Integration of vehicle operating cost and emission models

Review of the NZVOC model and the VEPM

September 2024

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NZ Transport Agency Waka Kotahi research report 730
Contracted research organisation – National Transport Research Organisation

NZ TRANSPORT AGENCY WAKA KOTAHI

Te Kāwanatanga o Aotearoa
New Zealand Government

ISBN 978-1-99-106898-9 (electronic)
ISSN 3021-1794 (electronic)

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Hall, B., Ainalis, D., Kochhan, R., Toole, T., van Dijk, J. & Greenwood, I. (2024). *Integration of vehicle operating cost and emission models: Review of the NZVOC model and the VEPM* (NZ Transport Agency Waka Kotahi research report 730).

The National Transport Research Organisation was contracted by NZ Transport Agency Waka Kotahi in 2023 to carry out this research.

Keywords: assessing model integration; New Zealand Vehicle Operating Cost model; Vehicle Emissions Prediction Model

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[1] This research was conducted June 2023-April 2024.

Acknowledgements

The authors would like to thank the project steering group:

- Sandy Fong, Principal Advisor, NZTA – Research Owner and Chair
- Sharon Atkins, Principal Environmental Specialist, NZTA
- Dave Brown, Vehicle Emissions Manager, NZTA
- Bryce Hartell, Lead Investment Advisor, NZTA
- Ed McGeehan, Economic Analysis Specialist, Department of Transport and Planning (Victoria, Australia)
- Levente Timar, Te Manatū Waka Ministry of Transport
- Haobo Wang, Principal Analyst, Te Manatū Waka Ministry of Transport

The authors would also like to thank Christopher Bennett, previously Lead Transport Specialist at The World Bank; and Robin Smit, Transport Energy/Emission Research as peer reviewers of this research report.

Abbreviations and acronyms

Abbreviation	Description
AN	Acceleration noise
ATAP	Australian Transport Assessment and Planning
CBA	Cost–benefit analysis
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
COPERT	European Computer Model to Calculate Emissions from Road Transport
EEM	Economic Evaluation Manual
EMFAC	Californian emission factor model
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
HBEFA	Handbook Emission Factors for Road Transport
HC	Hydrocarbons
HCV	Heavy commercial vehicle
HDM	Highway Development and Management
HDM-4	Highway Development and Management Model 4
HV	Heavy vehicle
ICEV	Internal combustion engine vehicle
LCV	Light commercial vehicle
LNG	Liquefied natural gas

Abbreviation	Description
LPG	Liquefied petroleum gas
LZEV	Low and zero emission vehicle
MBCM	Monetised Benefits and Costs Manual
MCV	Medium commercial vehicle
MoT	Te Manatū Waka Ministry of Transport
MOVES	Motor Vehicle Emission Simulator (USA)
MRS	Model road state
n0vem	Net Zero Vehicle Emission Model
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides (inclusive of N_2O and NO_2, etc.)
NTRO	National Transport Research Organisation
NZTA	NZ Transport Agency Waka Kotahi
NZVOC	New Zealand Vehicle Operating Cost
Pb	Lead
PC	Passenger car
PEM	Project Evaluation Manual
PHEM	Passenger Car and Heavy Duty Emission Model
PHEV	Plug-in hybrid electric vehicle
PM_{10}	Particulate matter with a diameter equal to or less than 10 micrometres
$PM_{2.5}$	Particulate matter with a diameter equal to or less than 2.5 micrometres
PMS	Pavement management system
PΔP	Power-delta-Power emissions model
SO_2	Sulphur dioxide
SUV	Sport utility vehicle
VCR	Volume-to-capacity ratio
VEPM	Vehicle Emissions Prediction Model
VFEM	Vehicle Fleet Emissions Model
VKT	Vehicle kilometres travelled
VOC	Vehicle operating cost

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Contents

Executive summary

This project, undertaken across 2023–2024, investigated how the New Zealand Vehicle Operating Cost (NZVOC) model and the Vehicle Emissions Prediction Model (VEPM) could be linked or integrated through a review of the models, engagement with key stakeholders and an options analysis.

The NZVOC model and the VEPM were reviewed in terms of each model's purpose, scope, and data inputs and outputs and their update frequency, and common and unique elements were identified. From the review, several potential opportunities were identified to align similar aspects of the models. These include aligning the current and forecasted vehicle fleet, as well as understanding the differences between the underlying speed models and the effect of road configuration on fuel consumption and emissions. In terms of the individual models, the NZVOC model was found to be not well maintained and requires updating, particularly the fleet profile, which is currently limited to diesel and petrol vehicles. The model is also not user friendly (or available to the public), unlike the VEPM, which has been developed into an online tool. For the VEPM, there are potential opportunities to improve various aspects, including improving the effects of low speed (without an increase in stop–start conditions) and incorporating the effects of varying road configurations. It was established that users need to have greater awareness around the limitations and uses of the models (or outputs) to ensure they are appropriately used for their intended task.

A stakeholder engagement workshop was held after the review to obtain feedback from model owners and users around the models' current uses and value, limitations and necessary or desirable future features. A set of potential integration options were presented to the stakeholders. Feedback from the stakeholders supported the option to retain both models and make improvements to both models, including improved documentation and live guidance at key input stages to assist users in appropriate model use.

Nine potential opportunities were identified that could improve and better align the models:

- Opportunity 1: Using consistent vehicle classes and fleet proportions
- Opportunity 2: Enabling the NZVOC model to recognise low and zero emission vehicles
- Opportunity 3: Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time
- Opportunity 4: Aligning the NZVOC model's emission outputs with the VEPM's emission outputs
- Opportunity 5: Aligning speed drive cycles with average speed profiles
- Opportunity 6: Enabling the VEPM to better reflect road condition and configuration effects
- Opportunity 7: Developing use-case guidance and worked examples
- Opportunity 8: Improving data collection and calculation transparency, and describing limitations
- Opportunity 9: Improving the usability of the NZVOC model.

Each opportunity was assessed according to four criteria: (i) clarity of scope, (ii) technical feasibility, (iii) benefit, and (iv) cost and complexity. The assessment also considered the benefits that would be associated by combining opportunities to create a unified suite of work to be completed. From the assessment, two separate packages of work are recommended: 'development' works, as described in Opportunities 1–4, and 'guidance' works, described in Opportunities 7 and 8.

Opportunities 5 and 6 are considered desirable but have inherent complexities that require further scoping and investigative research to determine their feasibility and the extent of their benefits. If NZ Transport Agency Waka Kotahi decides to proceed with these opportunities, we recommend conducting a further investigative study, including model testing, to determine a viable implementation pathway.

Opportunity 9 may be beneficial, but the implementation costs are likely to outweigh the benefits. Unless a strong user-benefit can be established, this opportunity is not recommended.

A specifications document outlining the scope of work for the ‘development’ and ‘guidance’ opportunities has been developed and included in Appendix A.

Abstract

The purpose of this research project was to understand the opportunity to link, integrate or better align two separate models used in New Zealand for estimating vehicle operating costs and predicting vehicle emissions.

The New Zealand Vehicle Operating Cost (NZVOC) model estimates vehicle fuel use as a component of total vehicle operating costs, which can then be used to estimate vehicle emissions. The Vehicle Emissions Prediction Model (VEPM) uses a comprehensive fleet model based on the New Zealand fleet profile and vehicle emission factors to predict vehicle emissions. Whilst noting differences in the models’ estimation approaches, input datasets, use cases and currency, NZ Transport Agency Waka Kotahi identified a potential opportunity to combine aspects that could build on the strengths of each and address their current limitations.

The research project compared key aspects or components of the models, engaged key stakeholders for model operations and use-case insights, proposed a number of practical improvement opportunities, and conducted an options analysis to identify future priorities.

Whilst the development of a hybrid model was ruled out, several potential opportunities were identified to align similar aspects of the models to improve the consistency of their outputs. These include aligning the current and forecasted vehicle fleet, as well as understanding the differences between the underlying speed models and the effects of road configuration on fuel consumption and emissions.

The research recommended further development of two packages of works: a ‘development package’ focused on enhancing and improving alignment of the models, and a ‘guidance package’ to provide users with better information on appropriate use cases and calculation transparency. The recommendations are supported by a specifications document outlining the scope of work for the ‘development’ and ‘guidance’ works packages.

1 Introduction

1.1 Background

The New Zealand Vehicle Operating Cost (NZVOC) model was first introduced as an input into transport cost–benefit analysis (CBA) in 1989. It uses manufacturers' vehicle data on engine capacity and type as the fleet model to estimate vehicle running costs, fuel costs, vehicle depreciation, maintenance and vehicle emissions. Its costs per kilometre are adjusted according to traffic and road conditions with speed change models. The NZVOC model's outputs are published in the *Monetised Benefits and Costs Manual* (MBCM) (and the MBCM's predecessors), with updates to the NZVOC model produced in 2002, 2008 and 2015.

The trend over time shows that vehicle efficiency improvements reduce the significance of fuel use as a component of vehicle operating costs (VOCs) to a transport project's overall economic impacts. For example, the 2002 update reduced the VOC impacts (due to cost changes and fuel efficiencies), and a further update with new inputs in 2015 reduced the costs by a further 12% (Cenek, 2015).

The Vehicle Emissions Prediction Model (VEPM) was first released in 2008 and uses a comprehensive fleet model based on the New Zealand fleet profile from Te Manatū Waka Ministry of Transport's (MoT) Vehicle Fleet Emissions Model (VFEM) and vehicle emissions standards cross checked with actual emissions data. The VEPM is updated more frequently than the NZVOC model (2011, 2012, 2013, 2017, 2019, 2020, 2021 and 2022).

NZ Transport Agency Waka Kotahi (NZTA) identified the potential opportunity to combine aspects of the NZVOC model and the VEPM into a potential hybrid model that could build on the strengths of each and address their current limitations. NZTA noted that:

- The VEPM has a better and more frequently updated fleet model than the NZVOC model and includes future fleet composition forecasts. However, it is more aggregated in terms of vehicle types. There may be opportunity to simplify the vehicle fleet model.
- The VEPM has battery-electric and hybrid-electric vehicle coverage in its vehicle fleet model whereas the NZVOC model does not.
- Fuel consumption from the VEPM could be used to calculate VOCs.
- Emissions estimates from the VEPM could be used to better integrate emissions costs into the transport CBA as the VEPM is used for modelled emissions estimates in the Health and Air Pollution in New Zealand study.
- The NZVOC model can model detailed traffic, road condition and road geometry. While these effects are implicitly incorporated in the VEPM, the model does not allow them to be adjusted by the user and they are unable to be assessed.
- The VEPM needs improvement for vehicle–pavement interactions. This interaction can result in a 2–3% increase in emissions (Brownjohn et al., 2019). The effects of pavement surfaces on emissions are included in the NZVOC model.
- There has been a longstanding objective to better model road and driving conditions in the VEPM (which the NZVOC model does by predicting the resource consumption at a microscopic mechanistic level that can then be used with any driving condition model to accurately predict the implications) as an average speed model has limitations at lower speeds in urban areas.

1.2 Research purpose

The National Transport Research Organisation (NTRO) was engaged by NZTA to undertake the research project *Integration of Vehicle Operating Cost and Emission Models* in 2023–2024. The project's key outcome is a recommendation for feasible changes to better integrate the inputs, outputs and updates of VOC and emissions models.

1.3 Research method and outputs

This project investigated how the NZVOC model and the VEPM could be linked or integrated through a review of the models, engagement with key stakeholders (ie, model owners and users) and options analysis.

The model review considered the key aspects or components of the two models and compared their similarities and differences, as well as their interactions with other models, approaches and publications in the NZTA evaluation suite.

The stakeholder engagement produced key insights to help understand:

- the models' current uses
- the value derived from each model
- the models' shortcomings (from a user perspective) and possible or expected future goals and needs (eg, accounting for a growing low and zero emission vehicle (LZEV) fleet, accounting for other air pollutant emissions in addition to greenhouse gas (GHG) emissions)
- desirable model capabilities (eg, refined low-speed zone emissions modelling, breadth vs granularity).

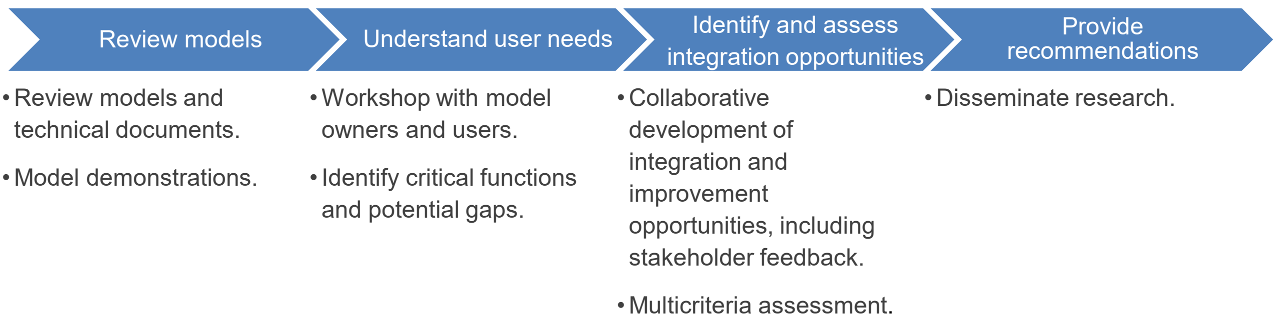
The options analysis identified a range of options, which were assessed through a two-stage evaluation process.

The project:

- reviewed the current state of VOC models and vehicle emission estimation models used for CBAs, including a review of technical documentation and model demonstrations
- developed an understanding of user needs and identified any gaps in the coverage and application of the models through a stakeholder engagement workshop
- identified and assessed the opportunities to integrate inputs and outputs between VOC models and emissions models
- provided a series of recommendations to better integrate the inputs, outputs and updating of VOC models with emissions models.

Figure 1.1 shows the overall project methodology.

Figure 1.1 Overview of the research methodology



The following outputs were produced during this research project:

1. a comprehensive research report (this document), inclusive of research approach, stakeholder engagement outcomes, analysis and recommendations to be published on the NZTA website
2. a detailed scope for model integration or updates for a potential implementation project in the future, included in Appendix A
3. communication via a recorded presentation (including slides) to share the research findings.

2 Review of the NZVOC model and the VEPM

The NZVOC model and the VEPM were reviewed in terms of each model's purpose, scope, data inputs and outputs, and update frequency, and their common and unique elements were identified. This section provides details from the review and a comparison between the models (and relevant international models).

2.1 NZVOC model

2.1.1 Overview and purpose

The NZVOC model is a tool for predicting VOCs for economic evaluations of transport-related projects and policies. It was first developed in the late-1980s (as NZVOC-DOS) and has been used by NZTA (then 'Transfund NZ') to generate the cost tables for their *Project Evaluation Manual* (PEM). In 2006, the PEM was replaced by the *Economic Evaluation Manual* (EEM) and, since 2020, by the MBCM. The latter document sets out the economic evaluation formulas and values to use when calculating investment returns and benefit–cost ratios for applications required by NZTA.

The mechanistic-empirical NZVOC model predicts vehicle resource consumption at a microscopic mechanistic level, which can then be used with any driving conditions to accurately predict the implications for road sections and projects. The model works by predicting the amount of VOC components consumed – for example, litres of fuel consumed – then multiplying these by the unit cost of each component to obtain the total cost. The VOC components are calculated based on the equations in the World Bank–developed Highway Development and Management Model 4 (HDM-4; Bennett & Greenwood, 2001) with these calibrated to New Zealand conditions. HDM-4 works on a first-principles basis by predicting fuel consumption as a function of road and vehicle conditions, then costs and emissions from that. The data are calibrated based on the techniques outlined by Bennett and Paterson (2000) and with local New Zealand data.

In 2001–02, NZTA commissioned HTC Infrastructure Management Ltd to update the NZVOC model and convert it into a software package (NZVOC-Win). This version moved beyond producing tables and provided the capacity to generate non-linear equations for predicting VOCs. The input data were based on a variety of sources, including public datasets and statistics, private and confidential datasets, and primary research through contacting suppliers and operators. These updates require a considerable level of expert judgement to make reasonable assumptions about the input data. These inputs have since been updated in 2008 and 2015. The 2008 update was relatively minor and only revised the economic costs of fuel, tyres, tyre retread, oil, maintenance labour and the percent-in-class data for buses.[2] The 2015 update by Opus (Cenek, 2015) comprehensively reviewed all components and modified the following elements: (i) percent-in-class data for all vehicle classes,[3] (ii) passenger car engine capacity bands/categorisation, (iii) economic unit costs of vehicles, trailers, fuel, tyres, oil and maintenance labour, (iv) fuel consumption, and (v) depreciation rate of imported Japanese cars.

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[2] The approach envisaged with the NZVOC model from the first version was that there would be regular running of the model (ie, once every two years) with updated unit cost inputs that would be used to generate simple update factors. More regular cost updates of the tables would be made at longer intervals.

[3] The NZVOC model has two approaches to modelling vehicles. There is a class of vehicles (eg, passenger cars) that has several vehicles whose individual costs are aggregated to give the cost of the class. Separately, there are road classes where there are percentages of different vehicle classes on the road. This simplifies the analysis since only the table for the road class of interest needs to be used.

Since the 2015 update, there have been significant developments around vehicle fuel efficiency, the emergence of LZEVs, and changes in purchase and operating costs that affect the accuracy of the model's outputs. These developments have not been embodied in an NZVOC update.

2.1.2 Scope and key structural elements

The NZVOC model is primarily used to generate parameter values for the MBCM. The model calculates estimates of dependent variables, primarily VOCs, but can also calculate the individual resource components (eg, fuel used) and produces outputs based on varying single or multiple independent variables. This means that the outputs are not directly linked to geographical locations or time of day or year, and they can be utilised in a more comprehensive traffic, CBA or pavement management system (PMS) tool to estimate VOCs. The NZVOC model categorises VOCs into running costs, road surface related costs, speed change cycle costs, congestion costs and costs while stopped. Values are provided by vehicle classes and for standard traffic compositions on four different road categories. VOCs for road sections are a function of the length of the section, traffic volume, and traffic composition, and they vary by road roughness condition, gradient, vehicle speed and level of congestion represented by a volume-to-capacity ratio (VCR) (Waka Kotahi, 2023b).

The total VOCs are calculated from the base running costs by speed and gradient, then adding the following marginal cost components if appropriate: (i) road roughness costs, (ii) road surface texture costs, (iii) pavement elastic deflection costs, (iv) congestion costs, (v) bottleneck costs, and (vi) speed change cycle costs.

The base VOCs relate to vehicle use while travelling on roads with different grades and free speeds, and comprise fuel, tyres, repairs and maintenance, oil and (the use-related proportion of) depreciation. Additionally, travel time costs can be included (work-related travel time or composite travel time and congestion), typically for cases estimating additional or reduced costs stemming from changes in road roughness and speed.

Vehicle fuel use is an intermediary component of the base VOC calculations and is not specifically reported in the output tables. Fuel use, however, is the key component necessary for estimating vehicle emissions and is a function of road surface condition, road geometry, speed, congestion and vehicle loading. Resource component consumption (ie, fuel, oil, tyres, parts, labour hours, etc) can be selected for output as an alternative to costs or aggregated costs as VOCs, and a suitable regression equation could also be generated as for total VOCs.

The NZVOC model estimates total VOCs based on representative vehicles for each vehicle class. These representative vehicles are modelled as hypothetical composites, based on averages of the range of attributes within each vehicle class (eg, age, engine power, gross mass). In practice, data on the full range of characteristics is not always available and an actual 'average vehicle' may be chosen in some instances. For example, vehicle mass or percent of maximum payload are key attributes that affect VOC resource consumption, emissions and road pavement damage; however, variation in these attributes cannot be captured within an 'average vehicle' typology.

The NZVOC model divides vehicles into 22 representative vehicle types across six vehicle classes and two fuel types (diesel and petrol). Table 2.1 shows these vehicle types and classifications along with the default vehicle fleet composition within each class.

Table 2.1 The default fleet vehicle classes and types in the NZVOC model

Number	Class	Abbreviation	Description	Percentage in class
1	PC	PC-S	Small passenger car	25%
2	PC	PC-M	Medium passenger car	56%
3	PC	PC-L	Large passenger car	19%
4	LCV	4WD	4WD sport utility vehicle	38%
5	LCV	Van	Van or mini-bus	16%
6	LCV	Utility	Utility vehicle	43%
7	LCV	LT	Two axle single tyred truck	3%
8	MCV	MCV-L	Two axle dual-tyre truck < 5 t	28%
9	MCV	MCV-H	Two axle dual-tyre truck > 5 t	72%
10	HCV-I	HT1-3	Three axle truck	30%
11	HCV-I	HT1-4	Four axle truck	64%
12	HCV-I	HT1-3-A	Three axle articulated truck	1%
13	HCV-I	HT1-4-A	Four axle articulated truck	5%
14	HCV-II	HT2-5-A	Five axle articulated truck	2%
15	HCV-II	HT2-6-A	Six axle articulated truck	12%
16	HCV-II	HT2-A	A train truck combination	0%
17	HCV-II	HT2-B	B double truck combination	24%
18	HCV-II	HT2-T-2	Heavy truck towing a two-axle trailer	1%
19	HCV-II	HT2-T-3	Heavy truck towing a three-axle trailer	5%
20	HCV-II	HT2-T-4	Heavy truck towing a four-axle trailer	56%
21	Bus	HB-2	Heavy bus or coach with two axles	85%
22	Bus	HB-3	Heavy bus or coach with three axles	15%

Note: PC = passenger car. LCV = light commercial vehicle. MCV = medium commercial vehicle. HCV = heavy commercial vehicle. HB = heavy bus.

