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ROAD IMPROVEMENTS AND GREENHOUSE GAS EMISSIONS

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Abstract

Reducing the roughness of roads is a means of reducing fuel consumption of vehicles, and therefore also of greenhouse gas emissions. This paper uses models developed by the Bureau of Transport Economics (BTE) in Australia to estimate costs and emissions reductions associated with progressively lower roughness levels of Australian highways. The analysis covers the period 1996-2015. Total, average and marginal costs are estimated for each of four 'snapshot' years: 2000, 2005, 2010 and 2015. The results provide an assessment of the cost-effectiveness of reducing the roughness of highways as a greenhouse gas mitigation measure. Other benefits and equity effects of such a measure are also discussed.

INTRODUCTION

Road passenger transport currently accounts for about 60 per cent of total CO_2 equivalent emissions in the Australian transport sector (BTCE, 1995a). Most of these emissions are from cars, with only 1.8 per cent of emissions attributable 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).

Improving the surface of roads can result in reduced emissions of greenhouse gases because it has been found in a number of studies that road surface roughness (also called 'evenness') is related to vehicle fuel consumption. The lower the roughness of roads, the lesser the amount of fuel consumed.

Decreasing the roughness of roads therefore has the potential to reduce greenhouse gas emissions without curtailing travel. This paper assesses the cost-effectiveness of reducing the roughness of the Australian National Highway System (NHS) and a major interstate highway (Pacific Highway) as a means of reducing greenhouse gas emissions from vehicles using the highways. Estimates are presented of costs and greenhouse gas reductions from cars and rigid and articulated trucks resulting from highway rehabilitation.

The total length of the NHS and the Pacific Highway is over 19 000 kilometres. 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.

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 vehicle operating costs (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 remedial action can also considerably reduce overall future road maintenance and rehabilitation costs.

ROAD ROUGHNESS AND ITS EFFECTS

Road condition is a many-faceted concept that 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).

Paterson (1987) 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 numerical scale of roughness, the roughness of a true planar surface would be zero.

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 that have been specified by

PIARC (1987). 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.

Roughness can be objectively measured using mechanical devices mounted on vehicles driven over the road surface. 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). The units of IRI are dimensionless because it is a slope statistic. In Australia, roughness is generally recorded in terms of National Association of Australian State Road Authorities (NAASRA) Roughness Meter (NRM) counts. Regression equations relating IRI to NRM are set out in Prem (1989). 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).

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. Roughness has an influence on vehicle fuel consumption, tyre/pavement contact, vehicle occupant comfort (due to high frequency vibrations) and noise. Increased roughness reduces surface drainage and increases water accumulation thereby 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. Although 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 life of a highway section comprises a number of cycles. As pavements progressively deteriorate and become too rough, they are rehabilitated (resurfaced or reconstructed). 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 in table 1.

When a pavement is rehabilitated, it commences a new life cycle from which point it begins to deteriorate again. 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.

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.

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 used in this study: sprayed seal reconstruction, asphalt reconstruction, asphalt overlay and Novachip overlay (table 1). Novachip (a proprietary product) is a type of ultra-thin asphalt. The most appropriate treatment was assumed to be applied to the various sections of the highways.

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 rehabilitation was carried out in all 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) remains constant regardless of terminal roughness, and therefore it has not been included in the analysis.

Roughness

The Road Infrastructure Assessment Model (RIAM), developed by the Bureau of Transport Economics (BTE) (the BTE was previously known as the Bureau of Transport and Communications Economics) in Australia, 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) to determine annual roughness levels based on pavement age, traffic volume and initial roughness. The model is described in the appendix.

Table 1 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 an asphalt industry formula: new roughness = 0.6 × current roughness + 5

Sources Australian Asphalt Pavement Association (personal communication) and BTE estimates.

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 Australian State authorities suggests that roughness after an asphalt reconstruction may be below 35 NRM, but is typically between 35 and 45 NRM. Post-rehabilitation roughness levels of between 39 and 52 NRM have been achieved for recent sprayed seal work on the Western

Highway in Victoria. The average roughness consequent to each type of rehabilitation was determined after consultation with road agency and industry sources (table 1).

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 (Highway Design and Maintenance Model version III) model as modified by the BTE. The BTE's modified version, known as HDM-C ('C' denoting congestion), enables the effects of congestion to be taken into account in estimating VOCs. The BTE'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 the appendix.

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 (1996). 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 generate some greenhouse gas emissions. OECD (1984) 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.

Savings in fuel consumed due to highway rehabilitation would effectively result in a decrease in the fuel costs of travel, which may tend to increase the use of motor vehicles (the 'rebound effect'). Available estimates of the rebound effect, such as in the study by Greene (1992) using American data, indicate that it is quite small (5-15 per cent or less). The rebound effect due to rehabilitation of the Australian highway system was considered small enough to be ignored in this study.

Costs and benefits

The change in total social costs due to pavement rehabilitation has been estimated as the sum of changes in VOCs, highway rehabilitation costs, fuel producers' costs and health 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 post-rehabilitation roughness and pavement depth estimates, an average rehabilitation cost based on data obtained from Australian State and Territory road authorities was used for the entire NHS and the Pacific Highway. These costs (in 1996 Australian dollars per square metre) were: sprayed seal reconstruction $30.00; asphalt reconstruction $37.50; asphalt overlay $17.50; and Novachip overlay $12.00.

