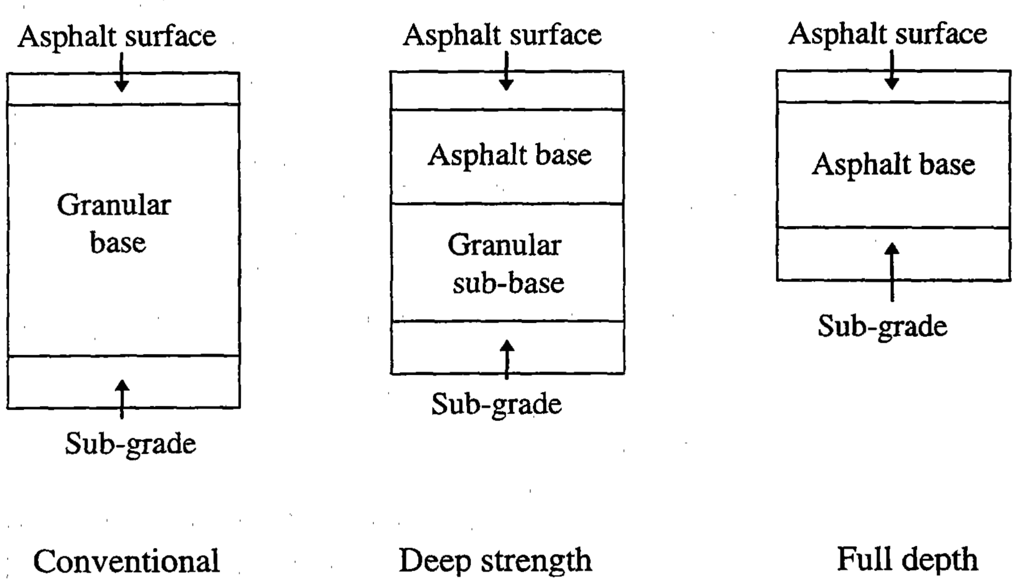
Asphalt (as well as concrete) is suitable for the construction of surfaces subject to heavy traffic, such as urban roads and arterials, highways, freeways, airport tarmacs, quays and dockyards. It is also used in pavement maintenance to repair cracks, ruts and potholes and for shape correction.

Asphalt has a number of characteristics which make it suitable for pavement construction. It strengthens pavements and is ideally suited for use in high traffic areas such as intersections and roundabouts. Because of its ability to correct pavement shape, it can provide a surface with good riding quality. Most types of asphalt provide a relatively skid-resistant surface, and certain types of asphalt such as open-graded asphalt and stone mastic asphalt provide excellent skid resistance. Asphalt also generates a relatively low level of tyre noise and water spray. Asphalt is normally heated during the production process and applied and compacted while hot.

Asphalt mixes are commonly used in flexible pavements (pavements other than concrete) but may also be used as a surfacing on concrete pavements. Asphalt may be used as a surface course on a pavement to provide a smooth, skid-resistant surface and to protect the sub-grade from water penetration. The surface course may, in some cases, be made up of a wearing course which is in direct contact with traffic and an intermediate course just below it.

Asphalt can also be used for all or part of the pavement: as a base course over a granular sub-base in a deep strength asphalt pavement or as a thicker base course over the sub-grade in a full depth asphalt pavement. Deep strength and full depth asphalt pavements are compared with a conventional asphalt pavement in figure III.2.

FIGURE III.2 CONVENTIONAL, DEEP STRENGTH AND FULL DEPTH ASPHALT PAVEMENTS



Source AAPA (n.d.).

Asphalt may be used as a levelling course to eliminate surface irregularities in a pavement before resurfacing is carried out. Resheeting refers to the reconditioning of the pavement surface by applying a new wearing course. Asphalt is also used as an overlay to strengthen an existing pavement and improve roughness.

Granular aggregates consisting of various naturally occurring materials, such as crushed igneous and sedimentary rocks, and gravels and sands, generally comprise over 90 per cent of asphalt mixes. Based on size, aggregates are classified as coarse aggregate, fine aggregate and filler. Coarse aggregate is obtained from crushed rock, river gravel deposits and slag, such as steel furnace slag. Fine aggregate is obtained from sand dunes, river sand or from sieving during the production of coarse aggregates. A small proportion of filler, which would pass through a 75-millimetre sieve, is generally used in asphalt mixes. Filler usually consists of rock or limestone dust, cement, hydrated lime or fly ash.

In an asphalt mix, the 'nominal maximum aggregate size' refers to the sieve size through which 85 to 100 per cent of total aggregate, will pass. For example, if 95 per cent of an aggregate passes through a 20-millimetre sieve, the mix is described as a '20-millimetre nominal mix'.

The grading of a mix is described as 'coarse' or 'fine' according to the percentage of stone in the mix that is larger than a sieve size of 4.75 millimetres. The terms also describe the texture of the pavement surface. A coarse grading produces a relatively rough-textured surface, whereas a fine grading results in a sandy or relatively smooth-textured surface.

The type of mix is usually described by the nominal maximum size of aggregate, the grade of aggregate and the particular layer in the pavement where the mix is placed. For example, a 20 BC (base course) dense-graded base mix refers to a 20-millimetre nominal size dense-graded base course.

Pavement sub-grade materials consist of solids such as aggregates, liquids including water, and gases such as air and water vapour. The air void ratio refers to the ratio of the volume of air and water vapour to the total volume of soil. Compaction refers to the process by which the soil particles become more closely packed together, thereby reducing the air void ratio. Compaction is usually carried out mechanically using rollers or vibratory compacters, and the action of traffic augments this process.

A material that is loosely compacted will tend to deform under pressure as the particles become more closely packed, and air and water are expelled. By contrast, a well-compacted material will sustain overall deformation only if deformation of the constituent particles occurs. Thus, well-compacted materials will have greater strength, deformation resistance under load, and water impermeability.

Dense-graded asphalt

The most common type of asphalt used in road construction and maintenance is dense-graded asphalt (also referred to as asphaltic concrete). It is a dense, continuously graded mixture of both coarse and fine granular aggregates (the particles fairly equally proportioned from coarse to fine grades), mineral filler and bituminous binder. The bitumen content of dense-graded asphalt is about 5 per cent by weight. The mixture is prepared, spread and compacted while hot. After compaction, it has a closed surface texture and low air void content (about 5 per cent by volume). The low air void content increases the resistance of the surface to water penetration and extends the life of the bitumen by preventing oxidation.

Dense-graded mixes enable small and intermediate-sized particles to fit into the interstices created by the contact between larger particles. This arrangement produces close interlocking of the particles and increased density of the mix.

The dense-graded asphalt mix can be varied to suit a variety of uses such as low-traffic streets, busy freeways and airports. Emulsified binders have been developed enabling asphalt mixes to be prepared and laid cold.

Open-graded asphalt

Open-graded asphalt is also called open-graded friction course asphalt or porous asphalt. Unlike dense-graded asphalt, open-graded asphalt has a relatively uniform-sized grading with a small quantity of fine aggregate. In contrast to dense-graded asphalt, it also has a relatively high proportion of air voids (about 25 per cent by volume). The stability of the mixture is mainly due to the mechanical interlocking of the aggregates. The bitumen content of open-graded asphalt is about 5.5 to 6.5 per cent by weight. Open-graded asphalt provides a surface with open texture having good drainage (better than dense-graded asphalt) and skid resistance and low tyre noise (better than sprayed seal).

The degree of aquaplaning, spray and noise generated by a dense-graded asphalt pavement can be reduced by means of an overlay of open-graded asphalt.

Gap-graded asphalt has more sand and filler (and sometimes more binder) and less aggregate than dense-graded asphalt. Consequently, compaction is easier and the proportion of air voids is low. Gap-graded mixtures are suitable for lightly-trafficked areas such as urban streets.

Stone mastic asphalt

Stone mastic asphalt (SMA) is a gap-graded mixture containing a high proportion of coarse aggregates. The interlocking of the aggregates provides structural strength and rigidity which resists rutting and shoving. SMA also provides good skid resistance. The mastic in SMA is obtained by using a high proportion of binder and filler. A small proportion of fibre is added to the mixture which prevents drying of the binder during application. SMA is applied in a relatively thin layer and is very durable due to its high filler and binder content. SMA is less open-textured than open-graded asphalt and has lower noise levels than dense- graded asphalt.

Other types of asphalt

Ultra-thin asphalt is an open-graded asphalt mix which is laid in a very thin layer on a thick layer of polymer-modified bitumen emulsion binder. It is similar to a sprayed seal and provides minor shape correction.

Sand asphalt (a mixture of bitumen and graded sand) and sheet asphalt (a mixture of bitumen and mineral material) are types of asphalt less commonly used for applications involving light traffic.

BOX III.1 DESIRABLE CHARACTERISTICS OF AN ASPHALT PAVEMENT

In designing an asphalt surface, the requirements of the road user, the road maintenance authority and the road paving crew need to be taken into account.

The road surface should satisfy the following requirements of the road user:

- The pavement must provide good, smooth riding conditions.
- The pavement surface should allow water to drain away so that splashing and aquaplaning do not occur.
- Skidding should not occur in any type of weather.
- The surface should minimise noise and have adequate light reflection.

The road maintenance agency requires an asphalt surface with minimal maintenance requirements.

The paving crew requires an asphalt mix which can be adequately applied and compacted at the specified working temperatures.

While all these properties of an asphalt road surface are desirable, economic constraints require an optimising approach in designing an asphalt mix. Achieving a suitable mix requires determining the grade of bitumen to be used and the proportions in which the aggregates, bitumen and other components are mixed.

Several pavement properties need to be considered in prescribing an appropriate asphalt mix. These properties are: stability, flexibility, durability, permeability, fatigue resistance and skid resistance.

Stability

Pavements have to withstand the traffic loadings to which they will be subjected. Stability implies that pavements must resist deformation. A lack of stability would result in rutting and disintegration of the pavement. Stability is related to the effect of climatic heat on the bitumen and the internal friction between the particles of aggregate (which depends on the surface texture of the aggregate and the degree of compaction).

Flexibility

Flexibility is the ability of a mixture to adapt to changes in the shape of a pavement over time. Changes in shape are caused by stresses resulting from the movement of the pavement's sub-grade due to changes in moisture levels. Pavement flexibility can be increased by increasing the amount of binder (bitumen) and the type of binder used (such as PMBs).

Durability

Durability of an asphalt mix refers to the degree of resistance to chemical changes brought about by ageing and traffic wear. Such chemical changes include the effects of water, oxidation and polymerisation. Durability in asphalt is improved by using a high binder content for effective surface sealing and good compaction, which reduces the surface area exposed to the elements.

Permeability

Permeability refers to the extent to which water, water vapour and air can penetrate the pavement. Road pavements require a low degree of permeability to prevent water from seeping into the lower pavement layers and to prevent oxidation of the bitumen binder. A pavement with low permeability will also prevent hardening of the binder due to the escape of volatile components. High binder content, dense-graded aggregate and good compaction all help in reducing permeability.

Fatigue resistance

Pavements which have high traffic intensities may show fatigue cracking of the asphalt pavement. These cracks are caused by elastic deflections of the pavement generated by the axle loadings of vehicles. Greater fatigue resistance could be achieved with high binder content, good compaction and by the use of PMBs and multigrade binders.

Skid resistance

Skid resistance involves the provision of sufficient frictional resistance between the road surface and vehicles to enable vehicles to come to a controlled stop within reasonable distances under various environmental and weather conditions. Skid resistance is especially important under wet conditions.

Apart from the physical condition of the road surface, skid resistance depends on substances on the pavement surface such as water, oil films, and a slippery combination of oil, rubber and grime.

Skid resistance is improved by using granular aggregates with a rough surface texture and relatively low binder content. The aggregate must also not be susceptible to polishing or smoothening by traffic. Minerals having dissimilar rates of wear are most suitable for use in asphalt mixes in order to provide high skid resistance. Open-graded mixes tend to be superior to dense-graded mixes in improving skid resistance. Mixes with a high proportion of sand, such as sand asphalt commonly used in tennis courts, would lower skid resistance.

It is evident that preparing a suitable asphalt mix involves a trade-off between the desirable characteristics of a pavement. A high bitumen content favours durability, flexibility, permeability and fatigue resistance, but can lower stability and skid resistance. Stability, durability and permeability are enhanced by dense gradings, whereas flexibility, texture and skid resistance are improved by open gradings.

Designing an asphalt mix therefore involves optimising the various performance characteristics of a pavement. In particular instances, some performance characteristics may be of overriding importance. For example, a site which has been prone to skidding will require a rougher surface treatment which, among other effects, will also increase the fuel consumption of vehicles using the site.

Skid resistance is discussed in greater detail in appendix II.

Sprayed seal

Rural roads are commonly constructed using various naturally occurring granular aggregates or crushed materials. These aggregates are compacted in layers in the process of pavement construction. Sprayed seals are bituminous surfaces applied to the compacted aggregates to protect the surface from the action of traffic loading and weather.

Sprayed sealing is generally used in rural areas and can be used in initial road construction as well as for re-treatment of existing surfaces. Sprayed seal work has a number of advantages including relatively low cost, good skid resistance, waterproofing, and ability to seal cracks in the surface. However, it also has several disadvantages. Sprayed sealing will not strengthen a pavement nor correct its shape. Its lack of resistance to heavy wear makes it unsuitable for use at signalised intersections, roundabouts and areas used intensively by heavy vehicles. Sprayed sealing is also ineffective if used to cover a surface with a lack of uniformity, such as a rutted road.

Sprayed seal work consists of various types of surface treatment including priming, primer sealing, surface enrichment, dust laying and sealing (or applying a seal coat).

Priming involves the application of a primer of appropriate viscosity to a new or rehabilitated pavement as a preliminary treatment. Priming helps to hold the surface aggregate together by coating the particles with a strongly adhesive priming substance, and provides an interface for bonding the pavement to a seal coat which can subsequently be applied. The application of a tack coat is a type of priming involving the application of a bituminous primer to a surface which has been primed earlier, or to an unprimed bituminous surface to enable another layer to be bonded to it. Priming is not durable and will deteriorate rapidly under traffic, unless covered by a seal.

Primer sealing is a more durable treatment than priming and involves applying a primer binder of suitable viscosity to a new or rehabilitated pavement, followed by a layer of aggregate. Primer sealing provides a surface that will last for a longer time under traffic than a surface treated with primer. A durable bituminous surfacing is generally applied within about one year after primer sealing.