2.1.3 Model operation, calibrations, inputs and outputs

This section describes the NZVOC model calibration and operation, along with its key inputs and outputs.

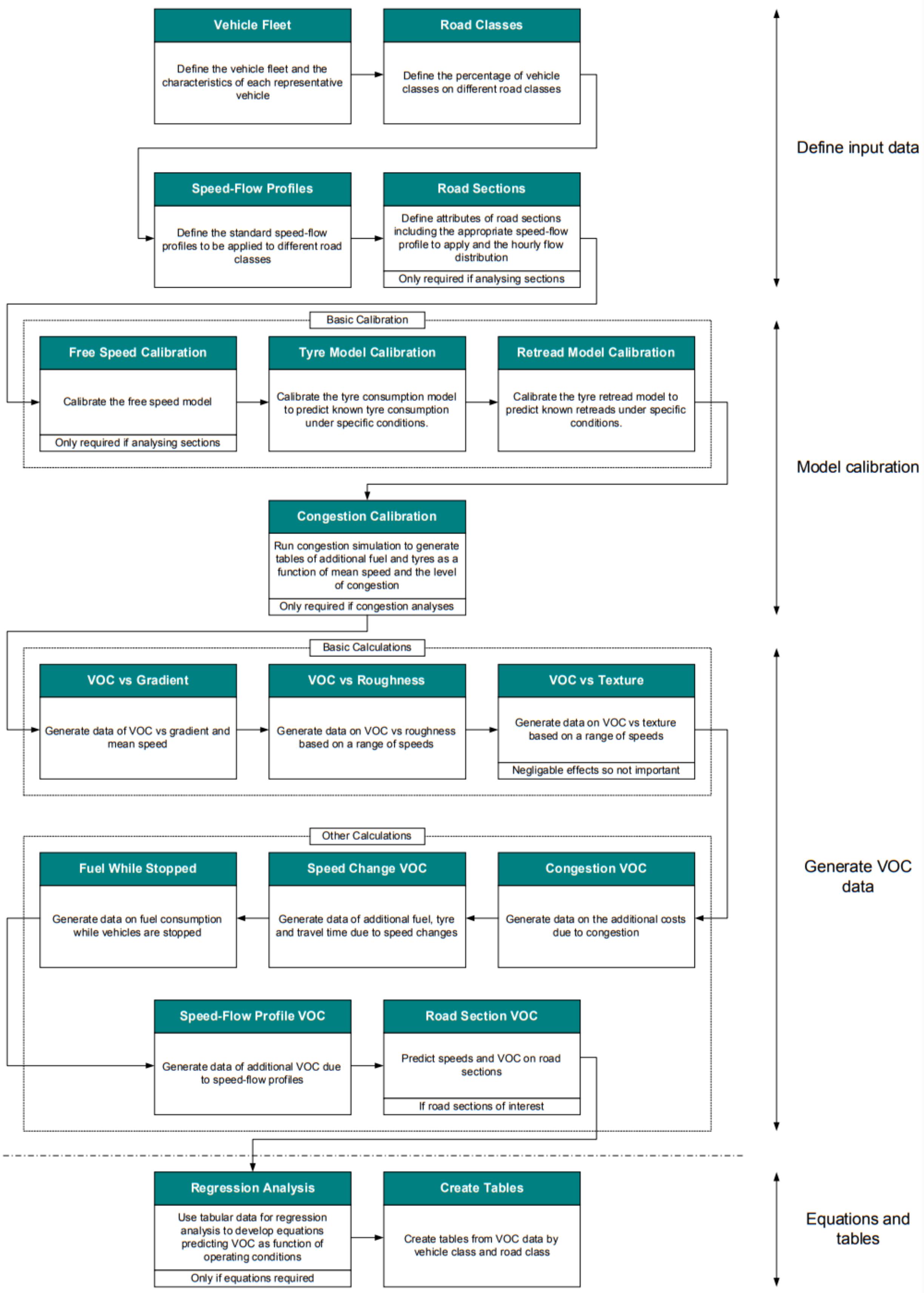
2.1.3.1 Operation and calibration

Operating the NZVOC model (Figure 2.1) involves the following steps:

1. defining the input data (ie, vehicle fleet, road classes, speed-flow profiles, road sections)
2. calibrating the model (free speed, tyres, congestion)
3. generating VOC data[4] as a function of operating conditions (VOC vs gradient, VOC vs roughness, VOC vs texture, fuel while stopped, speed change VOC, congestion VOC, speed-flow profile VOC, road section VOC)
4. preparing tables and equations of VOC as a function of operating conditions (regression analysis and tables).

[4] VOC data can be selected, modelled and output not only as a cost but also as resource component quantities consumed such as fuel, oil, tyres, parts, labour hours and emissions.

Figure 2.1 Flowchart summarising the process to use the NZVOC model (reprinted from Data Collection Ltd, 2003, p. 2)



The NZVOC model calibration process is undertaken in two stages:

1. Stage one is an initial ‘level 1’ HDM calibration for ‘critical parameters’.
2. Stage two is a final calibration that uses the initial calibration values to predict VOCs and their distributions and to compare these with actual New Zealand cost estimates. The following should be considered for the main resource components:
   - fuel model (based on HDM-4):
     - idle fuel consumption
     - power-fuel efficiency factor
     - efficiency factors
     - engine/accessory power factors
     - engine speed: calibrated using Gearsim, Monte Carlo simulation of engine speed as a function of road speed
     - effective mass ratio: calibrated using Gearsim
   - tyre model:
     - number of retreads
     - volume of wearable rubber
     - tread wear parameters
   - parts and labour model:
     - base costs: absolute/base value + roughness factor
     - calibration: parts model – function of service life and roughness
     - calibration: labour hours – based on 50% of total maintenance and repair costs
     - oil model: default HDM-4 values.

2.1.3.2 Inputs

The primary inputs of the NZVOC model cover the physical and economic aspects of the representative vehicles and the unit costs for consumables.

Representative vehicle characteristics include:

- percentage in class
- projected frontal area
- operating weight
- engine capacity
- rated engine power
- driving engine power
- braking engine power
- idle engine speed
- maximum engine speed
- replacement value
- average number of wheels
- wheel diameter
- wheel mass
- service life
- annual utilisation.

The model also requires representative vehicle unit costs to be input for fuel, maintenance labour, oil, tyres and vehicle replacement.

While not specifically analysed in this project, sport utility vehicles and large utility vehicles are particularly important from an energy and emissions perspective. Their specific vehicle characteristics, such as projected frontal area and operating weight, and the growth of the market segment warrant particular attention.

2.1.3.3 Outputs

The NZVOC model's intermediate outputs are obtained from the software and can be exported as a Microsoft Access file. This provides the equation parameter values resulting from the Monte Carlo simulations, such as the additional fuel and tyre consumption due to congestion and acceleration noise (speed change cycles). After calibration, the software's analysis settings can be modified to produce all the intermediate calculations in a file. Unit costs would normally be applied to the intermediate calculations to produce the VOC value tables. If the unit costs are excluded, the intermediate calculations would allow for the production of resource consumption (eg, fuel, tyres) value tables, rather than VOCs.

Emissions modelling parameters can also be defined in the analysis setup. Similarly, by excluding unit costs, emissions value tables can be produced for gradient, roughness, and texture ranges. Bennett and Greenwood (2001) established emission factors for hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), lead (Pb) and particulate matter (PM), which can be manually updated, calibrated or extended to other emission factors in line with the VEPM. Except for purely research purposes, the NZVOC model's emission values have not been made available and have been rarely used, if at all, in practical applications.

After confirming or modifying the inputs and calibrating the models, the model estimates the VOCs (or resources or emissions). The key outputs include: (i) VOC vs gradient, (ii) VOC vs roughness, (iii) VOC vs texture, (iv) fuel while stopped, (v) speed change VOC, (vi) congestion VOC, (vii) speed-flow profile VOC, and (viii) road section VOC.

2.1.4 Uses and users

The NZVOC model is not publicly available on the NZTA website, and the software model is not particularly user friendly. It was not designed as a model for general use but instead to be used on a regular basis (eg, every two years) to develop tables of values and regression equations that are inputs into CBA and PMS tools. Consequently, specialist consultants to NZTA periodically update certain model inputs and prepare various output data tables, which are incorporated into the MBCM (eg, Appendix 4). The NZVOC outputs provided in the MBCM are used in various applications, such as for project-level cost analyses, and in the National Land Transport Programme in combination with the VEPM for national emissions reporting.

Without significant changes, future uses appear to be limited to its current application. This limitation is not a problem in and of itself as the model was only intended for specialised uses. However, with limited user access and familiarity, detailed knowledge and experience running the NZVOC model rests with a small pool of specialist consultants, which may present continuity risks for future updates. Furthermore, if regular updates are not made to reflect changing costs and fleet profile, the results become less reliable. These risks could be mitigated by running the model more frequently (ie, every two years) and/or comprehensively documenting the model's inputs, assumptions and operations to generate updates to the MBCM formulas and tables. In line with these updates, it would be necessary to consider options for including new vehicle classes (ie, LZEVs) in the fleet and the availability of suitable input values and calculations.

2.2 VEPM

2.2.1 Overview and purpose

The VEPM is an average speed model that predicts fleet-weighted vehicle exhaust GHG emissions and air pollutants, and brake and tyre wear emissions, from vehicles in New Zealand under typical road, traffic and operating conditions (Metcalfe & Peeters, 2023). Emission rates are available for various speeds, gradients and traffic compositions, or other variables such as vehicle load (Waka Kotahi, 2023a). The VEPM was first released in 2008 and has been regularly updated. Version 7.0, publicly released in September 2023, included a major software update that transferred the model from an Excel spreadsheet into an online web-based platform.

While the methodology, assumptions and emission factors in VEPM 7.0 are identical to the previous spreadsheet version (Version 6.3, Metcalfe & Peeters, 2022), two functional changes were made:

- removal of some optional inputs to the defaults, including the option to remove the catalytic converter, the option to select petrol or diesel fuel types and the option to select heavy vehicle (HV) axle numbers
- reporting of only particulate matter (PM_{10} and $PM_{2.5}$) for brake and tyre wear without further user selections.

This review considers VEPM 6.3 as the basis for the key elements but also considers any documented changes made with the transition to Version 7.0. An additional update (Version 7.1) is in progress (Waka Kotahi, 2023a), adding some key features and updates – for example, Euro 6/VI emissions standard updates, some updated calculations and methodologies, and specific emission and electricity consumption factors for electric and hybrid vehicles.

2.2.2 Scope and key structural elements

The VEPM is an average speed model that predicts emission factors for New Zealand’s fleet, based on the different vehicle types and technologies present in the fleet and the vehicle kilometres travelled (VKT) by each vehicle type. As an average speed model, the VEPM is based on the average emission factor for a pollutant and vehicle type or technology, which varies as a function of the average speed during a trip over a complete driving cycle of several kilometres (Metcalfe & Peeters, 2023). The VEPM assumes typical driving conditions for the average speed; therefore, emissions from vehicles travelling on roads prone to congestion, on intersections or on roads in poor condition may not be accurately represented (Metcalfe & Boulter, 2022).

The VEPM provides a spatial representation of emissions and air pollutants. It can be used to analyse larger projects or areas; for example, by varying the default trip length in the model, which has an impact on the emission factors, noting that the actual speed cycles will be averaged and may not be accurately represented as stated above. VEPM users who were consulted during this project reported that they had used it to estimate emissions not only from road transport for regions or larger areas but also for shorter road links.

The VEPM fleet covers the main light and heavy vehicles in the New Zealand fleet. The vehicle classes are distributed by the gross vehicle weight (in tonnes) and fuel or powertrain type (petrol, diesel, hybrid, plug-in hybrid and electric). Table 2.2 shows the VEPM’s default vehicle classes and proportions of VKT as of 2023.

Table 2.2 The default vehicle classes and types in the VEPM

Number	Class	Weight category	Fuel or powertrain type	Percentage of VKT [a]
1	Cars	< 3.5 t	Petrol	60.38%
			Diesel	7.54%
			Hybrid	4.72%
			Plug-in hybrid	0.37%
			Electric	0.67%
2	LCVs	< 3.5 t	Petrol	2.70%
			Diesel	16.86%
			Hybrid	0.01%
			Plug-in hybrid	0.00%
			Electric	0.04%
3	HCVs rigid	3.5–7.5 t	Diesel	1.24%
4		7.5–10 t		0.36%
5		10–20 t		0.28%
6		20–25 t		0.30%
7		25–30 t		0.17%
8		> 30 t		1.24%
9	HCVs articulated	14–20 t	Diesel	0.02%
10		20–28 t		0.05%
11		28–34 t		0.28%
12		34–40 t		0.25%
13		40–50 t		1.19%
14		> 50 t		0.60%
15	HCVs electric	< 10 t	Electric	0.00%
16		> 10 t		0.00%
17	Buses	Urban ≤ 12 t	Diesel	0.27%
18		Urban 12–18 t		0.33%
19		Coach 12–18 t		0.08%
20		> 3.5 t	Electric	0.02%

[a] Percentages of VKT are the VEPM default values for 2023.

2.2.3 Model operation, inputs, and outputs

The sections below describe the VEPM's operation at a high level, as well as the model inputs and outputs.

2.2.3.1 Operation

The VEPM online tool (Version 7) has a graphical user interface that can be used to input data (or use default values) to generate the fleet-weighted emission factors per kilometre travelled. The VEPM requires a few user inputs with calculations incorporating parameter values, such as emission factors for different vehicle types. The tool can be used to generate a single run of outputs for a specific set of input values, or alternatively, it can be run multiple times with bulk input data defined by the user by populating a Microsoft Excel template.

2.2.3.2 Inputs

The key inputs for the VEPM are:

- the vehicle fleet composition, consisting of six vehicle classes (cars, LCVs, rigid HCVs, articulated HCVs, electric HCVs, and buses) and 20 weight categories, as shown in Table 2.2[5]
- the analysis year between 2001 and 2050, which determines the fleet composition for the selected year[6]
- the (average) speeds for the analysis, for each vehicle class (noting that rigid HCVs, articulated HCVs, and electric HCVs are grouped to HCVs in terms of average speed) (Metcalfe & Peeters, 2023).[7]

In addition to the key inputs, there are a range of optional inputs and settings that can be changed by the user to reflect their specific project or modelling requirements, including:

- the gradient of a road section to be modelled, noting that uphill sections increase emissions more than corresponding downhill sections, which lower the emissions[8]
- the HV load (default 50%, alternative settings 0% and 100%), with higher loads increasing emissions
- cold starts (included by default), which can significantly increase specific emissions if considered, but can be turned off if appropriate; for example, for longer trips outside urban areas
- vehicle degradation effects (default included), which assume an increase of emissions over time but can be turned off
- average trip length (default 9.1 km representing an average vehicle trip distance), which impacts the frequency of cold engine starts and, thus, the emissions
- the ambient temperature (default 13.1 °C for a typical Auckland winter), which is adjustable between −10 °C and +30 °C, and affects the emissions associated with cold engine starts (Metcalfe & Peeters, 2023).

Figure 2.2 shows a high-level overview of the emissions calculation methodology of the VEPM.

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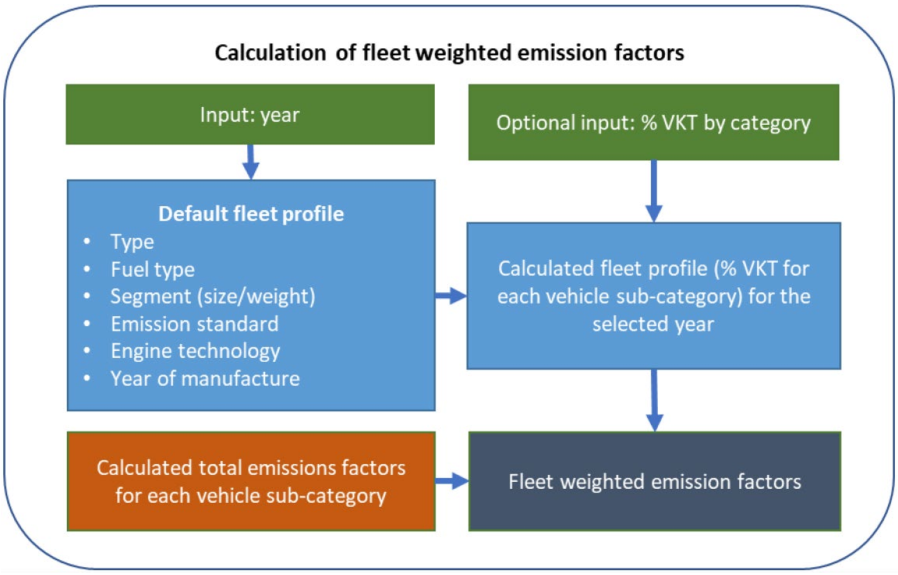
[5] The default fleet composition and VKT are based on the VFEM. Users can override the default fleet composition within the limits of vehicle availability in the fleet in the analysis year.

[6] One of the key features of the VEPM is its forecasted fleet model, which has predictions of the uptake of alternatively fuelled vehicles to 2050. The underlying data for the forecasted fleet model (uptake, upstream emissions, etc) are based on MoT modelling but not disclosed in the VEPM's technical documentation.

[7] Speeds for light vehicles (cars and LCVs) range between 10 and 110 km/h, and speeds for HVs (HCVs and buses) range between 6 and 86 km/h. (Average speed emission factors are intended to represent emissions as a function of mean vehicle speed over a complete driving cycle of several kilometres. Average speed data are often derived from traffic models.)

[8] A default value of 0% (flat) can be amended within the range of −6% to +6% in 2% increments.

Figure 2.2 Calculation of fleet-weighted emission factors in the VEPM (reprinted from Metcalfe & Peeters, 2023, p. 12)



2.2.3.3 Outputs

The outputs from the VEPM are fleet average VKT weighted vehicle emission factors (g/km) for New Zealand, or the modelled project or region as defined by the user. The outputs can be broadly grouped into the following three categories:

1. exhaust emission factors for harmful air pollutants, including CO, NO_X, nitrogen dioxide (NO_2), and volatile organic compounds
2. exhaust emission factors for GHGs, including CO_2, methane (CH_4), nitrous oxide (N_2O) and, based on these emissions, the carbon dioxide equivalent (CO_2-e) values[9]
3. non-exhaust emission factors for brake and tyre wear ($PM_{2.5}$ and PM_{10}).[10]

2.2.4 Uses and users

The VEPM is used for planning purposes in estimating traffic-related emissions in local areas or regions. Emission predictions can be used for a variety of purposes, including in CBA, benefits appraisals, air quality and GHG modelling and assessments, regional emissions inventories, and long-term planning.

The VEPM has linkages to a range of other models, tools and databases.

- The VEPM derives New Zealand–relevant factors based on emission factors from the European Computer Model to Calculate Emissions from Road Transport (COPERT), which is published by the European Environment Agency in a spreadsheet (European Environment Agency, 2019). The VEPM uses COPERT real-world emission factors and New Zealand correction factors for diesel but does not account for ‘in-service’ emission effects such as driver behaviour, gross emitters or effects of vehicle tampering, which can increase emissions (Waka Kotahi, 2023a).
- The VFEM projects the makeup of New Zealand’s future vehicle fleet and their travel, energy (fuel and electricity) use and GHG emissions, based on vehicle numbers, a range of factors on fuels and electricity

[9] Fuel consumption is also provided.

[10] Other non-exhaust emissions such as road wear and resuspended road dust are not included.

usage, and electric vehicle uptake predictions (Te Manatū Waka, 2022). The fleet profile and VKT from the VFEM are used in the VEPM (Metcalfe & Peeters, 2023).

- The Vehicle Emission Mapping Tool automates the calculation of both harmful air pollutants and GHG emissions to present emission data as maps. It uses vehicle emission factors from the VEPM to calculate the mass of pollutant per length of roadway (NZTA, 2024a).
- The Project Emission Estimation Tool estimates GHG emissions in the early stages of a land transport infrastructure project. It uses standard design examples and industry research for a high-level estimation of the GHG emissions through the life cycle of a project, including construction, operation and maintenance, and vehicle use where the VEPM is applied (NZTA, 2024b).
- The Traffic Model Emissions Tool can be employed to estimate the changes in vehicle emissions associated with a proposed transport project or a transport policy intervention. The tool applies emission values from the VEPM to intersection output data from a traffic model, based on the average traffic speed of road links (Waka Kotahi, 2022).
- The Health and Air Pollution in New Zealand study investigated the impact of air pollution on the health of New Zealanders. Vehicle emissions are one of the sources of air pollutants that are harmful to human health. The latest update focuses on the two most important air pollutants in New Zealand, fine particulate matter ($PM_{2.5}$ and PM_{10}) and NO_2 (Environmental Health Intelligence New Zealand, n.d.).
- The MBCM is New Zealand’s industry standard for the calculation of economic benefits and costs of land transport activities (Waka Kotahi, 2023b). Outputs from the VEPM should be used in economic evaluations of investments into land transport projects.