In this study, 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 it has been assumed that the 'rebound effect' is negligible, traffic volumes, and therefore also travel times, would not change with changes in roughness.

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, 1996).

Health costs due to changes in fuel use are likely to be very small, especially in rural areas. Only oxides of nitrogen (NO_x) and non-methane volatile organic compounds (NMVOCs) have measurable health costs, estimated at $0.02 per kilogram (BTCE, 1996).

EMISSION REDUCTIONS AND COSTS INVOLVED IN AUSTRALIAN HIGHWAY REHABILITATION

Table 2 shows changes in emissions and costs resulting from implementing appropriate rehabilitation at terminal roughness levels of 100, 90, and 80 NRM. 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.

As a means of reducing greenhouse gas emissions, highway rehabilitation is evidently quite costly. Overall, 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) 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, 1995b).

Emission reductions per kilometre of road length are quite 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 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 with a consequent increase in emissions due to rehabilitation.

Table 2 Rehabilitation of the National Highway System and the Pacific Highway: social costs[a] of reductions in emissions cumulated from 1996

(1996 Australian dollars)

(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 (1996 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.

Table 3 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.

EQUITY ISSUES

Total costs of rehabilitating the NHS and the Pacific Highway from 1996 to 2015 (discounted at a rate of 10 per cent) are $304 million at a terminal roughness of 100 NRM, $733 million at 90 NRM and $1 364 million at 80 NRM. Table 4, which details the components of total social costs for 2015, shows 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.

The Commonwealth Government would lose excise, sales tax and import duties and State and Territory Governments would lose fuel tax revenue. 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.

Highway rehabilitation results in lower fuel consumption and vehicle maintenance costs. Consequently, producers, wholesalers and retailers of fuel would lose revenue. The vehicle repair, maintenance and spare parts sectors would also lose revenue.

Highway rehabilitation generally causes some temporary disruption to traffic and inconvenience to motorists. The effects include reduced speed and delays, windscreen and chassis damage, increased crash risk due to altered road and traffic conditions and 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 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.

Table 4 Components of total social costs[a] of rehabilitating the NHS and the Pacific Highway from 1996 to 2015

	(1996 $ 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.

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.

CONCLUSIONS

Reducing the roughness of roads is a means of reducing greenhouse gas emissions without curtailing travel. However, as a greenhouse mitigation measure it is not highly cost-effective. A 9 per cent reduction in roughness from the basecase level (from 110 to 100 NRM) would result in a cumulative reduction of only about 0.4 million tonnes of CO_2 equivalent emissions between 1996 and 2015 at a marginal cost of about $250 per tonne.

With progressive reductions in roughness, cumulative emissions reduced would only rise modestly, but marginal costs would rise steeply. A reduction in roughness from 110 to 90 NRM would result in a cumulative reduction of 0.8 million tonnes at a marginal cost of $700 per tonne. A further decrease in roughness to 80 NRM would result in a cumulative reduction in emissions of 1 million tonnes at a marginal cost of over $1 500 per tonne.

Although greenhouse gas reductions would be quite modest, reducing the roughness of the Australian highway system would have several other benefits. These benefits would include a reduction in crash risk due to reduced driver fatigue and road condition, increased skid resistance, reduced damage to freight, improved passenger comfort, reduced windscreen and chassis damage to vehicles, and flow-on effects of lower transport costs to all areas of the economy. A possible disbenefit may be an increase in crash risk due to motorists tending to compensate for better driving conditions by behavioural adjustments such as increased speed and reduced attention to the driving task. There would also be some equity implications, including the large costs incurred by Federal and State governments on account of increased road expenditure together with reduced fuel excise revenue.

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REFERENCES

Australian Bureau of Statistics (1991) **Survey of Motor Vehicle Use, Australia, 30 September 1988** Cat. no. 9208.0. ABS, Canberra.

Australian Road Research Board (1996) **Road User Costs for Use in Economic Evaluation of Road Expenditures: Unit Values as at 30 June 1995**. Working Document WD AM 96/027. ARRB Transport Research Ltd, Vermont South, Victoria.

Austroads (1997) **Road Facts '96: An Overview of Australia's Road System and Its Use.** Austroads, Sydney.

BTCE (1990) **Pavement Management: Development of a Life Cycle Costing Technique**. Bureau of Transport and Communications Economics. Occasional Paper no. 100. Australian Government Publishing Service, Canberra.

BTCE (1994) **Adequacy of Transport Infrastructure: Intercity Roads**. Working Paper 14.1. Bureau of Transport and Communications Economics, Canberra.

BTCE (1995a) **Greenhouse Gas Emissions from Australian Transport: Long-Term Projections**. Bureau of Transport and Communications Economics. Report no. 88. Australian Government Publishing Service, Canberra.

BTCE (1995b), **Building for the Job: Commissioned Work, Volume 1: BTCE Report**. Bureau of Transport and Communications Economics. National Transport Planning Taskforce, Canberra.

