

## Revised vehicle operating cost models for Australia

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### Abstract

Updated vehicle operating cost (VOC) models are an important input to the economic evaluation of road projects. This paper presents revised VOC models for Australia updated as part of the National Guidelines for Transport System Management (NGTSM) review of parameter values. The paper first reviews the development of VOC models in Australia. It then outlines the methodology used to estimate revised rural (uninterrupted or free flow) models and urban (stop-start or interrupted flow) models. These are then available for modelling on the basis of different time periods, e.g. a.m. and p.m. peak periods, and day and night time off-peak periods, which provides a consistent approach to incorporating travel time and freight delay costs for general CBA with total RUC calculated using a common average travel speed/total link time.

In the NGTSM, VOC models are specified for an extended set of 20 vehicle types, over different traffic and road conditions (using road roughness & speed as key variables depending on gradient, curvature and road width) and their basis and effect is illustrated herein. Payload is also incorporated into the models as a variable. Model coefficients have been re-estimated for the specified models, as well as outputs of the models in physical consumption units and monetary values for fuel consumption and for total VOC. Finally, the paper provides a set of recommendations for further development of VOC models in Australia.

### 1. Introduction

Vehicle operating costs (VOCs) are an important input to the economic evaluation of road transport projects. VOC models need to be updated regularly to reflect changes in prices of inputs such as fuel, as well as to incorporate any changes in physical consumption units that may arise through technological changes (more efficient engines) or better information on VOCs over different road conditions (e.g. road roughness). This paper presents revised VOC models for Australia updated as part of the National Guidelines for Transport System Management (NGTSM) review of parameter values. It also discusses how the revised models enhance the level of information which can be generated from the new VOC parameters; it goes on to highlight how this can be used to estimate the productivity benefits to freight operators resulting from improvements in road infrastructure, and how these costs change under different operating conditions.

The paper first reviews the development of VOC models in Australia. It then outlines the methodology used to estimate revised rural (uninterrupted or free flow) models and urban (stop-start or interrupted flow) models. VOC models are specified for an extended set of 20 vehicle types, over different traffic and road conditions (using road roughness and speed as key variables depending on gradient, curvature and road width) for both rural and urban roads. Payload is also incorporated into the models as a variable. Re-estimated model coefficients are provided for the specified models, as well as outputs of the models in physical consumption units and monetary values (using the latest parameter values), for fuel consumption (litres / km) and for total VOC (\$ / km), and for the determination of total road

user costs (RUC). Finally, recommendations are made for further development of VOC models in Australia.

## **2. Types of VOC models**

VOC models can be either: mechanistic–empirical models or regression equation type models.

### **Mechanistic-empirical models**

‘Mechanistic-empirical’ models estimate resource consumption in terms of the underlying physics and mechanical engineering processes and can be adapted to suit a range of fleet and road operating conditions. The HDM-III (Watanadada et al. 1987) and HDM-4 (Bennett & Greenwood 2006 and Stannard & Wightman 2006) models are of this kind, and are structured in a mechanistic form, with the coefficients derived by the statistical analysis of observations. The latest models utilise the Australian Road Fuel Consumption Model (ARFCOM) fuel consumption model (Biggs 1988). Speed models have been calibrated to driver behaviour and the response of the mechanistic models using results of comprehensive speed studies undertaken in Australia in the late 1990’s and early 2000’s. Maintenance and spare parts models are also based on field observations in Australia (Thoresen & Roper 1999). New Zealand studies (OPUS International Consultants 1999) which form the basis for the NZ Economic Evaluation Manual (NZ Transport Agency 2013) and further Austroads studies (Austroads 2012a and Tan et al. 2012) have also confirmed the suitability of the models. Whereas these models were originally derived for application in non-urban conditions, they have been adapted for use in urban and stop-start environments as a result of Austroads funded studies (Cox & Arup 1996 and Thoresen 2004).

### **Regression equation models**

Regression equation type models, often described as ‘statistical’ models, possess a structure which does not seek to emulate the mechanical engineering processes. While these models can provide reasonable results for applications which are close to the original derivation of the models, including the scope and combination of parameters and parameter values tested, this also limits their potential application. These models were amongst the first used for VOC estimation, e.g. those derived by Hodges et al. (1975), and a number of the original NIMPAC models (Both & Bayley 1976). The derivation of the NIMPAC (NAASRA Improved Model for Project Assessment & Costing) model followed the extensive efforts undertaken in Australia to develop methodologies capable of estimating RUCs and their sensitivity to road conditions in both non-urban and urban settings (Lloyd & Thomas 1988). Work commenced in the late 1960s largely initiated by the former Commonwealth Bureau of Roads proceeded through the 1970s and 1980s under the National Association of Australian Road Authorities (NAASRA).