Surface enrichment involves the application of a light coating of bituminous material to a bituminous road surface. Surface enrichment increases the amount of binder on the surface and helps to improve surface quality and reduce the loss of aggregate. As the binder hardens over time due to oxidation, surface enrichment with a fresh application of binder is an inexpensive means of extending the life of a sprayed seal surface.

Dust laying refers to the application of a thin, slow-curing oil or bitumen emulsion to a dusty road surface. The oil or bitumen adheres to the dust particles, increasing their mass and thereby reducing the dust generated by traffic.

A seal or seal coat involves the application of a thin layer of bituminous binder subsequently covered by a layer of aggregate. If priming is carried out before sealing, the process is called a 'prime and seal'. A seal provides a waterproof surface which resists traffic wear and skidding and provides suitable riding quality. Sealing may involve single or multiple applications. Resealing involves the application of a seal coat to a bituminous surface as a maintenance measure.

Bituminous slurry surfacing

Bituminous slurry surfacing involves the application of bitumen emulsion combined with mineral aggregate, filler and additives. Mixing is carried out cold in a truck-mounted mixer and applied in a thin layer from equipment towed by the truck.

Bituminous slurry surfacing is commonly used for maintenance work in rural areas. It is an alternative to sprayed sealing and asphalt for certain purposes.

Bituminous slurry surfacing is relatively inexpensive, provides satisfactory skid resistance and can be used for limited shape correction such as filling ruts. It is a suitable treatment for areas which are subject to medium traffic levels. Among its limitations are its inability to strengthen a pavement, its lack of a high degree of resistance to water penetration, its limited shape correction ability, and its unsuitability for use over a cracked pavement.

There are two types of bituminous slurry surfacing: slurry sealing and microsurfacing. Slurry sealing involves the use of small aggregates and is generally applied in a layer less than 1 centimetre thick. Microsurfacing involves the use of larger aggregates with a polymer-modified bitumen emulsion as binder. It is generally used to fill ruts and potholes.

Novachip

Novachip is a proprietary product developed in France in 1988 and introduced in Australia in 1993. It is produced and distributed in Australia by Boral Asphalt. Similar products are produced by other companies and marketed as ultra-thin asphalt.

Novachip comprises a layer of specially designed open-graded hot mix asphalt applied over a heavy application of polymer-modified bitumen emulsion. It is applied by a purpose-built machine that spreads both the emulsion and asphalt in a single pass.

The Novachip concept is based on a combination of two established processes: spray sealing and the application of thin asphalt layers. However, Novachip differs from these two processes in several ways. In Novachip, the aggregates are bonded together by a bitumen mastic so that they can be laid in one or several layers, which eliminates the possibility of dislodgment of loose aggregates that cause vehicle and windscreen damage. The hot asphalt is smoothed by the action of a screed and can be applied in more than a single layer. Hence, unlike conventional sprayed seal, Novachip can be reshaped. The asphalt is smoothed while it is hot, thereby avoiding a jagged surface. This gives Novachip a noise level of 2 to 3 dB(A)[1] lower than a sprayed seal.

Novachip application is less sensitive to ambient temperature than spray sealing. This is because the emulsion is applied and covered with hot asphalt within a few seconds and the asphalt layer is immediately smoothed off. The quick application involves minimal disruption to traffic.

Novachip is intended for preventative maintenance or surface rehabilitation of pavements that are structurally sound, but is not suitable for high traffic areas such as roundabouts. Novachip has a lifetime of 7 to 12 years, depending on traffic. Prior to the application of Novachip, it is necessary to ensure that serious irregularities in the pavement are corrected and cracks sealed. Novachip is suitable for overlaying sprayed seal, asphalt and concrete pavements. Novachip restores skid resistance and surface impermeability and reduces noise.

Novachip also produces a limited improvement in roughness. Wonson (1996, p. 9) notes that tests on several Australian roads indicate that Novachip produces a reduction in roughness of around 50 per cent. However, the BTCE's discussions with several road engineers indicate that a reduction in roughness of around 30 per cent is a more realistic estimate.

Concrete

Concrete is a mixture of cement, aggregate and water. There are several types of concrete pavement.

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1. Noise intensity is measured in decibels (dB). A decibel is one-tenth of a bel—a unit named for Alexander Graham Bell, the inventor of the telephone. Sound is measured using a decibel meter, which has a scale calibrated in logarithmic units to avoid using the large numbers associated with measuring relative sound intensity. Sounds quieter than 10 dB are difficult for the human ear to detect (0 dB is the threshold of audibility), whereas sounds 120 dB or greater are usually painful. Normal conversation (at about 1 metre) has a sound intensity of about 60 dB. The relative intensity of a sound with intensity I is given by

$$10\log_{10}\frac{I}{I_0}$$

where I_0 is the reference intensity. The response of the human ear to noise is not uniform, as it depends on the frequency of the noise. The 'A' weighted decibel scale is used to take account of this effect and correlates satisfactorily with subjective human judgements of the loudness of noise. Decibel meters with special filters are used to measure sound in dB(A). The 'A' weighted decibel scale is generally used in measuring traffic noise. The RTA adopts a limit of 63 dB(A) as the environmentally acceptable level of noise.

Jointed plain (unreinforced) concrete pavements or short slab pavements involve the use of narrow contraction joints at about 5-metre intervals. In jointed reinforced concrete pavements, a reinforcing material such as mesh is used with dowelled joints incorporated at regular intervals. Steel fibre reinforced concrete involves the distribution within the concrete of a small quantity of randomly oriented, short steel fibres. The fibres provide increased strength and fatigue resistance and allow the pavement thickness to be reduced.

Continuously reinforced concrete pavements (CRCPs) have steel longitudinal reinforcement along the entire length of the pavement, obviating the need for transverse joints. As the pavement shrinks, an increasing number of fine cracks develop on the surface. Widening of these cracks is prevented by the steel reinforcement and sub-base friction. CRCPs have higher initial costs, but may be preferred to other types of concrete pavement, especially when it is expected that there will be relatively large differential movement of the sub-grade over time.

CRCPs were introduced in Australia in the 1970s. In 1992, a CRCP on the Pacific Highway, built in 1975, was still maintenance-free except for work on its sealed gravel shoulders (Bennett & Moffatt 1995, p. 7). However, the same authors report that, of 14 Australian CRCPs that had been studied, five had various types of distress or failure. They conclude that construction quality is of paramount importance and that a well-constructed CRCP will remain close to being maintenance-free for the first 20 to 25 years of its life.

There are two types of concrete pavement surface in use: exposed aggregate finish and modified hessian/tined finish.

The exposed aggregate finish involves the use of a relatively small size of stone. After application of the concrete, it is coated with a substance which retards the setting process. The next day, the surface is brushed with a large mechanical rotary broom to partly expose the stones by removing a thin layer of mortar. This type of surface finish is in an experimental phase in Australia.

The modified hessian/tined finish is obtained by using standard paving concrete. A strip of hessian is dragged longitudinally along the surface to decrease the roughness of the surface. To produce a surface suitable for high-speed traffic, a shallow flexible comb is drawn transversely across the surface before the concrete sets. Combing produces grooves which provide a means for water to drain away to prevent aquaplaning. Combing is not generally carried out for roads which have speed limits of up to 80 kilometres per hour.

The characteristics of bituminous and concrete pavements are discussed in appendix VI.

DEFECTS IN FLEXIBLE PAVEMENTS

Cracking

Cracks are fissures caused by the fracturing of the road surface. When exposed to air and light over time, bitumen oxidises causing hardening, which eventually results in cracking. Other factors that cause cracking include poor quality construction, deformation of the pavement, and transference to the surface of cracking that occurs in the underlying layers of the pavement. The following are some of the effects of cracks on a pavement:

- The surface loses its ability to spread the loads resulting from traffic.
- The surface layer is unable to provide a waterproof seal.
- There is reduced comfort during travel due to surface erosion and damage.
- Penetration of water into lower pavement layers accelerates pavement deterioration.
- The pavement develops an unsightly visual appearance.

There are various types of cracks, generally described by their shape or form, such as block cracks, crescent-shaped cracks, crocodile cracks (resembling the skin of a crocodile), diagonal cracks, longitudinal cracks, meandering cracks and transverse cracks.

Surface texture deficiencies

Surface texture deficiencies involve loss of surface materials. Surface texture deficiencies do not generally reflect structural deficiencies of the pavement, but determine the pavement's serviceability in regard to quality of travel and skid resistance. If surface deficiencies are not rectified, they could eventually undermine the structural integrity of the pavement. There are several types of surface deficiencies including flushing, polishing, ravelling, stripping and delamination.

Flushing involves the coating of stone aggregates in bitumen, which reduces friction between tyres and stone and causes skidding. Flushing is usually, though not always, associated with sprayed seals, and is evidenced by a smooth black surface with very little texture. In hot weather, flushing may cause bitumen to adhere to tyres. Flushing is generally caused by excessive use of binder and can be remedied by removing and replacing the affected area or by applying an asphalt overlay.

Ravelling (or fretting), which is generally associated with asphalt surfaces, describes a condition where binder has hardened and stone has eroded over time. Ravelling may be caused by deterioration of the binder and stone, insufficient compaction, or poor asphalt mix design, among other factors. Ravelling may be corrected by resurfacing.

Stripping, which is usually associated with sprayed seal surfaces, refers to a condition involving the loss of stone, but not binder. Consequently, the bitumen may adhere to the tyres in hot weather. Stripping may be caused by a number of factors including low binder content, deterioration of stone, poor adhesion of binder to stone, or improper mixing of binder with stone. Stripping may be corrected by appropriate resurfacing.

Delamination is a condition involving loss of areas of uniform thickness from the wearing course layer. The wearing course layer appears detached from the layer below. Delamination can occur with asphalt surfacing and spray sealing, and is caused by inadequate cleaning before application of the upper layers. Delamination may be corrected by removal of affected areas followed by patching and overlay.

DEFECTS IN CONCRETE PAVEMENTS

As concrete pavements age, the sealing compound used in joints tends to become brittle, allowing water and soil to penetrate into the joint. The problem may be rectified by removing the brittle material, cleaning the joint and resealing.

Edge spalling occurs when pieces of concrete break away from the pavement due to stress caused by axle loads at the edge of the pavement or by cracking due to lower-than-specified concrete strength. Surface spalling occurs when small pieces of concrete break away from the surface.

Cracking in concrete does not necessarily constitute pavement failure. It is uncontrolled cracking that would result in pavement distress. Cracking of concrete allows entry of water which will hasten pavement deterioration. Cracks may be repaired by sealing or by a process known as cross-stitching. Cross-stitching involves drilling angled holes on either side of a deep crack, commencing from the pavement surface and passing through the crack. Steel bars are then inserted into the holes and sealed. Alternatively, it may be necessary to remove and replace the affected sections. A defective concrete surface may also be rehabilitated by applying an asphalt or concrete overlay. However, if the concrete has deteriorated substantially, cracks will also appear in the asphalt overlay over time.

Concrete pavements are susceptible to pumping if the sub-base is made of easily erodable material or if overall construction is of poor quality. The process may be exacerbated if the pavement is subjected to excessive exposure to water. Due to the repeated passage of heavy vehicles, the concrete slabs tend to deflect downwards. After the passage of the vehicles, the slabs return to their original position. Such repetitive action over long periods weakens the joints and allows water to penetrate between the slabs and the sub-grade. Over time, the water dissolves soil in the sub-grade and forces the mixture to the surface. As the support provided by the sub-grade weakens, the slab would tend to crack. The effects of pumping may be rectified by a process known as slabjacking, which involves pumping cement through small holes drilled in the affected areas of the pavement. The cement fills the gaps in the sub-grade, providing the uniformity of support lost due to pumping.

Concrete slabs can also settle for a variety of reasons, including faulty drainage and subsidence of land fill comprising the pavement base. It may be possible to rectify settlement defects by slabjacking. In some cases, replacement of the affected slabs may be necessary.

APPENDIX IV THE BTCE's RIAM AND HDM-C MODELS

The two models used to generate the results presented in this paper are the BTCE's Road Infrastructure Assessment Model (RIAM) and the HDM-C model, a version of the World Bank's HDM-III model that has been modified by the BTCE to account for congestion effects. RIAM determines the roughness profile of sections of road over their lifetime. HDM-C estimates the effects of changes in roughness on VOCs, including fuel consumption. Both models were developed by the BTCE for previous work on road infrastructure, but the versions of the models used in this paper differ somewhat from the versions developed for previous BTCE work.

RIAM

RIAM estimates the deterioration in roughness over time for flexible pavements. For the purpose of this paper, flexible pavements include pavements constructed or rehabilitated using asphalt, sprayed seal and Novachip. Concrete pavements are classified as rigid, and therefore RIAM cannot be used to estimate the deterioration in their roughness.

RIAM is quite data-intensive, requiring information on road characteristics and traffic. Each input file in RIAM contains:

- current daily traffic volume (measured in AADT);
- annual traffic growth rate;
- proportions of rigid and articulated trucks and passenger vehicles;
- road section length (variable);
- terrain type (1=flat, 2=hilly, 3=mountainous);
- road standard (derived from the number and width of lanes); and
- most recent value of road roughness (in NRM) and year of measurement.

Paterson's algorithm (Paterson 1987, p. 304), which has been incorporated into RIAM, estimates roughness for each year of the analysis. Roughness is measured in International Roughness Index (IRI) units and converted to the Australian standard of NAASRA Roughness Meter (NRM) units. Paterson's algorithm for roughness is:

$$R(t) = \left[R_0 + k(1+SNC)^{-4.99}\gamma(t)\right]e^{mt}$$

where:

t	=	time in years since the last rehabilitation
$R(t)$	=	roughness at time t in IRI units
R_0	=	roughness at time zero (initial roughness)
k	=	a constant reflecting the effect of traffic on the pavement
SNC	=	modified structural number (a measure of pavement strength)
$\gamma(t)$	=	millions of cumulative equivalent standard axle loads (ESALs)[1] per lane from time zero to time t
m	=	a constant reflecting the effect of time and weathering on the pavement

In Paterson's algorithm, pavement strength is measured using the modified structural number (SNC) of the pavement. The SNC derives from the concept of the structural number (SN), which originated in the United States (AASHTO 1986). The SN concept is a means of describing the structural strength or load-bearing ability of a pavement in cumulative ESALs in terms of a single number, without regard to the type of construction of the pavement. The concept was intended to take account of the fact that different types of pavement, constructed using different materials and methods and having different thicknesses, could have the same SN. During the development of the suite of HDM models, the World Bank devised a method of estimating the contribution of the sub-grade of the pavement to the strength of the pavement, expressed in SN units. The resulting value for pavement strength, which includes sub-grade strength, is referred to as the SNC.