Outputs from the VEPM will also feed into Monty, New Zealand’s agent-based model (‘digital twin’) that is under development. Monty will contain a collection of models for understanding the travel behaviour of New Zealanders and their response to policy changes (Te Manatū Waka, 2020).

Refer to Appendix C for VEPM linkages to other relevant models, tools and databases in New Zealand.

2.3 Comparison between the NZVOC model and the VEPM

2.3.1 High-level comparison

The NZVOC model and the VEPM share many common aspects in terms of calculating fleet-based vehicle fuel consumption as an interim prediction to different ends (ie, for VOCs or emission prediction). However, the similarities are quite limited.

The VEPM is a top-down, average speed model, while the NZVOC model is a bottom-up instantaneous speed mechanistic model that operates on a first-principles basis. Average speed models are best suited to large-scale and generalised analyses, such as regional or national emission inventories, and they have become the de facto standard approach to estimating emissions from a road project in ‘local’ assessments, including near-road air quality modelling (Metcalfe & Boulter, 2022). It is also acknowledged that, at a local scale, the VEPM may underestimate or overestimate emissions, but on average, emissions estimates are expected to be valid.

The NZVOC model is a mechanistic-empirical model that provides a basis for more accurate modelling of a section of road by producing outputs as tables of values or as regression equations. These values and equations represent the physical characteristics of the section (roughness, gradient, etc) and the level of congestion (from free or uninterrupted flow to congested or interrupted flow) with this being applied based on independent modelling of traffic conditions, including time of day to represent peak and non-peak periods. This allows users to apply the model to any operating conditions since there is no assumed speed behaviour. See Appendix E for further information about the HDM-based models.

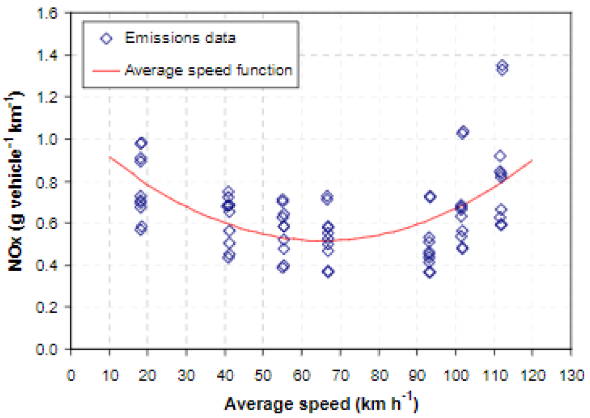
The differences in the underlying speed models produce a significant disparity between them. Box 2.1 describes the differences in average speed and drive-cycle speed models.

Box 2.1 Average speed vs drive-cycle speed models

VEPM (average speed):

- The VEPM produces emission output values that are a function of the average speed.
- The average speeds are based on the European COPERT model and consider real-world drive cycles that account for driving conditions, congestion, typical vehicles etc (ie, these parameters cannot be modelled separately in the VEPM but are considered as part of the average speed).
- In the VEPM, the user defines an average speed across the distance (default value 9.1 km, can be modified by the user), which then determines the emission values used by the model.
- Smit et al. (2010) found that more complex models do not perform systematically better than simpler models in terms of emission prediction errors.

The chart below provides an example of the NO_x emissions data that are used to establish the emissions as a function of the average trip speed. Lower and higher speeds lead to higher emissions, considering high fuel usage at higher speeds (requiring higher engine power to overcome aerodynamic drag) and lower speeds (impacted by stop–start driving and congestion).

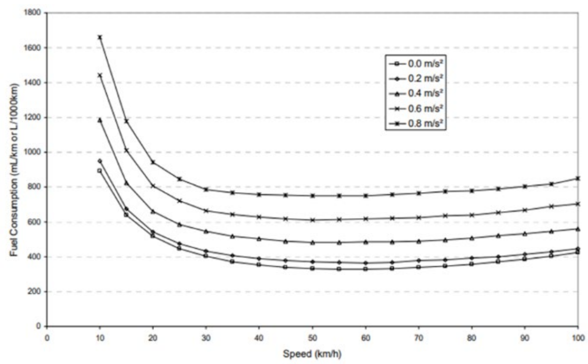


Source: reprinted from Metcalfe and Peeters (2023, p. 61)

NZVOC model (drive-cycle speed):

- The NZVOC model produces VOC or resource consumption output values which are a function of vehicle component consumption and wear and tear.
- The user defines a speed profile if appropriate.
- It is a mechanistic-empirical model that predicts vehicle resource consumption at a microscopic mechanistic level, based on each traffic flow period and corresponding VCR (and other input values). See Appendix E for further details of the model.
- By combining multiple (shorter) road segments, VOC for longer distances can be calculated as an aggregation of short segments.
- The base or default parameter values originate from HDM-4, which considers drive cycles (ie, speed profiles). The base component consumption in the NZVOC model can be adjusted for specific road and traffic, including, for example, (average) speed on the (short) road segment by traffic period, pavement surface roughness, deflection, texture, gradient and vehicle mass.

The chart below provides an example of the typical ‘family’ of curves produced by HDM-based models of fuel consumption, shown below for the upcoming Australian Transport Assessment and Planning (ATAP) PV2 update (ATAP Steering Committee Secretariat 2024). The selected curve depends on the vehicle speed and acceleration noise (which increases with high congestion levels).



Source: reprinted from ATAP Steering Committee Secretariat (2024, p. 19)

The VEPM fleet profile forecast has been regularly updated to enable it to be used for predicting future emissions based on current and future vehicle fleets, including LZEVs. The NZVOC model fleet profile has not been updated and is currently based on internal combustion engine vehicles (ICEVs), namely diesel and petrol. The fleet profile of the NZVOC model can be edited by users to include LZEVs and changing fleet mixes, and the model can be re-run several times to represent the different vehicle fleets; however, this has not yet been conducted.

The key inputs and outputs of, and interactions between, the NZVOC model, the VEPM, and other New Zealand models are presented in Appendix C.

2.3.2 Detailed comparison

Table 2.3 and Table 2.4 present a comparative evaluation of the inputs and outputs of the NZVOC model and the VEPM, and they also provide comments on potential actions required to improve the individual tools and their use, including in achieving greater alignment.

Table 2.3 Comparison of the inputs for the NZVOC model and the VEPM

Model input		VEPM	NZVOC	Comments
Model year		User entry (2001–2050)	User entry with a static fleet. Defined by the latest update (2015), but dynamic modelling is possible through multiple runs.	Update to the NZVOC model would be useful.
Fleet data	Vehicle fleet	20 classes defined by vehicle weight, across 6 vehicle types (cars, LCVs, HCVs rigid, HCV articulated, HCVs electric, buses).[a] Data from the VFEM with recent updates.	22 vehicle types, across 6 classes defined by vehicle axles. PC from NZTA registration; LCV from MoT registration; MCV & HCV from NZTA weigh-in-motion data.	A common fleet could be created recognising the vehicle classes and the technology (ie, ICEV and LZEV). The approach adopted should reflect the traffic counting approaches used to collect data in the field.
	Fuel or powertrain types	5 types: petrol, diesel, hybrid, plug-in hybrid, electric.	Petrol and diesel.	Extend the NZVOC model's scope to include alternative fuel or powertrain types, notably LZEVs, through use of multiple fleets and rerunning the model.
	VKT	Fleet distribution by VKT percentage.	Distribution of light vehicles by registration, and HVs by weigh-in-motion counts.	Consider where fleet VKT changes are required for new vehicles based on model inputs and VEPM/NZVOC model use cases.

Model input		VEPM	NZVOC	Comments
Vehicle data	(Base) fuel consumption	Implicit as part of COPERT emission factors. Note: New Zealand real-world fuel consumption correction factors are applied to light duty diesel vehicles in the VEPM (Metcalfe & Peeters, 2023).	Idle fuel consumption for each vehicle type and base fuel consumption determined from minimum using free-flow speed effects (for further detail, see Appendix E).	The NZVOC model contains a comprehensive process and equations for determining fuel consumption under free and interrupted traffic flow. Such tables and regression equations have not been prepared, but there is opportunity to do so to estimate emission factors that are consistent with the quality and level of detail of the NZVOC model and compared with the VEPM and COPERT values.
Road data	Roughness	N/A	Input as independent variable. Default assessment range: 0–20.	The NZVOC model and similar HDM models display significant sensitivity to roughness with fuel consumption also impacted. The minimum roughness considered is an International Roughness Index (IRI) of 4, which is high compared to other uses of HDM and similar technology.
	Deflection	N/A	Employed if user selected.	Account for where estimates are sourced from new NZVOC models. Additional research and analysis needed to validate the sensitivity of road surface deflection on fuel use and vehicle emissions in New Zealand conditions.
	Texture	N/A	Input as independent variable. Default assessment range: 0–2.	Additional research and analysis needed for the NZVOC model to validate the sensitivity of road surface texture on fuel use and vehicle emissions, noting the additional values included in the MBCM are small.
	Gradient	Input of ranges possible. Default 0%, adjustable from −6% to +6% in 2% increments.	Input as independent variable. Default assessment range: −12% to +12%.	The VEPM and the NZVOC model (and similar HDM-style models) display sensitivity to gradient with fuel consumption significantly impacted.
Traffic data	Congestion	Implicitly considered – emission factors represent typical congestion levels at the defined input speed.	Modelled across a range of speed and acceleration effects.	The NZVOC model and similar HDM-style models display sensitivity to congestion effects, with fuel and tyre consumption significantly impacted.
	Speed	Average speed defined by user entry.	Speed input based on time period and VCR. Default range: 10 to 120 km/h.	

Model input		VEPM	NZVOC	Comments
Trip data	Average trip length	Default 9.1 km, adjustable by user.	User-defined road segment length.	
	HV load	Default 50%, adjustable to 0%, 50% or 100%.	Set total vehicle weight, not load.	Load effects could be a useful additional output from the NZVOC model based on sensitivity.
	Cold starts	Default on, can be turned off.	N/A	Sensitivity to be determined in future research.
	Degradation	Default on, can be turned off.	Based on age-based efficiency factors or can be turned off.	
Environmental data	Ambient temperature	13.1 °C, adjustable from −10 °C to +30 °C.	N/A	Sensitivity to be determined in future research.
	Emission factors	Factors adapted from COPERT, which inherently considers road traffic conditions, such as traffic flow and congestion.	Modelled based on HDM-4 using fuel consumption and catalytic conversion.	Future research could compare and validate the similarities and differences of emission factors based on different calculation approaches.

[a] The VEPM's classification for HCVs, mixing rigid and articulated (vehicle type) with electric to classify HCVs, is inconsistent with the HCV classifications used in the NZVOC model.

Table 2.4 Comparison of the outputs produced by the NZVOC model and the VEPM

Model output		VEPM	NZVOC	Comments
Emissions	GHG exhaust emissions	• CO_2 • CH_4 • N_2O • CO_2-e (based on above)	• CO_2 • HC	The NZVOC model's emission outputs are limited in coverage, requiring further work to calibrate before use.
	Air pollutant exhaust emissions	• CO • $PM_{2.5}$ • NO_x • NO_2 • Volatile organic compounds	• CO • PM • NO_x • SO_2 • Pb	
	Brake and tyre wear particulate emissions	• $PM_{2.5}$ • PM_{10}	N/A	The NZVOC model calculates tyre wear but requires inclusion of an emission factor to estimate emissions.
Costs	Vehicle operating costs	N/A	Fuel, tyre, maintenance and repairs, oil, depreciation, interest, travel time (optional). Resource consumption and costs modelled for each vehicle type and class and/or road segment.	The NZVOC model can output the resource quantities by component; for example, fuel, oil, tyres, maintenance parts and labour.

2.4 Comparison to international models

We reviewed various international models and approaches to predict VOCs and vehicle emissions. The project steering group and the expert peer reviewers advised on potential models to be reviewed and on aspects that would best relate to the NZTA models. The review focused on the applicability of aspects in comparable models and approaches to inform potential improvements that could be made to the NZVOC model and the VEPM.

2.4.1 International vehicle operating cost models

There are a small number of comparable VOC models that are available for review. The two relevant models examined are HDM-4 – which is the basis for the NZVOC model – and the approach adopted by Australia through the updates to the Australian Transport Assessment and Planning (ATAP) guidance, also based on HDM-4. The key findings from the review of international VOC models found that:

- The HDM suite of models, which are the foundation of the NZVOC model, have been developed, adapted and calibrated over many decades of international research, notably in Australia, Canada and New Zealand. They are calibrated for individual countries (or regions) to recognise differences in vehicle fleets and their management, which correspond to unique fuel and resource consumption rates.
- HDM models predict vehicle speeds under different operating conditions, accounting for congestion and speed change cycles. This provides a basis for estimating resource consumption, including fuel consumption, by time-of-day accounting for the differing traffic conditions from free-flow conditions to congested traffic. These traffic conditions result in significant differences in fuel consumption. Additionally, forced speed change cycles, through traffic interventions or speed limit changes, can be accounted for.
- HDM models can be applied for analyses at different geo-spatial scales – for example, macroscopic (national, regional or city-scale), mesoscopic (link-level) and microscopic (road segment).
- The latest Australian approach (publication forthcoming) provides a multi-parameter suite of models that could provide a transferrable or portable solution when working with multiple tools to estimate differences in fuel consumption and total VOCs. Having similar models available for New Zealand would allow consistent inputs for any NZVOC-related analysis, noting that the building blocks already exist in the NZVOC model.

For further details, see Appendix E.

2.4.2 International vehicle emission prediction models

There are several vehicle emission prediction models used around the world. See Appendix F for a comparison of relevant models. Here are the key findings from the review of international emission prediction models:

- Large economies such as Europe and the USA generally have broad and well-developed models (eg, COPERT and Motor Vehicle Emission Simulator (MOVES)).
- Models that are not regularly maintained or updated lose their currency and usefulness or are overtaken by newer models and approaches.
- There are several different speed and traffic modelling approaches used as the basis for fuel consumption estimation and emission prediction. Several Australian and international models used average speed approaches, similar to the VEPM, while others used generalised traffic situations (eg, free-flowing, interrupted, congested) and actual or modelled drive-cycle speed profiles (similar to the

NZVOC model, which also adds congestion effects for different traffic situations). Each approach has strengths and weaknesses, and care should be exercised to identify the most appropriate use cases.

- Several Australian models have been developed (namely, COPERT Australia and n0vem), which account for the major differences in the fleets compared to Europe.
- No international vehicle emission prediction models reviewed considered the impacts of the pavement surface condition and texture on fuel consumption and emissions in a comparable way to the HDM-based models. Many models, like the VEPM and the NZVOC model, consider road gradients (eg, MOVES, Handbook Emission Factors for Road Transport (HBEFA)).
- Various approaches exist to characterise vehicle fleets. The selected approach is largely dependent on data availability and pre-existing structures. Harmonised fleet categories allow for models and approaches to translate across jurisdictions.
- In terms of forecasting the future fleet, and in particular the transition to LZEVs, at a minimum, a detailed understanding of upcoming interventions such as emissions standards and phase-out dates is needed. Some models, such as MOVES and the Californian emission factors model EMFAC, account for interventions and current and future policies on the uptake of LZEVs (eg, future emission standards).
- Emission outputs are variable and can include total emission inventories or emission rates at various scales from an individual project level up to a regional or national level. Most models included, at a minimum, CO_2-e, volatile organic compounds/non-methane volatile organic compounds, NO_x, $PM_{2.5}$, PM_{10}, and individual GHGs of CO_2, N_2O, and CH_4. Some models, however, have highly detailed outputs – for example, COPERT and COPERT Australia include 116 air pollutants and GHGs. Various models include outputs specified by their source – for example, exhaust, brake and tyre wear, surface wear, and evaporation. COPERT, HBEFA and ATAP models also capture upstream ‘well-to-tank’ emissions from electric vehicles utilising grid-connected electricity. The ‘best’ selection of emission outputs is highly dependent on the intended application of the models.

2.5 Summary

A review and comparative evaluation of the NZVOC model and the VEPM was undertaken to identify strengths, limitations and opportunities for improved alignment and integration.

2.5.1 Opportunities to align similar but differing aspects

From the review, a set of opportunities to improve the models and align their functionalities were identified.

2.5.1.1 Vehicle fleet data

Both models use vehicle fleet data to determine the fleet composition (mix of vehicle types). The VEPM uses the VFEM, which provides historical data points (from 2001) as well as a prediction of future vehicle fleets until 2050. The underlying data for the forecasted fleet are not transparently described. The fleet defines 20 vehicle types by weight category across 6 vehicle classes and is disaggregated by fuel or powertrain type, including electric and hybrid vehicles.

The NZVOC model uses a standard fleet composition dataset of 22 vehicle types across 6 vehicle classes informed by historical research and classifications that were possible to collect using Transit New Zealand (1994) axle-based traffic counting guidelines but has not been updated to reflect current traffic counting technologies. The NZVOC model does not include fleet data for LZEVs.

As such, there appears to be an opportunity for the NZVOC model to be adapted to cover the VFEM inputs and bring alignment with the VEPM. This is considered a straightforward process with the existing NZVOC model but requires further resources to update and bring it into alignment with the current and future fleet. There is also an opportunity to provide transparency in the underlying assumptions of the forecasted fleet for users.

Looking to Australia, New Zealand's fleet vehicle types are similar to – but not the same as – the Austroads vehicle classifications (Appendix B of Austroads, 2019), which are based on vehicle length and axle configuration.[11] There may be benefits realised through harmonising with Australia, such as harnessing collaborative development, maintenance and funding opportunities. It is worth noting, however, that New Zealand has a different vehicle fleet and vehicle classifications to Australia (and Austroads), so a full alignment may not necessarily be desirable. For example, the New Zealand fleet includes buses and does not have larger HVs such as triple road trains. Potential benefits in harmonisation with Australia should be evaluated prior to pursuing such work. Appendix B shows the differing fleet classifications used in the NZVOC model, the VEPM and the VFEM.

2.5.1.2 Speed input and effects

The VEPM employs an average speed approach (over the user-defined average trip length). The average speed is a key input, along with a range of other input parameters as outlined in section 2.2, used to predict vehicle emissions.

In contrast, the NZVOC model utilises data representing the estimated speed under specific road section conditions, including at different levels of congestion, represented by the VCR for different time periods and locations as defined by the user. The NZVOC model's outputs are parameters (and equations) that form an input to a modelling tool (CBA, PMS, etc). The NZVOC model's starting premise is to estimate free speeds based on vehicle and road section characteristics and to adjust these further in response to operating conditions. These characteristics and operating conditions account for speed cycles, speed-flow parameters, and congestion effects where speeds are interrupted through greater vehicle interaction. Detailed discussion is provided in Appendix E.

Alignment of some of the speed input parameters may be possible but may not be desirable.

2.5.1.3 Road gradient

Both models incorporate similar road gradient information, which impacts fuel use. The VEPM allows for an adjustable input gradient from −6% to +6% in 2% increments. The NZVOC output (VOC vs gradient and, potentially, fuel vs gradient) tables provided in Tables A79 to A88 in Appendix 4 of the MBCM (Waka Kotahi, 2023b) include road gradient ranges between 0% and 12% (in 1% increments) as the average of uphill and downhill gradients.

Both models have a gradient range of 12 percentage points. The VEPM includes positive gradients to model ascents and negative gradients for descents. The NZVOC model can aggregate uphill and downhill gradients (for bi-directional road segments). Whilst there appears to be slightly different modelling approaches for considering road gradients, further research is needed to determine if any changes or harmonisation of approaches would provide a measurable benefit to users.

[11] NZVOC vehicle types were established originally to match the (then current) Transit NZ axle-based traffic counting guidelines, but this has not been updated yet.

2.5.1.4 Model usage and limitations

The VEPM is more widely used as it is a public-facing tool, while the NZVOC model is designed to be used by specialist consultants to produce outputs that are used in CBA and PMS tools. For both, it is important that the limitations of the models are well understood by users to ensure they are used for suitable applications (eg, vehicle-level analyses, project-level assessments and regional or national inventories). The onus is on the user to be informed and to make the correct model selection. Clear guidance on the application of the models (through reports and interactive tooltips) should be provided to ensure their correct application and to produce meaningful outcomes.

2.5.2 NZVOC model improvement opportunities

There are two major gaps identified with the NZVOC model. The first gap is that, contrary to its original design, the vehicle fleets and their associated unit costs have not been regularly updated. This has led to a significant divergence in the accuracy of NZVOC predictions over time. The second gap is the need to introduce additional representative vehicles to the NZVOC fleet for LZEVs. As the model predicts fuel (energy) use as a function of power (in kW), based on forces that oppose motion (eg, gradient, road surface roughness), LZEVs could be modelled by pricing in electricity instead of conventional fuels. This would require further research and modelling work. Both could be, in part, addressed through a periodic updating process.

The NZVOC model has the capability to generate resource consumption quantities, including fuel use, as interim VOC outputs. These interim outputs, however, have not been produced, except for research purposes, and have not been made broadly available to users of the NZVOC model’s outputs, who have focused on the VOC tables. Resource quantity estimates would be simple to generate by an NZVOC user and useful for emission modellers when published.

The NZVOC model also has limitations in terms of considering the impact of variations in loading and gross vehicle mass on the VOC outputs and resource components. This could be addressed by reconfiguring the model to produce outputs for changes in vehicle characteristics as it does for changes in road characteristics, such as by gradient, congestion, etc. A possible use is for application in economic analysis in support of mass limit changes for heavy vehicles, including future LZEVs.