Either of the models may be employed to produce more user friendly formats, either as a suite of tables or as a set of derived equations based on specific operating conditions and vehicle related assumptions.

## **3. Development of VOC models in Australia**

VOC models have been developed or adapted through various Austroads studies, and there has been a stated requirement to provide models which possess the following attributes, and which can be applied and updated in a clear and consistent manner to:

1. better accommodate changes in vehicle technology and a changing vehicle fleet, including under different loading conditions and regulations

2. be amenable for application across networks subject to uninterrupted and interrupted/stop-start conditions
3. be capable of application to general cost benefit analysis studies at a network level and for major capital projects, including employing the results of traditional 4–5 stage transport models.

The background to how models have evolved in the last twenty years is described below, and provides a recommended set of models and guidance on their application consistent with the above requirements.

### **3.1 Rural (uninterrupted or free flow) VOC models**

In Australia, achieving consistency between different rural/uninterrupted flow models has previously been the subject of a harmonisation process where algorithms, procedures and values could be used by agencies to benchmark their models to agreed costs and technologies. This culminated in an Austroads Road User Cost Steering Group (RUCSG) program covering the period 1994–2005 (Peters 2001). The program provided the basis to calibrate models such as NIMPAC and RURAL (Both & Bayley 1976), which formed the basis of the evaluation procedures of road agencies. An example of the technical documents which contained parameter values in a set of lookup tables is provided in Thoresen and Roper (1996). These continue to provide the basis for evaluation models in use in Australia at present with the output of the ‘mechanistic empirical’ models now used as the benchmark.

Since the mid-2000s, however, improvements of rural RUC estimation methodologies in Australia have been ad hoc, or have been undertaken as part of non-VOC dedicated projects (Michel et al. 2008). Notably, the parameter values and tables used in current road agency models have benefited from the outputs of the harmonisation process.

### **3.2 Urban (stop-start or interrupted flow) VOC models**

Austroads material on urban VOC models extends over a significant period of time, with developments in the specifications of the model. This is reflected in Lloyd and Tsolakakis (2000) for example which provides an overview of urban road user cost (RUC) models, as well as addressing the issue of harmonisation of such models. It describes the Traffic Modelling System (TRAMS) model developed for Western Australia, based mainly on NIMPAC models with the ARRB ARFCOM fuel consumption model. However, the model was never adopted across jurisdictions in Australia, although NIMPAC has been the basis for models in Australia while ARFCOM remains the basis of fuel consumption models in Australia as well.

Austroads (2004) presented an alternative urban stop-start model and a freeway (uninterrupted flow) model on a per-trip basis, drawing on studies by Austroads reported by Cox and Arup (1996). The models initially employed an adaptation of the HDM-III and ARFCOM models for urban conditions, with the final models based on use of ‘Australianised’ HDM-4 models. The performance estimates for vehicle maintenance and spare parts, tyre consumption, and fuel and oil consumption are based on applying multiplicative factors or alternative models to produce estimates for urban conditions. Capital depreciation and interest is accounted for through reduced fleet utilisation because of the lower journey speeds. The free flow version of these models is consistent with the earlier mentioned rural uninterrupted flow models, thus offering the potential for consistency in VOC and RUC estimation across different parts of the network.

In Austroads (2005) and Austroads (2008), the approach taken was to provide models for ‘at grade’ and freeway models (Austroads 2008) for all day average speeds, including representative traffic conditions, with model parameters produced on the basis of outputs

from the TRAM. This approach has formed the basis of VOC models presented in the most recent update (Austroads 2012b). Austroads (2012b) involved the aggregation of RUC components (VOC added to travel time), whereas earlier updates had presented coefficients for VOC both excluding travel time and then including travel time (vehicle occupants and freight travel time). This was identified as an area that required disaggregation of VOC (i.e. excluding travel time) for this analysis.

However, the latter models have proved difficult to calibrate for urban conditions, with some practitioners, e.g. Transport for New South Wales (TfNSW) in their VEHOP model (TfNSW 2013a) and appraisal guidelines (TfNSW 2013b), preferring to continue to use the models developed in Austroads (2004). The presentation of a set of VOCs excluding travel time has also been a key objective that has directed the review of parameter values for the NGTSM review, with the objective of obtaining cost data for VOC components (excl. travel time) for urban stop-start conditions and freeway models.

In addressing the third requirement, consideration has been given to the operating conditions and modelling complexity which can be reasonably modelled for cost benefit analysis purposes. In particular, under interrupted flow conditions performance is highly dependent on factors such as traffic volume and mix, road configuration, geometry and layout (and therefore capacity and speed), intersection types and spacing (including the provision of graded separated or at grade intersections), and signal controlled intersections. A number of these factors are directly accounted for in current CBA oriented modelling.