Data on the SNCs of pavements are not readily available. RIAM therefore assumes that the pavement has been built to NAASRA design standards. Pavements with higher 'design traffic' will be constructed with higher SNCs. The design traffic is the number of ESALs per lane forecast for the next 20 years. RIAM obtains SNCs from a regression equation derived in BTCE (1990, p. 28) relating structural number to design traffic:

$$SNC = 0.40 * \log_{10} DT + 3.00$$

where DT is design traffic in millions of ESALs.

Post-rehabilitation roughness (R_0) is highly variable and is usually unknown for specific road sections. For the purpose of this analysis, an average post-rehabilitation roughness has been assumed for each type of rehabilitation (see table 2.2 in chapter 2).

1. RIAM assumes that each commercial vehicle contributes 2.5 ESALs and that cars do not contribute any ESALs.

Terminal roughness is the maximum allowable roughness of the road before resurfacing is assumed to be undertaken (a basecase of 110 NRM is assumed in this analysis). RIAM uses the roughness of sections of the NHS in 1996 (drawn from the BTCE highways database) and corresponding AADT values to estimate when the last rehabilitation was carried out and to predict future annual roughness values. For each year, RIAM checks if the roughness of the pavement section is above terminal roughness. If it is found to be so, RIAM assumes that the section will be rehabilitated, changes the roughness value to the initial value and records the cost of the rehabilitation. In years when no rehabilitation is required for a particular section, RIAM sets rehabilitation costs to zero and moves on to successively evaluate the following years.

Rehabilitation is initiated when terminal roughness levels are attained. The costs per square metre of different types of rehabilitation used in the analysis are in table 2.4. Costs will vary from section to section of a particular road depending on terrain and distance from sources of raw materials, and these cost estimates therefore represent a national average. RIAM does not take account of ongoing minor maintenance costs.

HDM-C

HDM-C was used to estimate VOCs for all years between 1996 and 2015 using the roughness estimates obtained from RIAM.

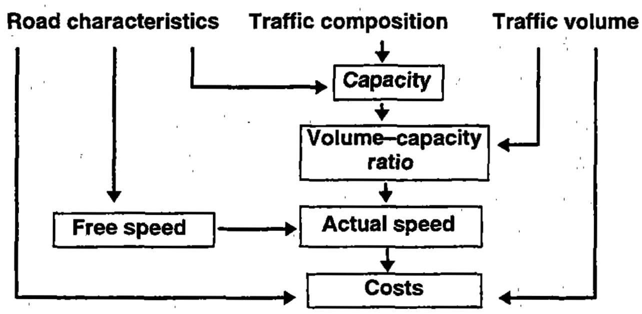
HDM-C needs detailed information on each section of road including:

- roughness measured in NRM
- terrain type (as for RIAM)
- daily traffic volume (measured in AADT)
- whether the section is divided or undivided
- width of the pavement[2] (in metres)
- number of lanes
- length of the link (in kilometres)
- proportion of rigid and articulated trucks
- width of lanes (in metres)
- width of shoulders (in metres)

HDM-C is made up of five modules which estimate free speed, capacity, volume–capacity ratio, actual speed, and costs. Figure IV.1 shows the linkages between the different modules.

2. Pavement width is defined as that part of the road used for regular travel, and does not include the shoulders.

FIGURE IV.1 FLOW CHART OF THE HDM-C MODEL



Source BTCE.

In this analysis, free speed (speed achieved on an uncongested road) was set equal to the speed limit. Other versions of HDM-C have specific calculations for estimating free speed based on road terrain and roughness. Given that the NHS is of a high standard and the analysis only considers a relatively small range of roughness, fixing free speed is considered a reasonable assumption.

Road capacity is equal to the product of a series of factors. These factors incorporate the effects of the number of lanes, the number of carriageways, the width of lanes and shoulders, and non-regular traffic. Capacity is measured in PCUs (passenger car units) rather than AADT to allow for the effects of heavy vehicles. The number of PCUs allocated to each heavy vehicle depends on the terrain of the road (table IV.1).

TABLE IV.1 CONVERSION OF TRUCKS TO PCUs

	Truck type	
Terrain type	*Rigid*	*Articulated*
1 (flat)	1.7	3
2 (hilly)	4	9
3 (mountainous)	7	15

Source BTCE (1994, p. 61).

Because traffic is not constant throughout the day, HDM-C determines actual traffic volume on an hourly basis. The BTCE has developed histograms to show the variation in the volume of traffic for each hour over the year (table IV.2). Each histogram contains a series of blocks with the height of the block equal to the percentage of daily traffic in any hour of the year and the width representing the number of hours in the year.

For example, in the rural section of table IV.2, 2 per cent of daily traffic occurs for 1482 hours of any year. Rural roads generally have very few peak hours (about 30 hours annually), but they have high peaks (of around 20 per cent of daily traffic). The remaining hours of the year have a very low proportion of daily traffic. Urban roads have a flatter profile. The morning and afternoon peaks on these roads lead to a large proportion of hours in the year having around 6 per cent of the daily traffic. Due to the rural nature of most of the NHS system, a typically rural profile is appropriate for most roads. This choice may lead to some inaccuracy close to the towns along the NHS.

TABLE IV.2 ANNUAL HOURLY TRAFFIC DISTRIBUTION HISTOGRAMS

Percentage of AADT	*Rural histogram hours in year*	*Quasi-urban histogram hours in year*
22	3	-
20	3	-
18	10	-
16	17	3
15	18	3
14	30	7
13	45	13
12	71	26
11	107	48
10	161	90
9	241	185
8	354	309
7	509	546
6	714	848
5	967	1252
4	1242	1640
3	1467	1736
2	1482	1375
1	1017	600
0	308	85
Total	8766	8766

Source BTCE estimates.

As traffic volume is different in each block of the histogram, speed is calculated individually for each block. Actual speed is linearly related to the volume–capacity ratio as represented by the following equation:

$$speed = \frac{4}{3} freespeed(1 - \frac{volume}{capacity})$$

HDM-C estimates the avoidable vehicle operating costs listed in table IV.3. Avoidable costs are costs that are not incurred if the journey is not undertaken. For a private vehicle, the decision to undertake a particular journey will not affect the capital costs incurred by the vehicle's owner. However, trucks are often part of a fleet, and therefore the time saving experienced by not undertaking particular journeys could lead to a reduction in the fleet size. Thus, for trucks comprising fleets, depreciation and registration costs are potentially avoidable.

TABLE IV.3 AVOIDABLE VOCs

Cars	*Heavy vehicles*
Fuel	Fuel
Oil	Oil
Maintenance parts	Maintenance parts
Maintenance labour	Maintenance labour
Tyres	Tyres
Occupants' time	Crew wages (time)
	Depreciation
	Overheads
	Registration (financial cost only)

Source BTCE.

Pavement roughness is a key variable in determining VOCs in terms of fuel, oil, tyres and maintenance (parts and labour). As roughness increases, these costs also increase. As speed is assumed to be unaffected by roughness over the range of roughness considered in the analysis, all time-related costs (vehicle occupants' travel time and vehicle registration and depreciation) will not vary with roughness.

Most of the parameter estimates used in the analysis are those in ARRB (1996). However, the estimates of vehicle-kilometres travelled have been derived from information in BTCE (1996a). These estimates relate to the total vehicle-kilometres travelled by a vehicle up to the average age of the vehicle class (see table IV.4). For example, the average age of articulated trucks in Australia is 10.5 years, so the vehicle-kilometres travelled by articulated trucks is taken as the sum of the estimated vehicle-kilometres from year zero to year ten. This method of estimation takes account of the effects of skewed travel profiles of vehicles over their lifetimes. Generally, annual vehicle-kilometres travelled are high when vehicles are new and they fall steadily as vehicles age.

TABLE IV.4 VEHICLE-KILOMETRES[a] TRAVELLED BY VEHICLE TYPE

Vehicle type	*('000) Vehicle-km*
Cars	180
Rigid trucks	342
Articulated trucks	1138

a. The estimate of vehicle-kilometres refers to the number of kilometres a vehicle of each type travels up to the middle of its average lifetime.

Source BTCE estimates.

Unit vehicle-related and occupant costs used in the analysis are set out in table IV.5. HDM-C estimates both economic and financial costs. Financial costs are the costs incurred by vehicle owners, operators and occupants, and include taxes. Taxes, however, are transfers from vehicle owners and operators to government and therefore are not a cost to society as a whole. Economic (or social) costs are costs to society and therefore do not include taxes.

TABLE IV.5 UNIT COSTS USED IN THE ANALYSIS

	Cars		*Rigid trucks*		*Articulated vehicles*	
Item	*Financial*	*Economic*	*Financial*	*Economic*	*Financial*	*Economic*
Fuel ($/L)	0.74	0.34	0.70	0.30	0.67	0.27
Oil ($/L)	3.78	3.10	3.54	2.90	3.29	2.70
Value of vehicle ($)	26 239	23 001	127 566	111 822	213 016	186 725
Maintenance labour ($/hour)	50	50	50	50	50	50
Tyre ($/tyre)	115.53	94.70	566.32	464.20	601.95	493.40
Time ($/hour/person)[a]	10.2	10.2	na	na	na	na
Crew ($/hour)	na	na	15.86	15.86	15.86	15.86
Overhead (%)	na	na	10%	10%	10%	10%
Registration ($/year)	na	na	1 702	na	5 098	na

na not applicable

a. It is assumed that there are, on average, 1.6 persons, including the driver, in each car.

Sources BTCE estimates based on ARRB (1996), ATO (pers. comm., August 1996), NRMA (pers. comm., August 1996), RTA (pers. comm., March 1996), ABS 1991.

HDM-C provides a wide range of results. In this analysis, only total VOCs (both financial and economic) and costs of individual components such as fuel, oil and tyres have been estimated. Fuel consumption calculations form the basis of estimates of greenhouse gas emissions.

APPENDIX V PAVEMENT REHABILITATION COSTS

This appendix sets out pavement rehabilitation costs for different treatments obtained from Australian State and Territory road authorities. Some estimates of changes in roughness due to the treatments, which have also been provided by State and Territory road authorities, are included in this appendix. Sprayed seal (also known as chip seal) is the predominant type of pavement surfacing used on the NHS and the Pacific Highway.

ACT

Novachip treatment costs between $12 to $15 per square metre and reduces roughness by about 30 per cent.

NSW

In tables V.1 to V.6, 'AC' refers to dense-graded asphaltic concrete (asphalt) and 'OG' to open-graded asphalt. The numerical values following these abbreviations refer to the maximum size of the aggregates (in millimetres) contained in the mix.

TABLE V.1 DEEP LIFT ASPHALT WITH HIGH BITUMEN LAYER OVER HEAVILY BOUND SUB-BASE

Treatment	*Year*	*Cost ($/m^2)*	*Comment*
Mill 40 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	10	19.10	Mill costs $3.10/m^2 40 mm AC14 is $8/m^2 Sprayed seal is $2/m^2 30 mm OG10 is $6.10/m^2
Mill 70 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	30	20.90	Mill 70 mm costs $4.80/m^2 40 mm AC14 is $8/m^2 Sprayed seal is $2/m^2 30 mm OG10 is $6.10/m^2
1% heavy patching	20, 30	0.80	
Mill 70 mm Provide 90 mm AC14 + sprayed seal + 30 mm OG10	20	34.50	Mill 70 mm costs $4.80/m^2 90 mm AC14 is $21.60/m^2 Sprayed seal is $2/m^2 30 mm OG10 is $6.10/m^2

TABLE V.2 DEEP LIFT ASPHALT WITH HIGH BITUMEN LAYER OVER ROLLER COMPACTED CONCRETE

Treatment	Year	Cost ($/m²)	Comment
Mill 40 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	10	19.10	Mill costs $3.10/m² 40 mm AC14 is $8/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²
Mill 70 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	30	20.90	Mill 70 mm costs $4.80/m² 40 mm AC14 is $8/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²
1% heavy patching	20, 30	0.80	

TABLE V.3 DEEP LIFT ASPHALT OVER ROLLER COMPACTED CONCRETE SUB-BASE

Treatment	Year	Cost ($/m²)	Comment
Mill 40 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	10	19.10	Mill costs $3.10/m² 40 mm AC14 is $8/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²
Mill 70 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	30	20.90	Mill 70 mm costs $4.80/m² 40 mm AC14 is $8/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²
1% heavy patching	20, 30	0.80	
Mill 70 mm Provide 90 mm AC14 + sprayed seal + 30 mm OG10	20	34.50	Mill 70 mm costs $4.80/m² 90 mm AC14 is $21.60/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²

TABLE V.4 DEEP LIFT ASPHALT WITH HIGH BITUMEN LAYER OVER MACADAM SUB-BASE

Treatment	Year	Cost ($/m²)	Comment
Mill 40 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	10	19.10	Mill costs $3.10/m² 40 mm AC14 is $8/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²
Mill 70 mm Provide 40 mm AC14 + sprayed seal + 30 mm OG10	30	20.90	Mill 70 mm costs $4.80/m² 40 mm AC14 is $8/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²
1% heavy patching	20, 30	0.80	
Mill 70 mm Provide 90 mm AC14 + sprayed seal + 30 mm OG10	20	34.50	Mill 70 mm costs $4.80/m² 90 mm AC14 is $21.60/m² Sprayed seal is $2/m² 30 mm OG10 is $6.10/m²

TABLE V.5 CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

Treatment	*Year*	*Cost ($/m²)*	*Comment*
0.2% pavement replacement	10, 15, 20, 25, 30, 35	0.22	Pavement replacement @ $260/m²
30% surface re-texture	20	1.20	$4/m²

TABLE V.6 PLAIN CONCRETE PAVEMENT

Treatment	*Year*	*Cost ($/m²)*	*Comment*
Cross stitching of 20 m of cracks per lane-km 10% of cracks will also require routing, cleaning and sealing	2, 6, 12, 20	0.13	Cost of cross stitching is $15/m Cost of routing, cleaning and sealing is $6/m
0.5% slab replacement	2, 5, 10, 15, 20, 25, 28, 30, 33, 35, 38	1.23	Slab replacement @ $245/m² over 0.5% of the total area
Cross stitching of 40 m of cracks per lane-km 10% of cracks will also require routing, cleaning and sealing	28, 36	0.25	Cost of cross stitching is $15/m Cost of routing, cleaning and sealing is $6/m
Remove and replace joint sealant	10, 20, 30	2.03	Cost is $6/m for say 10 m of transverse joint and 4.2 m of longitudinal joint per 42 m² of pavement
30% surface re-texture	20	1.20	$4/m²

SOUTH AUSTRALIA

Novachip

Costs vary from $7 to $11 per square metre and an additional $5 per square metre for a correction layer. This treatment can reduce roughness from 110 NRM to about 80 NRM.

