The quantification of sustainability outcomes for unsealed road pavements

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ABSTRACT: Sustainability reporting is changing from that with a focus on environmental management to more comprehensive sustainable development associated considerations. This has led to the advent of a number of sustainability assessment frameworks, each with a particular purpose and outcome. One of these, the Infrastructure Sustainability Council of Australia identified 3 sustainability outcomes (environmental, social and economic) and 15 categories. Whereas sustainability outcomes of sealed roads are reasonably well covered in sustainability rating systems, unsealed roads have received very little attention, despite the significant portion of the road networks in many countries. In Australia unsealed roads comprise about 500,000 km (out of a total of 900,000 km) of public roads, with almost 400,000 km of these managed by Local Government Entities.

The paper discusses how available unsealed road surface properties prediction models (gravel loss, roughness, slipperiness and dust), as well as economic and emission evaluation models, can be used to quantify the sustainability outcomes of pollution (dust), road safety (slipperiness and dust), depletion of resources (gravel loss), emissions (vehicle operating costs and increased maintenance) and cost (vehicle operating costs and increased maintenance). This quantification of the sustainability outcomes will assist agencies and councils in the assessment of the design and maintenance of unsealed road pavements covering life cycle assessments, comparison of wearing course types, review of maintenance strategies, climate change consequence predictions, overall network sustainability performance reviews and pavement management.

KEYWORD: Life cycle assessment, Pavement surface properties, Performance management, Sustainability outcomes, Unsealed road performance.

1 Introduction

The length of unsealed roads in Australia is extensive with around 500,000 km of the 911,000 km public roads unsealed. Approximately 400,000 km (or 80% of the total) of this length is managed by Local Government Council entities. The National State of the Assets 2015 report [1] by the Australian Local Government Association reported that Councils had $12.2 billion unsealed roads under management, with $6.7 billion of these managed by rural councils. Nineteen percent of all these unsealed roads were in a poor to very poor condition and 33% in a fair condition.

The unsealed roads form crucial elements of the economies in rural areas and have significant asset value and sustainability consequences. The Australian Rural Roads Group (ARRG) summarised the situation regarding rural (including unsealed) roads as follows [2]: “Local roads represent almost 80% of all roads in Australia, when measured in kilometres. In rural, regional and remote Australia, these roads are often the biggest single factor for business efficiency, domestic and export market success, social connectedness and community safety. Yet only 41% of Australia’s local roads are even sealed in bitumen! By any measure, these roads are a nationally-significant infrastructure asset. But they are ageing fast and falling into increasingly poor condition. These roads are failing to support efficient agricultural business. They are not ready to support the huge development of mining activity occurring in many of Australia’s rural areas. Together Australia’s local roads are valued at around $75 billion dollars, but Australia does not manage this asset centrally or strategically. Local roads are underfunded by around 3 billion dollars each year. Local roads are the lifeblood of much of the Australian economy”

2 Sustainability

The World Commission on Environment and Development (WCED) defines sustainable...
development as “meeting the needs of the present population without compromising the ability of future generations to meet their own needs” [3], while the Infrastructure Sustainability Council of Australia (ISCA) defines Infrastructure Sustainability as “Infrastructure that is designed, constructed and operated to optimise environmental, social and economic outcomes of the long term”.

There has been a change over the first part of this century “in the focus of environmental reporting in roads agencies, from the current practice of ‘environmental management’ which seeks to minimise ecological disturbance, to a second generation of reporting that expands this scope to include sustainable development associated considerations, …and the potential for alternative ‘low-carbon’ options.

Such a shift in focus will form an important part of a road authorities approach to issues of growing concern such as increasing energy costs and increasing impacts from climate change, such as greater weather damage to road infrastructure. The shift in environmental reporting focus has been heralded by the emergence of an array of sustainability assessment frameworks, all with varying purposes, reporting requirements, and outcomes.” [4].

The 3 sustainability outcomes identified by ISCA and others can be broken down into sub-outcomes (see Table 1), i.e.

- Social – injury, death and health
- Environmental – resources, emissions/energy and pollution
- Economic – direct and indirect cost

Whereas the sustainable design of sealed roads is covered in detail in most sustainability measurement procedures (e.g. Greenroads, INVEST, IS rating tool) [4], very little has been published about the assessment of the sustainability design of unsealed roads. Although unsealed roads carry a much smaller number of vehicles that sealed roads, the network is much larger, unsealed roads require significant construction and maintenance budgets, contribute to pollution and road accidents.