Bowyer et al. (1985) offered a classification of urban fuel consumption modelling which provides an insight to the complexity of the problem, with the physical estimates drawing on performance models such as the ARRB ARFCOM fuel consumption model (Biggs 1988), and the modelling framework reflected in software such as aaSIDRA (see Akcelik & Besley 2003). The classification is as follows:

- Instantaneous models (traffic management schemes, individual road sections, individual intersections, small networks where instantaneous speed data is available)
- Elemental models (incorporating four elements of cruise, idle, acceleration, deceleration). Same application as instantaneous, but used where only speed data are available for elements. (Modified for non-urban application)
- Running speed models. Travel is split into running and stopped components. Use at a trip level but not for traffic management modelling. Trip length > 1km.
- Average travel speed model. Travel speed includes stop time. Used for large scale transport modelling, including traditional 4–5 stage component models. Accurate for average travel speeds < 50 km/h.

The average travel speed model, based on the total time on a link calculated as the sum of the time to traverse a link at the estimated operating speed based on speed flow considerations and the intersection delay, is considered as a suitable basis for CBA. This method was also employed by Cox and Arup (1996), and in both the preceding and subsequent studies which underpinned the Austroads (2004) urban stop-start model and a freeway (uninterrupted flow) model. These models also adopt the mechanistic-empirical VOC models used to benchmark other model variants, and incorporate the ARRB ARFCOM model which remains the core of fuel consumption models in Australia for both urban and non-urban conditions. Use of this method also provides a consistent approach to incorporating travel time and freight delay costs, including modelling on the basis of different time periods, e.g. a.m. and p.m. peak periods, and day and night time off-peak periods. This therefore provides a clearly defined and generic basis for general CBA with total RUC calculated using a common average travel speed/total link time.

## 4. Vehicle classifications

The vehicle types included in the VOC model development follow the 20 vehicle classification (Thoresen and Ronald 2002) subsequently used in HDM-4 in Australia, as well as the Austroads 12 bin classification (Austroads 2004 and more recently Austroads 2013) as far as possible. These vehicle types, as well as their assumed vehicle weights, payloads, pavement damage factors in equivalent standard axles (ESA)<sup>1</sup> and passenger car equivalent units (PCUs) are presented in Table 1. An overview of the vehicle classifications used in Australia and their changing basis over time is described in Transport and Infrastructure Council (2015).

**Table 1: Vehicle parameters used in NGTSM parameter values**

Vehicle type	GCM (tonnes)	Max. payload (tonnes)	ESAs per vehicle at 75% payload	ESAs per vehicle at 100% payload	ESAs per vehicle at 125% payload	Engine power (kw)	Annual km
01. Small Car	1.2	0.4	0.0002	0.0003	0.0004	65	23,000
02. Medium Car	1.4	0.4	0.0005	0.0006	0.0006	80	23,000
03. Large Car	1.6	0.4	0.0008	0.0010	0.0011	110	23,000
04. Courier Van-Utility	2.15	0.85	0.0024	0.0031	0.0039	60	30,000
05. 4WD Mid Size Petrol	2.73	0.93	0.0066	0.0081	0.0097	132	30,000
06. Light Rigid	3.75	2.15	0.01	0.01	0.02	56	30,000
07. Medium Rigid	10.4	7.2	0.53	0.69	1.28	130	40,000
08. Heavy Rigid	22.5	13.5	2.72	3.59	6.17	190	86,000
09. Heavy Bus	19	7	1.17	2.32	3.51	200	70,000
10. Artic 4 Axle	31.5	20.5	3.96	5.07	8.95	190	86,000
11. Artic 5 Axle	39	26	4.4	5.65	10.08	260	86,000
12. Artic 6 Axle	42.5	27.5	3.89	4.97	8.54	300	86,000
13. Rigid + 5 Axle Dog	59	40	5.44	7.04	12.65	320	86,000
14. B-Double	62.5	40.5	4.93	6.35	11.02	350	86,000
15. Twin steer + 5 Axle Dog	64	43	4.49	7.58	13.66	360	86,000

<sup>1</sup> Practitioners are therefore able to use the payloads as inputs to the VOC models, with corresponding ESAs for their analysis. This provides a link for practitioners between VOCs which can be estimated using these models and vehicle loading which also has an effect on road pavement, especially as loads increase. For sealed granular pavements, the most common type in Australia, this is based on a simple model where the relative damage (in ESA or Standard Axle Repetitions) = (Axle load/Standard load)<sup>4</sup>, hence the commonly used term '4<sup>th</sup> power law'. For example, considering a standard load of 80kN and an actual load of 100 kN, the relative damage for an increase in total load of 25% is approximately (100/80)<sup>4</sup> or 2.45 times the effect of a standard load. For further guidance, reference should be made to the Guide to Pavement Technology Part 2: Pavement Structural Design (Austroads 2012c) and specialist advice sought in its application.