Overall costs of $16 per square metre would reduce roughness from 130 NRM to 70 NRM.

Overall costs of $11 per square metre would reduce roughness from 110 NRM to 70 NRM.

Slurry

This treatment costs between $5 and $7 per square metre. The materials required are carried in a truck and applied from the truck. The treatment corrects ruts more than roughness. Slurry sealing can improve roughness slightly (from 110 NRM to 80–90 NRM).

TASMANIA

Slurry seal (micro-asphalt) to a depth of 25 to 30 millimetres costs $10 per square metre and reduces roughness from 120 NRM to 40 NRM. Material costs $150 per tonne (2.5 tonnes per cubic metre).

VICTORIA

(a) Size 10-millimetre ($1.80 per square metre) and 14-millimetre ($2.50 per square metre) sprayed seals. These do not reduce roughness but substantially reduce the rates at which pavements deteriorate.

(b) Geotextile sprayed seals ($5.50 per square metre). These are used on distressed pavements and do not reduce the roughness but substantially reduce the rate at which pavements deteriorate.

(c) Asphalt regulation (to about 20 millimetres) costs about $5 per square metre followed by options (a) or (b). This treatment can be expected to reduce the roughness by 20 to 30 NRM.

(d) Periodic asphalt maintenance (about 40 millimetres of asphalt) costs about $10 per square metre. This will reduce roughness by 20 to 30 NRM.

(e) Rehabilitation using asphalt overlays (generally 70-plus millimetres of asphalt) costing about $20 per square metre. As this treatment involves two or three layers of asphalt, there is a substantial reduction in roughness (recent work near Seymour reduced the roughness to about 50 NRM).

(f) Rehabilitation by ripping the existing sprayed seal surfacing, strengthening the pavement with crushed rock and resealing. This treatment costs between $34 and $58 per square metre. This treatment can reduce roughness to 50 to 60 NRM.

The above costs include construction and line marking. Inclusion of other costs (such as administration, design and specification) would increase the above costs by about 10 per cent.

WESTERN AUSTRALIA

Asphalt overlay (30 millimetres thick)

Urban area cost: $8 to $10 per square metre.

Rural area cost: $12 to $15 per square metre.

Improvement in roughness: 30 to 50 per cent.

Cold plane then asphalt overlay

This treatment is similar to asphalt overlay but includes the cold planing of 30 millimetres of the existing layer of asphalt to remove the old degraded mix and ensure the final levels after a 30-millimetre overlay remain the same. It is common to also include a SAMI seal to waterproof the pavement and prevent reflection cracks, at an additional cost of $2.50 to $3.00 per square metre above that quoted.

Urban area cost: $10 to $12 per square metre.

Rural area cost: $14 to $18 per square metre.

Improvement in roughness: 30 to 50 per cent.

Cold mix surface correction

Localised correction with cold mix is commonly used in rural situations to reduce roughness before resealing (before applying a sprayed seal coat to the whole road). The cost of localised correction depends on the proportion of the total road requiring correction. If too high a proportion is involved, an alternative strategy is used. The practice is usually limited to major deficiencies in shape.

Rural cost: $14 to $18 per square metre of actual area repaired (excluding reseal costs of $2 to $2.50 per square metre) or $5 per square metre of total road.

Improvement in roughness: 10 to 30 per cent.

Rip/recompact/prime and seal

This practice is seldom used as the structural capacity of the pavement is usually increased at the same time by increasing thickness with a granular or stabilised overlay or by stabilising before recompacting. In this case, pavement roughness is usually an indication of a structural deficiency and reinforcement is required before resurfacing.

Urban and rural area cost: $15 to $20 per square metre (including the addition of a nominal 50-millimetre top-up with base to bring back to original levels).

Improvement in roughness: Returns pavement to as new condition (40 to 60 NRM).

Rip/150-millimetre granular overlay/recompact/prime and seal

Urban area cost: $28 to $35 per square metre.

Rural area cost: $25 to $30 per square metre (overlay materials are cheaper).

Improvement in roughness: Returns pavement to as new condition (40 to 60 NRM).

Rip/cement stabilise/recompact/prime and seal

Urban area cost: $14 to $15 per square metre.

Rural area cost: $15 to $20 per square metre (overlay materials are cheaper).

Improvement in roughness: Returns pavement to as new condition (40 to 60 NRM).

APPENDIX VI BITUMINOUS AND CONCRETE PAVEMENTS

Pavements for heavy-duty use are generally constructed predominantly of concrete or of material having significant bituminous content (such as asphalt or sprayed seal). Both pavement types are described in appendix III. Bituminous pavements are flexible, compared with concrete pavements which are relatively rigid. The BTCE does not claim to have the expertise to make independent assessments of the relative advantages and disadvantages of each type of pavement. However, having recourse to available information, the characteristics of each pavement type and issues relating to their comparative assessment are discussed below.

PAVEMENT SURFACE DETERIORATION

Wallace et al. (1996, p. 27) report roughness levels of 50 NRM for concrete sections on the Western Ring Road in Melbourne compared with 35 to 40 NRM for asphalt sections on the same road. In their analysis of the Logan Motorway to Nerang upgrade of the Pacific Highway in New South Wales, Wallace et al. assumed a roughness of 35 NRM for asphalt and 40 NRM for concrete.

Roughness deterioration data for concrete pavements are sparse. Wallace et al. (1996, p. 28) cite a United States study by Bednar (1989) which indicates that 20- to 30-year-old concrete pavements in the United States have deteriorated by about 1 to 1.5 NRM per year. This rate was roughly half the rate for asphalt pavements in the United States. However, Wallace et al. (1996) predict a deterioration rate of about 0.7 NRM per year for new Australian concrete roads due to improvements in concrete pavement design. Each asphalt overlay at intervals ranging from 10 to 15 years restores surface quality, whereas, in the case of concrete, roughness continues to increase until the pavement is reconstructed or overlaid with asphalt.

The more rapid deterioration in roughness of asphalt pavements means that VOCs, including fuel consumption, would increase over time at a higher rate than for concrete pavements. The periodic resurfacing of asphalt pavements would of course restrict such increases in VOCs, as road maintenance costs are typically a small proportion of aggregate VOCs over time.

NOISE GENERATION

Dash (1995, p. 45), citing Sandberg (1992), observes that, generally, engine and gear box noise drowns out tyre and road noise at speeds below 50 kilometres per hour for cars and 70 kilometres per hour for trucks. Noise from tyres and the road surface predominates at higher speeds. Samuels (1982) collected and analysed data for a wide range of road surface macrotextures and tyre types. He found that roadside noise levels increased with increasing vehicle speed, macrotexture coarseness, engine speed, and (generally) tyre tread coarseness. Samuels (1982, p. 7) notes that the generally postulated form of the relationship between sound pressure level (SPL) and speed, based on truck data, is:

$$SPL = 40 \log V - 8.16$$

where *SPL* is the sound pressure level 15 metres from the vehicle path in dB(A)[1] and *V* is vehicle speed in kilometres per hour. Noise suppression therefore assumes greater importance on high-speed roads such as highways and major arterial roads.

Open-graded asphalt pavements generally generate less noise than dense-graded asphalt and concrete. Two concrete sections of the F3 (Sydney to Newcastle Freeway) had to be treated with a 30-millimetre layer of open-grade 10-millimetre asphalt very soon after being opened to traffic in response to traffic noise complaints (RTA 1994, p. 9). One section was constructed with continuously reinforced concrete (Wahroonga to Kuringai Chase Road) and the other with plain concrete (Kuringai Chase Road to Mt Kuringai).

Although advancements in the surface treatment of concrete pavements, such as hessian dragging, can significantly reduce noise (Decicorp 1994, p. 85), estimates of the differences in noise levels between open-graded asphalt and dense-graded asphalt or concrete vary in the range of 2 to 10 dB(A), depending on construction quality and maintenance (Wallace et al. 1996, p. 11). On average, open-graded asphalt has a lower noise level relative to concrete of the order of 4 dB(A) (Wallace et al. 1996, p. 11).

Samuels and Glazier (1990) conducted a study of the noise levels generated by different pavement types in the Sydney area in 1989. The pavements included different types of concrete and open-graded asphalt pavements, dense-graded asphalt, cold overlay slurry seal, and 14-millimetre chip seal. The study found that the pavements produced a substantial 9.7 dB(A) variation in traffic noise levels. Open-graded asphalt was found to be the quietest surface, offering reductions of 3.3 dB(A) over hessian dragged concrete, 6.3 dB(A) over shallow grooved concrete, and 5.9 dB(A) over dense-graded asphalt.

Reynolds (1992) evaluated various noise-abatement options (incorporating mounds and barriers of different heights and sections where the road passes

1. See footnote 1 in appendix III for an explanation of dB(A).

through a cutting) for a section of the Phillip Parkway in Sydney. The basecase was a new concrete pavement with no noise-abatement devices, and the alternatives were dense-graded asphalt and open-graded asphalt. Dense-graded asphalt and open-graded asphalt were found to provide reductions of about 3 dB(A) and 6 dB(A) respectively compared with concrete. A cost–benefit analysis showed that open-graded asphalt had community benefits which exceeded the costs and was the most economically viable of the three options.

Dash (1995) reports results of investigations carried out by the RTA on a variety of road surfaces. The investigations began in 1992 and involved seven different combinations of hessian drag and tranversely tined concrete surfaces. Before trafficking, measurements were made of texture depth, skid resistance and road noise, and these measurements were compared with traditional concrete and open-graded asphalt surfaces. In 1994, the investigation was extended to Victoria, where trafficked stone mastic asphalt, bituminous slurry surfacing, exposed aggregate concrete, dense-graded asphalt, open-graded asphalt, and sprayed bituminous surfacing were tested.

Cars and trucks respond differently to variations in surface texture. The results of the investigation by Dash (1995) indicated that, for cars, the quietest surface was new open-graded asphalt, which was about 4 dB(A) quieter than dense-graded asphalt, light longitudinally textured concrete and 14-millimetre exposed aggregate concrete. Stone mastic asphalt was about 2 dB(A) noisier than new open-graded asphalt. It was also found that there was little noise difference for cars between old open-graded asphalt, dense-graded asphalt and concrete surfaces.

The study by Dash (1995) also found that road noise for trucks was 8 to 10 dB(A) higher than for cars travelling at the same speed. For trucks at 80 kilometres per hour, two groups of surfaces produced different noise levels. Each group of surfaces had truck noise levels spread over about 2 dB(A). The quieter group included exposed aggregate concrete, open-graded asphalt, slurry surfacing, stone mastic asphalt and a 10-millimetre sprayed seal. The other group, which was about 4 dB(A) noisier, comprised dense-graded asphalt and other concrete surfaces.

Several of the studies reviewed above indicate the superiority of open-graded asphalt and, to a lesser extent, other flexible pavement types, in reducing noise. However, the relative noise reduction advantage of open-graded asphalt and other flexible pavements tends to diminish over time. The combined effect of weathering, dirt, oil spillage and wear caused by traffic tends to reduce the porosity of flexible pavements. Dash (1995, p. 54) reports that noise testing of similar types of road at different sites showed a range of about 2 dB(A), except in the case of open-graded asphalt where the range doubled for surfaces of different ages. As the pores and interstices become increasingly clogged, noise levels tend to increase, as does the possibility of aquaplaning due to reduced surface water dispersal. After several years of service, open-graded asphalt requires cleaning with high-pressure hosing of the surface (Bennett & Moffatt 1995, p. 16). Flexible pavements also generally require surface maintenance at 10- to 15-year intervals to maintain performance.

TRAFFIC SAFETY EFFECTS

In the study reported by Dash (1995), all the surfaces tested had acceptable skid resistance. However, concrete surfaces were found to have a relatively higher skid resistance than asphalt surfaces due to the siliceous sand in the concrete mixes used. In general, the coarser the surface texture, the lower the risk of aquaplaning. Exposed aggregate concrete and a 10-millimetre sprayed seal were found to have the highest surface textures (over 1 millimetre). Dense-graded asphalt had the lowest surface texture of about 0.3 millimetre.

The black surface of an asphalt pavement enhances the visibility of contrasting traffic markings and lines, especially at night and in dry conditions. The contrast is less effective during the day and night-time wet conditions. Concrete pavements have good visibility at night because of their relatively lighter colour which reflects more light, but they can also increase glare during the day. Concrete pavements can be produced in a variety of colours, strengths and surface textures.

Dense-graded asphalt has poorer high-speed, wet-surface skid resistance properties than open-graded asphalt or textured concrete. A more detailed discussion of road surface characteristics and safety is provided in appendix II.

MACROECONOMIC EFFECTS

Sandler, Denham and Trickey (1984) observe (in the context of the United States) that two reasons are generally provided in support of the assertion by the cement and concrete industry that concrete pavements generate a significantly greater local earnings and employment impact than asphalt. One is that concrete pavement construction is more labour-intensive than asphalt. The other is that asphalt is a component of imported petroleum, whereas cement and concrete products, being locally produced, have a greater economic impact.

Sandler, Denham and Trickey (1984) carried out an economic impact analysis using an input–output model to test the relative impacts of concrete and asphalt pavement construction using costs for one-mile sections of pavement. They note that such input–output analysis has its limitations and various sources of imprecision, especially in regard to dealing with substitution effects in the construction industry over time and taking proper account of society's collective rate of time preference in assessing future benefits in present value terms. BTCE (1996b) also discusses the limitations of input–output analysis.

