REVIEW OF VEHICLE OPERATING COSTS AND ROAD ROUGHNESS: PAST, CURRENT AND FUTURE

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ABSTRACT

Lower vehicle operating costs associated with reduced pavement roughness are an established key component of road improvement benefits. The increasing emphasis of road agencies on asset management, a major component of which is economic evaluation of whole of life pavement options, has made accurate estimation of road roughness vehicle operating cost (VOC) relationships of increasing importance. However, in Australia, since the mid 2000s a shift in emphasis from research to application has resulted in a relative hiatus in further development of VOC roughness relationships. Renewed interest by transport agencies coupled with advances overseas have generated momentum to increase research in the area. However, prior to this, there is a need to establish a VOC road roughness baseline, an issue explored in this paper.

This paper seeks to consolidate local and international research, and establishes whether overseas and Australasian investigations and modelling have improved the VOC – road roughness linkages. It traces the evolution of knowledge, starting from past decades covering international work to recent Australian efforts. Roughness effected VOC components, namely, fuel consumption, repairs and maintenance costs, tyre wear and lubricating oil costs are examined in light of model applications and empirical findings. Recent Australian work is compared with international experience. Effects of roughness on travel time costs are not specifically covered.

The paper suggests a way forward for future Australasian research. Options canvassed include a gap analysis of current models vis-à-vis user needs, revisitation of the now defunct Austroads Road User Cost Steering Group (RUCSG) program, and linkages to the European Union (EU)-sponsored MIRIAM project. The latter demonstrates the influence of road surface condition measures other than roughness, e.g. micro, macro and mega texture, on VOC. The review highlights a critical need for further investigation and updating of Australasian road surface condition VOC relationships.

INTRODUCTION

Road surface roughness is one of a multiplicity of factors determining vehicle operating cost (VOC), which are often grouped under three headings: vehicle, road, and traffic. Both domestically and overseas, the impact of individual factors (such as road roughness) have been evaluated using fairly standard methodologies, where the effect of the factor on individual VOC components is examined with all other factors being held constant where possible. Despite similarities in approach, portability of results across national boundaries has been limited, and coverage and adequacy of relationships varies across jurisdictions. Lack of portability cannot be solely attributed to expected factors such as differing vehicle types, technology, road types, traffic levels and composition, but can also reflect experimental approach and modelling approaches used to report results. For example, analyses reporting outcomes in monetary units, or via equations where parameter values are purely statistical and do not reflect physical attributes, have limited portability. Since the mid 1990s, two inter-related strategies have been developed to address these issues. The first has been the more widespread use of ‘mechanistic’ modelling processes in which the effects of independent variables, such as road
roughness, measured in reproducible physical units on VOC components, such as fuel consumption, are measured and modelled in terms of underlying engineering and physics. Conversion to monetary units is achieved via application of appropriate unit costs. HDM-4 technology (Odoki & Kerali 2000) is a case in point, which has been readily adapted to Australian conditions due to its mechanistic structure (Thoresen & Ronald 2002). The second approach has been to use an overarching mechanistic model such as TRARR (Botterill 1997) to derive underlying physical estimates, which are then subsequently modified to suit the evaluation project into which these are embedded. However, despite these approaches, and a growing portability in approach across jurisdictions and national boundaries, the extent and application of knowledge on road roughness VOC relationships is currently fractured.

This paper seeks to address this issue by consolidating local and international research on VOC and road roughness into a single source and establishes if a consistent scientific relationship can be reached for the Australian context, based on the work of Austroads (2011). The evolution of the research is traced, covering international work from the US, UK, Europe, Australia and developing countries. Road roughness is assessed against the key VOC components of fuel consumption, repairs and maintenance costs, tyre wear and lubricating oil costs. The empirical findings are reviewed in light of the VOC components. Modelling considerations are formed and a way forward is suggested on how the research on road relationships underpinning road user costs (RUC) can proceed.

**EVOLUTION OF KNOWLEDGE**

A chronological review of VOC model development is of use as it allows existing VOC models to be placed in context. The evolution of knowledge on VOC – roughness relationships can be distinguished into four phases: pre-1970s, 1970s/1980s, 1980s and beyond, and the current period (Figure 1) terminating in 2012.

![Figure 1: Evolution of knowledge: VOC – roughness relationship](image)

Pioneering overseas work started in the pre-1970s where the research was characterised as broad-level with observable correlations between VOC and road roughness (Law & Kinnear-Clark 1881; Agg 1923; Moyer & Winfrey 1939; Winfrey 1963, 1969). Throughout the 1970s/1980s, the science and framework for VOC – roughness relationship formulation was improved, with numerous empirical studies being undertaken, often using data collected from developing countries using regression techniques to transform findings into predictive equations for use in road project evaluation packages (Hide et al. 1975; Hodges, Rolt & Jones 1975). Regression equation type is often described as ‘statistical’, as its structure did not seek to emulate the mechanical engineering processes which limit and generate road user resource use. The post-1980s witnessed the formation of ‘mechanistic’ models (i.e. HDM-III and HDM-4) which modelled resource consumption in terms of underlying physics and mechanical engineering processes and could be adapted to suit a range of road conditions in developed and developing countries. To date, application of VOC models has become widespread and mechanistic models lend themselves to ready adaptation to handle updated vehicle technology and a changing vehicle fleet. It should be noted that most developments related to VOC
relationships are applied in non-urban or non-congested contexts (uninterrupted flow), with far less work being carried out in congested (interrupted flow) traffic contexts.

In parallel, extensive efforts were undertaken in Australia to develop methodologies capable of estimating RUCs and their sensitivity to road conditions in both non-urban and urban settings (Lloyd 1988). Work commenced in the late 1960s largely initiated by the former Commonwealth Bureau of Roads, proceeded through the 1970s and 1980s under NAASRA, and culminated in an Austroads Road User Cost Steering Group (RUCSG) program covering the period 1994–2005 (Peters 2001). This program provided a harmonisation process where algorithms, procedures and values could be used by agencies to benchmark their models to agreed costs and technologies often compatible with overseas models. Research findings from Australia and overseas were blended to update archetype models such as NIMPAC and RURAL (Both & Bayley 1976), which formed the basis of evaluation procedures of road agencies.