Vehicle type	GCM (tonnes)	Max. payload (tonnes)	ESAs per vehicle at 75% payload	ESAs per vehicle at 100% payload	ESAs per vehicle at 125% payload	Engine power (kw)	Annual km
16. A-Double	79	48	6.5	8.42	14.34	370	86,000
17. B Triple	82.5	48.5	5.99	7.73	12.88	380	86,000
18. A B Combination	99	60	7.54	9.80	16.73	380	86,000
19. A-Triple	115.5	71.5	9.1	11.86	20.61	390	86,000
20. Double B-Double	119	72	8.59	11.18	19.13	400	86,000

Source: ARRB Group Ltd.

## 5. Revised rural (uninterrupted flow) VOC models

### 5.1 Basis of uninterrupted flow models

The simplified model was developed by employing the 'Australianised' HDM-4 VOC models to generate estimates of VOC for a wide range of vehicles and operating conditions and using this data as input for developing multiple regression equations, and these were applied in populating the tables of values for VOC estimates. The underlying VOC component models have been the subject of extensive calibration studies. This has led to the development of an Austroads harmonised version with a vehicle fleet and model configuration specifically created for application in Australia.

A number of simplified, aggregate models are available from several sources, and have been re-estimated using the outputs of a structured analysis. The resulting models comprise a multi-variate regression equation which includes a number of terms, with parameters and coefficients. The model is generated by first defining and running a series of analysis cases and using the raw outputs to subsequently derive coefficients through regression analysis of multiple HDM-4 outputs.<sup>2</sup>

#### 5.1.1 ARRB aggregate model

ARRB developed an aggregate model based on regression of HDM-III, and later HDM-4, outputs for use in the Pavement Life Cycle Costing (PLCC) tool (Linard et al. 1996). The model formed was later applied in the Freight and Mass Limits Investigation Tool (FAMLIT) (Michel & Hassan et. al 2008). Vehicle speed was not used as an input or output, but is inherent in the model set up where the speed is estimated internally based on a separate free or desired speed model. This model is specified as follows:

$$\text{VOC} = a_1 \cdot (1 + a_2 \cdot \text{NRM} + a_3 \cdot \text{Rise\&Fall} + a_4 \cdot \text{Curvature} + a_5 \cdot \text{Payload})$$

<sup>2</sup> Regression results were assessed in terms of their robustness (e.g. levels of confidence) where appropriate. However, because the outputs were dependent upon mechanistic models embedded in established tools they could not be altered, and therefore are reliant on the original underpinning research, eg.g as reported by Cox and Arup (1996).

where:

VOC = vehicle operating costs in cents per km  
 NRM = road roughness in NAASRA counts per km  
 Rise&Fall = the cumulative sum of all rises and falls in m/km  
 Curvature = the accumulated curvature in degrees/km  
 Payload = the weight of good carried, i.e. above tare weight, in kg  
 a<sub>1</sub> to a<sub>5</sub> = model coefficients.

### 5.1.2 Alternative aggregate model

An alternative aggregate model reported by Phedonos (2006) and applied in international studies by ARRB and by the NZ Transport Agency (2013) resulted in a base set of VOCs and a set of coefficients that uses speed and roughness as key input parameters, with the following specification:

$$\text{VOC} = \text{BaseVOC} * [k_1 + k_2/V + k_3 * V^2 + k_4 * \text{IRI} + k_5 * \text{IRI}^2]$$

where:

BaseVOC = lowest VOC point in curve from raw HDM-4 output  
 V = Vehicle speed in km/h  
 IRI = International Roughness Index in m/km  
 k<sub>1</sub> to k<sub>5</sub> = model coefficients.

### 5.1.3 Model variables

In order to generate the uninterrupted flow models, ranges of various attributes were selected to represent the breadth of operating conditions, including:

- rise and fall and curvature
- road roughness
- road widths
- vehicle types, weights and payloads parameters.