The results of the analysis by Sandler, Denham and Trickey (1984) indicated that, in the first year after construction, the concrete pavement has a greater absolute employment impact (30.9 versus 18.7 full-time equivalent persons) and a 17.6 per cent greater employment impact per $10 000 of construction cost. However, during the assumed 20-year life span of the projects, the concrete pavement has a smaller relative absolute employment advantage (34.3 versus 31.4) but a slightly larger employment impact (24 per cent) per $10 000 of construction cost. The authors note that, to a public decision maker interested in employment impacts, the short-run first-year impact would be more significant.

Roy and Ray (1984) challenge some of the assumptions of the Sandler, Denham and Trickey (1984) analysis. These two studies are discussed in more detail in relation to life cycle costing issues later in this appendix.

Decicorp (1994) published a study commissioned by the Steel Reinforcement Institute of Australia (SRIA) which examined various issues in regard to the competitiveness of continuously reinforced concrete pavements (CRCPs) compared with alternative flexible pavements. The study included a sensitivity analysis using a 5 per cent reduction in bitumen demand (due to an increase in the use of concrete) and an assessment of the GDP multipliers for each of the material supply industries. The study found that, based on average 1992–93 prices and production and consumption levels, the change in bitumen demand could have reduced Australia's balance of payments deficit by $4.4 million. Employment multipliers in the concrete and cement industries were estimated to be relatively high. Consequently, the total increase in GDP from both construction and maintenance of CRCPs was estimated to be about $49.1 million—about $6 million more than if dense-graded asphalt had been used.

ROLLING RESISTANCE AND VEHICLE FUEL CONSUMPTION

A wheel travelling over a pavement produces a 'bow-wave' effect as the pavement surface in front of the wheel and alongside it rises slightly because of the compression under the wheel. Cenek, Jamieson and Ball (1996) have studied the effect of pavement deflection on rolling resistance of commercial vehicle tyres. The shape and size of the bow-wave depends on the weight of the vehicle and the degree of rigidity of the pavement. For a rigid pavement the deflection takes the shape of a moving dish, but for a flexible pavement the deflection causes a wave to move ahead of the wheel, and also produces a relatively flat dish under the wheel. Cenek, Jamieson and Ball (1996, p. 2) note that, intuitively, a flexible pavement is likely to provide a greater tractive resistance for the same wheel load than a rigid pavement, resulting in higher fuel consumption and tyre wear.

Cenek (1996, p. 8) reports that rolling resistance measurements for commercial vehicles obtained in several studies increase by as much as 45 per cent on gravel roads relative to sealed roads. This increase has been attributed to the deflection bowl that forms under a heavy wheel, and can therefore also contribute to increased fuel consumption in the case of flexible sealed pavements.

Cenek, Jamieson and Ball (1996) report the results of a road test program undertaken in New Zealand to establish how and to what extent flexible pavements affect the rolling resistance of trucks. A truck was tested with a rear axle load of 8 tonnes ('full' load) and 3.6 tonnes ('half' load). The results confirmed the intuitive belief that pavement rigidity is a significant factor in truck operating costs: a 63 per cent difference in rolling resistance was measured between the stiffest and most flexible pavement tested under full load. A similar difference was measured under half load. Assuming that a 5 per cent reduction in rolling resistance produces a saving of 1 per cent in fuel consumption (Descornet 1990), Cenek, Jamieson and Ball conclude that the 63 per cent measured difference in rolling resistance corresponds to a potential fuel consumption saving of about 13 per cent for trucks. They note that their findings are consistent with those of Zaniewski et al. (1982) and Zaniewski (1989), who found that in the United States, the fuel consumption of trucks operating on asphalt pavements was about 20 per cent greater than that of trucks operating on concrete pavements.

The depth of water on pavement surfaces can have an appreciable effect on fuel consumption. Wallace et al. (1996, p. 29) report results based on the Swedish computer program VETO, which was developed by the Swedish Road and Traffic Institute to calculate transport costs as a function of road standard. The results indicate increases in car fuel consumption of 10 per cent for a water film of 0.5 millimetre (7 per cent for trucks) and 22 per cent for a film of 1 millimetre (16 per cent for trucks). As the thickness of the water film on an open-graded asphalt surface is negligible compared with dense-graded asphalt and concrete, the fuel saving benefits of open-graded asphalt surfaces during wet weather are likely to be relatively greater. It must be noted, however, that VETO has been developed for Scandinavian road conditions and it is not clear to what extent water films will affect fuel consumption for Australian pavement types and weather conditions.

PAVEMENT MAINTENANCE

In a flexible asphalt pavement there is slight movement of the pavement under traffic, which contributes to a smooth ride. Asphalt is laid continuously and does not have joints that require sealing. The layered process of construction allows work to be carried out at several points at the same time. The life of asphalt pavements can be extended by strengthening the base layers or applying a new wearing course. Although both asphalt and concrete pavements can be trenched and covered over if utility lines under the pavement need to be accessed, the task is relatively more difficult in the case of concrete.

A number of advantages have also been claimed for concrete pavements. Concrete surfaces are durable, retain good skid resistance over long periods in both wet and dry conditions and, if well constructed, do not need costly maintenance. Concrete pavements are especially suited for heavily trafficked roads and roads with weak sub-grades. Continuously reinforced concrete has considerable ability to withstand settlement. If damage or deterioration occurs to concrete pavements due to faulty construction or other reasons, substantial reconstruction costs are likely to be incurred as well as extended disruption of traffic. Faulty construction of asphalt pavements also requires timely repair to prevent substantial costs being incurred later.

Asphalt pavements involve less initial cost but require relatively more periodic maintenance than concrete pavements. Resurfacing of asphalt pavements is generally carried out every 10 to 15 years. Disruption costs, such as delays, increased VOCs, crash risk, vehicle damage and driver stress, are likely to be relatively greater in the case of asphalt pavement maintenance (see 'Life cycle cost issues' below).

Data for 1992–93 relating to the F3 (Sydney to Newcastle Freeway), which has both asphalt and concrete sections, indicate that routine maintenance costs for both pavement types are quite low (RTA 1994). In this context, routine maintenance refers to essential pavement repairs that cannot be delayed. The total routine maintenance cost for an asphalt section of 257 000 square metres was $8000 (3.1 cents per square metre). The total cost for another asphalt section of 430 000 square metres was $11 500 (2.7 cents per square metre), and for a concrete section of 360 000 square metres it was $4100 (1.1 cents per square metre).

LIFE CYCLE COST ISSUES

Life cycle cost (LCC) analysis (also known as whole-of-life cost analysis) is the preferred method of evaluating alternative pavement designs. LCC analysis applied to roads involves estimating the cost of constructing and maintaining a road over its serviceable life and expressing the cost in current dollars. The technique is useful in comparing the relative costs of different pavement options such as asphalt and concrete. However, from a practical perspective, the difficulty is to develop an adequate data base from which to establish realistic maintenance regimes and unit costs, particularly for concrete.

Concrete pavements have a relatively higher initial cost but they are generally claimed to have lower maintenance costs and longer service lives than asphalt pavements. There are several issues that need to be taken into account in comparing alternative concrete and asphalt pavement designs using a life cycle approach.

There is uncertainty in estimating the future price of materials. In particular, it is difficult to estimate future prices of bitumen, which is a petroleum derivative and a key component of asphalt.

Discount rates can significantly affect the analysis. A high discount rate will have the effect of discounting more heavily the costs incurred later in the life of a project, resulting in a lower life cycle cost. A low discount rate will have the opposite effect.

Both bitumen and concrete can be recycled. Recycled steel may also be used in the production of reinforced concrete. It is difficult to estimate salvage values of pavement materials because of the uncertainties in predicting the materials, equipment and technology that would be used for road construction several decades in the future.

A study conducted in the United States by Sandler, Denham and Trickey (1984) is illustrative of some of the issues involved in LCC analysis. Although the principles and issues involved in the study are universally relevant, the relative costs are not necessarily relevant to Australia. The study involved a comparative economic analysis of asphalt and concrete pavements using an LCC cost comparison (to estimate net present value of the pavements) and an economic impact analysis (to estimate employment effects of pavement construction). The analysis was carried out using hypothetical one-mile sections of a typical rural four-lane interstate project in Florida that was designed to provide adequate capacity and structural strength for 20 years. It was assumed that, after this period, traffic would increase up to the thirtieth year, from which time the carrying capacity of the road would be exceeded and major widening and reworking would be required, marking the end of the economic life of the initial road.

The asphalt pavement design involved a stage construction concept that provides an initial pavement and base thickness sufficient for traffic during the first 10 years, with a planned second stage pavement layer to be added after the tenth year. The combination of the first and second stage construction provides an asphalt pavement design equivalent to the concrete pavement design. The asphalt pavement consisted of a 4.5-inch surface course on a 12-inch rock base. Major maintenance after 10 years involved a two-inch surface course. The concrete pavement involved an 11-inch non-reinforced concrete surface layer and a six-inch stabilised base of sand and stone.

The analysis was carried out in 1983 US dollars. Estimates of annual expenditures on routine maintenance for each pavement type for the hypothetical one-mile section were $528 for asphalt and $1044 for concrete, based on historical expenditures for interstate roads incurred by the Florida Department of Transportation. Terminal salvage values used were $0 per tonne for concrete and $8 per tonne for asphalt. The discount rate used was 7 per cent (tested for sensitivity at 5 and 10 per cent). Sensitivity testing was also carried out for an economic life of 40 years.

Largely because of the use of stage construction for the asphalt pavement, the results of the analysis indicated a clear and decisive advantage of asphalt over concrete for all discount rates and for economic lives of 30 and 40 years. For the purpose of sensitivity analysis, the real price of asphalt was assumed to increase at a compound annual rate of 2.6 per cent per annum (the same rate of increase predicted for United States oil). The increase of 2.6 per cent was applied to the asphalt material contained in stage 2, as well as to the recycling component of the asphalt at the end of the project life. The results were still in favour of asphalt and remained so even under the most extreme parametric assumptions (2.6 per cent real increase in the price of asphalt, 5 per cent discount rate and 40-year project life).

Roy and Ray (1984) of the US Portland Cement Association take issue with the study by Sandler, Denham and Trickey (1984) on three grounds: real discount rates, the time span between resurfacing of asphalt pavements, and the salvage value for concrete pavements. By applying different values for these variables, Roy and Ray obtain results which favour concrete over asphalt.

Roy and Ray calculate real interest rates by subtracting the price deflator for personal consumption from the 91-day United States Treasury bill rate. They argue, on the basis of long-term trends in the treasury bill real rate, that the expected real rate of interest virtually always falls between 0 and 4.5 per cent, with a typical value somewhere between 1 and 2.5 per cent.

With regard to the time interval between resurfacing of asphalt pavements, Roy and Ray (1984) argue that the weighted average age to second stage resurfacing of Florida interstate roads is 6.4 years—not 10 years, as assumed by Sandler, Denham and Trickey. Roy and Ray suggest that a realistic terminal value for concrete is $4 per tonne rather than the $0 per tonne assumed by Sandler, Denham and Trickey. However, Sandler, Denham and Trickey argue that subtracting the rate of inflation from the yield of a short-term security does not reflect an average rate of return on private investment. They also point out that their analysis was intended to assess the implications of using (then) current design standards rather than to repeat historical experience which would have, in any event, penalised concrete because of premature distress being experienced on some interstate concrete highways.

There are a few Australian LCC studies which evaluate different types of pavement. A study by Porter, Tinni and Bethune (1994) evaluated five-kilometre lengths of 15 road pavements using unit costs in 1993 and an 8 per cent discount rate (the paper essentially presents the conclusions of a 1994 study commissioned by the Australian Asphalt Pavement Association). The LCC approach used involves both net present worth (NPW) and equivalent annualised cash flow (EACF) analysis. The EACF is equivalent to the sinking fund value required in current dollars to finance the project's capitalisation and maintenance and is less sensitive to project life than NPW.

The three cheapest pavement options identified in the study were:

1. lean mix concrete sub-base (125 millimetres) with modified design asphalt base (185 millimetres);
2. lean mix concrete sub-base (125 millimetres) with CRCP base (190 millimetres); and
3. lean mix concrete sub-base (125 millimetres) with traditional dense-graded asphalt base (200 millimetres).

The results of the analysis were tested for sensitivity to alternative discount rates. It was found that pavement designs involving full-depth asphalt and conventional deep-strength asphalt over unbound sub-base as well as CRCPs were relatively insensitive to variations in discount rates. This was because these pavement types have high initial construction costs and relatively low ongoing maintenance costs.

A study by Handley (1995) evaluated three tenders called in 1992 by the RTA for the construction of the pavement for State Highway 23 (Newcastle inner city bypass). Three types of pavement were evaluated: CRCP, open-graded asphalt and dense-graded asphalt. The analysis was carried out over a 40-year time frame at a discount rate of 7 per cent and alternative rates of 4 per cent and 10 per cent. At a 7 per cent discount rate, the estimated present worth was $66.07 per square metre for CRCP, $70.42 per square metre for open-graded asphalt and $66.81 per square metre for dense-graded asphalt. The pavement was constructed with CRCP, which, as shown by the LCC analysis, was marginally cheaper than the asphalt alternatives.

The aforementioned LCC studies highlight the fact that small differences in final net worth estimates can result in the commitment of large capital and ongoing expenditures. Small changes in the value of parameters can swing the outcome of these analyses one way or another. Many LCC analyses are carried out from the perspective of the road agency and seek to minimise costs to the agency. Raniga (1995) raises the issue of including road user costs (VOCs, travel time and crash costs) in the analysis. Indeed, it is arguable that LCC analysis should properly take into account all social costs (including externalities such as noise, emissions and the ecological impacts of road construction and maintenance) of particular options and the results would then reflect comparisons based on the objective of minimising the cost to society. It is possible that the preferred option arising from such an analysis would not be the one that minimises the total cost to the road authority. The social approach would, of course, have implications in terms of funding and cost recovery of projects.

LCC analysis is particularly sensitive to a few key parameters, notably the discount rate, initial project cost, and times at which maintenance is carried out. Salvage value of pavement materials may also be relevant, but its present value is usually considerably diminished by discounting.

Higher discount rates will tend to discount costs incurred later in the project life relatively more heavily than costs incurred sooner. Hence, projects which involve major maintenance in the future, or construction in stages, will appear favourable with high discount rates. By the same token, projects where most of the costs are incurred initially would not be overly sensitive to discount rates. For these reasons, asphalt pavements usually turn out to be less costly in LCC terms when moderate to high discount rates are applied.