An issue is that the RUCSG program is not well known to current practitioners, as the reports are technical documents and circulated to a limited targeted audience. Since the finalisation of the RUCSG in the mid-2000s, improvements of RUC estimation methodologies in Australia have been ad hoc, or have been undertaken as part of non-VOC dedicated projects (Michel et al. 2008). As a consequence, practitioners have been challenged with keeping up-to-date with developments, and a scientific consensus on adequacy of the VOC – roughness relationship and development needs has yet to be reached.

**OVERVIEW OF VOC ROUGHNESS LITERATURE**

Table 1 presents a brief overview of both national and international literature on VOC – roughness studies extending across both developed and developing countries. This review investigates the modelling approaches and empirical findings, and determines which relationships established internationally can be used in formulating modelling considerations for Australia.

<table>
<thead>
<tr>
<th>Country</th>
<th>Fuel consumption</th>
<th>Tyre use</th>
<th>Repair and maintenance</th>
<th>Lubricating oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Zealand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 A feature is the development by agencies of their own model variants based on these archetypes, e.g. TRARR traffic modelling package (Botterill 1997) and ARFCOM fuel consumption package (Biggs 1989).
<table>
<thead>
<tr>
<th>Country</th>
<th>Fuel consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>Young (1988)</td>
</tr>
<tr>
<td>France</td>
<td>Laganier &amp; Lucas (1990)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Descornet (1990)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Sandberg (1990)</td>
</tr>
<tr>
<td>Other countries</td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>du Plessis, Visser &amp; Curtayne (1990)</td>
</tr>
<tr>
<td>Caribbean</td>
<td>Hide (1982)</td>
</tr>
<tr>
<td>Kenya</td>
<td>Hide et al. (1975)</td>
</tr>
<tr>
<td>Korea</td>
<td>Ko et al. (2009)</td>
</tr>
<tr>
<td>International</td>
<td>Bennett &amp; Greenwood (2000)</td>
</tr>
<tr>
<td></td>
<td>Bennett &amp; Greenwood (2000)</td>
</tr>
<tr>
<td></td>
<td>Bennett &amp; Greenwood (2000)</td>
</tr>
<tr>
<td></td>
<td>Bennett &amp; Greenwood (2000)</td>
</tr>
</tbody>
</table>

Note:
1. Further information on modelling road user and environmental effects in HDM-4 for international countries can be found in Bennett and Greenwood (2000).
2. In the TRB (n.d.) study, there is a large body of research available on the effects of pavement conditions on VOCs and models used to estimate these effects. Many of the models were developed on data generated some 30 years ago in other countries for vehicle fleets that vary substantially from those used currently in the US and for the roadways that differ from those built in the US.

**FUEL CONSUMPTION**

Fuel consumption studies have received a large proportion of the attention on VOC – roughness relationships since they allow for ease of modelling and experimentation.

**Modelling approaches**

Two modelling approaches are identified, namely, regression models and mechanistic models. Regression studies examine the effect of road types on fuel consumption but they do not capture an objective roughness measure as the International Roughness Index (IRI) was not yet invented. Examples include De Weille (1966) for sealed versus unsealed roads, Claffey (1971) for paved versus hard-packed gravel, and Bonney and Stevens (1967) for bitumen versus improved or unimproved earth roads. Later studies apply a roughness measure but mixed findings were reported. A positive roughness – fuel consumption relationship was reported in Ross (1982) and Zaniewski et al. (1979), but a later work by Zaniewski (1983) found the roughness effects to be insignificant.

Overall, regression models have not succeeded in achieving consistency in the results. Regression techniques are not easily transferrable to new vehicle technology e.g. petrol-fuelled heavy vehicle studies are obsolete in view of diesel technology (Bonney & Stevens 1967; De Weille 1966; Winfrey 1969) and there is a need to adequately account for all of the pavement condition characteristics, an area which has not been researched adequately in the past (du Plessis, Visser & Curtayne 1990). There is also some experimental error and lack of robustness.
associated with on-board measurement of fuel, e.g. roughness effects were insignificant or small compared to alignment effects (Moyer 1939; Claffey 1971).

Mechanistic models are established from recognised mechanical principles of motion and vehicle kinematics, i.e. Newton's First and Second Laws of Motion. Two types prevail in Australia: NIMPAC and HDM-type models. The general NIMPAC-style models are expressed as:

\[
\text{Fuel consumption} = \text{Basic fuel/speed relationship} \times \left[ 1 + \text{Engine efficiency adjustment} + \text{Gradient adjustment} + \text{Curvature adjustment} + \text{Road roughness adjustment} + \text{Traffic congestion adjustment} \right]
\]

The HDM equations are less standardised in terms of structure and do not have the added simplicity of NIMPAC-style models. Fuel consumption in HDM-III models is expressed as:

\[
\text{Fuel consumption (litres/1000 km)} = \text{Engine efficiency adjustment} \times \left[ \text{Fuel use at idle} + \text{Grade (adjustment + roughness)} \times \text{Vehicle mass adjustment} \times \text{Air speed} + (\text{resistance} \times \text{speed}^2) \right]
\]

In HDM-4 models, the World Bank replaced the fuel consumption algorithm in HDM-III models with those derived from ARFCOM (ARRB Road Fuel Consumption Model) initially developed in the late 1980s (Biggs 1989). By appropriate manipulation of ARFCOM which is a fully implemented mechanistic model, it is possible to generate steady speed fuel consumption relationships for a range of road and traffic conditions, including roughness which is modelled as impacting on rolling resistance. When ARFCOM is used in this fashion, the traditional U-shape fuel—speed relationship is replaced by a ski-slope shape, which demonstrates the impacts of technology improvements like electronic fuel injection, better aerodynamic design, radial tyres with lower rolling resistance, etc. which have come into effect since initial studies were undertaken in the late 1960s.