Typical assumptions for gradient and curvature have not changed since Thoresen and Roper (1996) and the categories typically used together are presented in Table 2, and have also been used in the analysis of uninterrupted flow VOC presented in this report:

**Table 2: Gradient and curvature categories assumed for road stereotypes in Australia**

Variable	Categories
Gradient (Rise & Fall)	Flat (0%), 4%, 6%, 8% & 10%
Curvature (Terrain type)	Straight (20°/km) Curvy / Hilly / Winding (120°/km) & Very Curvy or Very Winding (300–320°/km)

## 5.2 Model structure and coefficients for uninterrupted flow conditions

Two models were developed, namely for total VOC (including fuel consumption) and for fuel consumption specifically.

### 5.2.1 Structure and coefficients for uninterrupted flow VOC model

The total VOC model for uninterrupted (free flow) conditions is as follows, with coefficients and a full set of values presented in Transport and Infrastructure Council (2015):

$$\text{VOC} = \text{BaseVOC} * (k_1 + k_2/V + k_3*V^2 + k_4*IRI + k_5*IRI^2 + k_6*GVM)$$

where:

VOC, vehicle operating costs in cents/km

BaseVOC = lowest VOC point in curve from raw HDM-4 output

V = Vehicle speed in km/h

IRI = International Roughness Index in m/km

GVM = gross vehicle mass in tonnes

k<sub>1</sub> to k<sub>6</sub> = model coefficients.

The coefficients estimated for the model specified above are contained in Transport and Infrastructure Council (2015)<sup>3</sup> for a specified set of road (geometry and roughness) and traffic conditions, and across all 20 vehicle categories.

### 5.2.2 Structure and coefficients for uninterrupted flow fuel consumption model

The fuel consumption model for uninterrupted flow conditions is as follows, with coefficients presented in Transport and Infrastructure Council (2015).

$$\text{Fuel consumption (litres/km)} = \text{BaseFuel} * (k_1 + k_2/V + k_3*V^2 + k_4*IRI + k_5*GVM)$$

BaseFuel = lowest fuel consumption point in curve from raw HDM-4 output

where:

V = Vehicle speed in km/h

IRI = International Roughness Index in m/km

GVM = gross vehicle mass in tonnes

k<sub>1</sub> to k<sub>5</sub> = model coefficients.

The coefficients estimated for the model specified above are contained in Transport and Infrastructure Council (2015).

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<sup>3</sup> Coefficients for the various models, road (geometry and roughness) and traffic conditions and across vehicle types have not been included in this paper due to space limitations as the tables extend across several pages. If readers wish to obtain examples of the coefficients, they are advised to obtain a copy of Transport & Infrastructure Council (2015). The model has been set up to accommodate a range of variables.



### 5.3 Updated uninterrupted (free flow) speed vehicle operating costs for Australia

For practitioners who wish to use tables of values, the coefficients in the tables can be used to estimate VOC (cents per km) and fuel (litres per 100 km) consumption using the most recent unit values (in this case for June 2013) for selected vehicle types. Applicable speeds were derived from NIMPAC and HDM approaches and VOC and fuel consumption outputs calibrated to those speeds for appropriate vehicle types.

A roughness level of 2 IRI was assumed for the uninterrupted flow VOC modelling analysis, with an assumed 75% payload for freight vehicles as an example in Transport and Infrastructure Council (2015). Other VOC estimates can be made applying the model specified and adjusting appropriately for payload.

## 6. Revised urban (interrupted flow) VOC models

### 6.1 Basis of interrupted flow VOC models

The approach adopted for interrupted flow VOC models involved the development of a suite of models for application to interrupted flow conditions, as experienced on urban and sub-urban arterials and freeways depending on variables such as time of day, traffic capacity and intersection types. The model development involved the reconstruction of the models reported by Cox and Arup (1996) and Austroads (2004), with a simplified vehicle operating cost model and fuel consumption model produced for typical operating conditions, again for a 20 vehicle fleet.

The development of the models adapted the outputs from the uninterrupted flow analysis by modifying the estimates for the different VOC components, as follows:

- fuel and lubricating oil consumption, through application of a multiplication factor based on average travel speed:

Cars and light commercial vehicles

$$F_{F\&LCL} = 1.9 * (1 - 0.004 * \text{Speed})$$

Medium and heavy commercial vehicles and buses

$$F_{F\&LHV} = 2.5 * (1 - 0.004 * \text{Speed})$$

- repairs and maintenance costs, and tyre consumption, through application of a multiplication factor which varies by vehicle type (Table 3) with the full factor applied at 30 km/h and a greater or lesser factor applied at lower and higher speeds with zero additional effect (factor of 1) at a user defined upper value (selected as 100 km/h)
- capital and interest, by accounting for reduced utilisation in lower journey speed environments and therefore higher per km costs through application of a multiplication factor:

$$F_{C\&I} = 60 / \text{Speed (in km/h)}$$

**Table 3: Multiplication factors for maintenance, labour, spares & tyre consumption under interrupted flow**

Vehicle type	Factor
Cars and light commercial vehicles	1.25
Rigid trucks	1.4
Articulated trucks and buses	1.6