**Table 1: Sustainability outcomes**

<table>
<thead>
<tr>
<th>Sustainability outcome</th>
<th>Description and causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social</td>
<td></td>
</tr>
<tr>
<td>Injury and death</td>
<td>Accidents (road safety) Effect of dust, surface friction and road roughness on road safety (and subsequent injuries and deaths due to accidents)</td>
</tr>
<tr>
<td>Health</td>
<td>Dust causing respiratory problems</td>
</tr>
<tr>
<td>Resources</td>
<td>Depletion of natural resources (gravel)</td>
</tr>
<tr>
<td>Carbon emissions/energy</td>
<td>Vehicle fuel consumption due to road roughness Construction (affected by pavement type, thickness and construction method) Maintenance (affected by frequency and type of maintenance)</td>
</tr>
<tr>
<td>Pollution</td>
<td>Dust in the air Sediment in waterways (due to erosion)</td>
</tr>
<tr>
<td>Direct cost</td>
<td>Construction cost (affected by pavement type, thickness and construction method) Maintenance cost (affected by frequency and type of maintenance) Vehicle operating cost due to road roughness Road accidents</td>
</tr>
<tr>
<td>Indirect cost</td>
<td>Dust causing damage to agriculture</td>
</tr>
</tbody>
</table>
3 Methodology
Models to determine unsealed road surface properties and to predict changes are well-established, while existing economic assessment produces and emission prediction models are available to quantify various sustainability outcomes. However, these sustainability outcomes have not been converted into models for unsealed roads and have not been linked to surface characteristics.

This available information was used to develop models to determine sustainability outcomes. The main sources of information were widely used surface property models, economic assessment procedures used in Australia and New Zealand [5-7], the US Environmental Protection Agency dust pollution models [8, 9], and recognised carbon emission calculation procedures [10, 11].

Figure 1 depicts the interaction between the relevant surface properties and sustainability outcome models (for accident rate and cost, emissions, friction, loss of resources, dust pollution, vehicle operating and maintenance cost) developed in this study.

4 Prediction of Surface Properties
The properties of the wearing course which would affect the sustainability outcomes are roughness (which includes corrugations), rutting, shape loss, potholes, dust and friction. These properties can be measured or estimated from the wearing course material properties, traffic and environmental factors.

The first formal models to predict changes in roughness and gravel loss were developed in the 1970s and 1980s as part of a World Bank study into the design and maintenance of roads. This led to the development of the Highway Design and Maintenance Standards Models, the first which were released as HDM-3 [12]. Updated models, referred to as HDM-4 models, were published in 1990s [13, 14]. During this time the HDM models were calibrated or additional models developed to model the deterioration of unsealed roads in Australia, New Zealand and elsewhere [15, 16] [17, 18].

In addition to these models to predict shape and slope loss [17], erosion [19, 20], friction [21, 22] and dust [9, 23, 24] have been developed.

5 Sustainability Outcomes
The sustainability outcomes shown in Table and Figure 1 are discussed in detail below.

5.1 Road safety (accidents)
Studies [25] found that unsealed roads generally have higher rates of crash incidence than two-lane sealed roads if the lower traffic volumes on unsealed roads are factored in. Fourteen percent of rural road casualties occur on unsealed roads where poor surface quality and low levels of surface friction have been identified as contributing factors [26]. Seventy seven percent of the casualty crashes on Australian unsealed roads are classified as run-off-road (combined off-curve and off-straight), while 56% of these crash types occur on sealed roads. In New Zealand the percentages are 61% and 52%, respectively [27].

When travelling on unsealed roads, drivers tend to choose the ‘best’ path (often the centre
of the carriageway) rather than keeping to the left side of the road as demonstrated by New Zealand crash causation factor data, which shows a higher proportion of crashes on unsealed rural roads where vehicles failed to keep left (28%) than sealed rural roads (12%). Loss of control (58%) was also a dominant factor in unsealed road crashes in New Zealand, which is likely to be associated with the surface condition of the road and cross-sectional issues.

Accidents are caused by a combination of road features, which include the geometric design, cross section, road signage and surface characteristics. Remedial treatments would therefore also address hazardous road geometry (alignment, cross fall, intersections), inadequate signage and poor wearing surfaces.

The condition of the wearing surface is one of a number of factors which would affect the road safety and the contribution will vary. Poor condition of the wearing course could result in low friction/skid resistance (skidding), high roughness (with relationships developed between crash rate and roughness, e.g. Cairney [28]) and production of dust (poor visibility). All of these can vary considerably, both spatially and along the length and width of an unsealed road and with time.

5.2 Friction (Skid resistance)
Lea [22] identified three different mechanisms which can cause skidding on unsealed roads, i.e.

- Intersurface friction, which is the classical mechanism of skidding and is mainly influenced by the texture of the surface material. Page-Green [21] developed models to determine friction from wearing surface material properties.
- Sliding, where the tyre slides on loose material present between the tyre and the road surface.
- Plowing, where the tyre is forced through a thick layer of loose material. This has been found to take place when more than 1kg of dry loose material is present on a 1 m² patch.

Typical friction coefficients (or drag factors) for unsealed pavements range from 0.4 to 0.85 [21, 22].