The NZVOC model was not designed to be used on a regular basis by general users. It is a specialised model that has very few experienced users who can run it to generate its output tables of values and equations. As explored above, there are many potential use cases and adaptions that could be made to derive greater benefits from the model, but opportunities to realise these are limited. More frequent updates and the publication of additional output tables (including interim outputs) and equations would be beneficial to transport modellers and other technical users.

2.5.3 VEPM improvement opportunities

Metcalfe and Boulter (2022) found that the emission estimates in the VEPM were unable to appreciate and accurately estimate emissions in low-speed zones where traffic flows relatively freely. In the worked example, the VEPM overestimated emissions when modelling a reduction of the speed limit at low speeds – for example, from 50 to 30 km/h. In this example, the VEPM predicted an increase in emissions as a result of a speed reduction because it assumes stop–start or congested travel at lower speeds, whereas there should be an emissions reduction or no significant change of emissions as a result of lower travel speeds in a low-speed zone with relatively freely flowing traffic. A key reason for this discrepancy is that the VEPM assumes more stop-and-go type traffic at lower speeds, which increases fuel consumption and emissions (Metcalfe & Boulter, 2022). This is an example of an application that is outside the scope of the VEPM due to its lack of a second variable to quantify the level of speed fluctuation. In the USA, Europe and Australia, there are several modelling frameworks that provide access to different types of emission models for different applications, as summarised in Appendix F. It is important to consider that for low speeds (below 40 km/h), the mechanistic approach of the NZVOC model also shows an increase in fuel consumption; however, this could be because the separate effects of speed and congestion are not represented in the analysis.

The real-world effects of congestion and speed on fuel consumption, and consequently emissions, have been shown to be very significant at a local level (Metcalfe & Boulter, 2022). If applied at a section level, congestion and speed effects would contribute to identifying sources of fuel consumption and emissions. It could also provide a basis for estimating the emissions response from infrastructure investment or management measures.

3 Opportunities for integration and alignment

This section outlines the identified opportunities for integration and alignment of the NZVOC model and the VEPM. A set of five potential integration options were presented to users during the stakeholder engagement workshop, from which a refined set of 9 opportunities are presented and assessed.

3.1 Initial integration options

Five potential integration options were initially considered:

1. Retain and improve both models.
2. Develop a hybrid model.
3. Incorporate one model into the other.
4. Retain both and determine pre- and post-analysis steps.
5. Do nothing.

These options were presented to users of the NZVOC model and the VEPM during the stakeholder engagement workshop, which sought to gather their perspectives and insight into the models' current uses and value, limitations, future needs and opportunities and suggested integration options (see Appendix D for details of stakeholder engagement). Based on stakeholder views, options 2 and 5 were struck out and were not considered. The key stakeholders noted that developing a hybrid model (option 2) would need to satisfy the established user needs without any significant compromises in scope and functionality. As such, the stakeholder group agreed that developing a hybrid model was both unfeasible and undesirable given the different purposes of models. Option 5 to 'do nothing' was not considered a preferred option given the presence of many issues and a range of simple solutions.

The stakeholder workshop revealed that regular NZVOC model and VEPM users:

- agreed that model inputs should be aligned and consistent as far as possible (eg, utilising the VEPM's fleet model in the NZVOC model, aligning CO_2 and CO_2-e outputs)
- agreed that better documentation and live information provided at key input stages would help inform users about model parameters and inputs
- noted that there could be value in developing a separate model that generates the desired inputs for use in both the NZVOC model and the VEPM.

Future features and opportunities were centred around improved consistency, alignment and guidance. Priority should be given to seeking opportunities for improved consistency and alignment of:

- the vehicle fleet profile and/or projections, including LZEVs
- traffic speed profiles, with recognition of congestion effects
- outputs, such as using CO_2-e rather than simply CO_2.

The project steering group, stakeholder user group and project team broadly agreed that the preferred opportunities centred around option 1 'retain and improve both models' by improving the alignment and consistency between the two models and their outputs. There was also strong support for producing improved guidance on when and how to use each model and their outputs most appropriately and effectively. There was also agreement around a potential opportunity to integrate some model inputs, such as the New Zealand fleet models, to help achieve better alignment.

3.2 Identified opportunities

In consultation with the project steering group and other key stakeholders, we identified nine opportunities:

- Opportunity 1: Using consistent vehicle classes and fleet proportions
- Opportunity 2: Enabling the NZVOC model to recognise LZEVs
- Opportunity 3: Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time
- Opportunity 4: Aligning the NZVOC model's emission outputs with the VEPM's emission outputs
- Opportunity 5: Aligning speed drive cycles with average speed profiles
- Opportunity 6: Enabling the VEPM to better reflect road condition and configuration effects
- Opportunity 7: Developing use-case guidance and worked examples
- Opportunity 8: Improving data collection and calculation transparency, and describing limitations
- Opportunity 9: Improving the usability of the NZVOC model.

These opportunities represent a suite of possibilities, and a combination of several of them is likely to provide the best overall outcome. The remainder of this section provides a detailed description of the identified opportunities.

3.2.1 Opportunity 1: Using consistent vehicle classes and fleet proportions

Aligning vehicle classes and fleet proportions is a critical step towards aligning the outputs produced by the NZVOC model and the VEPM. The NZVOC model and the VEPM use different approaches to the categorisation of vehicle classes. The NZVOC model uses an axle-based categorisation approach[12] with 22 vehicles classes and two fuel types (petrol and diesel). The VEPM uses a mass-based approach with only 6 individual vehicle categories, but it covers more fuel and powertrain types, including hybrid and battery electric vehicles for 28 vehicle fuel and powertrain type combinations. The VFEM, which informs the VEPM fleet model, uses a combination of engine capacity for vehicles less than 3.5 tonnes and mass for trucks and buses for 31 vehicle types and 9 fuel and powertrain types (for up to 279 combinations). A summary of the vehicle classes across the VFEM, the VEPM and the NZVOC model is presented Appendix B.

There are two components to this opportunity. The first is to understand the current (historical) and future fleet compositions in New Zealand. This opportunity would involve undertaking a vehicle class matching exercise to show equivalence between axle-based and mass-based vehicle classes, using information from the VFEM for validation. In some cases, assumptions may be needed.

The second component is to decide on the most appropriate representation of the fleet for both models going forward. An assessment on which vehicle categorisation is best suited should consider the following questions.

- What level of detail is needed (ie, how many vehicle-fuel and powertrain type combinations are needed)?
- How is the emission control technology type (associated with emission standards) captured?
- What is the preferred vehicle categorisation basis (eg, axle-based, mass-based or engine power-based)? For instance, is there a preference to retain or improve the VEPM vehicle classification structure, or replace it with the NZVOC structure, which has similarities with the Austroads classification? Note: The vehicle categorisation for the VEPM is based on the VFEM but requires some assumptions for categories in the emission factors database (Metcalfe & Peeters, 2023).

[12] An axle-based categorisation is used as traffic counters provide axle-based classifications – that is, axle-based vehicle classification data are easily available for economic analysis.

- How does the vehicle categorisation align with Australian approaches, such as Austroads' axle-based vehicle classes, or COPERT Australia and similar models designed for fuel consumption, energy use and emissions?

Once a classification system is determined, the current (and future) vehicle fleet proportions should be mapped to the categorisation structure with data from the VFEM (some assumptions may be necessary as currently occurs with generating the VEPM fleet). The single source of vehicle classes and fleet proportions could then be implemented appropriately in the NZVOC model and the VEPM to create a consistent fleet profile.

3.2.2 Opportunity 2: Enabling the NZVOC model to recognise low and zero emission vehicles

The current NZVOC model is limited to assessing petrol and diesel vehicles. The anticipated growth in electric vehicles makes it necessary to incorporate LZEVs, including hybrid and fully electric vehicle technology, into the NZVOC model and its published outputs. To do so, the NZVOC model must be calibrated or adapted to generate reliable results.

Abdalla (2021) demonstrated a methodology to calibrate HDM-4 (the basis for the NZVOC model) for electric vehicle user costs. This calibration focuses on the mechanical forces that drive energy use in an electric vehicle using the fuel use component of the model, applying the fuel-to-electricity conversion and estimated engine efficiency factors.

For the NZVOC model, the calibration factors would need to be reassessed for the New Zealand context but could be validated against the UK study and other international datasets. This process would be required for all LZEV classes, which would need to be developed. There would be significant benefit in aligning the NZVOC model's LZEV classes with those used in the VEPM.

3.2.3 Opportunity 3: Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time

The static NZVOC model is run periodically (most recently in 2015) by updating input values and calibrating values to reflect the New Zealand conditions. Its regression equations are used to determine the VOC values that are published in the MBCM. Annual update factors are then published to adjust the most recent MBCM values to the current time, with the most recent update factor for VOC of 1.43 being released in April 2023.

The adjustment factor represents two distinct changes in vehicle technology:

1. adjustments in the VOC parameters of a given vehicle type (ie, ongoing efficiency improvements of ICEVs over time)
2. the changing mix of vehicle types within a vehicle class over time (ie, transition from ICEV to LZEV).

Running NZVOC more frequently and publishing an associated update factor is an appropriate means of dealing with item 1 above. This is consistent with what has been occurring with the NZVOC model and the MBCM (and EEM previously) and is not covered further in this report. It is considered that some minimum frequency of updating of NZVOC base parameters and rerunning should be set, as having a model being 43% on average across all vehicle types (the update factor of 1.43 does not vary by vehicle types or road usage) indicates an inherent lack of accuracy.

The April 2023 updates followed a formal study that resulted in a change from an update factor of 1.15 the prior year to the new figure of 1.43. Resetting the NZVOC model at five-yearly intervals would be a reasonable trade-off between cost and accuracy and would eliminate such significant step changes. For advanced analysts, there could be benefit in exporting the VOC components (ie, fuel, oil, parts etc) from the NZVOC model for use in subsequent analysis tools.

The second of the two adjustments that is noted above, a changing fleet mix, has two components to it. Firstly, the new vehicle technologies need to be modelled appropriately within the NZVOC model. Secondly, there is the need to determine the best method to model the shifting fleet mix over time for the determination of the parameters to include in the MBCM. With MoT publishing the expected future fleet statistics through to 2055, the challenge is how to then take the data for each individual vehicle type (ie, petrol car, hybrid car, electric car, etc) within the NZVOC model and address the changing proportions of these vehicle types over time. The four available approaches to modelling this are summarised in Table 3.1.

Table 3.1 Summary of approaches for modelling a changing vehicle fleet mix

Option	Description	Accuracy	Impact on end user	Effort to implement
(a)	Discrete value of VOC (and components) for each year of the analysis. The MBCM would present tables of different VOC values for each year (ie, until 2050) for each vehicle class.	Most accurate	Significant	Large change to MBCM required
(b)	Regression of values vs year included into MBCM. Developing models of how VOC changes by year using the results of the adjustments in the VOC parameters (as explained in item 1 above). Working these into the MBCM formulas and spreadsheets.	Quite accurate	Significant	Large change to MBCM required
(c)	Fleet change parameter (can be incorporated into annual update factors). Determining an 'average' factor to adjust the Base Year VOCs using the results of the adjustments in the VOC parameters (as explained in item 1 above) to reflect the changing fleet mix over the analysis period.	Less accurate	Minor	Relatively easy
(d)	Model fleet mix at a future time (eg, 12 years) to reflect average changes over analysis period.	Least accurate	None	Easy – no change to tools required

Option (a), while mathematically simple, would require a significant change to the analysis framework within the MBCM as for each year of the analysis a separate lookup table of VOC numbers would be required. Assessing the feasibility of major changes to the MBCM is outside of this review's scope; however, this option would present a significant implementation challenge.

Option (b) would eliminate the need for the multiple lookup tables of VOCs in option (a) with a regression equation. While this option is simpler compared to option (a), it would still require a significant change to the MBCM and would have a large impact on the end user.

Option (c) could result in either an additional adjustment factor or a repurposing of the current VOC update factor to reflect both the increasing costs over time for a given vehicle fleet (as at present), along with an adjustment to reflect the changing vehicle fleet. While less accurate than options (a) or (b), this change would not require significant amendments to the MBCM beyond explaining what the new factor represents. An additional ‘vehicle fleet factor’ would simply be a multiplier to existing VOC estimates.

Option (d) is the simplest approach. Only a single vehicle fleet mix is analysed with this chosen to reflect the expected vehicle fleet at, say, the mid-point of the analysis period. This would require no changes to any of the MBCM or from the end user. The actual ‘future year’ that is chosen would need to be determined to best reflect the changing fleet.

Practically, options (c) or (d) are the only two viable approaches. Given that option (c) is simple to implement and avoids the need to pick a single future year to model, option (c) is preferred. If taking this approach, there would need to be a decision on amending the current update factor to also incorporate the vehicle fleet mix changes, or, if it would be preferable, keep the two separate and introduce an additional multiplier.

3.2.4 Opportunity 4: Aligning the NZVOC model’s emission outputs with the VEPM’s emission outputs

The VEPM’s emission outputs are broadly consistent with those of other emission prediction models, including the key emissions for individual GHGs, air pollutant emissions from the tailpipe, and brakes and tyres. While the NZVOC model is able to generate emission outputs (as interim outputs in its fuel use predictions), the current emission outputs are not aligned with current standard emission reporting practices.

This opportunity would amend the NZVOC model to apply GHG emission factors to convert fuel use estimates into a range of emission outputs that are aligned with the VEPM emission outputs. GHG emission factors for petrol and diesel are accessible and accepted as standard practice. Other emissions, such as NO_x, SO_x, volatile organic compounds and PM are not as easily converted from petrol and diesel use estimates and may require additional data inputs, including engine size, engine operation (ie, cold starts) and environmental factors (ie, air temperature) to be built into the NZVOC to enable robust results.

The VEPM also reports on non-exhaust emissions such as brake-wear and tyre-wear. The NZVOC model already predicts tyre consumption, so this could be converted to equivalent VEPM parameters. The NZVOC model also includes vehicle deterioration and maintenance costs, which may have the potential to be amended to enable brake- and tyre-wear estimates and emissions. This would require further research to determine the feasibility.

The VEPM includes up-stream (well-to-tank) emissions from electricity generation used to power electric vehicles (but this is not publicly reported), and this could be included as an additional enhancement to the NZVOC model to estimate LZEV emissions more comprehensively. The ATAP guidelines on Environmental Parameter Values (ATAP Steering Committee Secretariat, n.d.) adopt a translation methodology to adopt European well-to-tank emission estimates for the Australian vehicle fleet. NZTA could adopt these values given the similarities of the Australian vehicle fleet and technology adoption or adopt a similar translation approach.

Opportunity 4 would rely on the implementation of Opportunities 1 and 2 for greatest benefit. If up-stream (well-to-tank) emissions were explicitly accounted for, alignment with Opportunity 3 would be additionally beneficial.

3.2.5 Opportunity 5: Aligning speed drive cycles with average speed profiles

The NZVOC model is a mechanistic-empirical model based on instantaneous speed, which is implicitly different to the average speed approach in the VEPM. It is not straightforward to simply align the two underlying approaches, and it is critical to investigate the fine details behind each model and any associated assumptions (Appendix E provides further details on the HDM-based speed models).

This opportunity requires further research to accurately scope. This initial research includes:

- an initial evaluation to verify that the outputs of both models are the same (or different) when given an identical input drive cycle
- deciding on the preferred model to align with
- developing an implementation plan to modify and align the models.

Once this work is completed, a suitable development pathway could be defined and adopted.

3.2.6 Opportunity 6: Enabling the VEPM to better reflect road condition and configuration effects

The primary road condition effect considered in the VEPM (and similar international models) is road gradient. Technically, road condition effects (ie, surface roughness impacts) are implicit in the emission factors as they are based on real-world measurements. While it is well established that road gradient has by far the most significant impact on fuel consumption and emissions, road roughness and texture also have an appreciable influence on fuel consumption and emissions. Other factors such as tyre pressure and condition and weather effects should have a similar effect on fuel consumption and emissions. Road condition factors are particularly important in the context of the MBCM as they are used for pavement investment decisions. For example, several studies have found that overall use-phase emissions can increase by 2–3% depending on the surface roughness (Brownjohn et al., 2019; Cenek, 1996; Waka Kotahi, 2023b; Zaabar & Chatti, 2010).

Another possible avenue is to incorporate road configuration (ie, different road types) into the VEPM and develop a set of high-level road types (eg, by motorway, urban, rural) to quantify the impacts on emissions. This could be investigated by directly estimating speed-flow characteristics based on the HDM models where traffic interaction is considered, with this accounting for temporal and spatial effects.

3.2.7 Opportunity 7: Developing use-case guidance and worked examples

Developing guidance and documentation on use cases with worked examples would provide users with clear guidance on appropriate model selection for various applications and would ensure it is only used for its intended application. While recommendations made in this report are focused on the VEPM and the NZVOC model, there may be other models and approaches that could be included in the use-case guidance. The guidance should focus on clearly communicating to users when and when not to use each of the two models or their outputs. The primary question to be answered is whether users would read such guidance documents, and it is important that it is effective in reaching people (ideally before they begin using the models). While this is unlikely for the NZVOC model due to it not being publicly available, this information would need to be disclosed where its outputs are used, such as in the MBCM or companion documents. For the VEPM, this could be introduced through a user warning on the main page with a few points and a link to guidance documentation (eg, a ‘Before using this software warning’).

Implementing this opportunity would require some resources to develop the additional documentation, along with some minor development work for the VEPM to provide interactive links through tooltips or on the main page. Key development steps in improving use-case guidance and worked examples include the following.

1. Identify and develop a range of use cases to demonstrate appropriate model selection and use.

2. Assess whether other models, datasets or analytical approaches could be used for these use cases.
3. Develop a toolkit in the form of a flowchart to provide users with a quick overview of appropriate model selection, with links to a separate report (or reports) with detailed use-case guidance.
4. Provide clear and simple warnings in the VEPM about intended use and applications and provide easily accessible links to further resources and information.
5. Provide clear and simple warnings where NZVOC outputs are used as well as easily accessible links to further resources and information.

Opportunity 7 complements the following Opportunity 8 well.

3.2.8 Opportunity 8: Improving data collection and calculation transparency, and describing limitations

The use of both the NZVOC model (through the MBCM equations and tables) and the VEPM is highly dependent on various input data and calculation methods. To most users, the models are 'black boxes' where data go in and results come out. Whilst technical documents have been produced, there is not enough clarity, transparency or understanding of the models' calculation methodologies, assumptions and limitations. Improving the transparency of such complex tools requires a balance between comprehensive, detailed technical descriptions and more user-focused tips to enhance user understanding.

There is a significant library of technical documentation that supports the VEPM, which can be found on the NZTA website. For the NZVOC model, the 2015 Opus report (Cenek, 2015) provided transparency of the updated calibration parameters, but users need to go back to earlier documentation (now nearly 20 years old) to get an understanding of how the model works.

This opportunity is focused on improving existing data and calculation transparency, filling any gaps and making it accessible to users. This opportunity overlaps with Opportunity 7; it can be envisaged that the use-case guidance is a supplementary resource to help describe limitations to users. As with Opportunity 7, there should be some work done to provide interactive tooltips or user warnings in the VEPM that can provide succinct guidance or warning to users and can direct them to relevant materials.

Key steps for improving specific data and calculation transparency include the following.

1. Describe the forecasting of the future fleet, particularly the introduction and uptake of LZEVs: the breakdown and percentage of vehicles by type and propulsion technology, demand changes in terms of VKT, and the national grid emission factors used. This should also include a description of the calculation methods and assumptions used as needed.
2. Incorporate further guidance via tooltips that explain how inputs will affect the results (eg, what is the implication for ambient temperature or cold starts on the outputs).

At the stakeholder engagement workshop, some users commented that many model users would not read technical reports, and therefore, something more accessible is needed. Where possible, effort should be made to make as much of the data and calculation methods publicly available. This should be in the form of brief reports (or a slide deck) consisting of summary charts, data tables and methodology for calculations. It is relatively inexpensive to improve the transparency of the data, calculations and limitations as these can generally be produced in the form of a short report (or series of reports) that could be accessed online.

This may require agreement and input from MoT or other government departments. There would also be some minor additional development work in the VEPM to provide brief interactive clarifications (ie, via tooltips) and links to the specific reports and resources where this information is hosted.

The outcomes of this opportunity would strongly complement the work in Opportunity 7.

3.2.9 Opportunity 9: Improving the usability of the NZVOC model

The NZVOC model is not currently available for public use, and the software itself is old and not particularly user friendly. Operating the model is complex and needs many engineering and physical parameters to appropriately calibrate the model to generate reliable results, requiring an expert operator to calibrate and run the model.

This opportunity would involve reviewing the software model and its parameters and advising on a pathway to develop a user-friendly interface such that everyday professional users (with a general competency in engineering or economic modelling) could operate the model and generate reliable results. This opportunity may require the development of a new software interface and accompanying user guidance. Additional research to identify and assess simplification opportunities would be beneficial.

A further consideration is whether the tool should be substantially redeveloped or replaced – for example, by utilising the forthcoming HDM-5 model and/or the modules for VOCs rather than developing and maintaining a separate tool for New Zealand.