## 6.2 Model structure and coefficients for interrupted flow models

The form of the interrupted flow VOC models relevant to interrupted flow conditions contains a stop-start and free-flow component, of the following form (Austroads 2004):

**Stop-start model:**  $c = A + B/V$   $c = A + B/V$

**Free-flow model:**  $c = C_0 + C_1V + C_2V^2$

where:

$A, B, C_0, C_1, C_2$  = model coefficients

$c$  = Vehicle operating cost (cents/km)

$V$  = Average travel speed in km/h

As was the case of Austroads (2004), the stop-start model can be used for estimating the VOC on urban and sub-urban arterial roads, or freeways, at average journey speeds of < 60 km/h, while the free-flow model is aimed at estimating VOC where average journey speeds are > 60 km/h.

A set of revised coefficients for interrupted flow conditions for all travel speeds and across all vehicle types is contained in Transport and Infrastructure Council (2015).

### 6.2.1 VOC coefficients for interrupted (stop-start) flow conditions

The VOC coefficients for the models were re-estimated using 2013 unit values by adapting the outputs from the uninterrupted flow models as described earlier. In Transport and Infrastructure Council (2015), however, a single set of operating conditions in terms of road geometry, road width and gross vehicle mass were considered and applied for all 20 vehicles<sup>4</sup> by way of example. The resulting coefficients are presented in Transport and Infrastructure Council (2015).

### 6.2.2 Fuel consumption coefficients for interrupted (stop-start) flow conditions

Fuel consumption coefficients for the same range of conditions were estimated and are contained in Transport and Infrastructure Council (2015) by way of example.

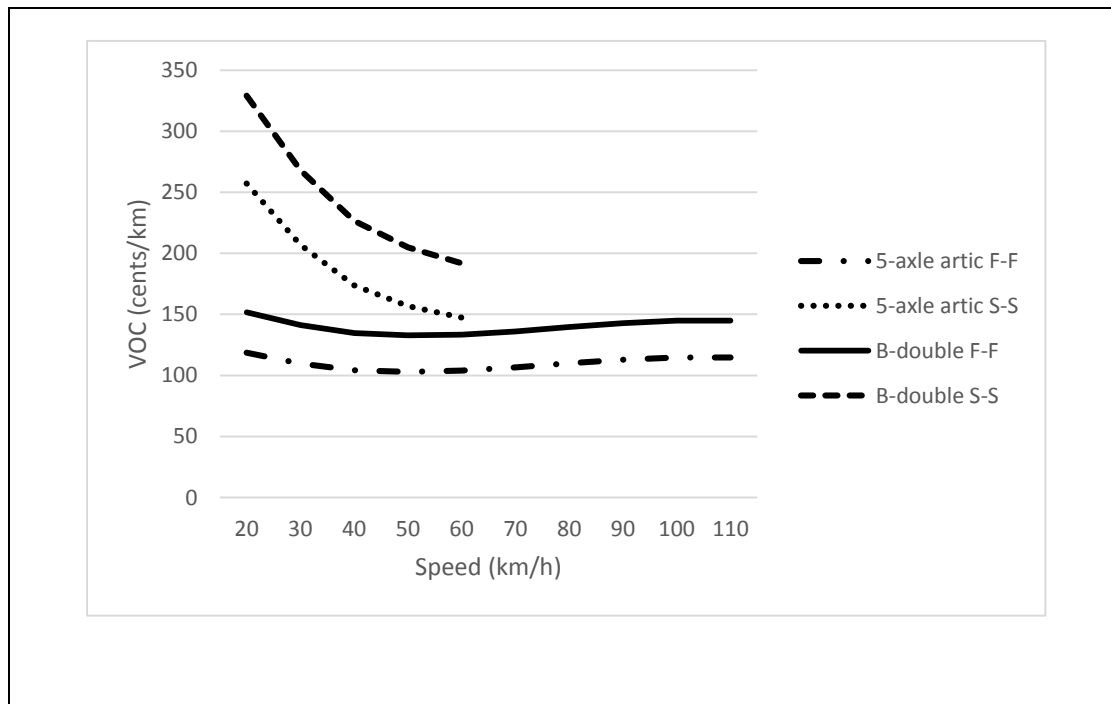
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<sup>4</sup> The extension of the number of vehicle categories from the limited number in Austroads (2004) to the 20 vehicle classification in the NGTSM highlights the importance of what is assumed to be a representative vehicle in a particular category where a limited number of vehicle types is used. These differences are reflected in the coefficients in the model over time.