The Allen Consulting Group (1994) produced a report on alternative road pavements for the Steel Reinforcement Institute of Australia (SRIA). The report estimates that the appropriate discount rate for general investment in roads is 6 per cent or lower, having taken into account the low risk associated with most private sector investments in utilities (the discount rate recommended by the Commonwealth Department of Finance is 8 per cent for general government investments). In presenting a case for the 6 per cent rate, the report argues that social returns from general investment in roads are likely to be less risky than returns to typical private sector investments in utilities. The Allen Consulting Group notes that the use of an 8 per cent discount rate to evaluate alternative pavements, rather than the rate of 6 per cent which they consider more appropriate, disadvantages CRCP relative to asphalt.

The report of The Allen Consulting Group also identifies the lack of neutrality in the tax treatment of investment and maintenance in roads as another factor that disadvantages CRCP relative to asphalt. Taxation regulations allow the maintenance expenditures on roads to be written off in the year in which they occur, although they have the characteristics of investments (the effects of the maintenance produce benefits for many years). The report argues that taxation provisions provide an advantage to asphalt roads, which typically require maintenance every 10 years. The report also argues that the bias against CRCP is made worse by the disruption costs imposed on the community by the maintenance of asphalt roads which, although receiving favourable tax treatment, are not fully taken into account by the provider of the road.

Maintenance also imposes various costs on road users and road maintenance workers and these costs should be incorporated into an LCC analysis. Although periodic disruption is common in the case of asphalt roads, disruption costs for concrete roads can also be substantial if reconstruction is required due to severe distress or failure. Estimating such costs for concrete is usually quite difficult.

Disruption costs include: increased travel time and VOCs; higher levels of stress; the dissatisfaction of road users and its impact on local authorities; damage to the chassis, tyres and windscreens of vehicles; a higher risk of crashes; the risk of injury to maintenance workers; inconvenience to residents and commercial establishments (and possible loss of business) due to detours; delays in the delivery of goods and services; and increased air and noise pollution. To minimise inconvenience to motorists, maintenance is sometimes carried out at night. Although night-time maintenance could improve productivity, it also raises labour costs.

Decicorp (1994, pp. 6–7) observes that, of all available options for road pavements in Australia, CRCP (without an open-graded asphalt overlay) offers the lowest maintenance requirements over the life of the road. Decicorp (1994) surveys estimates of various components of disruption costs and notes that the limited use of CRCP roads in Australia may in part reflect the exclusion of maintenance-induced disruption costs from LCC analyses.

In 1996, Decicorp was commissioned by the SRIA to undertake the second stage of an economic study (Decicorp 1996) of the competitiveness of CRCP. The study focused on five types of pavement: CRCP, plain concrete, full-depth asphalt, cement treated base with asphalt overlay, and granular overlay asphalt. The study found that of all road pavements, CRCP has the lowest maintenance requirement and life cycle cost at a zero discount rate. However, pavements with lower initial construction costs but higher maintenance requirements become more competitive at higher discount rates. Using a net present value approach (over a 40-year life of a selected road project at a discount rate of 6 per cent), the study found that the disruption costs imposed on motorists due to maintenance activity were at least $17 million lower on a CRCP road than for all other pavement options.

ENERGY AND ENVIRONMENTAL IMPACTS

Wonson (1980) reports the results of a study conducted by the United States Asphalt Institute on the energy requirements for constructing different types of road pavements. The study took account of the energy requirements for the manufacture of all materials incorporated in pavements as well as the handling, processing, drying, mixing, hauling, placing and compaction of these materials and, where relevant, the energy requirements ancillary to the basic operation. According to the study, the energy required to produce a tonne of bitumen is 685 megajoules, as compared with 8810 megajoules for cement and 24 425 megajoules for steel reinforcing. Table VI.1 sets out the energy requirements for some typical pavement sections.

TABLE VI.1 ENERGY REQUIREMENTS FOR SOME TYPICAL PAVEMENT SECTIONS

		Approximate energy required	
Pavement type	*Description*	*MJ/m²*	*Equivalent fuel oil per lane-km (L)*
Conventional flexible	50 mm asphalt surface 375 mm granular base	290	27 100
Deep strength asphalt	190 mm asphalt surface and base 100 mm granular base	320	29 900
Full depth asphalt	235 mm hot mix asphalt	324	30 300
Concrete (unreinforced)	200 mm concrete 80 mm granular sub-base	720	67 300
Concrete (continuously reinforced)	200 mm concrete 80 mm granular sub-base Reinforced steel	830	77 600

Note 1. Sections are approximately of equal design.

2. One litre of fuel oil is equivalent to 38.5 megajoules.

Source Wonson (1980, p. 3).

The estimates provided by Wonson (1980) suggest that it takes 2.75 tonnes of cement to construct the same amount of pavement that can be constructed in full depth or deep strength asphalt with one tonne of bitumen, and that the construction of an asphalt pavement requires 2.5 to 3 times less energy than the construction of a concrete pavement. However, it has been pointed out by George Vorobieff of the Cement and Concrete Association of Australia (pers. comm., 19 May 1997) that the data for concrete in table VI.1 are probably based on cement manufacture using the wet kiln process, which has since been replaced by the more energy-efficient dry kiln process. Steel reinforcement for concrete is produced using the mini-mill technique introduced in the 1990s, which is also an energy-efficient process (Vorobieff, G., pers. comm., 19 May 1997).

Recent developments in concrete technology using supercritical carbon dioxide ($SSCO_2$), as reported in *New Scientist* (1997), indicate the possibility of rapid hardening of concrete products accompanied by substantial reductions in carbon dioxide emissions. Supercritical carbon dioxide is a special form of carbon dioxide which dissolves compounds like normal liquids, but diffuses easily, like a gas, through materials. It is formed when normal carbon dioxide is compressed at a pressure of 73 atmospheres and at a temperature above 31 degrees Celsius.

Cement is made from limestone in a process that converts calcium carbonate into calcium oxide, while releasing substantial amounts of carbon dioxide. Total emissions generated in cement manufacture, including those from external power generation, range from 800 to 1400 kilograms of carbon dioxide per tonne of cement (Potter 1992, p. 4). Concrete continues to harden for many years after it has set. The hardening process involves calcium compounds in cement slowly reacting with carbon dioxide in the atmosphere, thereby changing these compounds back to calcium carbonate, which is much harder than the original cement. Experimental pumping of supercritical carbon dioxide through concrete is reported to greatly accelerate the hardening process, as well as doubling the compressive strength and increasing the tensile strength by about 75 per cent. It is not clear when such a product would be commercially available and whether it would be economically feasible for use in road construction.

OECD (1984a) provides comprehensive estimates of the energy required to construct and maintain roads, including the energy required for the manufacture of various types of concrete and asphalt. A controversial issue in assessing energy requirements is whether or not the potential energy of materials (especially bitumen) should be included. The energy estimates from OECD (1984a) include the following:

- cement manufacture: 4 635 megajoules per tonne
- bitumen manufacture: 630 megajoules per tonne
- reinforcing steel: 27 200 megajoules per tonne

The energy required to construct one kilometre of a 2x2 lane motorway is 30 466.1 gigajoules (excluding potential internal energy of bitumen) or 46 750.1 gigajoules per kilometre (including potential internal energy of bitumen). Table VI.2 sets out OECD (1984a) estimates of energy required for the manufacture of concrete and asphalt mixes.

OECD (1984a, p. 160) compares the energy expended in building and maintaining 1 kilometre of motorway with the energy consumed by traffic over the same section during a 20-year period. The total energy outlay for construction and maintenance over 20 years was estimated at 31 512 gigajoules (51 346 gigajoules if the potential internal energy of bitumen is included). Total daily traffic is assumed to be 10 000 vehicles with 10 per cent heavy vehicles. Fuel intensity of 8 litres per 100 kilometres was assumed for cars and 40 litres per 100 kilometres for trucks. The mean value for the calorific energy of petrol and diesel was assumed to be 33.75 kilojoules per litre. On the basis of these assumptions, the energy expended by vehicles over the 20-year period is 275 940 gigajoules, which is nine times the energy outlay in building and maintaining the road. If the internal energy of the bitumen is taken into account, the proportion reduces from nine to five times.

TABLE VI.2 ENERGY[a] REQUIRED FOR MANUFACTURE OF CONCRETE AND ASPHALT MIXES

Type of material	*Energy required (MJ/t)*
Rich concrete[b]	881
Continuously reinforced concrete[c]	3919
Hot mix[d]	368
Bituminous concrete (asphalt)[e]	
Dense mix for surface course (6% bitumen)	535
Mix for wearing course (8.5% bitumen)	542
Dense-graded mix for base course (5% bitumen)	529

a. The figures for energy consumed include energy for extracting and processing raw materials and production, transport (based on assumed average loads and trip lengths) and laying of the finished product under assumed 'average' conditions. The energy figures do not include the potential internal energy of materials, especially bitumen.

b. Rich concrete comprises 61% crushed stone, 17% natural sand, 15.5% cement and 6.5% water.

c. Continuously reinforced concrete contains 0.85% steel reinforcement.

d. Open-graded mix with 4.5% bitumen (excludes internal energy).

e. The three asphalt mixes contain varying proportions of crushed stone, crushed sand, natural sand, filler and bitumen (excludes internal energy).

Source OECD (1984a, pp. 154–55, 162).

Asphalt can be recycled to provide additional energy savings. Tideman, Stacy and Todd (1996) have used the ecologically sustainable development (ESD) methodology proposed by Farmar-Bowers (1994) to conduct a preliminary evaluation of two asphalt replacement processes in South Australia. They used resource use analysis and payments analysis to compare the hot-in-place-asphalt-recycling (HIPAR) process with the conventional asphalt replacement process. HIPAR was developed in Europe to rehabilitate the failed asphalt surface layer on a road and to restore its surface properties. The HIPAR process involves the use of a large machine called a re-mixer which moves slowly along the pavement, removing, modifying and re-laying the asphalt surface in a single operation. Conventional asphalt replacement involves the shallow milling of failed areas and the removal of this waste material for dumping (or recycling in some instances). New asphalt from a production plant is used to replace the removed asphalt.

Tideman, Stacy and Todd concluded that the HIPAR process tended to meet ESD objectives to a greater extent than the conventional process. The process was estimated to cost about 20 per cent less than the conventional method.

Some concern has been expressed about the effects of discharges from hot bituminous mixes on the health of workers who prepare and lay such mixes, although techniques for limiting these discharges have been developed by the industry (PIARC 1996, p. 487). PIARC notes that special attention must be given to organic gases, particularly polycyclic aromatic hydrocarbons, because of their effects on health. Bitumen has not been classified as carcinogenic by the International Agency for Research on Cancer (PIARC 1996, p. 489). However, PIARC reports that several European organisations have jointly decided to undertake an epidemiological study in seven European countries to assess the long-term health of workers.

Information on side-effects, if any, on the health of workers involved in concrete and steel production for pavements could not be obtained for this paper.

APPENDIX VII POTENTIAL EMISSION REDUCTIONS AND CHANGES IN SOCIAL VEHICLE OPERATING COSTS DUE TO PAVEMENT REHABILITATION

POTENTIAL EMISSION REDUCTIONS DUE TO PAVEMENT REHABILITATION

Tables VII.1 to VII.5 set out estimates of the annual reductions in vehicle emissions that can potentially be achieved by different types of road rehabilitation for one-kilometre sections of road at different traffic levels. The figures in each table represent the difference in emissions between a situation where no rehabilitation occurs (the basecase) and a situation where rehabilitation is undertaken immediately before the beginning of the first year. In the basecase situation, roughness is assumed to be 110 NRM in the first year and increases over the following nine years, as predicted by RIAM (see appendix IV). This set of tables may be used as a 'ready reckoner' by applying the unit figures (relating to one-kilometre lengths) to estimate the approximate emission reductions that may be achieved by rehabilitating a road of any length.

Traffic volume will affect the standard of road that is built. In this analysis it has been assumed that roads with less than 10 000 AADT will be wide two-lane roads, roads with 10 000 to 20 000 AADT will have four lanes, and roads with more than 20 000 AADT will have six lanes. Chapter 2 (tables 2.2 and 2.4) describes the types of rehabilitation to which these tables relate and details the indicative costs associated with each type of rehabilitation.

TABLE VII.1 CHANGES IN ANNUAL CO_2 EQUIVALENT EMISSIONS RESULTING FROM SPRAYED SEAL RECONSTRUCTION

(tonnes)

	AADT									
Year	500	1000	2500	5000	7500	10 000	15 000	20 000	30 000	40 000
1	-2.4	-4.6	-11.8	-23.5	-34.1	-47.1	-68.3	-92.6	-138.9	-197.8
2	-2.4	-4.7	-12.0	-24.3	-34.7	-48.7	-69.5	-94.2	-141.3	-204.1
3	-2.5	-4.9	-12.2	-24.7	-35.9	-49.5	-71.8	-95.8	-143.6	-207.2
4	-2.6	-4.9	-12.6	-25.5	-37.1	-51.0	-74.2	-98.9	-148.3	-216.6
5	-2.6	-5.1	-12.8	-26.3	-37.7	-52.6	-75.4	-102.0	-153.1	-222.9
6	-2.6	-5.1	-13.1	-26.7	-38.3	-53.4	-76.5	-103.6	-155.4	-226.1
7	-2.7	-5.3	-13.5	-27.1	-40.0	-54.2	-80.1	-106.7	-160.1	-232.3
8	-2.7	-5.3	-13.7	-27.9	-40.6	-55.7	-81.2	-109.9	-164.8	-241.8
9	-2.8	-5.4	-14.1	-28.6	-41.8	-57.3	-83.6	-111.5	-167.2	-244.9
10	-2.8	-5.6	-14.5	-29.4	-43.0	-58.9	-85.9	-116.2	-174.3	-254.3
Average	-2.6	-5.1	-13.0	-26.4	-38.3	-52.8	-76.6	-103.1	-154.7	-224.8

Note Sprayed seal reconstruction is assumed to involve between 150 and 200 mm of crushed rock and a seal and to cost $30 per m^2. Roughness after reconstruction is assumed to be 50 NRM. The figures in the table relate to vehicle emissions only (they exclude emissions produced during road work) for a one-kilometre section of road. The changes in emissions relate to the difference between undertaking a sprayed seal reconstruction and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in emissions.

Source BTCE estimates.