5.3 Vehicle operating cost (VOC)
Vehicle operating costs (VOCs) encompass fuel consumption, repair and maintenance costs, tyre wear and lubrication oil.

Positive correlations between fuel consumption and roughness for both light and heavy vehicles have been reported, with percentage fuel consumption increases in the range of 0.4 to 1.7% per unit IRI for light vehicles and 0.5 to 1.1% per unit IRI for heavy vehicles [29]. Similar trends have been found for VOCs with increase of 4 to 5% per unit increase in IRI oil [30].

However, due to the effect of roughness on speed, the resultant effect is indeterminate.

5.4 Dust (pollution)
Pollution due to the loss of fines (creating dust along roads, particle matter in the atmosphere and depletions of gravel sources) can be significant and dust from unsealed roads is widely recognised as a safety hazard, aesthetically undesirable, environmentally damaging and adversely affecting vehicle maintenance. The consequence of dust is not only the loss of fine material but also the loosening of the road surface which accelerates material loss and increases road roughness. More than 8 million tonnes of fines are lost from the 2.3 million km of unsealed roads in the USA every year [31], with 50% of all fine particle (less than 1 mm in size) emissions (under which dust from unsealed roads is categorised) attributed to road dust – 65% of this from unsealed roads. In Australia, about 160 million kg of fine particles are produced from roads [32]. It is estimated that dust produced on unsealed roads contributes up to 34% of the particulate matter in the atmosphere [33].

Particulate matter (PM) is the general term used for a mixture of solid particles and liquid droplets found in the air. These particles can vary in size, from fine (less than 2.5 micrometres in diameter, PM-2.5) to very coarse (more than 30 µm, PM-30). The coarser particles (e.g. PM-10) are generally emitted from sources, such as vehicles traveling on unpaved roads, materials handling, and crushing and grinding operations, as well as windblown dust. Air borne dust particles less than 1 mm in diameter are considered a health hazard and
road dust particles are in the range of 0.002 to 0.049 mm.

The amount of dust produced by vehicles travelling on an unsealed road depends on a large number of factors, e.g. the wearing course material properties (particle size, density, clay content, moisture content), the environmental conditions (wind speed), and vehicle features (speed, weight, dimensions, wheel configurations). Empirical models have been developed to predict dust emissions using the factors mentioned earlier, but relatively few to predict near-field dust. The most commonly used equation is the one developed by the US Environmental Protection Agency (EPA).

Dust generated by a vehicle travelling in front of a second vehicle or by approaching vehicles can severely restrict visibility. Dust reduces sight distances and intuitively has an influence on unsealed road accidents, but correlations between the amount of dust and accident rates have not been developed.

5.5 Emissions

Emissions generated by vehicles can be divided into those contributing to greenhouse gases and those contributing to pollution.

The main types of greenhouse gases (GHG) in the Earth’s atmosphere are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and ozone. Carbon dioxide equivalent (CO₂-eq) is the term used to reflect the contribution of all the GCG. CO₂ emissions (estimated to be 75 million tonne in 2010 in Australia) contribute to more than 98% of CO₂-e vehicle emissions in Australia [34].

Further pollution from vehicles in Australia comprise the following key pollutants per VKT, 3.9 g CO, 1.3 g NOx, 0.4 g VOC (Volatile organic compound), 49 mg PM2.5, and 17 mg benzene [34].

The cost of carbon emission can also be calculated but found to be very difficult due to, inter alia, several co-existing meanings for the term “CO₂ price” [35] and the calculation procedure [36].

5.6 Resources (depletion of natural resources)

The gravel lost due to traffic, erosion and wind has to be replaced. On average between 12 and 25 mm of gravel is lost every year and has to be replaced from natural resources.

As indicated earlier there are a number of gravel loss prediction models in use.

6 Models

As mentioned before available information, relationships and models were used to develop the sustainability outcome models. These models are listed in Table 3 along with the sources of the models.

<table>
<thead>
<tr>
<th>Sustainability outcome model</th>
<th>Source of information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accident rate</td>
<td>TMR [6]</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>Paige-Green [24]</td>
</tr>
<tr>
<td>Pollution, PM10</td>
<td>USA EPA [8]</td>
</tr>
<tr>
<td>Loss of resources</td>
<td>HDM4 [13]</td>
</tr>
<tr>
<td>Emissions</td>
<td>NZTA, TMR [5, 6]</td>
</tr>
<tr>
<td>Vehicle operating cost (VOC)</td>
<td>NZTA [5]</td>
</tr>
<tr>
<td>Accident cost</td>
<td>TMR [6]</td>
</tr>
<tr>
<td>Travel Time cost</td>
<td>TMR [6]</td>
</tr>
<tr>
<td>Safe travelling speed</td>
<td>HDM3 [12]</td>
</tr>
</tbody>
</table>

7 Application

The models can be used for a wide range of applications. Some of these applications are demonstrated in this section.