## 7. Model comparison

Figure 1 shows the importance of choice of representative vehicle for an analysis, where a limited number of vehicle types is used (or several vehicle types are aggregated), with differences in VOC for two heavy vehicle types, where the VOC for a B-double is some 25% to 35% higher than a 5-axle articulated truck for uninterrupted-flow and stop-start conditions respectively. This would be an important issue when comparing the limited number of vehicle categories used in the past in Austroads (2004) with the extended 20 vehicle classification used in Transport and Infrastructure Council (2015).

Likewise, care should also be exercised in escalating costs over an extended period of time, e.g. Austroads (2004) as a basis, compared to undertaking periodic comprehensive review and updating of VOC models. Indexation over a long period of time can result in values that might differ from re-estimated VOC models, especially for interrupted flow (urban stop-start) conditions with low traffic speeds (i.e. increased traffic congestion).



**Figure 1: Comparison of VOC (all conditions) for 5-axle articulate and b-double (June \$2013)**

## 8. Recommendations for further research

The work undertaken for the NGTSM on VOCs in Australia can be developed further in a number of potentially very useful directions which will assist practitioners:

1. Awareness is required of previous research into development of VOCs that has been undertaken in Australia to minimise 'reinventing the wheel' – this research has shown that a lot of work has been undertaken in the past but that also needs to be documented into an appropriate synthesis of which this could form the first part. Much of the earlier, extremely valuable research that has formed the basis of this work needs to be digitised for archival retrieval for example, to ensure it is not lost over

time and is as accessible to researchers as possible. An appropriate approach to knowledge management will also avoid the confusion that has arisen over the years as to what is incorporated into VOC, e.g. the inclusion and then exclusion of travel time and why this is important in the urban and rural context. This will require procedures be put in place to ensure this outcome. A systematic approach to documentation is required from practitioners and jurisdictions to ensure associated improvements of VOC models are well-documented and readily available to researchers and policy makers

2. Assessment of the effects of the re-estimated coefficients on the results of economic evaluations to properly understand their effects across the range of heavy vehicle types particularly, given the extension of vehicle classifications to 20 vehicle types from the limited number of vehicle types used previously. This involves careful consideration of what constitutes the 'representative' vehicle, especially in the case of aggregation of several heavy vehicle categories
3. Incorporation of the revised VOC models into jurisdiction traffic models and economic evaluation tools where appropriate.
4. Updating and re-estimation of the VOC models to reflect changes in engine technologies in terms of international emissions specifications, e.g. Euro 4, and their influence on Australian Design Rules. Most of the current VOC models are based on dated engine technologies albeit with adjustments along the way, but this is quite clearly a second best
5. Development of a VOC calculator / tool to reflect a range of road and traffic conditions that can also be available to practitioners
6. Linkage of VOCs with ESAs for policy analysis as this provides a direct linkage with operating costs and impact on the road network and ultimately informs policy on road user charging
7. Accurate assessment of the marginal cost of roadwear and productivity improvements resulting from road investment decisions
8. It is also necessary to ensure that users of VOC models have a better awareness of the additional research tasks required to increase the capability of VOC models to better examine the productivity impacts of variations in travel speeds of both private and business road users.

## References

- Akcelik, R & Besley, M (2003), Operating cost, fuel consumption and emissions models in aaSIDRA and aaMOTION, *Conference of Australian Institutes of Transport Research (CAITR)*, University of South Australia, Adelaide, SA, 15 pp
- Austrroads (2000) 'Estimating RUC for urban road networks: upgrading the TRAMS model', Austrroads, Sydney, NSW
- Austrroads (2004) *Economic evaluation of road investment proposals: unit values for road user costs at June 2002*, AP-R241-04, Austrroads, Sydney, NSW
- Austrroads (2005) *Economic evaluation of road investment proposals: harmonisation of non-urban road user cost models*, AP-R264-05, Austrroads, Sydney, NSW
- Austrroads (2008) *Guide to project evaluation: part 4: project evaluation data*, 3<sup>rd</sup> ed., AGPE04/08, Austrroads, Sydney, NSW
- Austrroads (2012a) *Update of vehicle/road relationships underpinning road user costs and externality costs*, AP-T189-11, Austrroads, Sydney, NSW
- Austrroads (2012b) *Guide to project evaluation: part 4: project evaluation data*, AGPE04-12, Austrroads, Sydney, NSW
- Austrroads (2012c) *Guide to Pavement Technology Part 2: Pavement Structural Design*, Austrroads Sydney, NSW
- Austrroads (2013) *Guide to Traffic Management Part 3: Traffic studies and analysis*, Austrroads Report AGTM 03/13, Austrroads, Sydney, NSW
- Bennett, CR & Greenwood, ID (2006) *Modelling road user and environmental effects*, Highway Development and Management Series vol. 7, World Road Association (PIARC), Paris
- Biggs, DC (1988) *ARFCOM: models for estimating the light to heavy vehicle fuel consumption*, ARR 152, Australian Road Research Board, Vermont South, Vic
- Both, G & Bayley, C (1976) *Evaluation procedures for rural road and structure projects*, Australian Road Research Board (ARRB) Conference, 8th, 1976, Perth, Australian Road Research Board, Vermont South, Vic, vol. 8, no. 6, pp. 6–25, 52–3
- Bowyer, D, Akcelik, R & Biggs, D (1985) *Guide to fuel consumption analyses for urban traffic management*, SR 32, Australian Road Research Board, Vermont South, Vic
- Cox, JB and Arup Transportation Planning (1996) *Models for predicting vehicle operating costs in urban areas*, Austrroads Project BS3.A.41, Contract Report 8748, Ove Arup and Partners, Melbourne, Vic
- Hodges, J, Rolt, J and Jones, T (1975) *The Kenya road transport cost study: research on road deterioration*, Laboratory Report LR 673, Transport and Road Research Laboratory: Crowthorne