Mechanistic models have greater application value as new vehicle technology in tyres or vehicle design can be incorporated by revising estimates for various coefficients without having to re-run a major experiment (McLean & Foley 1998). Such models have greater flexibility across vehicle types as fuel equations for a specific vehicle type can be easily adjusted to suit another by adjusting the relevant coefficients (du Plessis, Visser & Curtayne 1990). Given the greater application value, mechanistic models are recommended as more suitable for Australia.

**Empirical findings**

Table 2 presents studies pertaining to the roughness effects on fuel consumption (and rolling resistance) from mechanistic models. Most were conducted for different vehicle types covering ranges of roughness levels on sealed roads. Three methods were employed: direct fuel measurement, rolling resistance measurement³, and model calibration.

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² Further description of Newton’s First and Second Laws of Motion are found in du Plessis, Visser and Curtayne (1990).

³ For the rolling resistance method, there was a direct conversion from rolling resistance effects to fuel consumption effects. A factor of five for cars and four for trucks was used to convert results reported as change in rolling resistance to an equivalent change in fuel consumption. This factor was derived from Descornet’s (1990) report where for a 1% change in fuel consumption, there was a 5% change in rolling resistance for cars and a 4% change for trucks at constant speed.
Overseas studies for light vehicles

Studies covering light vehicles using direct fuel measurement over a range of road surfaces show a positive correlation between fuel consumption and road roughness. In Ross (1982) for the US, for a roughness range of 0.5 to 3.7 IRI, there was a 0.4% increase in fuel consumption per unit of IRI. The UK study (Young 1998) showed a rise in fuel consumption (0.8%) for a higher roughness range (1.7 to 5.4 IRI). Fuel consumption increased by 1.7% per unit of IRI for a higher roughness range of 1 to 6 IRI in Sweden (Sandberg 1990). Delanne (1994) reported that fuel consumption rose by up to 6% over a range of surfaces with increasing roughness levels in France.

Studies using rolling resistance measurement over a range of surfaces established that increasing roughness levels leads to greater fuel consumption for light vehicles driving on sealed roads. The lowest roughness range from the US study (1.4 to 5.5 IRI) reported a 0.5% change in fuel consumption per unit of IRI (Bester 1984). The change in fuel consumption per unit of IRI rose to 0.8% for a higher roughness range of 0.8 to 7.7 IRI for Belgium (Descornet 1990) and 1.2% for an IRI range of 1 to 6 for France (Laganier & Lucas 1990).

HDM-4 models were calibrated to suit US road conditions and also predicted a positive roughness effect for light vehicles in Zaabar and Chatti (2010). Over 1 to 5 IRI, there was a 0.9% rise in fuel consumption per unit of IRI for cars and a 0.4% rise for sports utility vehicles (SUVs).

Table 2: International studies: roughness effect on fuel consumption at constant speed

<table>
<thead>
<tr>
<th>Country/Source</th>
<th>Method</th>
<th>IRI range*</th>
<th>Vehicle type</th>
<th>Rolling resistance (% change per unit IRI)</th>
<th>Fuel consumption (% change per unit IRI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Ross (1982)</td>
<td>Direct fuel measurement – range of surfaces</td>
<td>0.5 to 3.7</td>
<td>Car</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>US Bester (1984)</td>
<td>Rolling resistance – range of surfaces</td>
<td>1.4 to 5.5</td>
<td>Car</td>
<td>2.6</td>
<td>0.5</td>
</tr>
<tr>
<td>US Zaabar &amp; Chatti (2010)</td>
<td>HDM-4 model calibrated to US conditions</td>
<td>1 to 5</td>
<td>Car (medium) Car (SUV) Truck (articulated)</td>
<td>0.9</td>
<td>0.4 0.6</td>
</tr>
<tr>
<td>Brazil Watanatada et al. (1987)</td>
<td>Rolling resistance – range of surfaces</td>
<td>2 to 14</td>
<td>Car Truck</td>
<td>2.5 1.8</td>
<td>0.5 0.5</td>
</tr>
<tr>
<td>UK Young (1988)</td>
<td>Coast-down – artificial roughness Direct fuel measurement – artificial roughness Direct fuel measurement – vehicles side by side</td>
<td>1.3 to 4.0 3.3 to 5.6 2.3 to 4.4 1.7 to 5.4</td>
<td>Truck Car Car Car</td>
<td>4.1 3.1 3.6 0.8</td>
<td></td>
</tr>
</tbody>
</table>
### Overseas studies for heavy vehicles

Studies examining heavy vehicles using rolling resistance measurement revealed a positive correlation between fuel consumption and roughness. For a given roughness range of 2 to 14 IRI, there was a 0.5% change in fuel consumption per unit of IRI for Brazil (Watanatada et al. 1987). Fuel consumption increased to 1.1% per unit of IRI when the range increased to 1.2 to 15 IRI for South Africa (du Plessis, Visser & Curtayne 1990). When the HDM-4 model was calibrated to suit US road conditions in Zaabar & Chatti (2010), there was a 0.6% rise in fuel consumption per unit of IRI over 1 to 5 IRI for articulated trucks.

Studies undertaken for the US and New Zealand also reveal a positive correlation between road roughness and fuel consumption. There was a 0.13% and 0.45% change in fuel consumption per unit IRI in Florida and Nevada, respectively (Epps et al. 2002; Jackson 2004; Sime & Ashmore 2000). In New Zealand, results from a Public Goods Science Fund (PGSF) study showed that at a steady speed of 70 km/h, truck fuel consumption was expected to increase by 0.8% per unit increase in IRI (Jamieson & Cenek 1999).

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* The US method of measurement was not stated in Gillespie and McGhee (2007).
**Australian studies**

Early Australian studies report a positive correlation between fuel consumption and road roughness. A BITRE study (then BTCE 1996) examined the impacts of road roughness on VOC for the Australian National Highway System (NHS). VOCs were derived from World Bank parameters calibrated with Australian cost figures from the National Roads and Motorists’ Association (NRMA) (1989) for cars and trucks. A 3% to 11% change in VOC per unit of IRI of roughness change was reported. Another HDM-type study on the effects of highway rehabilitation on VOCs was estimated in BTCE (1997) using hypothetical one-kilometre road sections with an average annual daily traffic (AADT) of 1000 over a roughness range of 1.2 to 5.8 IRI. In terms of fuel use, there was an increase of 0.9% for cars and 0.9 to 1.4% for trucks per unit increase in IRI.