4 Assessment of opportunities

4.1 First-pass unconstrained prioritisation

Table 4.1 presents a first-pass assessment of the nine identified opportunities and includes an examination of the current state of both the NZVOC model and the VEPM, an initial recommendation to meet the opportunities, and descriptions of the potential wider impacts of implementation and priority for resolution.

Table 4.1 First-pass assessment of the opportunities and priorities for resolution

Opportunity	Current VEPM	Current NZVOC model	Recommendation	Wider impacts	Resolution priority
1. Using consistent vehicle classes and fleet proportions	Mass-based categorisation with 6 individual vehicle categories, including petrol, diesel, hybrid and battery electric vehicles for 28 vehicle fuel or powertrain type combinations.	Axle-based categorisation approach with 22 vehicle classes and two fuel types (petrol and diesel).	Adopt a single fleet and associated database that feeds into both the VEPM and the NZVOC model.	None.	Essential for model alignment and to enable other opportunities.
2. Enabling the NZVOC model to recognise low and zero emission vehicles	Included.	Not included but could be broadly calibrated to model these with appropriate vehicle characteristics included.	Include LZEVs in the NZVOC model and include ability to account for the grid factor used to generate the electricity for the LZEVs. Single vehicle fleet database that feeds both the VEPM and the NZVOC model.	None.	Essential for model alignment and future proofing.
3. Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time	Addresses changes in vehicle fleet composition over time.	Static vehicle fleet.	Adopt the VEPM or nationally agreed database for changing fleet. Use this to develop different horizon year vehicle fleets to be run with the NZVOC model and integrate outputs for MBCM tables.	Review of how the MBCM uses outputs from the NZVOC model would be required.	Essential for model alignment and future proofing.
4. Aligning the NZVOC model's emission outputs with the VEPM's emission outputs	Included.	Not in the NZVOC model, but the underlying HDM-4 model does include.	Align emission outputs in both models.	Update MBCM outputs and guidance for emission modelling.	Essential for model alignment.

Opportunity	Current VEPM	Current NZVOC model	Recommendation	Wider impacts	Resolution priority
5. Aligning speed drive cycles with average speed profiles	Drive cycles and associated average speeds, with no recognition of what causes reduced speeds (eg, congestion or lower speed limit).	Steady-state speed, with congestion factor added.	Consider the viability of aligning the speed modelling approaches to ensure variation in traffic performance resulting from free and interrupted flow is captured.	None	Possible for improved model alignment, if demonstrated to be feasible.
6. Enabling the VEPM to better reflect road condition and configuration effects	Limited to gradient and implied road condition and effects.	Included in model.	Consider the viability of amending the VEPM to more broadly reflect road condition and configuration effects.	Requires detailed road configuration information from sources that may not be easily available.	Possible for improved model alignment, if demonstrated to be feasible.
7. Developing use-case guidance and worked examples	Reasonably well documented.	No use cases provided.	Develop case studies for network- and project-level studies.	Improved understanding and appropriate use.	Desirable.
8. Improving data and calculation transparency, and describing limitations	The VEPM provides lots of detail, but underlying data and assumptions are not always well documented.	Technical documentation on how the model works is nearly 20 years old.	Enable output of results at component levels. Provide improved transparency around input data and assumptions.	Improved confidence in the model operations and facilitates future enhancements.	Desirable.
9. Improving the usability of the NZVOC model	Excel or online tool that is publicly available.	Coded software that is not publicly available.	Consider the value of the likely investment.	None.	Possible.

4.2 Assessment framework

Each opportunity was evaluated against a set of qualitative assessment criteria. There are four high-level criteria accompanied by specific lower-level requirements, as described in Table 4.2.

Table 4.2 Assessment criteria and description

Criterion	Requirements
1. Clarity of scope	• How well the opportunity is defined • Clarity of scope boundaries in implementation design • Level of uncertainty in the expected outcomes
2. Technical feasibility	• From a modelling/programming perspective without significant or unacceptable loss of functionality • Availability of skills/resources to implement the changes
3. Benefit	• Value of improvements • Ability to meet future needs • Benefit of alignment
4. Cost and complexity	• Estimated development time and cost, vis-à-vis complexity • Level of skill/expertise needed to use the models/outputs (from an end-user perspective)

The criteria were qualitatively evaluated using a one to five rating, as outlined in Table 4.3.

Table 4.3 Assessment rating scale and description for the defined criteria

Rating	Description of rating for criteria 1–3	Description of rating for criterion 4
1	Poor/very low	Extremely complex/costly
2	Fair/low	Significantly complex/costly
3	Good/moderate	Moderately complex/costly
4	Very good/high	Somewhat complex/costly
5	Excellent/very high	Very simple/highly cost effective

4.3 Opportunity assessment

This section provides both a summary assessment and detailed assessments of the nine opportunities. The assessment results consist of a description of how the opportunity addressed each criterion, any outstanding questions or unknowns, and an assessment rating. In addition, consideration was also given to whether additional benefit or value may be realised through a combination of opportunities (ie, where the total benefit is greater than the sum of the parts). Initial assessment results were presented to and discussed with the project steering group and other specialised stakeholders. This discussion facilitated consensus on the preferred opportunities and implementation priorities.

4.3.1 Assessment summary

Table 4.4 provides assessment scoring results for the nine opportunities. Each opportunity is described in greater detail in the following section. There are two clear groups of opportunities that scored highly and are recommended for implementation and one group of opportunities that requires further investigation to determine their feasibility and benefit. Only one opportunity (Opportunity 9) is not recommended at this stage.

Opportunities 1 to 4 form a group of ‘development’ opportunities. Whilst individually these opportunities present good value for implementation, they have close linkages and dependencies and could be combined into a collective package of works that would provide additional benefit. For example, Opportunities 1 and 4 become more beneficial when considered in combination with Opportunities 2 to 4 and 1 to 3, respectively.

Opportunities 7 and 8 form a second group of ‘guidance’ opportunities. These opportunities both scored highly and are similarly scoped in that they provide written documentation to support the effective and best use of the models. They do not involve any significant changes to the models and, therefore, have relatively low complexity and risk whilst offering strong benefits. These options would be cost-effective but should be considered as highly valuable additions after considering or endorsing any changes to the models. The guidance material and transparency documentation may become outdated if significant changes are made to the models after their development. Ongoing maintenance of these guidance manuals would be needed as the models change and develop over time.

Opportunities 5 and 6 are desirable but have inherent complexities and require further scoping and investigative research to determine their feasibility and the extent of their benefits. If NZTA decides to proceed with these opportunities, it is recommended to undertake a further investigative study, including model testing, to determine a viable implementation pathway.

Opportunity 9 may be beneficial, but the implementation costs are likely to outweigh the benefit. Unless a strong user-benefit can be established, this opportunity is not recommended.

A phased implementation programme is recommended to prioritise the ‘development’ opportunities first, followed by the ‘guidance’ opportunities. This will minimise any potential duplication of effort in documentation if the models are significantly altered through Opportunities 1 to 4.

Should NZTA wish to proceed with further investigative studies into the viability of Opportunities 5 and 6, this could be done in advance of, or in parallel with, the implementation of the ‘development’ opportunities, but it should be done ahead of implementing the ‘guidance’ opportunities.

Table 4.4 Summary of the assessment scores for the identified opportunities

Opportunity	Criterion 1 (clarity of scope)	Criterion 2 (technical feasibility)	Criterion 3 (benefit)	Criterion 4 (cost/complexity)	Average score
1. Using consistent vehicle classes and fleet proportions	4	3	5	3	**3.75**
2. Enabling the NZVOC model to recognise low and zero emission vehicles	5	3	5	3	**4.00**
3. Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time	3	4	4	3	**3.50**
4. Aligning the NZVOC model's emission outputs with the VEPM's emission outputs	4	4	4	4	**4.00**
5. Aligning speed drive cycles with average speed profiles	2	3	3	2	**2.50**
6. Enabling the VEPM to better reflect road condition and configuration effects	4	2	2	2	**2.50**
7. Developing use-case guidance and worked examples	5	5	3	4	**4.25**
8. Improving data collection and calculation transparency, and describing limitations	4	5	3	4	**4.00**
9. Improving the usability of the NZVOC model	2	3	2	2	**2.25**

4.3.2 Detailed assessment of opportunities

This section provides a detailed assessment of each opportunity against the assessment criteria. The scope, technical feasibility, benefit, and cost and complexity of each opportunity are described in Tables 4.5 to 4.13.

Table 4.5 Assessment of Opportunity 1: Using consistent vehicle classes and fleet proportions

Criterion	Qualitative assessment	Score
1. Scope	Very good/high: • The objective, scope and method are well defined. However, there is some uncertainty around preferences to be resolved. • The VFEM would be a key data source, but it was not assessed in detail.	4
2. Technical feasibility	Good/moderate: • The vehicle classification matching and fleet proportion mapping approaches are well defined, proven and not overly complex. • Potential coordination is required with MoT if both fleets are derived from the VFEM (as the VEPM currently is). • There is a degree of uncertainty around the feasibility of incorporating the single source of fleet data into the NZVOC model and the VEPM.	3
3. Benefit	Excellent/very high: • There would be significant benefits in aligning the vehicle classes and fleet proportions in the NZVOC model and the VEPM: only one update would need to be made that could feed into the two models each time the fleet is updated. • Alignment of the vehicle classes and fleet proportions would provide good representation of the current and future New Zealand fleet across both models (and their applications). • Enables other options to be implemented.	5
4. Cost/ complexity	Moderately costly/complex: • Costs depend on approach taken for alignment. The complexity is significantly less if the NZVOC model adopts the VEPM fleet model.	3
	Average score	**3.75**

Table 4.6 Assessment of Opportunity 2: Enabling the NZVOC model to recognise low and zero emission vehicles

Criterion	Qualitative assessment	Score
1. Scope	Excellent/very high: • New vehicle categories, including hybrid and fully electric vehicles, need to be added to the NZVOC model to recognise the increasing uptake of LZEVs. • Reasonably clear and constrained research and development task.	5
2. Technical feasibility	Good/moderate: • There is an existing process for incorporating LZEVs into HDM-4. • NZTA would need to validate the process for the New Zealand context. • Requires specialised expertise and familiarity with the NZVOC model or HDM-4 to implement. • Implementation is linked with/dependent upon Opportunity 1.	3

Criterion	Qualitative assessment	Score
3. Benefit	Excellent/very high: • This opportunity is crucial, as the current NZVOC fleet profile is increasingly disconnected with the changing New Zealand fleet. Without this enhancement the NZVOC model will become increasingly outdated. • Opportunity 2 is linked to Opportunities 1 to 4. The benefits are strengthened if all opportunities are delivered together.	5
4. Cost/ complexity	Moderately costly/complex: • This is a research and development task requiring very specialised expert skills (ie, a small pool of suitably skilled resources). • Further research is needed to quantify the VOCs (not just emissions) associated with LZEVs, as current research is lacking.	3
	Average score	**4.00**

Table 4.7 Assessment of Opportunity 3: Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time

Criterion	Qualitative assessment	Score
1. Scope	Good/moderate: • The objective is clear; however, the implementation could be adopted through different sub-options, which require further scope development and evaluation.	3
2. Technical feasibility	Very good/high: • Various options with varying technical feasibility ratings: – Options (a) (discrete VOC values each year) and (b) (regression of values vs year) are the most accurate but are undesirable due to the significant changes required to the MBCM analysis framework. – Option (c) (add fleet change parameter) is the most practical to implement and the preferred approach. – Option (d) (model average future fleet mix) is the most straightforward but has the least accuracy.	4
3. Benefit	Very good/high: • This opportunity ensures the NZVOC model's outputs are up-to-date and reliable. • It allows new capability to model VOCs in future timescales. • Most practical implementation options are not as precise as the more complex options.	4
4. Cost/ complexity	Moderately costly/complex: • Sub-options have varying cost/complexity ratings. – Options (a) (discrete VOC values each year) and (b) (regression of values vs year) would require significant changes to the MBCM. – Option (c) (add fleet change parameter) is cost-effective and practical to implement. – Option (d) (model average future fleet mix) is straightforward.	3
	Average score	**3.50**

Table 4.8 Assessment of Opportunity 4: Aligning the NZVOC model's emission outputs with the VEPM's emission outputs

Criterion	Qualitative assessment	Score
1. Scope	Very good/high: • The objective and scope of work are clear and contained. • Consideration of up-stream (well-to-tank) emissions is a potential scope addition.	4
2. Technical feasibility	Very good/high: • Converting fuel consumption to consistent GHG emission outputs is simple and easily understood by a broad audience. • Converting fuel consumption to other harmful emission outputs is more complex, requiring new inputs and conversion calculation methods. The VEPM currently does this, so there is no technical obstacle.	4
3. Benefit	Very good/high: • This opportunity enables consistent emission calculations and outputs. • The benefit value is uncertain as NZVOC does not currently report emission outputs. • Existing users may not require emission outputs. • The development of NZVOC emission outputs could allow for significantly expanded use cases (especially if paired with Opportunities 7 and 8). • The benefit value improves if implemented with Opportunities 1 and 2. If up-stream (well-to-tank) emissions are included, alignment with Opportunity 3 would be additionally beneficial.	4
4. Cost/ complexity	Somewhat costly/complex: • Converting fuel consumption to consistent GHG emission outputs is simple, taking the latest fuel/energy conversation factors. • Converting fuel consumption to other harmful emission outputs is more complex, requiring new inputs and conversion calculation methods.	4
	Average score	**4.00**

Table 4.9 Assessment of Opportunity 5: Aligning speed drive cycles with average speed profiles

Criterion	Qualitative assessment	Score
1. Scope	Fair/low: • The scope would need to be defined in further detail, including an in-depth comparison of both models in contrasting environments, covering congested urban/suburban and free-flowing rural conditions.	2
2. Technical feasibility	Good/moderate: • In principle it is feasible but further assessment should be undertaken during the initial stages of a research project.	3
3. Benefit	Good/moderate: • Aligning speed drive cycles would provide some benefits and clarity. • Consolidating speed modelling approaches may reduce the intended functionality. • Extent of benefits needs further assessment.	3
4. Cost/ complexity	Significantly costly/complex: • Requires technical proficiency with the models employed in both the NZVOC model and the VEPM.	2
	Average score	**2.50**

Table 4.10 Assessment of Opportunity 6: Enabling the VEPM to better reflect road condition and configuration effects

Criterion	Qualitative assessment	Score
1. Scope	Very good/high: • The intent is clear and reputable models are available from international sources for testing impacts.	4
2. Technical feasibility	Fair/low: • This opportunity requires review and adoption of empirical mechanistic modelling approaches in the research phase. • It is unclear how this would interact with existing modelling approaches but comparisons with VEPM and NZVOC could be performed (relies on Opportunity 5).	2
3. Benefit	Fair/low: • Would provide some benefit if a distinction was made between broad road types or traffic situations (similar to EU and ATAP). • Road effects are implicit in real-world emission measurements used in VEPM. • Roughness effects can represent around 2–3% of total vehicle GHG emissions. • Requires the consideration of average road condition parameters which can be highly variable over long links or regions. • No other comparable models account for road surface condition impacts.	2
4. Cost/ complexity	Significantly costly/complex: • This opportunity requires significant effort to understand and calibrate existing factors or develop new factors.	2
	Average score	**2.50**

Table 4.11 Assessment of Opportunity 7: Developing use-case guidance and worked examples

Criterion	Qualitative assessment	Score
1. Scope	Excellent/very high: • The scope is clearly defined. • Some work is needed to identify suitable use cases and examples to cover the range of applications across both models (and potentially other models).	5
2. Technical feasibility	Excellent/very high: • This is mainly a research piece that is practical and achievable but may require other opportunities to be completed first. • Sub-opportunity to develop a toolkit to guide users on correct model selection.	5
3. Benefit	Good/moderate: • This opportunity would provide significant benefits to users to ensure models are being used for their intended applications. • Benefit realisation may be highly dependent on implementation of Opportunity 8.	3
4. Cost/ complexity	Moderately costly/complex: • This opportunity is a relatively simple task. • The complexity depends on the inclusion of other models in the use cases and worked examples.	4
	Average score	**4.25**

Table 4.12 Assessment of Opportunity 8: Improving data collection and calculation transparency, and describing limitations

Criterion	Qualitative assessment	Score
1. Scope	Very good/high: • The scope and method are clearly defined for the VEPM and supported by existing technical information. • The scope for the NZVOC model would include an updated and clear description of the model and its application.	4
2. Technical feasibility	Excellent/very high: • This opportunity is mainly a research and publication piece. • Some minor development work is required to add small features to the VEPM to interactively provide information and warnings to users. • Existing technical documentation can be summarised for improved accessibility.	5
3. Benefit	Good/moderate: • Improved transparency and accessibility enhance user understanding and ability to generate reliable results and communicate them effectively. • Providing transparency of certain key inputs, particularly the VEPM's fleet forecast, has been identified as a priority. • There is some concern around the implementation of this opportunity to ensure effectiveness (ie, read by users).	3
4. Cost/ complexity	Somewhat costly/complex: • A research project is needed to identify suitable use cases and produce short reports. • This opportunity may require some agreement and input from other government departments to publicly share data. • Minor development work is needed to add interactive guidance and links to resources in the VEPM.	4
	Average score	**4.0**

Table 4.13 Assessment of Opportunity 9: Improving the usability of the NZVOC model

Criterion	Qualitative assessment	Score
1. Scope	Fair/low: • A user-friendly NZVOC model could follow a similar design and development pathway to the VEPM. • International developments should be considered, including the planned HDM-5 model. • Significant investigation remains to scope this work and evaluate a minimum viable product against a fully developed product.	2
2. Technical feasibility	Good/moderate: • User-friendly software development is technically feasible and there are many comparable examples, including the VEPM. • Mechanistic attributes of the NZVOC model could be reproduced but would require replication in a user-friendly model. • The existing NZVOC model would require considerable redesign to make it user friendly, considering how its outputs are used. • The development would require comprehensive user guidance and support (including user training) to ensure reliable results can be generated.	3

Criterion	Qualitative assessment	Score
3. Benefit	Fair/low: • Making the NZVOC model user friendly would enhance its application and understanding of VOCs and vehicle emissions at the project level. • Extent of benefits is uncertain compared with using existing NZVOC outputs. • Workshop stakeholders expressed little appetite for an online NZVOC tool. Note: Only a few actual users attended the workshop, and most of them used the NZVOC model's outputs rather than the model itself. • Given the inherent complexity, regular updating of the NZVOC outputs in the MBCM may provide a similar level of benefit.	2
4. Cost/ complexity	Significantly costly/complex: • A user-friendly tool requires a significant investment to develop, support and maintain. • Alternatives such as the planned HDM-5 model could replace the need for a separate tool.	2
	Average score	**2.25**

5 Conclusions

This project investigated how the NZVOC model and the VEPM could be linked and/or integrated through a review of the models, engagement with key stakeholders and an options analysis.

A review of the NZVOC model and the VEPM was undertaken to understand each model's purpose, scope, operation, inputs, outputs, applications and users. From the review, a series of opportunities to improve the models were identified. For both models, there are potential opportunities to align similar aspects, such as aligning the current and forecasted vehicle fleet, and understanding the differences between the underlying speed models and the effect of road configuration. The NZVOC model was identified as not well maintained and requires updating, particularly around the fleet profile as it is currently limited to diesel and petrol vehicles. The model is also not user friendly, unlike the VEPM, which has been developed into an online tool. There are potential opportunities to improve various aspects of the VEPM, such as improved modelling of low-speed effects (without an increase in stop–start conditions) and incorporating the effect of varying road configurations. For both, it is crucial that users of either model (or outputs) understand the various limitations and select the most appropriate for their intended task.

After the review, a stakeholder engagement workshop was held to obtain feedback from model owners and users around the models' current uses and value, limitations, and necessary or desirable future features. A set of five initial integration options were presented to the stakeholders: (i) retain and improve both models, (ii) develop a hybrid model, (iii) incorporate one model into the other, (iv) retain both and determine pre- and post-analysis steps, and (v) do nothing.

The option to do nothing was rejected, as was the option to develop a hybrid model as the stakeholders found it both unfeasible and undesirable due to the different purposes of the two models. Of the remaining options, a broad consensus was reached that the preferred approach should focus on retaining and improving both models, with priority given to improving consistency and alignment across the models where possible. This would include alignment of key components such as the current and forecasted vehicle fleet, traffic speed profiles to better recognise congestion effects, and outputs (eg, CO_2-e rather than simply CO_2). There was also agreement that there should be improved documentation and live guidance at key input stages to assist users in appropriate model use.

Following the review and stakeholder engagement process, a suite of nine potential opportunities were identified and qualitatively assessed in terms of their clarity of scope, technical feasibility, benefit, and cost and complexity. From the assessment, there were two broad groups of opportunities that scored highly and could be produced together: development (Opportunities 1–4) and guidance (Opportunities 7–8). Developing multiple opportunities through a single, coordinated package of works would provide additional benefits and reduce the overall resources required to complete them individually. Based on this assessment, the final recommendations are outlined in Table 5.1. It is recommended to proceed with developing a works package for Opportunities 1–4 (scheduled to be completed first) and Opportunities 7 and 8 (upon completion of 1–4). A specification of these packages of work has been submitted to NZTA and is presented in Appendix A.

Opportunities 5 and 6 require a further research project to determine the feasibility and desired approach to be taken. This could be completed independently and ahead of the works package for Opportunities 1–4; if the outputs of the research show it to be feasible and beneficial, it could be built into this package of works.