Linard, K, Martin, T, & Thoresen, T (1996) *Optimisation Procedures for Pavement Life-Cycle Costing*, National Road Transport Commission Technical Working Paper 23 (ARRB TR: Vermont South, Victoria, Australia)

Lloyd, E. and Thomas, G. (1988) *Economic Evaluation Procedures for Urban Road Projects*, Perth, Advance Planning Section, Main Roads Department, WA

Lloyd, B & Tsolakis, D (2000) *Estimating RUC for urban road networks*, Contract Report RC90252, ARRB Transport Research, Vermont South, Vic

Michel, N, Hassan, R et al. (2008) *FAMLIT Freight Axle Mass Investigation Tool*, 23rd ARRB Conference, Adelaide, Australian Road Research Board, Vermont South

New Zealand Transport Agency (2013) *Economic evaluation manual*, NZTA, Wellington, NZ

OPUS International Consultants (1999) *Review of VOC-pavement roughness relationships contained in Transfund's project evaluation manual*, Opus International Consultants, Wellington, New Zealand

Peters, E (2001) *Austrroads road user costs projects*, Road System and Engineering Technology Forum, 2001, Brisbane, Queensland, Department of Main Roads, Road System and Engineering Group, Brisbane

Phedonos, J (2006) *Review of Vehicle Operating Costs and Updating of VOC Coefficients for Use with IRMS*, ARRB Contract Report, Improved Planning, Programming and Budgeting Procedures for Eastern Indonesia, Directorate General of Highways, Jakarta, Indonesia

Stannard, EE & Wightman, D (2006) *Analytical framework and model descriptions*, Highway Development and Management Series vol. 4, World Road Association (PIARC), Paris

Tan, F, Evans, C & Thoresen, T (2012) *Review of vehicle operating cost and road roughness: Past, present and future*. 25<sup>th</sup> ARRB Conference: Perth

Thoresen, T (2004) 'Quantifying the road user cost implications of incremental load pricing for heavy freight vehicles', contract report RC4189, ARRB Transport Research, Vermont South, Vic

Thoresen, T and Ronald, N (2002) *Consistent input parameters for use in HDM-4 under Australian conditions: Road user costs*. ARRB internal report for Austrroads project RC2062, Vermont South, March

Thoresen, T & Roper, R (1996) *Review and enhancement of vehicle operating cost models: assessment of non urban evaluation models*, ARR 279, ARRB Transport Research, Vermont South, Vic

Thoresen, T & Roper, R (1999) 'HDM-4 model testing for selected Australian conditions: review of road user effects models calibration assessment study (HDM-4 Beta version 3.0)', contract report RC90038-4, ARRB Transport Research, Vermont South, Vic

Transport and Infrastructure Council (2015) *NGTSM Review PV2: Road Parameter Values*. NGTSM Review. <http://ngtsmguidelines.com/parameter-values/road-transport/>

Transport for New South Wales (2013a) 'Existing methods and models used to estimate vehicle operating costs for high productivity vehicles (HPVs)', HPV Working Group working paper 1, TfNSW, Sydney, NSW

Transport for New South Wales (2013b) 'Principles and guidelines for economic appraisal of transport investments and initiatives', TfNSW, Sydney, NSW

Watanatada, T, Dhareshar, A & Rezende Lima, PRS (1987) *Vehicle speeds and operating costs: models for road planning and management*, John Hopkins University Press, Baltimore