Recent Australian work focussed on the effects of the National Transport Commission (NTC) 3rd Heavy Vehicle Road Pricing Determination on VOCs for heavy vehicles (Thoresen 2004). Over a roughness range of 1.9 to 3.2 IRI, an increase in fuel consumption of 4.5% for rigid trucks, 5.5% for articulated trucks, and 7% for B-doubles per unit increase in IRI was recorded. Over a higher roughness range of 3.2 to 3.9 IRI, fuel consumption rose further by 27.3% for rigid trucks, 27.8% for articulated trucks, and 51.2% for B-doubles on a per unit increase in IRI (Figure 2).

![Figure 2: Fuel consumption with roughness for heavy vehicles at constant speed](image)

**Source:** Thoresen (2004).

**Effect of Roughness: Variable Speed**

To determine the relationship between fuel consumption and roughness at variable speeds, the relation between (i) roughness and speed, and (ii) speed and fuel, should be examined. Studies examining the roughness–speed relation have established a negative correlation between the two as roughness serves to decrees ride comfort and drivers reduce their speed accordingly (Botterill 1996; Botterill 1997; Thoresen & Roper 1999). On the speed–fuel relationship, studies point towards a positive association. A recent study using HDM-4 models shows that at low speeds, increasing speed serves to decrease distance-related fuel consumption because a greater distance is covered during each unit of time-related fuel consumed. After an initial acceleration point, fuel consumption increases with speed (Figure 3).

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5 The NTC 3rd Heavy Vehicle Road Pricing Determination evaluates the feasibility of incremental and individual user pricing options for possible incorporation in road user charges for heavy vehicles in Australia, with a view to narrowing the range of viable options which could be implemented in Australia.
The negative roughness–speed and positive fuel–speed relationships imply a net effect in terms of fuel use and road roughness. These two effects offset each other and the net effect can be indeterminate (in terms of directional change). Recent Australian work under variable speed conditions illustrate that the roughness–fuel consumption relationship is indeterminate (Thoresen 2004). Over a roughness range of 1.9 to 3.2 IRI, a drop of 7.1% to 13.3% in fuel consumed for heavy vehicles on a per unit IRI basis was reported. However, over a roughness range of 3.2 IRI to 3.9 IRI, fuel consumption rose 3% to 27% on a per unit IRI basis.

**Summary of findings**

Roughness affects the amount of fuel consumed in vehicles. Under constant speeds, overseas and Australian models have displayed consistency in that an increase in roughness leads to higher fuel consumption per unit increase in IRI i.e. 0.5% to 1.7% increase in car fuel.
consumption and a 0.13% to 1.2% increase in heavy vehicle fuel consumption\(^6\). To the extent that the results are consistent across countries (including Australia), they are considered to be robust. This suggests that the ‘direct fuel measurement – range of surface’ and ‘rolling resistance – range of surface’ methods are reliable\(^7\).

The consistency ends with the imposition of the new NTC heavy vehicle charging regime. For Australia, the new regime leads to much higher fuel use for trucks per unit of IRI (4.5% to 7.0% for 1.9 to 3.2 IRI) compared to overseas models (0.5% to 1.2%) and the earlier Australian studies (0.9% to 1.4% for 1.2 to 3.3 IRI), escalating further with higher roughness levels (33 to 61% for 3.2 to 3.9 IRI).

Under variable speeds, the lack of consistency in the results is partially due to the countervailing effect. That is, while increasing roughness increases fuel consumption at any given speed, increasing roughness also reduces travel speed, which reduces fuel consumption per unit distance for most free running travel speeds. The net effect from the negative roughness-speed relation and the positive fuel-speed relation can sometimes be indeterminate, as these two effects offset each other.

**REPAIRS AND MAINTENANCE**

Next to fuel consumption, repairs and maintenance studies are quite sizeable in number. In Australia, two basic modelling approaches have been pursued, namely those associated with NIMPAC and HDM models. Overseas, a range of HDM and similar approaches have been adopted. A common feature of most studies is the limited extent to which it has been possible to implement a mechanistic approach.

**Modelling approaches**

In NIMPAC models, repair and maintenance costs are assumed to be sensitive only to variations in road surface type and conditions. The algorithm used to calculate the pavement condition index (PAVIND) as set out in NAASRA (1982) is:

\[
\text{PAVIND} = 5 \times \left(1 - \frac{\text{CNRM} - 50}{\text{NRMA}}\right)
\]

where CNRM is the current NAASRA roughness meter counts per km, and NRMA is the model parameter with a fixed value of 250. The relationship between road roughness and repairs and maintenance is indirect. PAVIND is then multiplied by a vehicle-type-dependent number to arrive at a factor to apply to both vehicle repairs and maintenance and to depreciation costs. Roughness counts are measured in NRM units, which are readily converted into International Roughness Index (IRI) units as used in HDM. Base repair and maintenance costs, and roughness relationships, have been the subject of limited investigation and verification (Thoresen 1999).

In HDM-III and HDM-4 road evaluation models, parts and labour costs are modelled sequentially. Parts’ costs are modelled as a proportion of the new vehicle price. Maintenance labour is partially based on maintenance parts consumption. Compared to the NIMPAC models, the HDM model estimates repairs and maintenance in a different manner, in that parts and labour costs are computed separately, repairs and maintenance costs are affected by average vehicle lifetime distance travelled and road roughness, and separate adjustment equations are applied to individual vehicle stereotypes. Both HDM and NIMPAC models are similar in that they incorporate road roughness into their estimation of repairs and maintenance, although the relationship is indirect in the latter.

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\(^6\) Excludes the Delanne (1994) study for France which did not specify the roughness range.