BTCE (1996) **Transport and Greenhouse: Costs and Options for Reducing Emissions.** Bureau of Transport and Communications Economics. Report no. 94. Australian Government Publishing Service, Canberra.

Greene, D.L. (1992) Vehicle use and fuel economy: How big is the "rebound" effect?, **The Energy Journal 13**, 117–43.

Martin, T.A. (1996) **Review of Existing Pavement Performance Relationships.** Australian Road Research Board Research Report no. 282. ARRB Transport Research Ltd, Vermont South, Victoria.

OECD (1984) **Road Binders and Energy Savings**, Organisation for Economic Cooperation and Development, Paris.

Paterson, W.D.O. (1987) **Road Deterioration and Maintenance Effects: Models for Planning and Management**. The John Hopkins University Press, Baltimore.

PIARC (1987) **Technical Committee Report on Surface Characteristics.** XVIIIth World Road Congress. Brussels, 13–19 September 1987. Permanent International Association of Road Congresses, Paris.

Prem, H. (1989) **NAASRA Roughness Meter Calibration Via the Road-Profile-Based International Roughness Index (IRI)**. Australian Road Research Board Report 164. ARRB, Vermont South, Victoria.

VicRoads (1992) **'A Stitch in Time' for Victoria's Arterial Roads.** VicRoads, Kew, Victoria.

APPENDIX : RIAM AND HDM-C MODELS

The two models used to generate the results presented in this paper are the BTE'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 BTE 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.

RIAM

RIAM estimates the deterioration in roughness over time for flexible pavements (asphalt, sprayed seal and Novachip)

Paterson's algorithm (Paterson, 1987), 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:

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

where t is the time in years since the last rehabilitation; $R(t)$ is roughness at time t in IRI units; R_0 is roughness at time zero (post-rehabilitation roughness); k is a constant reflecting the effect of traffic on the pavement; SNC is the modified structural number (a measure of pavement strength); $\gamma(t)$ is millions of cumulative equivalent standard axle loads (ESALs) per lane from time zero to time t (RIAM assumes that each commercial vehicle contributes 2.5 ESALs and that cars do not contribute any ESALs); and m is a constant reflecting the effect of time and weathering on the pavement.

Data on the SNCs of pavements are not readily available. RIAM therefore assumes that the pavement has been built to NAASRA design standards. RIAM obtains SNCs from a regression equation derived in BTCE (1990) relating structural number to design traffic:

$$SNC = 0.40 * \log_{10} DT + 3.00 \qquad (2)$$

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 (table 1).

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 highway sections in 1996 (drawn from a highways database) and corresponding annual average daily traffic (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 accordingly 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. Costs will vary from section to section of a particular road depending on terrain and distance from sources of raw materials, and cost estimates used 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 is made up of five modules which estimate free speed, capacity, volume–capacity ratio, actual speed, and costs. Figure 1 shows the linkages between the different modules.

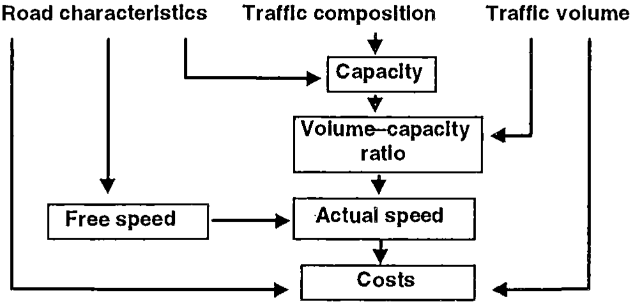

Figure 1 Flow chart of the HDM-C model

In this analysis, free speed (speed achieved on an uncongested road) was set equal to the speed limit. Given that the national highways are 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 and varied from 1.7 for a rigid truck on flat terrain to 15 for an articulated truck on mountainous terrain (BTCE, 1994).

Because traffic is not constant throughout the day, HDM-C determines actual traffic volume on an hourly basis. Histograms showing the variation in the volume of traffic for each hour over the year (BTCE, 1994) were used in the analysis.

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:

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

HDM-C estimates the avoidable vehicle operating costs including fuel, oil, maintenance parts, maintenance labour, tyres and occupants' time. 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.

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 Australian Road Research Board (1996). However, the BTE has separately estimated vehicle-kilometres travelled. These estimates relate to the total vehicle-kilometres travelled by a vehicle up to the average age of the vehicle class. 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 fall steadily as vehicles age.

Unit vehicle-related and occupant costs used in the analysis are set out in table 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 5 UNIT COSTS USED IN THE ANALYSIS

	Cars		Rigid trucks		Articulated vehicles	
Item	Fin[a]	Econ[b]	Fin[a]	Econ[b]	Fin[a]	Econ[b]
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)[c]	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. Financial costs (include taxes)

b. Economic costs (exclude taxes)

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

Sources BTE estimates based on Australian Road Research Board (1996), Australian Taxation Office (personal communication), National Roads and Motorists' Association (personal communication), Roads and Traffic Authority of New South Wales (personal communication), Australian Bureau of Statistics (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.