For the final opportunity on improving the usability of the NZVOC model (Opportunity 9), further consideration should be given into its value before proceeding with a specification of works.

Table 5.1 Final recommendations for the identified opportunities

Opportunity	Priority	Recommendation
1. Using consistent vehicle classes and fleet proportions 2. Enabling the NZVOC model to recognise low and zero emission vehicles 3. Enabling the NZVOC model (or its outputs) to reflect changing vehicle fleets over time 4. Aligning the NZVOC model's emission outputs with the VEPM's emission outputs	Highest	Proceed with developing a package of works incorporating these development opportunities.
7. Developing use-case guidance and worked examples 8. Improving data collection and calculation transparency and describing limitations	High	Proceed with developing a package of works for these guidance opportunities, subject to final scoping of Opportunities 1–4.
5. Aligning speed drive cycles with average speed profiles 6. Enabling the VEPM to better reflect road condition and configuration effects	Medium	Further scoping and research required to determine the feasibility and value. Further scoping and research are independent of other opportunities, but if feasible and viable, implementation should be phased considering changes made with Opportunities 1–4 and guidance materials developed with Opportunities 7 and 8.
9. Improving the usability of the NZVOC model	Low	Consider the relative benefits of this opportunity through further stakeholder consultation.

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Appendix A Stage 2 specifications

Table A.1 outlines the scope of works that could be used for a potential future implementation project.

Table A.1 Scope of works specifications

Title	Improving accessibility and use of the NZVOC model and the VEPM
Background and context	The New Zealand Vehicle Operating Cost (NZVOC) model was first introduced as an input into transport cost–benefit analysis in 1989. It uses manufacturers' vehicle data on engine capacity and type as the fleet model to estimate vehicle running costs, fuel costs, vehicle depreciation, maintenance and vehicle emissions. Its costs per kilometre are adjusted according to traffic and road conditions with speed change models. The NZVOC model is static and has a number of limitations, namely that it currently only considers diesel and petrol vehicles, and the inputs are updated infrequently, with the last update occurring in 2015. The Vehicle Emissions Prediction Model (VEPM) was first released in 2008 and uses a comprehensive fleet model based on the New Zealand fleet profile from MoT's Vehicle Fleet Emissions Model (VFEM), and vehicle emissions standards cross-checked with actual emissions data and is updated more frequently than the NZVOC model (2011, 2012, 2013, 2017, 2019, 2020, 2021 and 2022). A review of both the NZVOC model and the VEPM undertaken in 2023–24 (NZTA research report 730) outlined a series of recommendations to better integrate the inputs, outputs and updating of VOC models and emissions models. These recommendations form the basis for a new suite of works to be undertaken, which are described in this specification.
Knowledge gap	N/A
Purpose	The purpose of this work is to develop and improve the NZVOC model and the VEPM, along with their supporting documentation and guidance, and bring them into closer alignment.
Research objectives	The work required in this project can be broadly categorised into 'development' and 'guidance' work packages. **Part 1: Development** The first works package is focused on research and development to improve the NZVOC model (or its outputs). Activities for this part include: • deciding on preferred vehicle classes and fleet proportions to be used in the NZVOC model and aligning them with the VEPM if possible • enabling the NZVOC model to recognise low and zero emission vehicles • enabling the NZVOC model to reflect changing vehicle fleets over time • aligning the NZVOC model's emission outputs with the VEPM's emission outputs. **Part 2: Guidance** Once the first package of works has been appropriately scoped, the second works package will produce a variety of resources to support the effective and best use of the models by: • developing use-case guidance and worked examples • improving the data collection and calculation transparency, and describing limitations.

<table>
<tr><th>Title</th><th>Improving accessibility and use of the NZVOC model and the VEPM</th></tr>
<tr><td>Scope</td><td>The scope of works for both development and guidance are described below, with further details provided in the NZTA research report 730.

Part 1: Development
Different vehicle fleet categorisations are used by the NZVOC model (axle-based) and the VEPM (mass-based). This work should undertake a comprehensive review of the different approaches (including the VFEM) and decide on a pathway to alignment. As part of this work, the NZVOC model requires updating to incorporate new and emerging vehicle types, such as hybrid and plug-in electric vehicles, and ensure these are periodically updated to reflect changes over time due to the changing fleet profile. Particular attention should be given to enabling the NZVOC model to provide a consistent forecast of the future fleet, as is currently done in the VEPM, and that its outputs are periodically updated to reflect the changing vehicle fleet.

Finally, the NZVOC model emission outputs should be updated and aligned with those in the VEPM. Consideration should also be given to the upstream emissions for both models and may be included as part of the guidance documentation.

Part 2: Guidance
Development of documentation and information is needed to ensure users select and use the appropriate model and do not misuse or misunderstand the outputs. It is important that consideration be given to producing guidance that is effective in reaching as many model users as possible.

Work is needed to identify and produce a series of use cases that demonstrate appropriate model (or output) selection and usage (including limitations), and this would likely require knowledge of other relevant models used across New Zealand. The usage component relates to improving the transparency around the models' calculation methods and inputs, building on the existing technical documentation available and filling gaps. Key information gaps identified include the input assumptions and data around the forecasting of the future fleet and grid emission factors, and the effect of inputs such as ambient temperature or cold starts in the VEPM.

It is envisaged that a series of easily accessible reports (or a slide deck) are produced, and a toolkit (in the form of a flowchart) to provide a user-friendly overview with links to further resources (ie, case studies).

For both models, it is recommended that a series of clear and simple guidance notes or warnings be developed for the VEPM and outputs of the NZVOC model where they are presented, accompanied by links to further resources and information.</td></tr>
<tr><td>End use of research</td><td>The work will directly improve the two models and their uses across New Zealand. The NZVOC model is used to generate tables in the Monetised Benefits and Costs Manual (MBCM), while the VEPM is used for air quality and emission assessments to support transport planning and project appraisal.

Guidance documentation and resources will improve users' understanding of the models and facilitate appropriate model selection and use. It will also provide transparency around key assumptions and inputs to better enable future updates and build user confidence. Guidance documents will be easy to read and will be made publicly available via the NZTA website and integrated into the models or outputs where relevant.</td></tr>
<tr><td>Deliverables</td><td>Deliverables from the project will be:
• a clear framework for alignment of the NZVOC model and VEPM fleets
• updates to the NZVOC model fleet and emission outputs (according to the objectives), including a plan to periodically update the model and its outputs
• improved guidance and documentation through online reports and integrations into the VEPM online tool and the published MBCM tables.</td></tr>
</table>

Appendix B Comparison of fleet categorisation

This appendix presents a comparison of the fleet categorisation approaches for the NZVOC model (Figure B.1), the VEPM (Figure B.2) and the VFEM (Figure B.3).

Figure B.1 Vehicle fleet categorisation used in the NZVOC model

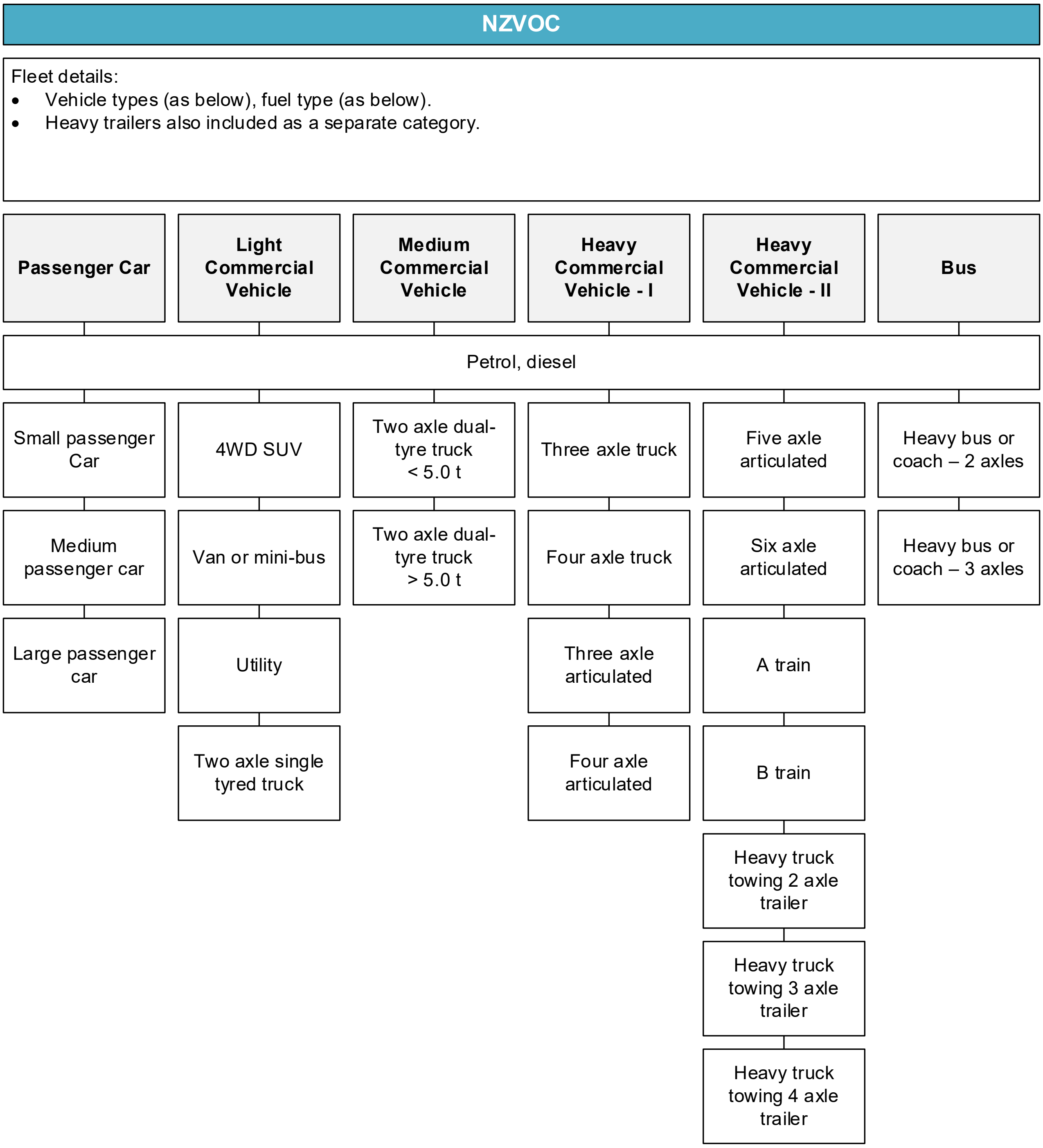


Figure B.2 Vehicle fleet categorisation used in the VEPM

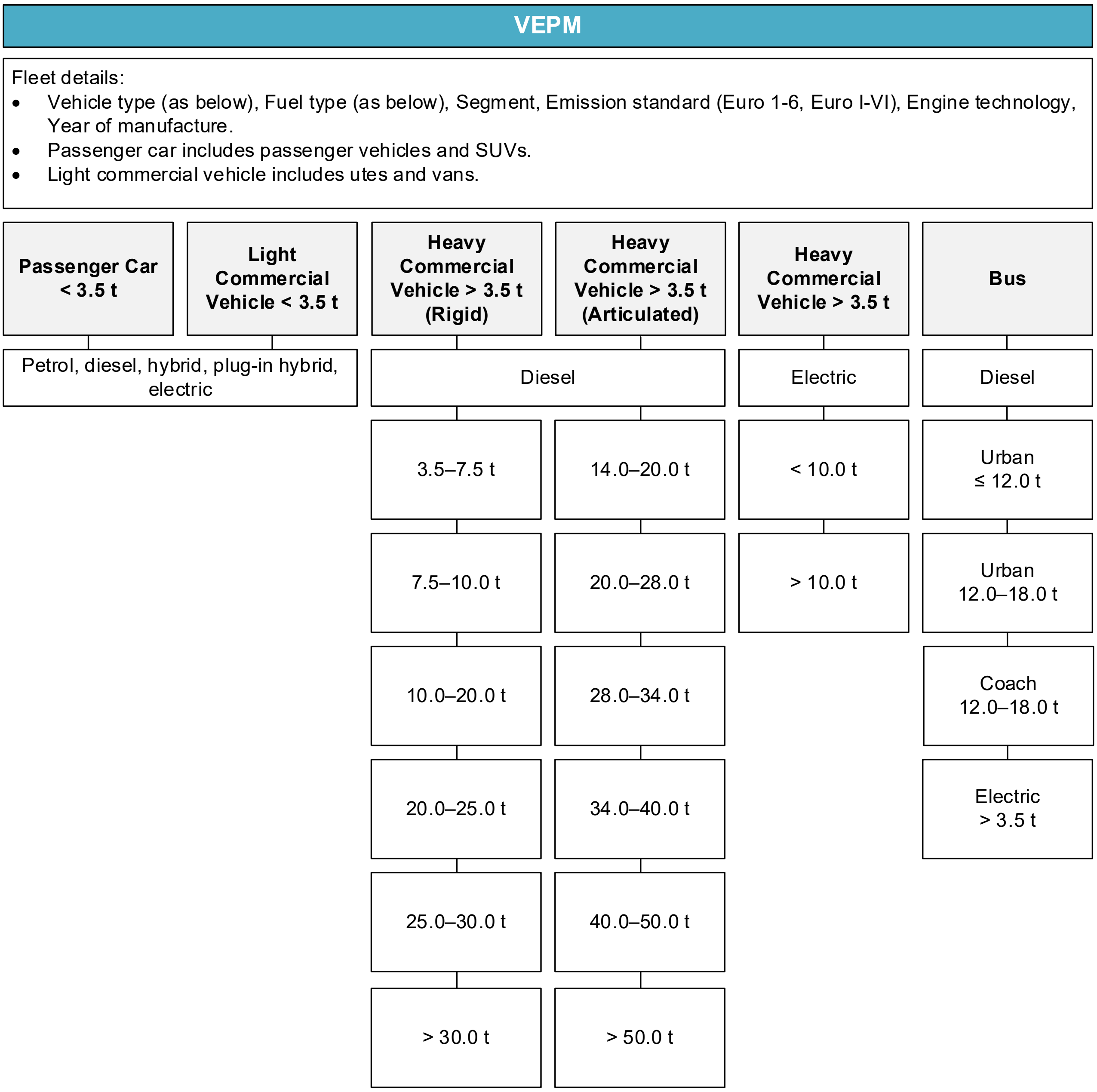
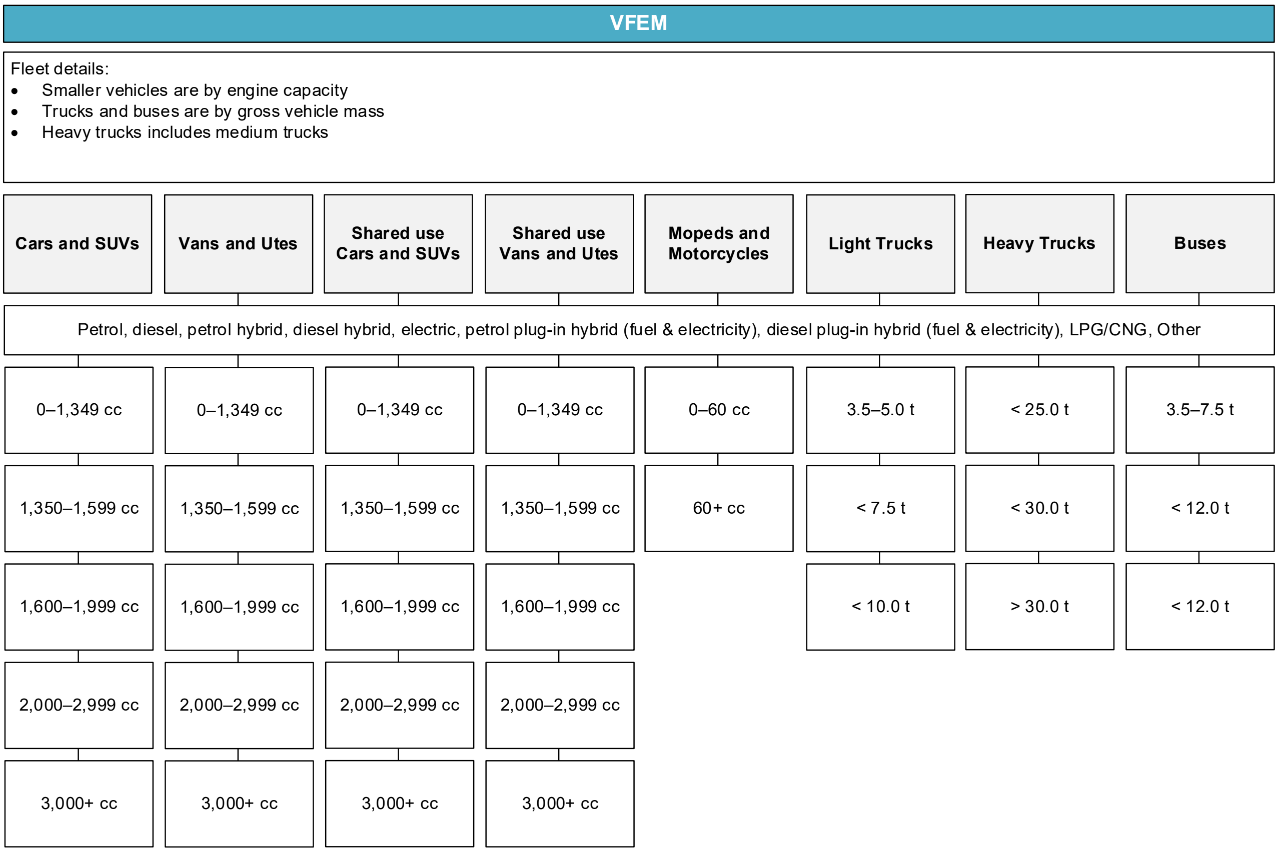


Figure B.3 Vehicle fleet categorisation used in the VFEM

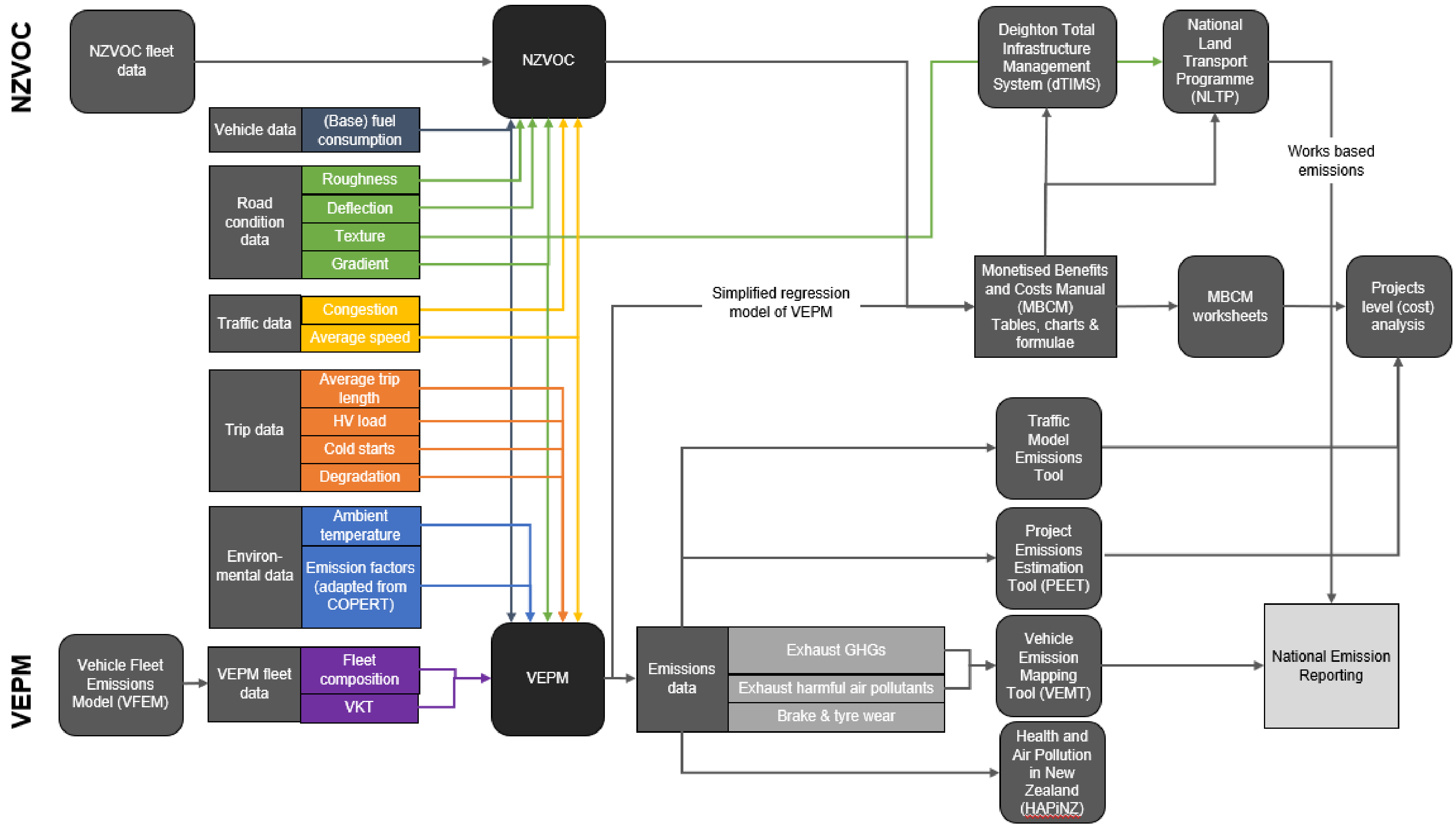


Note: CNG = compressed natural gas. LPG = liquefied petroleum gas. SUVs = sport utility vehicles.