\(^7\) This does not mean that the coast-down method is not reliable. There were an insufficient number of studies reported to arrive at a conclusion.
Overseas empirical findings

Empirical studies on repairs and maintenance costs were conducted for different vehicle types (cars and trucks) on a range of roads (sealed and unsealed). The two methods employed were via user surveys and experiments on test vehicles operating on sealed and unsealed roads.

Among light vehicles (cars), there was a 46% change in maintenance costs per unit of IRI for a roughness range of 2.7 to 5.8 IRI in South Africa (du Plessis & Meadows 1990) (Table 3). For a higher level of roughness range (3.3 to 8.5 IRI), there was a higher percentage change in maintenance costs of 80% for Kenya (Hide et al. 1975). When the roughness range rose to 4.6 to 9.5 IRI for poor quality surfaced roads, the change in maintenance costs per unit of IRI escalated to more than 100% in the Caribbean (Hide 1982).

Table 3: Studies relating repairs and maintenance (R&M) to road roughness

<table>
<thead>
<tr>
<th>Country/Source</th>
<th>Method</th>
<th>Vehicle type</th>
<th>IRI range</th>
<th>R&amp;M cost % Change per IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kenya</td>
<td>Survey. Vehicles operating on range of road types and conditions</td>
<td>Car</td>
<td>3.3 to 8.5</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck</td>
<td>3.3 to 8.5</td>
<td>24</td>
</tr>
<tr>
<td>Caribbean</td>
<td>Survey. Vehicles operating on different networks of poor quality surfaced roads</td>
<td>Car</td>
<td>4.6 to 9.5</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck</td>
<td>4.6 to 9.0</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Brazil</td>
<td>Survey. Vehicles operating on range of road types and conditions</td>
<td>Car</td>
<td>2 to 18</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck</td>
<td>2 to 18</td>
<td>22</td>
</tr>
<tr>
<td>South Africa</td>
<td>Test vehicles operated on paved and gravel roads</td>
<td>Car</td>
<td>2.7 to 5.8</td>
<td>46</td>
</tr>
<tr>
<td>du Plessis &amp; Meadows (1990)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>Survey. Vehicles operating on range of road types and conditions</td>
<td>Truck</td>
<td>3.1 to 11.5</td>
<td>45</td>
</tr>
<tr>
<td>Findlayson &amp; du Plessis (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>Hypothetical 1 km road with range of roughness</td>
<td>Car</td>
<td>1.2 to 5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>BTCE (1997)</td>
<td></td>
<td>Rigid truck</td>
<td>1.2 to 5.8</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Articulated truck</td>
<td>1.2 to 5.8</td>
<td>0</td>
</tr>
<tr>
<td>Australia</td>
<td>HDM-4 model calibrated to Australian conditions</td>
<td>Car</td>
<td>1 to 10</td>
<td>10</td>
</tr>
<tr>
<td>Thoresen &amp; Roper (1999)</td>
<td></td>
<td>Truck</td>
<td>1 to 10</td>
<td>26</td>
</tr>
</tbody>
</table>


Among heavy vehicles, for a roughness range of 3.3 to 8.5 IRI, there was a 24% change in maintenance costs per unit of IRI in Kenya. For a higher level of roughness range (3.1 to 11.5 IRI), Findlayson and du Plessis (1991) reported a 45% change in costs per unit of IRI for South Africa. When the roughness range rose to 4.6 to 9.5 IRI for poor quality surfaced roads, the change per unit of IRI escalated to at least 100% for maintenance costs in Hide (1982) for the Caribbean.

Therefore, the positive correlation between road roughness and repairs and maintenance costs for light and heavy vehicles is prevalent for international studies.
**Australian experience**

The same Australian study (BTCE 1997), using hypothetical one-kilometre road sections of a two-lane road with a width of 3.7 metres each with an AADT of 1000, estimated VOCs for flat, undulating and mountainous terrain for this road section. For an increase in the roughness level from 1.2 to 5.8 IRI, repairs and maintenance costs went up by 5.8% for cars and 11.2% for rigid trucks. It is noted that roughness does not affect the maintenance costs of articulated trucks until roughness levels exceed 11.5 IRI (or 300 NRM).

A later Australian study (Thoresen & Roper 1999) makes use of the HDM-4 default relationships calibrated to Australian road conditions. Maintenance costs went up by 10% per unit of IRI for cars and 26% per unit of IRI for trucks.

Both Australian studies point towards a positive roughness–VOC correlation for cars and rigid trucks. Compared to overseas models, the magnitude of change is lower for cars (22% to 100%) and the magnitude is at the lower end for rigid trucks (24% to 100%). Moreover, when the HDM-4 model was calibrated for Australian conditions and the unit values from this model were compared with the HDM-4 default values (used internationally), the resultant unit costs were found to be 30–40% of default values for medium cars and 10–20% for articulated trucks (Figure 4). Hence, the unit costs for default values (applied overseas) were overestimated.

The deviation between Australian and overseas results is due to the large reduction in the extent of vehicle overloading, earlier vehicle write-off at the end of the service life, differences in vehicle operation and maintenance strategies, a preference to reduce capital costs in favour of more significant labour inputs, and the nature of pavement damage where severe distress-related shocks are common. Outdated vehicle technologies, including the absence of modern road-friendly suspension systems, also have the effect of increasing costs, with each of the foregoing factors impacting the resulting models leading to higher unit costs.

![Medium Car Maintenance Cost v Roughness](image1)

![6 Axle Artic Maintenance Cost v Roughness](image2)


**Figure 4: Effect of calibration of parts consumption and labour models**
New Zealand study

Overestimation of the repairs and maintenance costs data was also established in a New Zealand study. In 1999, Transfund New Zealand (now NZ Transport Agency) assessed if the VOCs for cars and trucks (HCV-I) were overestimated. The data was examined from various sources: NZ VOC model, Fleetlease database, Automobile Association (AA), Ministry of Transport (MoT), Fleet Operator Surveys, and the Automatic Generator Control (AGC) Survey.