Construction and maintenance costs and related emission rates are required to apply the developed sustainability outcome models. These costs and emissions rates are influenced by the location, the method,
available materials, and can vary significantly. For the purposes of demonstrating the application of the models typical costs and carbon emissions for the construction and maintenance activities were derived from relevant information.

7.1 Sustainability outcomes for use in assessment schemes

Table 4 presents the sustainability outcomes for rural unsealed road pavements calculated from the models which can be used as input into sustainability assessment schemes, such as ISCA.

The information in the table shows how the performance of wearing course material (laterite and colluvial gravel in this case) can also be assessed against those recommended for use in Australian. The effect of the material properties on the sustainability outcomes vary with some almost negligible, but others significant (e.g. friction, pollution, loss of resources, regraveling costs and emissions).

**Table 4:** Sustainability outcomes for different wearing course materials (per km per year)

<table>
<thead>
<tr>
<th>Sustainability outcome</th>
<th>Wearing course type</th>
<th>Laterite gravel</th>
<th>Colluvial gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SOCIAL (per km per year)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accident rate</td>
<td>0.024</td>
<td>0.024</td>
<td>0.024</td>
</tr>
<tr>
<td>Friction</td>
<td>0.63</td>
<td>0.37</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL - dust and loss of material (t)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pollution, PM10</td>
<td>208</td>
<td>700</td>
<td>76</td>
</tr>
<tr>
<td>Loss of resources</td>
<td>126</td>
<td>157</td>
<td>117</td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL - CO2-e emissions (kg per km per year)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC</td>
<td>16,947</td>
<td>17,914</td>
<td>16,221</td>
</tr>
<tr>
<td>Grading</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Re-gravelling</td>
<td>335</td>
<td>424</td>
<td>311</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>17,782</td>
<td>18,838</td>
<td>17,308</td>
</tr>
<tr>
<td><strong>ECONOMIC ($ per km per year)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC</td>
<td>32,681</td>
<td>29,970</td>
<td>33,345</td>
</tr>
<tr>
<td>Accident cost</td>
<td>6,071</td>
<td>6,071</td>
<td>6,071</td>
</tr>
<tr>
<td>Travel Time cost</td>
<td>20,040</td>
<td>18,615</td>
<td>20,783</td>
</tr>
<tr>
<td>Grading cost</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Re-graveling cost</td>
<td>5,863</td>
<td>7,417</td>
<td>5,437</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td>65,656</td>
<td>63,072</td>
<td>66,636</td>
</tr>
</tbody>
</table>

7.2 Assessment of wearing course materials

Figure 2 shows a comparison of the sustainability outcomes of a number of locally available wearing course material types (sandy clay, laterite and sandstone) for the same hauling distances. The outcomes vary significantly.

![Figure 2: Comparison of the sustainability outcomes of wearing course types](image)

7.3 Assessment of maintenance strategy

Figures 3 and 4 illustrate how the models can be used to assess the effect of maintenance strategy (blading frequency) on the annual cost for 2 wearing course material types, e.g. crushed rock and sandstone, as well as haul distances of 10 km (for the locally available sandstone), 50 or 100 km (for the crushed rock). The large effect of the hauling distance on both the cost and the emissions is clear. The results also show that the annual maintenance cost and emissions remain reasonably constant for blading frequencies of more than 90 days, but the user costs increase continuously.
7.4 Cost-benefit analyses

Traditional cost-benefit or life-cycle analyses to determine the feasibility of sealing unsealed roads normally only consider costs, whereas more recent trends require social and environmental impacts to be incorporated in the assessments. The results in Figures 5 and 6 show that sealing an unsealed road can be considered from a cost-only perspective at traffic volumes of 200 (if crushed rock is hauled in from long distances to re-gravel the road) or 750 vehicles per day if locally available material is used, but sealing produces significantly lower CO2e emissions at all traffic volumes. The results demonstrate why decisions on cost alone can have sustainability consequences.
Conclusion

Sustainability reporting has changed from an environmental only focus to incorporating the 3 dimensions (or pillars) of social, environmental and economic outcomes. Despite unsealed roads comprising large percentages of the road network in many countries (albeit with low traffic volumes), models and approaches to quantify sustainability have not been developed for unsealed roads.

This paper describes the developed of such models using available information, mainly from economic assessment procedures and emission prediction approaches. This resulted in sustainability outcomes for accident rates and costs, vehicle operating costs and CO2e emissions, dust pollution, surface friction, loss of resources and maintenance costs and emissions for unsealed roads.

An initial assessment found the models to produce reasonable results.

The models was used to illustrate the application to calculate sustainability outcomes for a number of wearing course material types, blading frequencies, hauling distances and life cycle cost assessments.

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