Appendix C Interactions between the NZVOC model, the VEPM, and other New Zealand transport models

Figure C.1 presents an overview of the key inputs and outputs of, and interactions between, the NZVOC model, the VEPM, and other transport models used in New Zealand.

Figure C.1 Key inputs and outputs of, and interactions between, the NZVOC model, the VEPM, and other New Zealand transport models



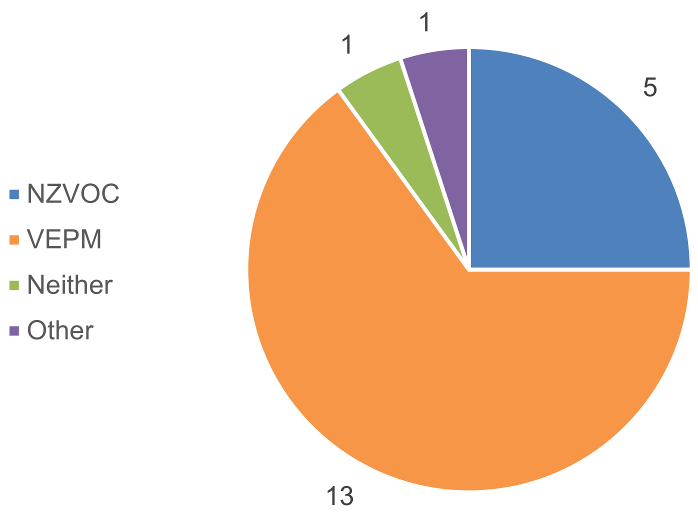
Appendix D Stakeholder engagement workshop

After the review and comparison of the models and initial integration options were developed, a stakeholder workshop was held on 25 September 2023 to gather user feedback and perspectives. The workshop aimed to engage with owners and users of the NZVOC model and the VEPM to understand the models' current uses, value and shortcomings and to identify desired capabilities and features that could be incorporated into the integration scope.

The workshop centred around a presentation of the project's purpose, initial findings from the model review and comparison, and an outline of the engagement approach. The engagement involved a short live survey (nine questions, < 5 minutes via Microsoft Forms), facilitated discussions on the models' strengths, limitations, inputs and outputs, calculation methods, etc, and an open discussion on future needs and desires for the models, and the users' preferences on potential model integration options.

A snapshot of the workshop participants' familiarity and experience with the models was collected, with 16 responses received via the online survey. First, the users were asked to indicate which model(s), outputs, etc they have used (Figure D.1). The majority of the workshop participants used the VEPM, with four respondents using both the NZVOC and the VEPM. One respondent was an interested stakeholder but had not used either model or its outputs, and another respondent also indicated familiarity with 'other' similar tools and outputs.

Figure D.1 Survey responses for which model(s), outputs, etc users have used (multiple selections possible)



Of these users, there was a range of years of experience with these models. Those who used the NZVOC model or output tables had at least 10 years' experience, often over 20 years. Those who used the VEPM were generally split between less than and greater than 5 years' experience with the model and outputs. A small number of users had over 10 years' experience working with the model. Next, the users were asked to describe what data sources they use (multiple answers possible). More than half of the respondents used the default input factors, and some also used their own or custom input factors, often provided by other transport or traffic models.

D.1 Stakeholder perspectives

D.1.1 Usage and outputs

Users were asked about how they used the outputs of the NZVOC and the VEPM and which key aspects of the models and outputs they valued most.

D.1.1.1 NZVOC model

The NZVOC users used the regression models and the output tables in the MBCM. Users valued having the option and flexibility to use either the regression functions or the output table results in undertaking cost–benefit analyses.

Some users valued the NZVOC model's first-principles, or mechanistic, approach of fuel-use estimation, which is responsive to road gradient and condition (amongst other things). However, others questioned this pursuit for precision at the expense of (or perceived expense of) overall accuracy.

D.1.1.2 VEPM

The VEPM users used the model for a range of purposes, including policy analyses and project-level assessments. Some used the VEPM's fleet models for vehicle forecasting and transport modelling. Others talked about the potential to use the VEPM as a basis for road user charging. This raised a discussion point around the models' intended uses and what they can possibly be used for and the risks of misrepresenting the results.

Users of the VEPM highlighted that the use of the VFEM and its detailed fleet forecasts (to 2050) as a key model input was a particular strength. The fleet model, based on the MoT fleet forecasts, include petrol, diesel, hybrid and electric vehicles, recognising the shift in vehicle propulsion technologies that has started and will continue to occur in future years.

Users emphasised that the ability to control the future fleet composition was critical in projecting future emissions. Other highly valued aspects were the VEPM's robustness of emission values (both GHG and air quality emissions), its detailed outputs, including results over time (eg, choice of input year) and its application for assessing and analysing different policies and scenarios.

The recent release of the online VEPM was valued as a positive step towards improved user experience.

D.1.2 Limitations

D.1.2.1 NZVOC model

Workshop participants observed a major limitation of the NZVOC model was its outdated fleet model (in terms of fuel consumption and lack of appreciation for LZEVs). Whilst updates and amendments to include LZEVs are possible, this would be a significant task.

The NZVOC model's emission outputs are derived from fuel estimates from HDM-4 and its iterations. The emission outputs were included as an add-on to the original model as a particular need arose; however, emissions modelling is not the core intent of the model. Workshop participants noted that the NZVOC model's outputs, such as CO_2 and HC, have not kept up with current carbon reporting standards (ie, CO_2-e and its constituent GHGs) and policy directions (ie, net zero GHG emissions). The NZVOC model's outputs would benefit from an update and alignment with the VEPM's outputs.

One participant, passing on comments from a colleague, noted that there may have been errors in the EEM's output tables in the past (note: the EEM was the predecessor to the MBCM). The participant was not sufficiently familiar with the issue to pinpoint the aspects or timings, so the comment was not necessarily valid. However, the comment did highlight that there may be some broader negative perceptions around the accuracy of the outputs, which may be compounded because the model is seen as a 'black box', whereby its inputs and calculation methods are not fully transparent.

D.1.2.2 VEPM

The VEPM is different from the NZVOC model and has different use cases. While the VEPM has some important strengths in vehicle emission prediction, it does not link emissions with economic costs (ie, operational or externality costs), which would make it more valuable for cost–benefit analyses.

Users most familiar with the VEPM highlighted that the model's limitations were well known and had been documented in a recently published review by Metcalfe and Boulter (2022). They note that average-speed models are comparatively easy to use, and there is a reasonably close correspondence between the required model inputs and the data generally available to users. However, they do have limitations. Average-speed models are considered valid over a network of roads within an urban area larger than approximately a half square kilometre.

In the workshop, some users expressed concerns about the accuracy of VEPM outputs based on the belief that the VEPM uses average/steady-state speed profiles. The VEPM owners clarified that the model does use average/steady-state speed profiles but that these were calibrated to reflect emissions in typical conditions (eg, typical driving behaviour and typical levels of congestion for the defined average speed). Metcalfe and Boulter (2022, p. 7) provide the following illustrative example:

> *…at speeds less than 30 km/h, VEPM emission factors will include the effects of a significant amount of stop – start driving. Conversely, at higher average speeds VEPM emission factors will be based on steadier speeds (for example, to achieve an average trip speed of 100 km/h it is necessary to be travelling at a high speed for most of the trip).*

It appears that users have limited, or differing, understandings of what the speed parameter represents, which could lead to inappropriate uses or misinterpretation of results.

One stakeholder from Australia commented on the temporal resolution of the speed data and suggested a more granular timescale (ie, to 1-hour or even 15-minute resolution) was needed for reliable results. The Metcalfe and Boulter (2022, p. 37) review identified this limitation and recommended that:

> *24-hour or 1-hour resolution speed data is appropriate for estimation of GHG emissions with VEPM. The most appropriate option will depend on the nature and scale of the project and the availability of good quality data. In general, it is recommended that 1-hour temporal resolution data should be used if good quality 1-hour data is available.*

Metcalfe recommended against higher resolution speed data (ie, less than 1 hour), indicating a potential point of difference with approaches being considered in Australia.

The VEPM's vehicle fleet model includes LZEVs (ie, hybrid electric and fully electric vehicles) in the mix. Some users noted that within the VEPM, assumptions around LZEV adoption rates were not clear, particularly into 2040 and beyond. LZEVs produce significantly reduced or zero 'tailpipe' emissions; however, electric vehicles – even fully battery electric vehicles – are still responsible for 'upstream' emissions related to electricity generation. Workshop stakeholders were unsure how electric vehicle emissions were calculated and how this was related to the progressive decarbonisation of the New Zealand electricity grid. Future guidance within the tool, not just in technical manuals, would be beneficial to help users understand the modelling assumptions used.

D.1.2.3 Other notes

Another user noted that both models were road-transport focused and not well suited for mode shift analyses, resulting in the use of other models for different modes that could create a misalignment in emissions modelling approaches.

Stakeholders in the workshop agreed that there are often trade-offs between comprehensiveness, precision and complexity, and a balance should be sought.

D.1.3 Future needs and opportunities

The next discussion centred around the future needs and opportunities for the models. One future need that was raised was the future carbon reporting requirements, which will include embodied carbon emissions of transport vehicles in the production, maintenance and end-of-life disposal. Without a major research study into embodied emissions of every vehicle type, and operational scenarios, interim estimates may be required. For example, with some calibration, it may be possible to use VOCs (eg, new vehicle purchase, tyre wear, maintenance) produced by the NZVOC model as a possible proxy for embodied emissions. Alternatively, emission factors could be applied to VEPM estimates based on typical vehicle use cases by vehicle types. Both possible methods would be ‘broad brush stroke’ estimates with significant levels of uncertainty.

Meanwhile, embodied carbon estimates of transport infrastructure are likely to be addressed by other supporting models and tools, such as the Project Emission Estimation Tool. However, it will be important for NZTA’s related emission models and tools to be aligned and integrated where possible.

Another future need identified was assessing the emission impacts of mode shift. While neither the VEPM nor the NZVOC model is designed for transport modes beyond road transport, consistency with emission estimation inputs (ie, emission factors) and methods used in other modal estimations would help ensure comparable results and allow for mode shift analyses.

The following potential improvement opportunities and features would be useful in both the NZVOC model and the VEPM.

- Consistency of input data across both tools was highlighted as a key feature and something that should be aimed for (ie, set inputs once and get the outputs for economics and emissions). The opportunity to improve the consistency of inputs was emphasised with respect to the fleet models and speed profiles.
- Consistency is needed in outputs and their calculations to ensure comparability of outputs between models and reliability of results.
- One participant highlighted that the OECD is moving towards using value ranges (for example, in risk-adjusted distributions of costs, but not for benefits yet). There is an opportunity to provide a distribution of benefits, which could be done via a Monte Carlo simulation to provide ranges and quantify the uncertainty of values.
- It was also identified that there would be value in enabling a link to the new Asset Management Data Standard model, as this will be a central tool used in the future.

Improvement opportunities specifically for the NZVOC model are as follows.

- Better representation of the current and forecasted fleet is needed to account for LZEVs (from the VEPM). This could be done by an updated dataset or adjustment factors in the MBCM.
- Update the outputs to generate emission results in line with VEPM and government policy targets. This means ensuring that emission outputs, at a minimum, include measures of CO_2-e (not just CO_2). Better alignment of other emission outputs, such as harmful emissions (NO_x, and particulate matter) would also be beneficial.

- Provide the ability to:
  - access the detailed parameters in the outputs (fuel, parts, emissions by components and intermediate outputs, such as fuel use estimates)
  - export data in more useful formats – for example, Excel tables as done in the VEPM.
- Link costs to broader outputs such as health and social costs.
- Depending on whether harmful emissions such as NO_x are to be built into the NZVOC model, cold start on/off switches may not be needed.

Improvement opportunities specifically for VEPM are as follows.

- Provide greater information on input values and modelling assumptions, notably:
  - New Zealand grid emission intensity factors for LZEV GHG emissions (ie, non-tailpipe)[13]
  - uptake rates of LZEVs.[14]
- Whilst significant progress has been made to improve the VEPM's user interface with the release of the online version (7.0), VEPM developers and owners acknowledge that further work is needed, such as providing in-tool tips, and enhanced data transparency, including modelling assumptions.
- Make it easier to generate outputs across multiple years by vehicle type.
- Provide the ability to:
  - incorporate real-world measured data and fuel consumption
  - integrate with other tools more seamlessly
  - consider vehicle condition of the fleet (ie, vehicle age and maintenance).

D.1.4 Suggested integration options

The workshop participants were asked to give their thoughts about integrating the models and what it could potentially look like, with five potential integration options presented to stimulate the discussion:

1. Retain and improve both models.
2. Develop a hybrid model.
3. Incorporate one model into the other.
4. Retain both and determine pre- and post-analysis steps.
5. Do nothing.

The participants questioned whether it was necessary to integrate the models into a single hybrid model as opposed to developing materials or the tools to improve users' understanding of how to produce the desired outputs. This was noted as something that has improved with the online version of the VEPM, but further work is needed. In addition, caution was needed to ensure that the individual models' functionality was not lost through integration, particularly for the VEPM.

Users were generally in agreement that at the very least, there should be some effort to improve the consistency and align inputs and outputs between the models. Some examples of improving consistency include (i) fleet composition and forecasts, (ii) traffic speed profiles, (iii) fuel consumption estimates, and (iv) clarity and consistency in outputs (eg, use of CO_2 vs CO_2-e).

[13] Workshop participants questioned whether these are aligned with Ministry for the Environment data, noting that no information is stated in the user guide, and whether this could be a custom input.

[14] There is value in enabling the use of different uptake scenarios for LZEVs or adding high/low uptake rates. This could be achieved with changes to fleet forecast or allowing manual fleet inputs.

To align or integrate the models, there would first need to be this consistency of inputs. As part of a roadmap to align inputs and integrate the models, there could be some interim time-series adjustment factors for the NZVOC model to calibrate the outputs to the VEPM.

Another suggestion was to create a separate hybrid model that provides a single forecast of fleet assumptions that feeds into both models. This would support the desire to have consistency of inputs for both models, address the NZVOC model's outdated fleet data and provide transparency to the fleet forecasting (and grid emissions) in the VEPM.

D.2 Summary of stakeholder workshop

The stakeholder workshop revealed that users of the NZVOC model and the VEPM:

- have no strong desire to integrate the NZVOC model and the VEPM into a single hybrid model[15]
- agree that model inputs should be aligned and consistent as far as possible (eg, utilising the VEPM's fleet model in the NZVOC model, aligning CO_2 and CO_2-e outputs)
- agree that better documentation and live information provided at key input stages would help inform users about model parameters and inputs
- noted that there could be value in developing a separate model that generates the desired inputs for use in both the NZVOC model and the VEPM.

Future features and opportunities are centred around improved consistency, alignment and guidance. Priority should be given to seeking opportunities for improved consistency and alignment of:

- the vehicle fleet profile and/or projections, including LZEVs
- traffic speed profiles, with recognition of congestion effects
- outputs, such as using CO_2-e rather than simply CO_2.

Stakeholder feedback from the workshop indicated that of the five potential integration options presented, options 2 (Develop a hybrid model) and 5 (Do nothing) could be excluded from further consideration. Option 1 (Retain and improve both models) appears to have the greatest level of support. However, this option may be complemented by aspects of option 3 (Incorporate one model into the other) and/or amendments to option 4 (Retain both and determine pre- or post-analysis steps).

[15] A big hindrance to any integration is the inconsistency of inputs between the current versions of models.

Appendix E Comparison of vehicle operating cost models

E.1 The Highway Development and Management (HDM) models

For over three decades, the suite of HDM models have been considered worldwide as the most comprehensive analytical tools, with a strong knowledge base that draws on theoretical and performance studies undertaken since the early 1970s. They have been most popular in developing and emerging countries, but they are also used in the developed economies of Australia, Canada and New Zealand (being the basis for the NZVOC model) and other countries in Europe and South and Central America. They are described here because of their adoption in New Zealand and Australia. More recent developments are also considered in the following text.

Initial studies were conducted in developing countries in the interest of providing an economic framework for investment, with this leading to the first operational road transport investment model – the Transport Research Laboratory's Road Transport Investment Model (Robinson, 1975) – and the initial HDM tools (HDM-I to HDM-III). The HDM-4 initiative of the 1990s drew heavily on studies in Australasia with significant calibration and adaptation studies in Canada and in Southeast Asia. The extended mechanistic-empirical suite of models (Bennett & Greenwood, 2001) that support the modelling framework and the primary sources of the models (Odoki & Kerali, 2006) are most relevant to this study. Table E.1 outlines the computation procedure and framework and sequence of VOC modelling in the HDM suite.

Table E.1 Computational procedure and sequence of VOC modelling in the HDM suite (adapted from Odoki & Kerali, 2006)

Step	Component or description
1. Calculate vehicle speeds	• Free speed by vehicle type • Congested speed by vehicle type and flow level by traffic period/road configuration • Average operating speed by vehicle type • Average traffic speed
2. Compute quantities of VOC resources	• Fuel • Lubricating oil • Spare parts • Maintenance labour hours • Capital costs
3. Cost vehicle resources	By applying unit costs to predicted quantities
4. Summarise and store results	For use in subsequent analysis and reporting

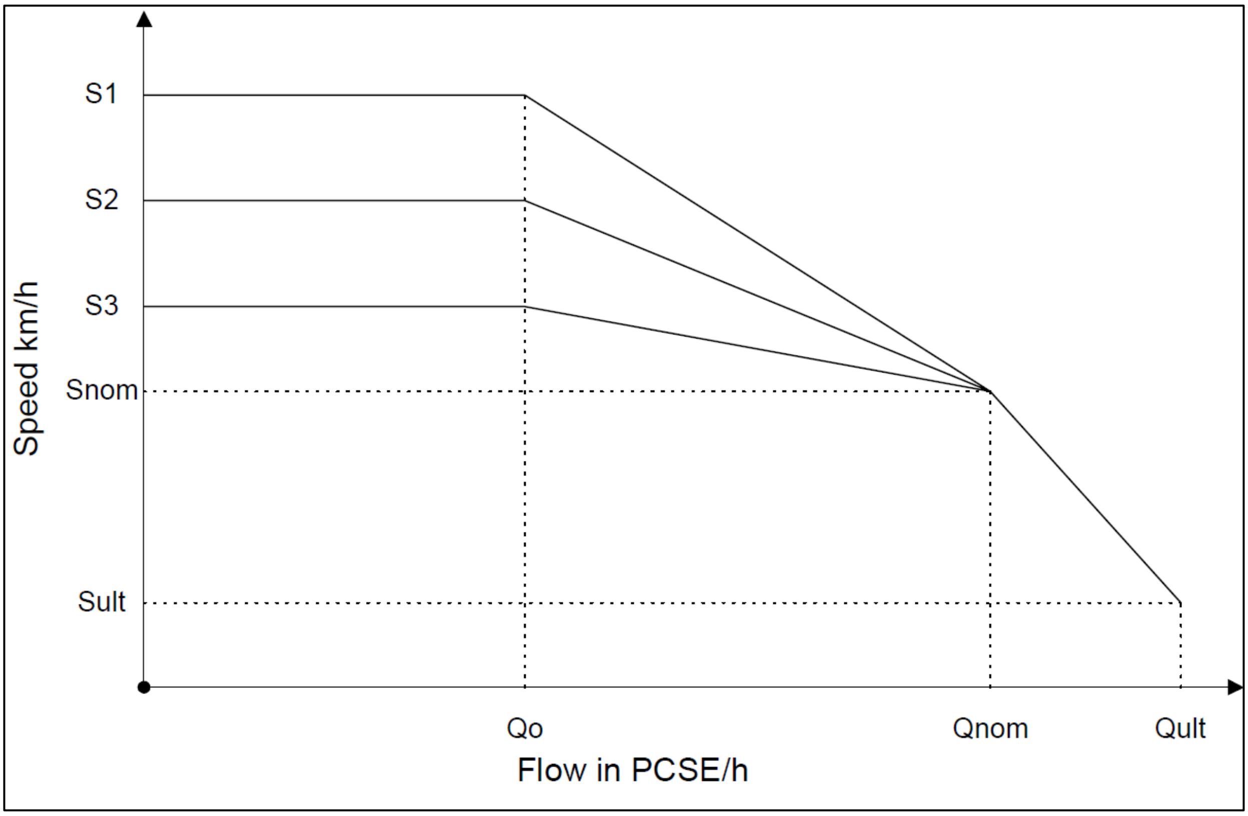
Note: HDM-4 also calculates travel times and passenger and freight travel hours as part of its integrated model.

E.1.1 Modelling of speeds and traffic interaction effects

The speeds in the HDM family of models are affected by several parameters, including vehicle characteristics, road layout, road geometry, road surface conditions, and motorised traffic volume and composition. In addition, there are two key inputs required to calculate the speed within the VOC component of HDM-4: free speeds and journey speeds. The free speeds are the speeds vehicles travel when unaffected by traffic (ie, traffic flow is essentially uninterrupted). The journey speeds are the speeds over a section of road for a given time period (peak, off peak, or hourly period) and include the effects of other traffic (including congestion) and, in an analysis, would account for intersection effects.