The repairs and maintenance costs for cars were observed to be overestimated by the NZ VOC model. The NZ VOC estimate of 16.7 cents/km was significantly higher than the figure from Fleetlease (1.5 cents/km), AA (7.6 cents/km) and MoT (10.7 cents/km) (Table 4). The higher MoT figure can be discounted as it was derived from government vehicle fleet records in the 1970s and 1980s, containing UK and Australian car models but not Japanese models. The high AA figure included replacement of the exhaust system, all rubber parts (e.g. air conditioning hoses, radiator hoses, belts), clutch plate, disk pads, shock absorbers, battery, etc. Fleetlease’s low figure of 1.5 cents/km is due to vehicle age (cars were 3–4 years old whereas the mean age of the NZ car fleet is 11.2 years) and a higher utilisation rate (averaged at 30 000 km/year, twice the utilisation assumed in the NZ VOC model).

There is similar major deviation in the costs for trucks. The NZ VOC estimates (28.5 cents/km) are close to the MoT figures (27.5 cents/km) although the latter is outdated. When compared to other sources, the NZ VOC figures are higher than the Operator Surveys (13 cents/km), Fleet Consultant (14.5 cents/km) and AGC Survey (10.7–13.3 cents/km).

The study showed evidence of repairs and maintenance costs being overestimated in the NZ VOC model. To align with motor industry expectations, some reduction to account for the improved technology is necessary. For cars, a three-quarters or 75% reduction in repairs and maintenance costs from 16.7 cents/km to 4.3 cents/km was recommended. For trucks, a one-third or 33% reduction from 28.5 cents/km to 19 cents/km was recommended.

Table 4: Comparison of resource component VOC for cars and trucks

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>16.7 (56.6%)</td>
<td>1.5 (10.6%)</td>
<td>7.6 (36.9%)</td>
<td>10.7 (45.4%)</td>
<td></td>
</tr>
<tr>
<td>Trucks (HCV-I class)</td>
<td>28.5 (46.3%)</td>
<td>13.0 (30.2%)</td>
<td>14.5 (34.2%)</td>
<td>27.5 (44.4%)</td>
<td>10.7–13.3 (39.2% – 29.6%)</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses refer to the proportion of the VOC component to the total.

The NZ study concluded the overestimation of repairs and maintenance unit values, similar to the Australian findings (as per Figure 4). Unit values should be updated to account for improved vehicle technology and a younger vehicle fleet, otherwise, the VOC–roughness relation and benefit-cost figures will be skewed upwards.

TYRE WEAR

There are studies relating tyre costs to road roughness. Both tyre wear and lubricating oil costs have been modelled in the NIMPAC and HDM models.
Modelling approaches

NIMPAC-style tyre wear models are adjusted for the effects of surface tyre, gradient, curvature, roughness and congestion. Road roughness is modelled directly and estimation of the roughness effect on tyre wear can be seen in Equation 4.

\[
\text{Tyre tread wear} = \frac{\text{Basic tyre/speed relationship}}{1 + \text{Gradient adjustment} + \text{Curvature adjustment} + \text{Road roughness adjustment} + \text{Traffic congestion adjustment}}
\]

The HDM-III models use different approaches to estimate tyre wear for different vehicle types. Estimation of the roughness effect is possible as tyre wear is sensitive to road roughness and the number of tyres per vehicle for cars; and for heavy vehicles, tyre wear is sensitive to speed, gradient, curvature and roughness.

Oversea empirical findings

International studies have analysed the effects of roughness on tyre wear for different vehicle types (cars and trucks) for a range of road conditions (Table 5). Studies examining light vehicles (cars) over a range of road conditions have been conducted for South Africa, Kenya and the Caribbean. For a roughness range of 2.7 to 5.8 IRI, a 29% change in tyre costs per unit of IRI was reported in South Africa (du Plessis & Meadows 1990). For a higher level of roughness range, i.e. 3.3 to 8.5 IRI in Kenya (Hide et al. 1975) and 4.6 to 9.5 IRI in the Caribbean (Hide 1982), the change in tyre costs per unit of IRI escalated by 113% and 60%, respectively.

For heavy vehicles, at a lower roughness range of 3.3 to 8.5 IRI, this resulted in a 9% change in tyre costs per unit of IRI for Kenya (Hide et al. 1975). When the roughness range rose to 3.1 to 11.5 IRI in Findlayson and du Plessis (1991) and 4.6 to 9.0 IRI in Hide (1982), the change in tyre costs rose accordingly by 23% and 11%, respectively.

It is evident that there is a positive correlation between road roughness and tyre costs for both light and heavy vehicles. The change per unit of IRI ranges from 29% to 113% for cars and 9% to 33% for trucks.

Table 5: Studies relating tyre wear and lubricating oil costs to road roughness

<table>
<thead>
<tr>
<th>Country/Source</th>
<th>Method</th>
<th>Vehicle type</th>
<th>IRI range</th>
<th>Tyre wear % Change per IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kenya Hide et al. (1975)</td>
<td>Survey. Vehicles operating on range of road types/conditions</td>
<td>Car</td>
<td>3.3 to 8.5</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck</td>
<td>3.3 to 8.5</td>
<td>9</td>
</tr>
<tr>
<td>Caribbean Hide (1982)</td>
<td>Survey. Vehicles operating on different networks of poor quality surfaced roads</td>
<td>Car</td>
<td>4.6 to 9.5</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck</td>
<td>4.6 to 9.0</td>
<td>11</td>
</tr>
<tr>
<td>Brazil Watanatada et al. (1987)</td>
<td>Survey. Vehicles operating on range of road types/conditions</td>
<td>Car</td>
<td>2 to 18</td>
<td>12</td>
</tr>
<tr>
<td>South Africa du Plessis &amp; Meadows (1990)</td>
<td>Test vehicles operated on paved and gravel roads</td>
<td>Car</td>
<td>2.7 to 5.8</td>
<td>29</td>
</tr>
<tr>
<td>South Africa Findlayson &amp; du Plessis (1991)</td>
<td>Survey. Vehicles operating on range of road types and conditions</td>
<td>Truck</td>
<td>3.1 to 11.5</td>
<td>33</td>
</tr>
</tbody>
</table>
Australian study

The Australian study (BTCE 1997) analysed the roughness effects on tyre wear using a hypothetical one-kilometre road section of a two-lane road, with a width of 3.7 metres each with an AADT of 1000, over a roughness range of 1.2 to 5.8 IRI. On a per unit IRI basis, tyre costs rose by 8.8% for cars, 2.7% for rigid trucks, and 2.8% for articulated trucks. The Australian study shows a positive correlation between roughness and tyre costs. However, the magnitude of change registered in Australia for cars (8.8%) and trucks (2.7% to 2.8%) is lower than that of the overseas studies (12% to 13%).