TABLE VII.2 CHANGES IN ANNUAL CO_2 EQUIVALENT EMISSIONS RESULTING FROM ASPHALT OVERLAYS

(tonnes)

	AADT									
Year	500	1000	2500	5000	7500	10 000	15 000	20 000	30 000	40 000
1	-1.6	-3.1	-7.5	-15.7	-21.8	-31.4	-43.6	-59.7	-89.5	-131.9
2	-1.6	-3.1	-7.5	-16.5	-22.4	-33.0	-44.7	-59.7	-89.5	-138.1
3	-1.6	-3.2	-7.7	-16.5	-23.0	-33.0	-45.9	-61.2	-91.8	-141.3
4	-1.7	-3.2	-7.8	-17.3	-23.5	-34.5	-47.1	-62.8	-94.2	-147.6
5	-1.7	-3.4	-8.0	-17.7	-24.1	-35.3	-48.3	-65.9	-98.9	-150.7
6	-1.7	-3.4	-8.2	-17.7	-24.1	-35.3	-48.3	-65.9	-98.9	-150.7
7	-1.8	-3.5	-8.6	-18.4	-25.3	-36.9	-50.6	-67.5	-101.3	-157.0
8	-1.8	-3.5	-8.6	-18.8	-25.9	-37.7	-51.8	-70.6	-106.0	-163.3
9	-1.8	-3.5	-8.8	-19.2	-26.5	-38.5	-53.0	-72.2	-108.3	-163.3
10	-1.9	-3.7	-9.2	-20.0	-27.7	-40.0	-55.3	-73.8	-110.7	-169.5
Average	-1.7	-3.4	-8.2	-17.8	-24.4	-35.6	-48.9	-65.9	-98.9	-151.3

Note Asphalt overlays are assumed to be between 40 and 60 mm thick and to cost $17.50 per m^2. Roughness after overlay is assumed to be 71 NRM. The figures in the table relate to vehicle emissions only (they exclude emissions produced during road work) for a one-kilometre section of road. The changes in emissions relate to the difference between undertaking an asphalt overlay and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in emissions.

Source BTCE estimates.

TABLE VII.3 CHANGES IN ANNUAL CO_2 EQUIVALENT EMISSIONS RESULTING FROM ASPHALT RECONSTRUCTION

(tonnes)

	AADT									
Year	*500*	*1000*	*2500*	*5000*	*7500*	*10 000*	*15 000*	*20 000*	*30 000*	*40 000*
1	-2.8	-5.5	-13.7	-27.9	-40.6	-55.7	-81.2	-108.3	-162.5	-226.1
2	-2.8	-5.6	-13.9	-28.6	-41.8	-57.3	-83.6	-109.9	-164.8	-232.3
3	-2.9	-5.7	-14.1	-29.4	-43.0	-58.9	-85.9	-113.0	-169.5	-238.6
4	-2.9	-5.8	-14.5	-30.2	-43.6	-60.4	-87.1	-116.2	-174.3	-248.0
5	-3.0	-6.0	-14.9	-31.0	-44.7	-62.0	-89.5	-120.9	-181.3	-254.3
6	-3.1	-6.0	-15.1	-31.4	-45.9	-62.8	-91.8	-122.4	-183.7	-257.5
7	-3.1	-6.2	-15.7	-32.2	-47.1	-64.4	-94.2	-125.6	-188.4	-266.9
8	-3.2	-6.3	-15.9	-33.0	-48.3	-65.9	-96.5	-128.7	-193.1	-276.3
9	-3.3	-6.4	-16.3	-33.8	-50.0	-67.5	-100.1	-131.9	-197.8	-279.4
10	-3.3	-6.6	-16.7	-34.9	-51.2	-69.9	-102.4	-136.6	-204.9	-288.8
Average	-3.0	-6.0	-15.1	-31.2	-45.6	-62.5	-91.2	-121.3	-182.0	-256.8

Note Asphalt reconstruction is assumed to involve an asphalt layer between 60 and 90 mm thick and to cost $37.50 per m^2. Roughness after reconstruction is assumed to be 40 NRM. The figures in the table relate to vehicle emissions only (they exclude emissions produced during road work) for a one-kilometre section of road. The changes in emissions relate to the difference between undertaking an asphalt reconstruction and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in emissions.

Source BTCE estimates.

TABLE VII.4 CHANGES IN ANNUAL CO_2 EQUIVALENT EMISSIONS RESULTING FROM NOVACHIP OVERLAYS

(tonnes)

	AADT									
Year	*500*	*1000*	*2500*	*5000*	*7500*	*10 000*	*15 000*	*20 000*	*30 000*	*40 000*
1	-1.4	-2.6	-6.3	-13.0	-18.2	-25.9	-36.5	-48.7	-73.0	-109.9
2	-1.4	-2.6	-6.3	-13.3	-18.8	-26.7	-37.7	-48.7	-73.0	-113.0
3	-1.4	-2.7	-6.5	-13.3	-19.4	-26.7	-38.9	-50.2	-75.4	-116.2
4	-1.5	-2.7	-6.7	-14.1	-19.4	-28.3	-38.9	-51.8	-77.7	-119.3
5	-1.5	-2.7	-6.7	-14.5	-20.0	-29.0	-40.0	-53.4	-80.1	-122.4
6	-1.5	-2.8	-6.9	-14.5	-20.6	-29.0	-41.2	-54.9	-82.4	-125.6
7	-1.5	-2.9	-7.3	-14.9	-21.2	-29.8	-42.4	-56.5	-84.8	-128.7
8	-1.5	-2.9	-7.3	-15.3	-21.8	-30.6	-43.6	-56.5	-84.8	-131.9
9	-1.6	-3.0	-7.5	-15.7	-22.4	-31.4	-44.7	-58.1	-87.1	-135.0
10	-1.6	-3.1	-7.7	-16.1	-23.0	-32.2	-45.9	-61.2	-91.8	-141.3
Average	-1.5	-2.8	-6.9	-14.5	-20.5	-29.0	-41.0	-54.0	-81.0	-124.3

Note Novachip overlays are assumed to be between 15 and 20 mm thick with a seal and to cost $12 per m^2. Roughness after overlay is assumed to be 77 NRM. The figures in the table relate to vehicle emissions only (they exclude emissions produced during road work) for a one-kilometre section of road. The changes in emissions relate to the difference between undertaking a Novachip overlay and basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in emissions.

Source BTCE estimates.

TABLE VII.5 CHANGES IN ANNUAL CO_2 EQUIVALENT EMISSIONS RESULTING FROM CONCRETE REHABILITATION

(tonnes)

	AADT									
Year	*500*	*1000*	*2500*	*5000*	*7500*	*10 000*	*15 000*	*20 000*	*30 000*	*40 000*
1	-2.8	-5.5	-13.7	-27.9	-40.6	-55.7	-81.2	-108.3	-162.5	-226.1
2	-2.8	-5.6	-13.9	-29.0	-42.4	-58.1	-84.8	-111.5	-167.2	-235.5
3	-2.9	-5.8	-14.3	-29.8	-44.2	-59.7	-88.3	-116.2	-174.3	-248.0
4	-3.0	-5.9	-14.9	-31.0	-45.3	-62.0	-90.7	-122.4	-183.7	-260.6
5	-3.1	-6.1	-15.3	-32.2	-47.1	-64.4	-94.2	-128.7	-193.1	-273.2
6	-3.1	-6.2	-15.7	-33.0	-48.9	-65.9	-97.7	-131.9	-197.8	-282.6
7	-3.2	-6.4	-16.5	-34.1	-51.2	-68.3	-102.4	-138.1	-207.2	-295.1
8	-3.3	-6.5	-16.9	-35.3	-53.0	-70.6	-106.0	-142.9	-214.3	-310.8
9	-3.4	-6.8	-17.3	-36.5	-55.3	-73.0	-110.7	-149.1	-223.7	-320.2
10	-3.5	-6.9	-17.9	-38.1	-57.1	-76.1	-114.2	-155.4	-233.1	-335.9
Average	-3.1	-6.2	-15.6	-32.7	-48.5	-65.4	-97.0	-130.5	-195.7	-278.8

Note It is assumed that roughness after rehabilitation is 40 NRM and that the concrete pavements deteriorate at half the rate of flexible pavements. The figures in the table relate to vehicle emissions only (they exclude emissions produced during road work) for a one-kilometre section of road. The changes in emissions relate to the difference between undertaking concrete rehabilitation and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in emissions.

Source BTCE estimates.

The figures in the tables suggest that types of rehabilitation which produce low post-rehabilitation roughness result in large reductions in vehicle emissions. Asphalt reconstruction and concrete rehabilitation, where the treatments result in a roughness of 40 NRM, are the most beneficial in terms of reducing greenhouse gas emissions from vehicles. In fact, concrete pavement rehabilitation is slightly more effective than asphalt reconstruction because of the relatively slower deterioration rate of concrete. Novachip rehabilitation, where the pavement has a post-treatment roughness of 77 NRM, provides less than half the emission benefits of a concrete pavement.

It must be noted that the figures in the tables relate to vehicle emissions only (they exclude emissions produced during the rehabilitation process). These figures must be contrasted with the emissions produced during initial and successive rehabilitation (a life cycle basis) to obtain an estimate of the net emissions produced. Although concrete and asphalt reconstruction result in similar reductions in vehicle emissions, the construction of a concrete pavement produces substantially greater emissions than those resulting from the construction of an asphalt pavement or an asphalt reconstruction. The vehicle emission reductions produced by Novachip are about 80 per cent of the vehicle emissions produced by an asphalt overlay, but laying Novachip produces only one-third of the emissions produced by an overlay.

POTENTIAL REDUCTIONS IN SOCIAL VEHICLE OPERATING COSTS DUE TO PAVEMENT REHABILITATION

Tables VII.6 to VII.10 show social VOCs for a one-kilometre section of road resulting from different types of pavement rehabilitation at different traffic levels. The costs include fuel, oil, tyres and maintenance (parts and labour) but exclude federal fuel excise, State and Territory business franchise fees (levied on fuel), sales taxes on vehicles, import duties on vehicles, parts and tyres, and vehicle registration charges. A 10-year period has been used, as longer time frames can significantly affect the results due to changes in traffic and road conditions. Social VOCs are expressed as net present values (1995–96 dollars) using a discount rate of 10 per cent.

As in the case of the previous set of tables, tables VII.6 to VII.10 may be used as a 'ready reckoner' to estimate the approximate reductions in social VOCs that may be expected by rehabilitating a section of road of any length.

TABLE VII.6 SOCIAL VOCs FOR SPRAYED SEAL RECONSTRUCTION
($'000)

	AADT									
Year	*500*	*1000*	*2500*	*5000*	*7500*	*10 000*	*15 000*	*20 000*	*30 000*	*40 000*
1	-2.1	-4.1	-10.4	-21.3	-30.1	-42.5	-60.2	-80.8	-120.9	-175.8
2	-2.2	-4.3	-10.9	-23.4	-33.1	-46.8	-66.2	-88.7	-132.7	-196.5
3	-2.4	-4.7	-11.7	-24.9	-36.3	-49.8	-72.5	-96.7	-144.6	-216.3
4	-2.5	-4.9	-12.5	-27.1	-39.5	-54.1	-79.0	-107.1	-160.3	-242.2
5	-2.6	-5.2	-13.3	-29.2	-42.5	-58.4	-85.0	-117.7	-176.1	-263.5
6	-2.7	-5.4	-14.1	-30.8	-45.6	-61.6	-91.2	-125.8	-188.4	-284.0
7	-2.9	-5.7	-15.2	-32.8	-49.8	-65.7	-99.6	-136.6	-204.5	-309.7
8	-3.0	-6.0	-16.0	-35.1	-52.9	-70.1	-105.8	-147.4	-220.7	-336.7
9	-3.2	-6.3	-16.9	-37.3	-57.0	-74.6	-114.0	-157.8	-236.3	-358.0
10	-3.3	-6.6	-18.0	-40.0	-61.1	-80.0	-122.2	-171.5	-256.7	-389.7
Total	-17.5	-34.6	-89.6	-193.4	-285.0	-386.8	-569.9	-779.4	-1166.6	-1751.4
Average	-1.8	-3.5	-9.0	-19.3	-28.5	-38.7	-57.0	-77.9	-116.7	-175.1

Note Sprayed seal reconstruction is assumed to involve between 150 and 200 mm of crushed rock and a seal and to cost $30 per m^2. Roughness after reconstruction is assumed to be 50 NRM. Social VOCs relate to a one-kilometre section of road and exclude federal fuel excise, State/Territory business franchise fees (on fuel), sales taxes on vehicles, import duties on vehicles and tyres, and vehicle registration charges. Social VOCs are estimated over a 10-year period and are expressed as net present values (1995–96 dollars) using a discount rate of 10%. The changes in VOCs relate to the difference between undertaking a sprayed seal reconstruction and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in VOCs.

Source BTCE estimates.

TABLE VII.7 SOCIAL VOCs FOR ASPHALT OVERLAYS
($'000)

	AADT									
Year	500	1000	2500	5000	7500	10 000	15 000	20 000	30 000	40 000
1	-1.9	-3.6	-8.9	-18.6	-25.9	-37.2	-51.9	-69.6	-104.3	-153.9
2	-2.0	-3.8	-9.4	-20.7	-28.9	-41.4	-57.8	-77.0	-115.3	-174.5
3	-2.1	-4.1	-10.2	-22.1	-31.9	-44.2	-63.8	-85.0	-127.2	-194.3
4	-2.2	-4.3	-10.9	-24.3	-34.9	-48.5	-69.8	-93.6	-140.1	-219.2
5	-2.3	-4.6	-11.7	-26.3	-36.1	-52.6	-72.3	-98.9	-148.1	-226.4
6	-2.4	-4.8	-12.3	-26.5	-36.4	-53.1	-72.7	-99.6	-149.1	-228.3
7	-2.6	-5.1	-13.0	-27.8	-38.4	-55.7	-76.8	-102.7	-153.8	-239.8
8	-2.7	-5.2	-13.0	-28.6	-39.5	-57.2	-79.0	-108.2	-162.0	-251.5
9	-2.8	-5.3	-13.4	-29.4	-40.7	-58.7	-81.5	-111.5	-166.9	-253.7
10	-2.8	-5.6	-14.0	-30.8	-42.8	-61.6	-85.7	-115.0	-172.2	-266.3
Total	-15.5	-30.3	-75.9	-165.5	-231.2	-331.1	-462.2	-623.8	-934.0	-1429.9
Average	-1.5	-3.0	-7.6	-16.6	-23.1	-33.1	-46.2	-62.4	-93.4	-143.0

Note Asphalt overlays are assumed to be between 40 and 60 mm thick and to cost $17.50 per m^2. Roughness after overlay is assumed to be 71 NRM. Social VOCs relate to a one-kilometre section of road and exclude federal fuel excise, State/Territory business franchise fees (on fuel), sales taxes on vehicles, import duties on vehicles and tyres, and vehicle registration charges. Social VOCs are estimated over a 10-year period and are expressed as net present values (1995–96 dollars) using a discount rate of 10%. The changes in VOCs relate to the difference between undertaking an asphalt overlay and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in VOCs.