Speed flow curves are employed to estimate speed as traffic increases above low traffic flow levels, as it transitions from uninterrupted to interrupted (congested and stop–start). The default speed curve used in HDM-4 was developed by Hoban et al. (1994) and has a three-stage structure as shown in Figure E.1. The figure demonstrates how HDM-4 handles the reduction in vehicle speed as the level of traffic and congestion increases.

Figure E.1 Default three-stage speed flow curve structure used in HDM-4 (adapted from Hoban et al. 1994)



Notes:

- PCSE = passenger car space equivalent units
- Qo = free flow capacity
- Qnom = nominal capacity
- Qult = ultimate capacity
- S1, S2 and S3 = three examples of free speeds for different road types
- Snom = the speed at Qnom
- Sult = the jam (or queuing) speed at Qult

As observed in Figure E.1, speed starts off at the free speed when there is very little traffic on the road. For traffic up to Qo, average speed is taken to be constant at free speed. As traffic increases beyond Qo, speed gradually falls. As traffic increases beyond Qnom, speed declines at a greater rate. When flow reaches Qult, speed reaches its lowest level, Sult. It is assumed to be constant for further traffic increases.

Increased vehicle interaction increases congestion and consequent acceleration noise (AN) which leads to increased fuel consumption. AN is defined as the standard deviation of measured accelerations at discrete, short time intervals.

The basis for the underlying model was established from the Australian Road Research Board (ARRB) ARFCOM fuel consumption model (Biggs, 1988). Bennett and Greenwood (2001) subsequently extended and developed the approach for practical application through the HDM-4 research programme. The updated approach extracted the two components of average speed and AN from speed-time profiles and used them in fuel consumption estimates.

Table E.2 illustrates the impacts of speed-flow curve parameter values, which differ by road type, or model road state (MRS) as employed in Australia, with examples for these and corresponding VCR and AN values presented.

Table E.2 Typical traffic capacity parameters and effects employed in HDM models for a speed zone of 100 km/h (adapted from ATAP Steering Committee Secretariat, 2024, p. 16)

Model road state	Qo	Qnom	Qult	S0 Free Speed	Snom = 0.85 * S0	Sult = jam	VCR at Qo	VCR at Qnom	VCR at Qult	AN at Qo	AN at Qnom	AN at Qult
MRS10, Undivided single carriageway	188	1,250	1,563	100	85	25	0.03	0.65	0.75	0.03	0.65	0.75
MRS20, Divided dual carriageway	750	2,000	2,500	100	85	25	0.05	0.61	0.75	0.05	0.61	0.75

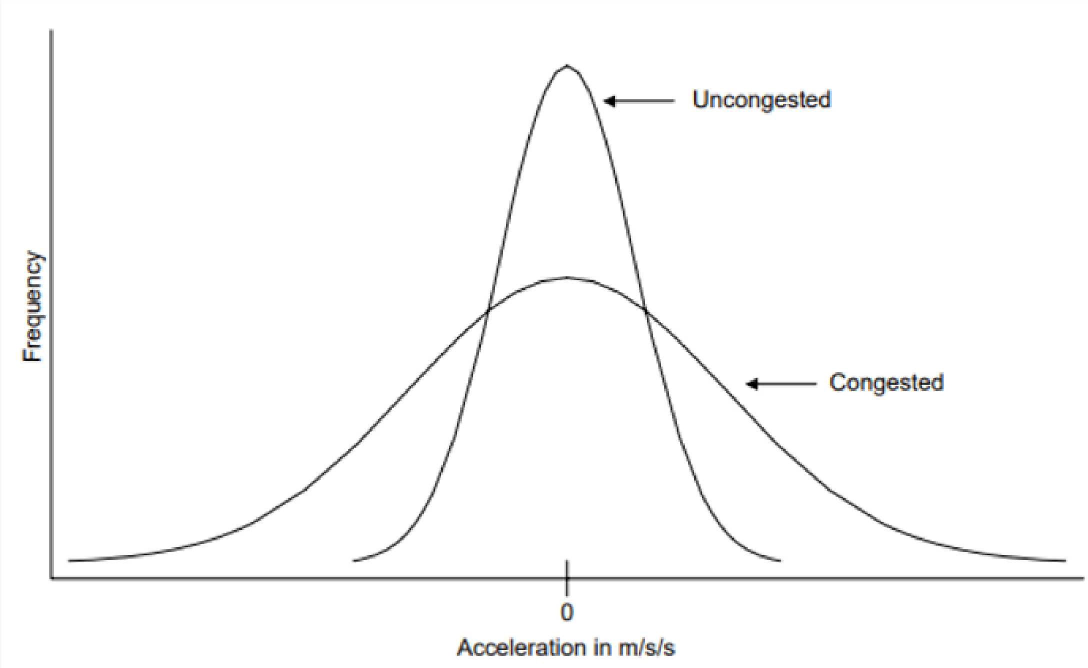
Notes:

- AN = acceleration noise
- MRS = model road state
- Qo = free flow capacity
- Qnom = nominal capacity
- Qult = ultimate capacity
- S0 = free speed
- S1, S2 and S3 = three examples of free speeds for different road types
- Snom = the speed at Qnom
- Sult = the jam (or queuing) speed at Qult
- VCR = volume-to-capacity ratio

Based on the above, the average speed is similar in HDM-4 and in the VEPM, provided time periods and the associated AN are recognised. For use in planning estimates (ie, in strategic models), the speed represents the sum of the mid-block and intersection delay for the specific section length and for each time period.

Consequently, average speed modelling is applied in the NZVOC model but with the AN accounted for based on the sum of the natural noise (road and driver factors) and traffic noise associated with traffic flow conditions. As illustrated in Table E.2 above, the parameters Q0 and Qult vary by road type, including number and width of lanes, whether divided or not, and whether access is limited or not. Idealised distributions of AN for uncongested and congested conditions are shown in Figure E.2, with the congested conditions displaying a higher magnitude of acceleration reflecting congested and stop–start conditions.

Figure E.2 Congested versus uncongested acceleration levels (reprinted from ATAP Steering Committee Secretariat, 2024, p. 19)

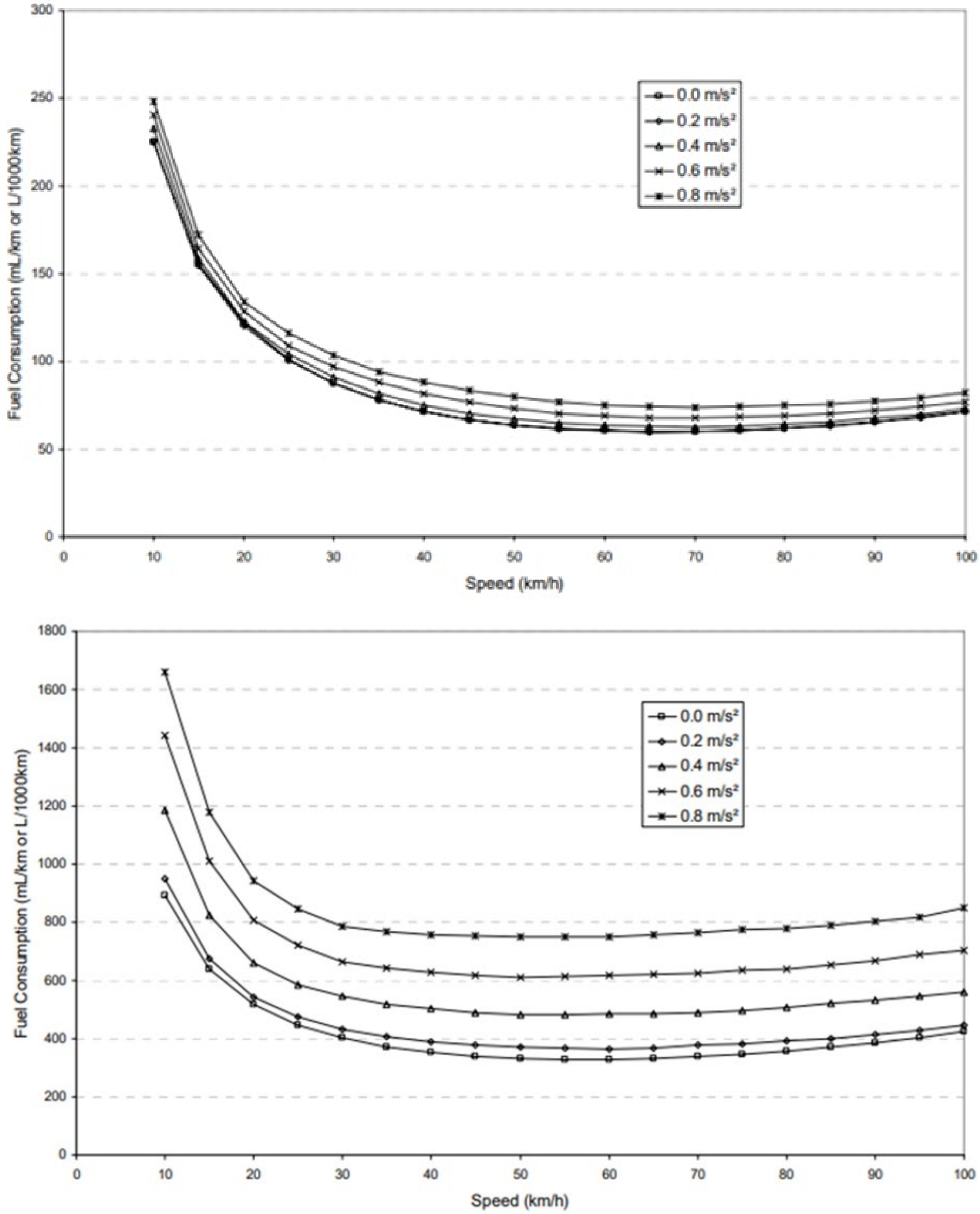


In determining fuel consumption, the following steps are applied:

1. Fuel consumption is first estimated based on free flow with instantaneous fuel consumption observed as being proportional to the total power required to overcome tractive forces, providing for engine accessories and internal engine drag (Biggs, 1988). Fuel consumption is defined as the maximum of the minimum fuel use (at idle) and the total power adjusted by an efficiency factor whilst the vehicle is travelling with a calibration factor applied to reflect local conditions (where field data are available).
2. The second step estimates additional fuel consumption from the AN. These calculations are based on the Bennett and Greenwood (2001) research which measured the actual AN and associated fuel consumption as speed and AN varied, with AN and fuel consumption increasing as congestion increased.

Figure E.3 provides example relationships between fuel consumption, operating speed and AN for a passenger car and an articulated truck (for low curvature and gradient) with the AN component shown to have a larger effect on the heavy vehicle as might be expected. The data used in the relationships was derived from simulations of vehicles driving along a road at different levels of congestion to inform an estimate of the incremental increase in fuel consumption due to congestion.

Figure E.3 Effect of speed and acceleration noise on fuel consumption for a typical passenger car (top), and articulated truck (bottom) (reprinted from ATAP Steering Committee Secretariat, 2024, p. 19)



These examples illustrate the importance of both the spatial and temporal resolution on the vehicle speed and fuel consumption. The spatial resolution is impacted by the road type, condition, geometry, and roadside environment. The temporal resolution is primarily affected by the traffic operating conditions and road type, which differ for each specific vehicle.

E.2 Australian Transport Assessment and Planning models

E.2.1 Background

Different methods to estimate fuel consumption and VOCs have been developed through various Austroads studies over the past five decades. In developing the latest published models (ATAP Steering Committee Secretariat, 2016), the ATAP Steering Committee outlined three requirements that the models must achieve:

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

   Two modelling approaches were considered: (i) mechanistic-empirical models, and (ii) regression equation models. Either model may be employed to produce either a suite of tables or a set of derived equations based on specific operating conditions and vehicle-related assumptions.

2. The models must be applied across networks subject to uninterrupted and interrupted or stop–start conditions.

   Austroads (2005) and (2008) provided models for ‘at grade’ and freeway models for all-day average speeds, including representative traffic conditions, with model parameters produced from traffic modelling system (TRAMS) outputs. Whilst this approach formed the basis of VOC models presented in recent updates, its application is questionable given it did not account for time periods where traffic performance and consequent fuel consumption and emission will differ greatly. Further, combining travel time and VOCs also leads to problems where the individual components cannot be isolated as required by the scope of this project.

3. The models must be applied to general CBA studies at the local and network levels and for major capital projects, including employing the results of traditional four- to five-stage transport models.

   In the ATAP models (ATAP Steering Committee Secretariat, 2016), users had to choose between either uninterrupted or interrupted models (both based on HDM-4) with the interrupted model presenting a shift upwards in resource consumption at any speed. They did not, therefore, allow a complete basis for modelling vehicle performance accounting for vehicle interactions at any speed and corresponding speed acceleration values. A challenge for the ATAP community, as is the case with NZVOC model users, has been understanding the models, starting from the most basic aspects of traffic flow and the resulting impacts on fuel consumption and other VOC consumables.

In addition, the models need to be able to be applied and updated in a clear and consistent manner.

E.2.2 Proposed revised models

The proposed revisions to the ATAP models adapt the HDM-4 mechanistic-empirical model and employ an average travel speed approach for each traffic period and homogenous section. This is consistent with Austroads (2004) and Transport for NSW (2013) for the purposes of general CBA and provides a preferred model, while noting that other models exist and could justifiably be used.

The revision process has thoroughly investigated the underlying effects, computations, interactions and presentations of HDM-4 to allow understanding and, therefore, confidence in their use. These developments comprehensively utilise the capability of HDM-4 and build a set of equations and outputs to illustrate the individual and combined effects of (i) uninterrupted flow, and (ii) interactions between vehicles (requiring acceleration, deceleration and braking).

The combination of these two effects models the actual interrupted flow observed in practice on a road. The interaction effect is captured by the relationship with congestion on the road – the greater the congestion, the greater the level of vehicle interaction up to the point where jam speed applies. The interaction effect is represented by a VCR term in the regression equation, with the remainder representing the uninterrupted flow effect with the model forms for fuel consumption and non-capital costs.

The end result is that HDM-4 produces a ‘family of curves’ across VCR levels, with these based on statistically significant equations. Outputs can be produced in various forms, including as tables of values, similar to those of the NZVOC model, which are structured to account for different input values and represent the various possible conditions on the network.

Appendix F Comparison of international emission prediction models

A summary of the various emission prediction models in use around the world is presented in Table F.1.

Table F.1 Summary of relevant international emission prediction models

Model (region, owner)	Geographic scale coverage	Time scale coverage	Time period	Fleet model/ vehicle classification	Vehicle type by fuel	Speed model	Pavement effects	Output type
Motor Vehicle Emission Simulator (MOVES) (USA, US EPA) https://www.epa.gov/moves	National, state, county, project	Hourly, daily, monthly, yearly	1999 to 2060	Comprehensive of highway vehicles in 13 categories (eg, motorcycles, passenger cars, passenger trucks, light commercial trucks). Forecasting includes impact of interventions (eg, federal emissions standards).	Petrol, diesel, compressed natural gas (CNG), ethanol, and electricity. Further characterisation by fuel subtype and fuel formulation possible.	Modal approach based on vehicle-specific power	Road gradient at smallest scale	Total and emission rates
Californian emission factors model (EMFAC) (California, CARB) https://ww2.arb.ca.gov/our-work/programs/msei/on-road-emfac	Area categories (country, metro, state-wide, etc)	Static, up to the user to define manually (can only change temperature and humidity)	2000 to 2050	Comprehensive for Californian fleet: cars, trucks (7 categories by weight), buses (3 categories: school, urban, other), motorhomes, motorcycles. Forecasting to 2050.	Petrol, diesel, natural gas, electric, and hydrogen	Average speed model (5 mph bin widths)	None	Emission rates (g/vkm)
Handbook Emission Factors for Road Transport (HBEFA) (Europe, INFRAS) https://www.hbefa.net/	Austria, France, Germany, Norway, Sweden, Switzerland	None, indirectly captured by traffic situation	Activity data available at least for 1994 to 2050 for countries specified	Utilises real-world measurements from various classes: passenger cars, light duty vehicles, heavy goods vehicles, urban buses, coaches, motorcycles.	Petrol, diesel, CNG, liquefied petroleum gas (LPG), kerosine etc (depending on vehicle type), some electric	Traffic situation (categorised by driving conditions; eg, free-flow motorway, stop and go)	None, implicitly captured by real-world measurement	Emission rates (g/vkm)
Transport Emission Model (TREMOD) (Germany, IFEU) https://www.ifeu.de/en/methods-tools/models/tremod/	Germany	As HBEFA	1960 to 2018, prediction till 2050	As HBEFA (passenger vehicles, motorised two-wheelers, light duty vehicles, heavy goods vehicles, buses)	Petrol, diesel, CNG, LPG, hybrid, plug-in hybrid electric vehicle (PHEV), electric	As HBEFA	As HBEFA	Emission rates (g/vkm)

Model (region, owner)	Geographic scale coverage	Time scale coverage	Time period	Fleet model/ vehicle classification	Vehicle type by fuel	Speed model	Pavement effects	Output type
Passenger Car and Heavy Duty Emission Model (PHEM) (Europe, TU Graz) https://www.itna.tugraz.at/en/research/areas/em/simulation/phem.html	Austria, Germany, Switzerland and entire EU vehicle fleet	Only covers actual input drive cycle	Same as HBEFA	Specified for individual vehicle (uses HBEFA average values to characterise individual vehicles)	Petrol, diesel, CNG, electric	Engine load based using actual drive cycles at 1 Hz resolution	Only road gradient	Emissions rates (g/s or g/mode)
ATAP PV5 (Australia, NTRO/ARRB) https://www.atap.gov.au/parameter-values/index	Australia-wide metro, urban, and rural values (adapted from EU28 factors)	N/A	Single year (June 2020)	Motorcycles, passenger cars, LCVs, urban buses, coaches, heavy vehicles Each with subcategories by weight/size	Petrol, diesel, CNG, LPG, electric	N/A	None	Economic impact values for various emission types in \$/tkm, \$/pkm and \$/vkt
PΔP (Australia, TER) https://www.transport-e-research.com/software-pdp	Australia and Hong Kong	1 second and then aggregation	Forecast to 2060	73 vehicle classes including passenger cars, SUVs, LCVs, rigid and articulated trucks and buses	Petrol, diesel	Engine load based using actual drive cycles at 1 Hz resolution	None (can be simulated with modified road load parameters)	Emissions rates (g/s or g/vkm)
COPERT (Europe, EMISIA) https://www.emisia.com/utilities/copert/	Europe	Typically 1 hour to 1 year	None	European fleet classification (760 vehicles), emissions standards Euro 1 to 6d, and Euro I to VI D	LPG, CNG/ liquefied natural gas (LNG), fuel cell electric vehicle (FCEV), hybrid, PHEV, electric, and biofuels	Average speed	None	Emission rates (g/vkm)
COPERT Australia (Australia, EMISIA) https://www.emisia.com/utilities/copert-australia/	Australia	Typically 1 hour to 1 year	Forecast to 2060	Detailed Australia-specific fleet characterisation with 15,200 vehicle classes (from Australian Fleet Model)	Petrol, diesel, E10, LPG	Average speed	None	Emission rates (g/vkm)

Model (region, owner)	Geographic scale coverage	Time scale coverage	Time period	Fleet model/ vehicle classification	Vehicle type by fuel	Speed model	Pavement effects	Output type
Net Zero Vehicle Emission Model (n0vem) (Australia, TER) https://www.transport-e-research.com/software-novem	Australia	Typically 1 hour to 1 year	Forecast to 2060	Detailed Australia-specific fleet characterisation with 15,200 vehicle classes (from Australian Fleet Model)	Petrol, diesel, E10, LPG, electricity, hydrogen	Average speed	None	Emission rates (g/vkm)
SIBYL baseline[a] (Europe, EMISIA) https://copert.emisia.com/sibyl-baseline/	Europe (EU27, Albania, Iceland, Lichtenstein, Montenegro, North Macedonia, Norway, Serbia, Switzerland, Turkey, UK)	As COPERT	1990 to 2060	As COPERT, some additional vehicles categories with alternative powertrains	Petrol, diesel, electric, hybrid, PHEV, FCEV, LPG, CNG/LNG	As COPERT	As COPERT	As COPERT
SIDRA Trip[b] (Australia, SIDRA) https://www.sidrasolutions.com/software/sidra-trip	Australia (international)	Simulation (second-by-second possible)	None	Custom fleet (use input)	Petrol, diesel	User-defined based on GPS data	None (effects of infrastructure measures can be modelled)	Total emissions (kg for simulation run)

[a] SYBIL baseline: This model is based on COPERT and uses emissions and energy information calculated with COPERT. It covers all major pollutants, heavy metals, particulate matter and GHGs as well energy consumption compatible with the COPERT vehicle classification. Datasets to go beyond the COPERT vehicle classification by introducing alternative powertrains.

[b] SIDRA Trip: This model is a vehicle trip assessment model using GPS data and for quick scenario analysis – for example, to evaluate alternative routes or the impact of infrastructure measures. Outputs can be used to calibrate network microsimulation models such as heavy vehicle acceleration–deceleration profiles or macroscopic models such as excess fuel consumption and emission factors.