LUBRICATING OIL COSTS

Lubricating oil costs constitutes a smaller component of VOC compared to fuel costs and repairs and maintenance costs. Both the NIMPAC and HDM models have modelled lubricating oil costs. In NIMPAC models, oil is expressed as a function of surface type, vehicle type, vehicle speed, fuel type, engine oil consumption, and gear oil use.

The HDM model uses a simpler algorithm, where oil consumption is expressed as a function of vehicle type and road roughness, with the relative roughness effect assumed to be the same between vehicle types. The model equation is as follows:

\[
OC(J) = CO_0(J) + 0.0055704 \times NRM
\]

where

- \(OC(J)\) = oil consumption for vehicle type J in litres per 1000 km
- \(CO_0(J)\) = constant term for oil consumption for vehicle type J
- \(NRM\) = road roughness in NAASRA roughness meter counts per kilometre.

An ongoing issue is that with modern technology, except in extreme conditions, oil use represents a very small component of vehicle resource use, and varies minimally with road condition, alignment and traffic. As a result, oil consumption tends to be estimated by models as opposed to empirical observations.

A direct relationship between road roughness and the costs associated with lubricating oil is evident from an Australian study (BTCE 1997). For an increase in the roughness range from 1.2 to 5.8 IRI, oil is expected to escalate by 250.5% for cars, 54.8% for rigid trucks, and 38.9% for articulated trucks (refer to Table 5).
AUSTRALIAN HARMONISATION PROCESS

The review has shown that the Australian findings differ from overseas experience in terms of the magnitude of change of roughness on the VOC components. A further feature of the Australian experience was that in the early 1990s, economic evaluation models employed across different Australian states and territories could yield different estimates of VOCs when confronted with the same road parameter, for example, roughness. This led to a fairly successful harmonisation process in Australia to synchronise the findings across models. To assist practitioners in the harmonisation process, parameter values have been developed for each model type and are available for use in Austroads (2005).

Fuel consumption

In NIMPAC models, harmonisation efforts have arrived at harmonised values for each term for each vehicle type in the basic fuel—speed relationship, adjustment factors which model the energy efficiency adjustment term and modify the effects of gradient and effects of curvature and congestion impacts, and adjustment factors for the road roughness term.

To harmonise the HDM models, the equation was evaluated for each vehicle type to account for the effects of geometry and road roughness. General RUC parameter values are used, together with parameter values buried in the model’s source code and not normally available to end users. In addition, there are a small number of fuel-consumption-specific variables, which may be modified to calibrate HDM-III to local road conditions. Harmonised values for the latter parameters have been developed in Austroads (2005).

Repairs and maintenance

In NIMPAC-style models, there have been regular updates of basic repairs and maintenance costs by vehicle type (Austroads 2003a, 2003b) and harmonised values to adjust for the effects of surface type and condition.

Harmonisation of the HDM-III estimates of repairs and maintenance costs can be achieved by use of parameter values for repair and maintenance algorithms set out in Austroads (2005). Apart from numerical changes to some of the coefficients, to obtain reasonable harmony between HDM and NIMPAC estimates, it was necessary to maintain the non-linear relationship between parts’ costs and roughness for articulated trucks and combination vehicles for higher roughness levels. Prior to 1996, linearity had been assumed (Thoresen & Roper 1996).

Tyre wear

There are limits to the harmonisation process for tyre wear. The harmonisation is achievable for cars caused by sensitivity to roughness only. Problems can be experienced when harmonising results for other vehicle types. This occurs because HDM-III tyre wear models are, by their structure, intrinsically more sensitive to gradient and less sensitive to curvature than their NIMPAC equivalent. Variations in parameter values within allowable ranges did not prove sufficient to counter this tendency and achieve harmonisation between the two modelling approaches.

Lubricating oil

For the NIMPAC lubricating oil models, recent Austroads work has updated and improved values for the basic oil consumption and speed relationship for various vehicle types. As NIMPAC models allow road roughness to affect engine oil usage indirectly via speed variation, the revised basic engine oil consumption and speed relationship will indirectly alter the relationship between engine oil usage and roughness.
With reference to HDM models, to achieve a degree of harmonisation with NIMPAC-style models, values of the constant parameter as per Equation 5 were modified so that comparable levels of oil use were achieved at a running speed of 80 km/h with an assumed road roughness of 50 NRM counts per kilometre. Harmonisation beyond this adjustment is not achievable given the fundamental difference between oil use algorithms. Constant parameters for only a sub-set of vehicle stereotypes were required, with parameter values for all other vehicles remaining unchanged at the default values accompanying each model. Revised parameter values have been derived to ensure harmonisation between models are set out.

MODELLING CONSIDERATIONS

Following this literature review, and in order to improve the scientific relationship between road roughness and each VOC component, the following modelling considerations are supported and apply:

- Continue to adopt mechanistic models as per the current practice in Australia, or simplified regression models based on the results of multiple mechanistic model test scenarios.
- Examine the analysis for vehicle types (light and heavy vehicles). For heavy vehicles, vehicle masses associated with the new NTC fee charging regime should be considered.
- Continue to ensure that models apply to the latest vehicle fleet and vehicle technology as per the current practice in Australia. The New Zealand research has shown that an older vehicle fleet produces outdated data for maintenance costs.
- Update the NIMPAC and HDM models using harmonised values developed for the VOC components. This draws upon the recent harmonisation work in Austroads (2005), and is aimed at achieving some degree of harmonisation in the results across Australia.
- Update unit values to reflect improved vehicle technology and a younger vehicle fleet; otherwise, this leads to less accurate roughness–maintenance cost predictions and some degree of upward bias in the benefits calculation in project appraisal.
- For fuel consumption, initially restrict the analysis to sealed roads, as the majority of vehicles in Australia operate on such roads, and conduct experiments based on a constant speed assumption given the robustness of results. Extend analysis to include effects of roughness on travel speeds. This has been the subject of previous analysis (Botterill & Thoresen 1996), but requires revisiting.
- For repairs and maintenance costs, conduct the experiments for an expanded roughness range. It is observed that the starting point of the roughness range is higher for the repairs and maintenance studies than for fuel consumption studies.