Source BTCE estimates.

TABLE VII.8 SOCIAL VOCs FOR ASPHALT RECONSTRUCTION
($'000)

	AADT									
Year	500	1000	2500	5000	7500	10 000	15 000	20 000	30 000	40 000
1	-2.3	-4.4	-11.1	-22.7	-32.3	-45.4	-64.6	-86.1	-128.7	-185.2
2	-2.4	-4.6	-11.6	-24.8	-35.5	-49.7	-70.9	-94.0	-140.6	-205.9
3	-2.5	-5.0	-12.4	-26.5	-38.7	-53.0	-77.3	-102.5	-153.3	-226.7
4	-2.7	-5.2	-13.2	-28.7	-41.7	-57.3	-83.3	-112.9	-169.0	-252.6
5	-2.8	-5.5	-14.0	-30.8	-44.9	-61.6	-89.8	-124.0	-185.6	-274.0
6	-2.9	-5.7	-14.8	-32.4	-48.2	-64.8	-96.3	-132.2	-197.9	-294.4
7	-3.0	-6.1	-16.0	-34.6	-52.2	-69.1	-104.4	-143.0	-214.0	-321.2
8	-3.2	-6.3	-16.7	-36.8	-55.5	-73.6	-111.0	-153.8	-230.2	-348.3
9	-3.3	-6.6	-17.6	-39.0	-59.8	-78.0	-119.6	-164.8	-246.7	-369.5
10	-3.4	-7.0	-18.7	-41.9	-63.9	-83.8	-127.8	-178.4	-267.1	-401.3
Total	-18.5	-36.7	-94.2	-204.2	-301.4	-408.5	-602.6	-820.0	-1227.1	-1822.1
Average	-1.9	-3.7	-9.4	-20.4	-30.1	-40.8	-60.3	-82.0	-122.7	-182.2

Note Asphalt reconstruction is assumed to involve an asphalt layer between 60 and 90 mm thick and to cost $37.50 per m^2. Roughness after reconstruction is assumed to be 40 NRM. Social VOCs relate to a one-kilometre section of road and exclude federal fuel excise, State/Territory business franchise fees (on fuel), sales taxes on vehicles, import duties on vehicles and tyres, and vehicle registration charges. Social VOCs are estimated over a 10-year period and are expressed as net present values (1995–96 dollars) using a discount rate of 10%. The changes in emissions relate to the difference between undertaking an asphalt reconstruction and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in VOCs.

Source BTCE estimates.

TABLE VII.9 SOCIAL VOCs FOR NOVACHIP OVERLAYS
($'000)

	AADT									
Year	500	1000	2500	5000	7500	10 000	15 000	20 000	30 000	40 000
1	-1.8	-3.4	-8.5	-17.7	-24.7	-35.3	-49.5	-65.9	-98.7	-146.5
2	-1.9	-3.6	-9.0	-19.7	-27.7	-39.3	-55.4	-72.0	-107.8	-166.1
3	-2.0	-3.9	-9.6	-19.9	-28.9	-39.7	-57.8	-74.7	-111.9	-172.9
4	-2.1	-4.0	-9.9	-21.1	-29.1	-42.3	-58.1	-77.6	-116.2	-179.2
5	-2.2	-4.1	-10.0	-21.8	-30.1	-43.7	-60.3	-80.6	-120.7	-185.3
6	-2.2	-4.2	-10.3	-22.0	-31.2	-43.9	-62.4	-83.4	-124.9	-191.5
7	-2.3	-4.4	-11.0	-22.7	-32.3	-45.4	-64.7	-86.5	-129.5	-198.1
8	-2.3	-4.4	-11.0	-23.4	-33.4	-46.8	-66.8	-87.2	-130.6	-204.9
9	-2.4	-4.5	-11.4	-24.2	-34.6	-48.3	-69.2	-90.3	-135.3	-211.4
10	-2.4	-4.7	-11.7	-25.0	-35.8	-49.9	-71.6	-96.0	-143.8	-223.6
Total	-14.2	-27.2	-67.4	-143.0	-202.3	-286.1	-404.6	-534.7	-800.7	-1230.9
Average	-1.4	-2.7	-6.7	-14.3	-20.2	-28.6	-40.5	-53.5	-80.1	-123.1

Note Novachip overlays are assumed to be between 15 and 20 mm thick with a seal and to cost $12 per m^2. Roughness after overlay is assumed to be 77 NRM. Social VOCs relate to a one-kilometre section of road and exclude federal fuel excise, State/Territory business franchise fees (on fuel), sales taxes on vehicles, import duties on vehicles and tyres, and vehicle registration charges. Social VOCs are estimated over a 10-year period and are expressed as net present values (1995–96 dollars) using a discount rate of 10%. The changes in emissions relate to the difference between undertaking a Novachip overlay and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in VOCs.

Source BTCE estimates.

TABLE VII.10 SOCIAL VOCs FOR CONCRETE REHABILITATION
($'000)

	AADT									
Year	500	1000	2500	5000	7500	10 000	15 000	20 000	30 000	40 000
1	-2.3	-4.4	-11.1	-22.7	-32.3	-45.4	-64.6	-86.1	-128.7	-185.2
2	-2.4	-4.6	-11.6	-25.0	-35.7	-49.9	-71.3	-94.5	-141.4	-206.9
3	-2.5	-5.0	-12.4	-26.6	-39.1	-53.3	-78.1	-103.5	-154.9	-229.8
4	-2.7	-5.2	-13.3	-28.9	-42.3	-57.8	-84.5	-115.1	-172.1	-256.8
5	-2.8	-5.6	-14.2	-31.2	-45.7	-62.4	-91.4	-126.7	-189.5	-280.2
6	-2.9	-5.8	-15.0	-32.9	-49.2	-65.8	-98.3	-135.4	-202.6	-302.8
7	-3.1	-6.1	-16.2	-35.2	-53.6	-70.5	-107.1	-147.2	-220.3	-330.6
8	-3.2	-6.4	-17.1	-37.6	-57.1	-75.2	-114.2	-158.6	-237.3	-359.7
9	-3.4	-6.7	-17.9	-39.9	-61.6	-79.9	-123.1	-170.6	-255.3	-383.1
10	-3.5	-7.1	-19.1	-42.9	-65.9	-85.9	-131.8	-184.7	-276.5	-417.0
Total	-18.6	-37.0	-95.2	-206.9	-306.8	-413.9	-613.4	-837.0	-1252.4	-1862.4
Average	-1.9	-3.7	-9.5	-20.7	-30.7	-41.4	-61.3	-83.7	-125.2	-186.2

Note It is assumed that roughness after rehabilitation is 40 NRM and that the concrete pavements deteriorate at half the rate of flexible pavements. Social VOCs relate to a one-kilometre section of road and exclude federal fuel excise, State/Territory business franchise fees (on fuel), sales taxes on vehicles, import duties on vehicles and tyres, and vehicle registration charges. Social VOCs are estimated over a 10-year period and are expressed as net present values (1995–96 dollars) using a discount rate of 10%. The changes in emissions relate to the difference between undertaking concrete rehabilitation and a basecase involving no rehabilitation (assuming a roughness of 110 NRM in the first year). A negative sign indicates a decrease in VOCs.

Source BTCE estimates.

As would be expected, treatments which bring about the largest reductions in vehicle emissions also result in the largest falls in overall VOCs. Concrete pavements produce the greatest reduction in VOCs, followed by asphalt reconstruction, sprayed seal reconstruction, asphalt overlay and Novachip overlay.

ASPHALT OVERLAY VERSUS ASPHALT RECONSTRUCTION

Road authorities generally have two broad options for reducing the roughness of asphalt pavements: the application of an asphalt overlay or an asphalt reconstruction. Asphalt reconstruction involves the application of a thicker layer of asphalt, usually between 60 and 90 millimetres, and often involves removing at least a part of the existing surface. On average, following asphalt reconstruction, the road will have a roughness of 40 NRM.

A comparative analysis of the costs and emission reductions associated with asphalt overlays and asphalt reconstruction for different AADTs over a 20-year period are presented in table VII.11. For the purpose of the analysis it has been assumed that roads are rehabilitated in the first year, and again whenever their roughness exceeds 110 NRM over the remaining 19 years. The emissions resulting from each treatment have been taken into account in this analysis (total emissions include emissions due to the treatment and vehicle emissions).

TABLE VII.11 EMISSIONS RESULTING FROM ASPHALT OVERLAY AND ASPHALT RECONSTRUCTION

(tonnes CO_2 equivalent)

AADT	*Asphalt overlay*	*Asphalt reconstruction*	*Difference in emissions*[a]
500	1 596	1 592	4
1 000	3 148	3 114	34
2 500	7 858	7 693	165
5 000	15 545	15 301	244
7 500	22 732	22 431	301
10 000	31 214	30 721	493
15 000	46 564	45 957	607
20 000	61 276	60 588	688
30 000	91 883	91 858	1 025
40 000	118 588	117 484	1 104

a. The difference in emissions equals the emissions from asphalt overlay minus the emissions from asphalt reconstruction. Emissions include emissions resulting from each treatment and vehicle emissions at each AADT level.

Source BTCE estimates.

Over the 20-year time frame, asphalt reconstruction results in marginally lower emissions than asphalt overlay. The process of asphalt reconstruction results in a higher level of emissions than asphalt overlay. However, the initial emissions advantage of the overlay treatment is overwhelmed by the combination of lower initial roughness on reconstructed roads and the need to apply overlays more frequently during the 20-year time frame.

ABBREVIATIONS

AADT	average annual daily traffic
AAPA	Australian Asphalt Pavement Association
AC	asphaltic concrete
ADT	average daily traffic
ARFCOM	ARRB Road Fuel Consumption Model
ARRB	Australian Road Research Board (changed to ARRB Transport Research Ltd on 1 July 1995)
ASSHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
ATO	Australian Taxation Office
BC	before Christ
BTCE	Bureau of Transport and Communications Economics
°C	degrees Celsius
CFCs	chlorofluorocarbons
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CRCP	continuously reinforced concrete pavement
dB	decibel
dB(A)	'A'-weighted decibel
DT	design traffic
EACF	equivalent annualised cash flow
ESA	equivalent standard axle
ESAL	equivalent standard axle load
ESD	ecologically sustainable development
FNOS	Financial Planning Network Optimisation System
GDP	gross domestic product
GJ	gigajoule (10^9 joules)
HDM	Highway Design and Maintenance (model)
HDM-III	Highway Design and Maintenance model version III
HDM-4	Highway Design and Maintenance model version 4
HDM-C	version of HDM-III modified by the BTCE to incorporate a congestion module
HIPAR	hot-in-place-asphalt-recycling
hr	hour

HSTM	High Speed Texture Metre
IPCC	Inter-Governmental Panel on Climate Change
IRI	International Roughness Index
kg	kilogram
KJ	kilojoule
km	kilometre
L	litre
LCC	life cycle cost
m	metre
m^2	square metre
m^3	cubic metre
MJ	megajoule (one million joules)
mm	millimetre
NAASRA	National Association of Australian State Road Authorities
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
NIVA	Norwegian Institute for Water Research
NMVOC	non-methane volatile organic compound
NO_x	oxides of nitrogen other than nitrous oxide
NPS	National Protocol System
NPW	net present worth
NRM	NAASRA Roughness Meter
NRMA	National Roads and Motorists' Association
NRRL	Norwegian Road Research Laboratory
NSW	New South Wales
O_3	ozone
OECD	Organisation for Economic Cooperation and Development
Pa.s	pascal seconds
PCU	passenger car unit
pH	percentage hydrogen
PIARC	Permanent International Association of Road Congresses
PMB	polymer-modified binder
PSI	Pavement Serviceability Index
PUR	Pavement User Rating
PVC	polyvinyl chloride
QI	Quarter-car Index
RACV	Royal Automobile Club of Victoria
RIAM	Road Infrastructure Assessment Model
RTA	Roads and Traffic Authority (NSW)
SAM	strain alleviating membrane
SAMI	strain alleviating membrane inter-layer
SMA	stone mastic asphalt
SMTD	sensor-measured texture depth
SMVU	survey of motor vehicle usage
SN	structural number
SNC	modified structural number

SPL	sound pressure level
SRIA	Steel Reinforcement Institute of Australia
$SSCO_2$	supercritical carbon dioxide
t	tonnes
TRB	Transportation Research Board
UK	United Kingdom
US	United States
VETO	computer program for calculation of transport costs as a function of road standard (developed by the Swedish Road and Traffic Institute)
VicRoads	Roads Corporation Victoria
VKT	vehicle-kilometres travelled
VOCs	vehicle operating costs
VTI	Swedish National Road and Transport Research Institute

REFERENCES

ABBREVIATIONS

AAPA	Australian Asphalt Pavement Association
AASHTO	American Association of State Highway and Transportation Officials
ABS	Australian Bureau of Statistics
AGPS	Australian Government Publishing Service
ARFCOM	ARRB Road Fuel Consumption Model
ARRB	Australian Road Research Board
ASTM	American Society for Testing Materials
BTCE	Bureau of Transport and Communications Economics
FHWA	Federal Highway Administration
IPCC	Inter-governmental Panel on Climate Change
NAASRA	National Association of Australian State Road Authorities
NCHRP	National Cooperative Highway Research Program
NRMA	National Roads and Motorists' Association
OECD	Organisation for Economic Cooperation and Development
PIARC	Permanent International Association of Road Congresses
RTA	Roads and Traffic Authority
SAE	Society of Automotive Engineers
TRB	Transportation Research Board
TRRL	Transport and Road Research Laboratory
VicRoads	Roads Corporation Victoria
VTI	Swedish National Road and Transport Research Institute

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