THE WAY FORWARD

The review undertaken in this paper indicates that despite progress both locally and internationally with regards to variations in VOC data and models used to estimate and quantify roughness impacts, a need persists to develop improved relationships that are reflective of road conditions and the current vehicle fleet. Three outcomes achieved in the review process are significant, namely:

- The literature review across Australasia, Europe, the US and the developing countries verifies the establishment of a scientific relationship (in terms of the directional impact) between each VOC component and road roughness.
- A previously established harmonisation process has ensured that different models utilised to estimate road user costs will generate similar estimates when applied to specified scenarios, road infrastructure and traffic characteristics. Australian jurisdictions can maintain their own models and reconcile their results with the harmonised parameters to estimate for local conditions. The process will however need to be maintained.
A quantifiable relationship between roughness and each VOC component can be reached provided certain modelling considerations apply. The degree to which it has been reached varies between VOC components. The continued adoption of mechanistic models, examining data for various vehicle types and a changing vehicle fleet, incorporating the work undertaken for NTC, and updating values based on the harmonisation process is supported by results achieved.

The paper suggests a way forward for the Australasian research. The options include:

- A gap analysis of current models vis-à-vis user needs, which might necessitate a survey among Australian jurisdictions.
- Revisitation of the RUCSG program that wound up in 2004. There is a need for model renewal due to changes in technology in terms of updating the Australian models to reflect the latest set of RUC unit values (as at 2010) and updating the latest Australian physical vehicle parameters. These can influence benefit-cost analysis procedures and results.
- Linkages to the European Union (EU)-sponsored MIRIAM (Models for Rolling Resistance in Road Infrastructure Asset Management systems) project, which demonstrates the influence of road surface conditions, e.g. micro, macro and mega texture, on VOC. MIRIAM will be kept under a watching brief, as revised rolling resistance parameters and outcomes may be applied to improve, extend and update algorithms associated with estimating VOCs. To date, results have not been sufficiently targeted or definitive for inclusion into Australasian models.

These research options point towards a critical need for Australia to update the VOC models with a focus on the relationship with road condition, and more specifically, roughness and evolving related measures, and keep abreast of the latest technology. It is considered that further research on this topic in the future is critical if European projects such as MIRIAM find that road conditions, other than roughness, have a measurable impact on VOC.

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Fiona Tan

Fiona Tan holds a PhD in Economics from the University of Western Australia. Her thesis topic was to resolve the unemployment crisis through sectoral labour mobility during the post-Financial Crisis era. Her honours dissertation focused on the economic and socio-demographic determinants and outcomes of labour migration in the Middle East.

Fiona was formerly Senior Assistant Director with Singapore’s Department of Statistics and worked towards formulating national business, household and population data. She was appointed Senior Assistant Superintendent for the Population Census 2000, which received accreditation at the United Nations (UN) as the world’s first Internet and Asia-Pacific’s first register-based Census, and she received an Honoraria for national services rendered. She held a concurrent appointment as Assistant Director in International Relations where she worked with the UN, ASEAN and IMF.

Since joining ARRB Group as Senior Economist, she has worked in areas including the development and methodological revision of RUC unit values, road pricing, probabilistic risk modelling, wider economic benefits, benefit-cost analyses for bus access and heavy vehicle PBS length limits, review of funding agreements, skid resistance data processing methods and more recently, in the willingness-to-pay study of crash costs for Australia.

Thorolf Thoresen

Thorolf Thoresen, a Principal Economist at ARRB Group, is one of the leading Australian experts on road user costs and road expenditure evaluation methods. He is an economist with over 20 years experience in roads and road transport, with a specific interest in statistics and quantitative methods. He holds an honours economics degree and a Masters degree in Applied Statistics, and has had considerable experience working at the interface between engineering and economics.

At ARRB Group, Thorolf has undertaken or managed a wide range of projects in the transport economics area for both local and overseas clients. He also has previous experience with the Commonwealth Government in shipping and land transport. He is a member of a number of key Austroads committees and working groups, including the Road User Cost Steering Group and the Transport Economics Liaison Group, and is the author of some 50 research reports and papers. In particular, Thorolf has made significant contributions in the Harmonisation and Improvement of Australian Non Urban Road User Cost Estimation Methods, Linking Victorian Accident Trends to Economic Activity and Countermeasures, Development of Whole of Life Pavement Life Cycle Costing Models and Integrating Road User Costs into the New South Wales Pavement Management System.

Caroline Evans

Caroline Evans holds a Bachelor of Business (Economics and Finance) from RMIT University and a Postgraduate Diploma in Economics from the University of Melbourne. She has twelve years of professional economic research and policy analysis experience in such diverse areas as valuing environmental externalities, analysis of environmental issues, economic analysis, and investment/project appraisal.

She worked as an Economist for the Victorian Department of Infrastructure (2000 - 2004) and for the Bureau of Transport and Regional Economics (BTRE) (2003-2004 secondment) and (2004 - 2005). Projects included, the ATC National Guidelines for Transport System Management in Australia and the National Transport Data Framework, receiving a Departmental Australia Day Achievement Award for these contributions.

Caroline has been employed with ARRB Group for 6 years as a Senior Economist and has been involved in a range of environmental projects, and more recently, has contributed to the development of the Australian Low Carbon Transport Forum (a joint collaboration between
ARRB, CSIRO and BITRE). She has also been appointed as an Australian Corresponding Member on a World Road Association (PIARC) Technical Committee for Climate Change and Sustainability.

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